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The Use of Waste-derived Materials in Road Construction

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The cover image shows the construction of the Echline Recycled Road c. 2000.

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EXECUTIVE SUMMARY

Introduction

The Scottish road network is diverse, ranging from motorways, trunk roads and 'A'-roads, through city and town streets, to remote rural roads, including single-track roads with passing places. Roads are key facilitators for socio-economic activity and growth, linking industry and markets, supporting tourism and providing communities with access to employment, health, educational, social and leisure opportunities and activities.

Road authorities must ensure an adequate level of service, including that the road is safe and fit for purpose. In order to achieve this aim published standards and specifications are used to define, or specify, the required quality, performance, compatibility and compliance of materials and products used in road construction, operation and maintenance.

The use of recycled and waste-derived materials in road construction has been a key topic of discussion within the roads construction and maintenance industry for several decades. In recent years the use of waste-derived glass, rubber and plastics in bitumen or asphalt has been promoted, sometimes with claims of dramatically increased performance and/or as an effective means of managing such wastes that would otherwise be destined for landfill or used as fuel.

A great deal of focus is currently placed, nationally and internationally, on the creation of new construction products incorporating wastes or waste-derived materials that can substitute for virgin raw materials or enhance product performance. Manufacturers, some with little or no construction and/or materials background, are driving this 'innovation' often without robust processes being followed to ensure the technical efficacy and performance of products, thorough assessment of their whole life environmental impacts and costs, or the development of robust standards and specifications.

For those who procure road surfacing materials, the volume and credibility of information is a cause for concern. With constrained budgets and political pressure to increase the green credentials of infrastructure construction and maintenance, a single authoritative reference, pulling together the outcomes, results and conclusions of recent studies, is required to inform decision-making so that costly and environmentally damaging mistakes can be averted.

This report focuses primarily, but not exclusively, on road surfacing materials containing waste-derived glass, rubber and plastic, referencing information from the past five years or so, from within Scotland and the rest of the UK, as well as internationally where relevant.

Following an introduction, Section 2 addresses key issues related to sustainability and waste including how innovation can be achieved sustainably, the principles of waste management, and the use of waste-derived materials in asphalt. Section 3 reviews available information on the use of the three materials considered here – waste-derived glass, rubber and plastic – as additives to bitumen and asphalt. This includes health and safety considerations, life cycle assessment and material costs. Section 4 considers emissions to the environment and the recyclability of these materials once they reach their end of life.

While the core of this report considers surfacing materials , opportunities for the use of waste-derived rubber and plastic, in particular, in other parts of road infrastructure are described in Section 5. In order to encourage the use of innovative materials and processes in road surfacing a preliminary protocol is proposed (Section 6) for their introduction in a controlled fashion so that adequate technical performance and environmental scrutiny is achieved.

In Section 7 the current state regarding the potential use of waste-derived glass, rubber and plastic is discussed in road surfacings. Issues related to the release of nano and microplastics to the environment and the potential future use of waste-derived glass, rubber and plastic are also discussed. Conclusions are drawn and recommendations made in Section 8.

Key Conclusions

The use of glass in road surfacings, or other parts of the road asset, is unlikely to progress further in the context of the strong lead being provided by the UK glass industry towards a system of closed-loop recycling that effectively keeps waste-derived glass within that industry.

The use of waste-derived rubber may increase if the claimed performance benefits of rubberised road surfacings can be proven in the UK, particularly as currently there is a lack of capacity for sustainably treating end of life tyres. However, concerns remain regarding waste-derived material quality control (including the potential for contaminants and the suitability of tyres for processing into asphalt additive materials) and the potential for the release of microplastics during pavement service and at end of life.

The case for waste-derived plastics to improve the performance of bitumen or asphalt is far from proven. There are also concerns around the quality control of mixed waste-derived plastics and this needs to be addressed to prevent batch and ultimately pavement performance variation.

Uses of plastic in roads in Scotland to date largely constitute demonstration projects rather than formal trials to assess technical performance. The demonstrations all appear to use the dry process, in which plastics, are added to the asphalt mix as a binder extender or enhancer. No evidence is available to suggest that a formal design process has been undertaken to optimise the performance of the final mix.

In addition, and as for rubber, there are significant concerns around the release of microplastics to the environment. The Scottish Government has signalled its intention to tackle the microplastic problem and has gone so far as to introduce legislation to prevent the sale of goods such as cosmetics and personal hygiene products which contain plastic microbeads (The Environmental Protection (Microbeads) (Scotland) Regulations 2018). Scotland is also a signatory to the Ellen MacArthur Foundation’s New Plastics Economy global commitment to end plastic pollution and it is questionable therefore whether the use of waste-derived plastics in road surfaces is aligned with government policy.

Modular plastic roads made with waste-derived materials have also been trialled, most notably in the Netherlands. These also raise concerns regarding the release of microplastics to the environment, particularly as a result of wear during their service life.

The issue of microplastics is one that is of great concern to society and in isolation would point to a decision to cease the use of waste-derived plastics in road surfacings. In combination with the lack of clear performance benefits from the addition of waste-derived plastics to bitumen or asphalt a decision to not use such materials seems straightforward.

The use of waste-derived rubber or plastics in pavement foundations, earthworks and unbound and bound lower pavement layers is also not recommended due to the same concerns surrounding the release of microplastics at the end of the service life. It is perhaps noteworthy that Highways England ceased the use of fibre reinforced soil in late-2018. For footway, cycleways and car parks, where increased performance is not required, the use of such materials can only be described as a means of linear landfill. This is not intended to include fully-accredited geosynthetic materials that form discrete layers within the structure rather than exist within the mix in a random distribution.

Where there does seem to be some potential to allow for the use of waste-derived plastic in parts of the road asset is where these are non-composite/single-material, quality controlled products. These might include drainage elements, kerbs, street furniture, signs, barriers, traffic cones and environmental barriers. Indeed, the authors are aware of moves within the industry to promote, trial and use such products. Notwithstanding this, there is a need to ensure the control of the potential release of microplastics, particularly if the products may need to be cut during construction. In addition, as with all such products particular attention would need to be paid to ensuring in-service durability, including resistance to the deleterious effects of UV-light on material stability, and end of life applications. Closed-loop recycling of such products is to be encouraged.

A protocol for the introduction of innovative materials and processes, including those containing waste-derived materials, to the road network has been proposed. This is tentative and intended as a starting point for further development prior to implementation. The protocol considers technical, financial, environmental, and health and safety aspects of innovative materials and processes. The focus is on pavement surfacing materials but it could be extended to encompass other asset features albeit that other disciplines, earthworks for example, would require a rather different approach to the detailed evaluation process.

This work will help Scottish roads authorities to continue to assist and contribute to the delivery of government priorities, including those related to climate change.

Recommendations

Recommendation 1: Based on the evidence currently available there is, as yet, no viable technical, environmental or economic case for the use (addition or replacement) of waste-derived glass or plastic in asphalt.

Recommendation 2: While the research is further advanced for waste-derived rubber (addition or replacement) than for plastic, the available technical and environmental case for its use in asphalt does not yet fully-support its use. Further research and trials are needed in this area including through the use of the protocol described in Section 6.

Recommendation 3: It is recommended that waste-derived (or virgin) rubber or plastic not be used in unbound pavements layers, including the foundation layer(s), or in earthworks other than as fully-accredited geosynthetic materials.

Recommendation 4: It is recommended that in the future the use of waste-derived materials in road surfacing and other structural and foundation layers should be subject to the scrutiny of the Transport Scotland Pavement Forum (TSPF) under the protocol described in Recommendation 6.

Recommendation 5: Opportunities should be sought to use waste-derived materials and products in other non-composite/single material-type, quality controlled products. These might include drainage elements, kerbs, street furniture, signs, barriers, traffic cones and environmental barriers. Such use should be subject to a full evaluation of the technical, financial, environmental, and health and safety efficacy and impacts of the product.

Recommendation 6: A protocol to steer the appropriate and constructive use of waste-derived materials and products in pavements should be introduced.

Recommendation 7: That the protocol in Recommendation 6 be extended to include innovative (non-waste) materials, products and processes that are proposed for use in pavements and innovative (waste-derived and non-waste) materials, products and processes in other elements of the road asset.

1 INTRODUCTION

The Scottish road network is diverse, ranging from motorways, trunk roads and ‘A’-roads, through city and town streets, to remote rural roads, including single-track roads with passing places. Roads are key facilitators for socio-economic activity and growth, linking industry and markets, supporting tourism and providing communities with access to employment, health, educational, social and leisure opportunities and activities.

Road authorities must ensure an adequate level of service, including that the road is safe and fit for purpose. In order to achieve this aim published standards and specifications are used to define, or specify, the required quality, performance, compatibility and compliance of materials and products used in road construction, operation and maintenance.

The use of recycled and waste-derived materials in road construction has been a key topic of discussion within the roads construction and maintenance industry for several decades. In recent years the use of waste-derived glass, rubber and plastics in bitumen or asphalt has been promoted, sometimes with claims of dramatically increased performance and/or as an effective means of managing such wastes that would otherwise be destined for landfill or used as fuel.

A great deal of focus is currently placed, nationally and internationally, on the creation of new construction products incorporating wastes or waste-derived materials that can substitute for virgin raw materials or enhance product performance. Manufacturers, some with little or no construction and/or materials background, are driving this ‘innovation’ often without robust processes being followed to ensure the technical efficacy and performance of products, thorough assessment of their whole life environmental impacts and costs, or the development of robust standards and specifications.

For those who procure road surfacing materials, the volume and credibility of information is a cause for concern. With constrained budgets and political pressure to increase the green credentials of infrastructure construction and maintenance, a single authoritative reference, pulling together the outcomes, results and conclusions of recent studies, is required to inform decision-making so that costly and environmentally damaging mistakes can be averted.

This report focuses primarily, but not exclusively, on road surfacing materials containing waste-derived glass, rubber and plastic, referencing information from the past five years or so, from within Scotland and the rest of the UK, as well as internationally where relevant.

This project seeks to:

- Identify road surfacing materials and products that are currently being used by, and/or promoted to, Scottish road authorities.
- Evaluate the use of such materials and products against robust suitability criteria.
- Identify future opportunities to meet such criteria and assist in the meeting of targets for reduced greenhouse gas emissions.

Specific aims of this project are as follows:

- The provision of consistent advice to Scottish road authorities on the relevance and applicability of currently available new and innovative road surfacing materials incorporating waste or waste-derived materials.
- Challenge claims of long-term benefits, including those related to technical performance, cost-effectiveness, environmental credentials and end-of-life issues.
- Identify emerging areas where further research and development could be beneficial to Scottish road authorities.
- Identify materials that could enhance the road sector contribution to national environmental objects and priorities.
- Point towards the development of a process for assessment and control of the introduction of new and/or innovative surfacing materials containing waste-derived materials.

Section 2 addresses key issues related to sustainability and waste including how innovation can be achieved sustainably, the principles of waste management, and the use of waste-derived materials in asphalt. Section 3 reviews available information on the use of the three materials considered here – waste-derived glass, rubber and plastics – as additives to bitumen and asphalt. This includes health and safety considerations, life cycle assessment and material costs. Section 4 considers emissions to the environment and the recyclability of these materials once they reach their end of life.

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The work presented in this report has been informed by consultation with the Scottish road authorities (the local authorities, via the SCOTS Roads Working Group, and Transport Scotland), the Scottish Environment Protection Agency (SEPA), trade bodies, professional associations, manufacturers and other UK road authorities. A survey of Scottish local authorities was undertaken as reported in Appendices A and B, while the details of information requests made to manufacturers of waste-derived materials are contained in Appendix C. Details of UK road trials using waste-derived materials are given in Appendix D.

2 SUSTAINABILITY AND WASTE

2.1 Background

The road construction and maintenance industry in Scotland, and more widely, has an enviable track record in reusing and recycling waste materials. As an industry that operates within challenging budget constraints there is a continued incentive to source cost-effective materials, rationalise labour and plant usage, and compress the construction programme where it is both safe and technically possible.

In addition to purely economic factors, the drive in recent years has been toward reduced carbon use, in support of greenhouse gas emission targets, and increased asset and network resilience, in order to improve network availability and improve journey time reliability. The economic, environmental and resilience drivers in road transport are linked by both simple relations, as is the case for fuel costs and carbon dioxide (CO_2) emissions, and by more complex relations as is the case for travel costs and resilience.

Such activities were given a greater focus by the declaration of a 'climate emergency' by Scotland's First Minister in April 2019; Scottish Government and local authorities have been tasked with improving their environmental credentials within their procurement policies and activities. Whilst data from the European Asphalt Pavement Association (EAPA) estimates that up to 80%[1] of asphalt planings generated from road maintenance are recycled, there is an increasing awareness of the potential to substitute virgin materials with less traditional materials such as waste-derived glass, rubber and plastics in asphalt mixes. This is not a new concept, but despite extensive research activity, particularly related to the use of rubber, in the last 20 years or more there has been limited interest in the widespread use of products containing such materials until recently.

There has also been an increasing global awareness of the need to 'remanufacture' products (closed-loop recycling) to reduce reliance on the use of virgin raw materials. Currently technology gaps, processed capacity, increased CO_2 and costs associated with remanufacturing still mean that alternative uses for some waste-derived products are a preferable option.

The route to market acceptance for waste-derived materials in the construction industry is complex. There is no single source of reference information for both technical and environmental acceptance of asphalts incorporating wastes or waste-derived materials other than conventional asphalt planings and often the requirements of these two different forms of acceptance can seem contradictory.

Whilst innovation is welcomed within the road construction industry, this needs to be controlled. In the case of waste-derived materials it is clear that the use of such materials is beneficial to the broad objectives of sustainable construction if it is at least as technically effective as the conventional alternative, it does not increase and preferably decreases CO_2 (or other greenhouse gas) emissions, and it does not create other unacceptable environmental emissions including noise and air and water borne pollutants.

[1] https://www.asphaltadvantages.com/en/advantages/sustainability/81 (interrogated September 2020)

In order to meet sustainability and by association, climate change criteria, the following must be considered as a minimum by those procuring road surfacing materials:

- Adequate technical product performance (i.e. suitability for use recognising that different asphalt mixes are required depending on road usage and local conditions).
- Acceptable longevity to ensure resilience of the network.
- Ensure end of life issues are adequately dealt with and that future reuse or recyclability is assured (Figure 1).
- Environmental impacts (also considering carbon usage and CO_2 emissions during product manufacture), including whether the use of a particular waste-derived material as a substitute for a virgin component in asphalt is the best option or simply a disposal route.
- Value for money.
- The health and safety of workers and the general public during processing, application and use are assured. In the case of road surfacing materials this includes emissions such as noise, air and water borne pollutants, and the skid resistance throughout the life of the product.

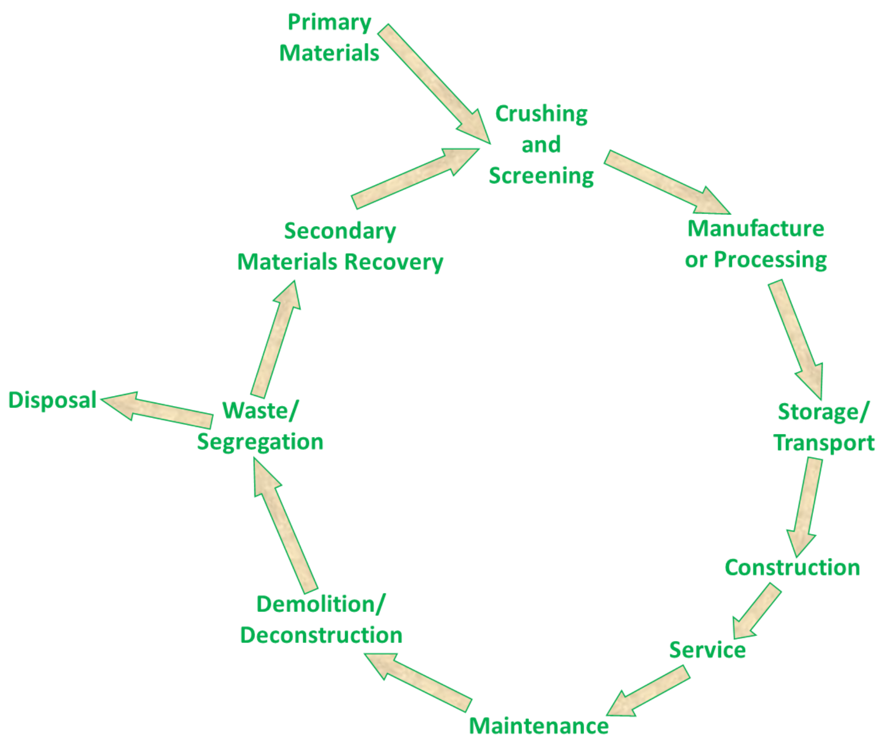

Figure 1. Cycle of aggregate use and potential reuse from extraction to final disposal (from Winter & Henderson 2001, modified from Kennedy 1999).

This accords with circular economy principles and that of the waste hierarchy, namely prevention, minimisation, reuse, recycling, energy recovery (not relevant for this project) and disposal.

2.2 Sustainable Innovation

New materials and products comprising or containing waste-derived materials rarely emerge fully-formed from within an industry, and construction is no exception. More typically such ideas emerge from those outside the industry who make a link between an available waste material (which is often problematic to manage within the circular economy framework) and a common construction material-type to create an apparently green solution or opportunity. Often relatively little knowledge of the construction industry or the true function of the asset that it is proposed to replace, or be incorporated into, is brought to bear during the development of the product.

Typically, the introduction of a new material to the construction market follows the sequential stages set-out in Figure 2. First applications are often undertaken with little civil engineering input. However, where these are successful, and the beneficial properties and cost advantages of the materials are clear these will often lead to the involvement of professionals and to research, development, and demonstration and trial projects. Again, if these are successful, there may be an opportunity to develop standards and specifications that conform to national requirements. At this point large civil engineering contractors may begin to take an interest in the product. Indeed, this mirrors the experience of tyre bales that were used in the repair works on Interstate Highway 30 (Prikryl et al. 2005) in Texas and the construction of a major English strategic road, the A421, linking the A1(M) and M1 (Winter 2011). Another example is steel slag which now appears in Portuguese construction standards (Gomes Correia et al. 2016).

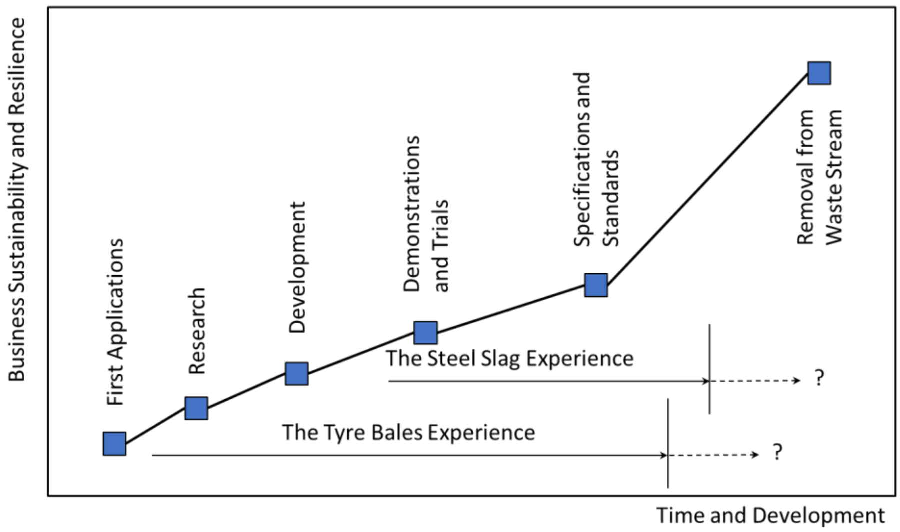

Figure 2. The development of business-based on the production and sale of waste-derived material products (from Winter & Gomes Correia 2019).

During this period, the interest in using the product can be significant, but the experience in the UK is that actual take-up is limited by environmental regulation constraints and the limitations imposed on stock and distribution networks. For those materials that have been removed from the waste stream at the point of production (e.g. recovered aggregates in the UK) the uptake in use can be significant; figures from industry body the Mineral Products

Association (MPA) suggest that the use of recycled aggregate in the UK increased by almost 10% from 2015 to 2017 while remaining relatively constant for 2018[2].

The process outlined in Figure 2, while somewhat idealised, broadly represents the sequence of activities in bringing products containing waste-derived materials to the market. However, marketing aimed at the public and elected members unfamiliar with the rigorous testing required to support manufacturers' claims, can sometimes influence the procurement of these products before adequate evidence of performance and risk assessment has been provided. This ultimately creates a financial risk for road authorities, and particularly for local authorities where budgets are tight, in that poor performance and legacy issues can further erode resources in the long term.

This process broadly mirrors the Gartner Hype Cycle in which new products and techniques go through five sequential development phases: the technology trigger, the peak of inflated expectations, the trough of disillusionment, the slope of enlightenment and the plateau of productivity. The latter is only reached as the product or technique becomes widely accepted and ceases to become viewed as novel and no longer requires to be trialled (Hansford 2016; Jones et al. 2017; Winter et al. 2018).

2.3 Waste Management

The fundamental principle of waste management is that it must be undertaken without endangering human health and without harming the environment, and in particular:

a) without risk to water, air, soil, plants or animals;

b) without causing a nuisance through noise or odours; and

c) without adversely affecting the countryside or places of special interest.

This precautionary approach has formed the basis for all waste regulation in the European Union since the first Waste Framework Directive in 1975.

This predicates that where the consequences of an action are unknown it should either not be permitted or should only be allowed subject to adequate controls being in place to eradicate, as far as possible, any potentially negative consequences. In the context of this project this might be applied to the potential for waste-derived material in road surfaces to reach the aquatic and soil environments as a result of road surface wear or to consider suitability for use where there is a lack of certainty on the end of life reuse options of road surfaces containing these materials.

Another principle of effective waste management, which is also included in the Directive, relates to proximity. At its most basic this means that there is a preference for dealing with waste close to its point of arising, often meaning the reuse of site-won materials. The construction industry has used this principle in the balancing of site-won materials in cut and fill for earthworks operations since the onset of the first large-scale formally-designed

[2] https://mineralproducts.org/documents/Contribution_of_Recycled_and_Secondary_Materials_to_Total_Aggregates_Supply_in_GB_in_2018.pdf (interrogated September 2020)

infrastructure networks for canals and railways in the eighteenth and nineteenth centuries, respectively.

The term waste-derived material is used throughout this report for two reasons:

1. Some materials may be classified as waste when used in asphalt production, and the asphalt or bitumen manufacturing process and potentially the subsequent use of the asphalt may need to be regulated in accordance with waste regulatory controls.
2. Some materials that were waste may be considered to be fully recovered for the purpose they are being used for (in asphalt), usually if it can be shown that they will be a substitute for a virgin equivalent material or will enhance the material they are being used in. The exception to this will be if the use of the waste is likely to increase the potential impact of the asphalt on the environment and/or human health. If a waste is fully recovered, it is classified as a product and waste regulatory controls do not apply.

As mentioned in Section 2.1, the best environmental option for most wastes is to use them in the manufacture of similar products (e.g. use glass cullet to produce more glass products, and so on) and many industries have signed up to commitments to do this. Despite this, there will inevitably be instances where remanufacturing technology, capacity, facility proximity, unacceptable increases in carbon use, CO_2 emissions and cost, amongst other factors, will mean that this is not always feasible and alternative beneficial uses of the waste need to be identified.

2.4 Waste-derived Materials in Asphalt

The focus in this report is on the use of waste-derived materials as an alternative to, or an enhancement of, virgin materials in the manufacture of asphalt. Asphalt planings (except where they include waste-derived additives) are specifically excluded as their recyclability is well-documented and controlled by current standards and specifications.

The concept of using problematic waste streams as a material substitute for virgin raw materials from finite natural resources is a potentially environmentally acceptable approach. However, it is important to establish the benefits associated with using the recovered waste materials before adopting them, to ensure that solving one problem does not create another. In addition, it is necessary to be sure that this does not compromise a more effective and sustainable solution to the original waste problem.

Glass, rubber and plastic are the most commonly considered potential asphalt additives, but some of the more unusual wastes that have been considered on an experimental basis include cooking oil, cigarette butts and products derived from the pyrolysis of pig manure (Tahmoorian at al. 2018). It is important to question whether the use of such waste-derived materials in road construction constitutes a beneficial use or is simply an alternative means of disposal, by creating a linear landfill. It is also important to establish whether asphalt containing waste-derived additives can be recycled and whether any additional special measures need to be taken to facilitate recycling at the end of the material life.

When considering the suitability for use of waste in asphalt, as a minimum, the following questions must be posed:

- Is the waste-derived material a direct substitute for virgin material?
- Does it enhance the properties and quality of the binder/asphalt?
- Are there any additional health and safety precautions during manufacture and construction to consider?
- Are there any additional environmental impacts associated with the use of asphalts containing the waste-derived material?
- Is the use of the material cost-effective for the road industry?
- Can the asphalt subsequently be recycled at the end of life and are special precautions necessary?

Conventional asphalt planings are generally fully recyclable and provide an exemplar of closed-loop recycling; SEPA provides definitive guidance on when such materials have been fully-recovered to the extent that it has ceased to be waste (SEPA Undated). An exception to this is where coal tar has been used in asphalt manufacturing. Due to its high resistance to oil corrosion and the fact it readily adheres to the aggregate components of asphalt, coal tar was used as a binder until the mid-1980s in the UK at which point it became apparent that surfaces containing it had low ductility and resistance to wear. It was subsequently established that coal tar contains components that are hazardous to the environment and human health and as such, coal tar planings are classified as hazardous (special) waste under European (and UK) legislation. Consequently, the management of this waste is problematic and costly and until relatively recently, the best option of dealing with it has been to dispose of it in hazardous waste landfills. Methods to stabilise and encapsulate coal tar planings so that they may be used in road construction below the surface layers, have been developed and emphasise the importance of the precautionary principle when considering the use of any materials in asphalt (McHale & Gordon 2020).

2.5 When Recycling Becomes Disposal

Clearly it is positive to substitute virgin material with a waste-derived alternative, if it can be shown that it will perform in the same way or the material can result in product enhancement, and there is no increased risk to the environment or human health. There is however a point at which a waste recovery operation can cross the line to become a disposal operation.

If a waste or waste-derived material is used in greater quantities than is necessary to fulfil its function or the use is unnecessary, then this is disposal as it is clearly a means of getting rid of the material. This is sometimes referred to as ‘sham recovery’ and is an area that regulators have been clamping down on in the last 20 years. What may have been considered to be a waste recovery activity initially, will therefore fall back under waste regulatory controls due to excessive use.

A recovery operation may also be deemed to be disposal if end-of-life uses are negatively impacted; an example is where the use of a waste-derived material may provide benefits, but inclusion beyond a certain mass or volume, even if benefits are still evident, prevents future re-use. In terms of asphalt recycling, this is dealt with further in Section 4.4.

This problem has been encountered by the construction industry where it was discovered that hazardous waste had been used in some precast concrete block products manufactured overseas. Whilst the concept of encapsulating hazardous waste in construction materials was reasonable in principle, there had been no consideration of how the concrete would need to be managed when the time came to discard it (end of life). Clearly, the potential risk to human health and the environment makes conventional on-site crushing and screening of this type of waste untenable as it would potentially lead to the release of hazardous particles; the future use of such materials would also be limited.

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3 MATERIALS

Scotland's road network is one of our largest and most visible assets, supporting the nation's economic and social well-being by facilitating connectivity. Around 93% of the 56,000km road network is the responsibility of the 32 unitary authorities while the remaining 7%, comprising the trunk road network which has an estimated construction value of £20bn and carries 35% of all Scotland's traffic, is the responsibility of Transport Scotland (Anon. 2016, 2020).

While all roads perform the same basic functions they are engineered differently depending on their situation and the type of traffic using them. Trunk and other A-roads, for example, must be able to withstand greater traffic numbers, higher vehicle speeds and heavier (by weight) traffic. Rural roads tend to have less traffic with slower vehicle speeds, whilst roads in conurbations often have to withstand more vehicle braking and surfaces may need to have more noise reduction properties than those in other areas. Factors such as junctions and bends are also a consideration along with local climate and morphology.

There is therefore a number of different types of asphalt mix designed for the conditions they are to be used in. While road user safety is the main concern for those procuring road surfacing materials, cost is also a factor as budgets will not always accommodate the highest standards if there are cheaper acceptable alternatives.

Asphalt is the surfacing material for over 95% of all UK roads and is also used for footpaths, playgrounds, cycle ways and car parks. Asphalt is a mixture of aggregates (crushed rock, sand, gravel or slag), binder and filler materials. Its inherent qualities of flexibility, efficiency of construction, ease of maintenance and value for money make it the number one choice, with 20 million tonnes of asphalt produced each year in the UK[3].

In asphalt, bitumen is the agent most commonly used to bind the aggregate and it also protects the aggregates from environmental effects; the amount of bitumen typically used in asphalt in Europe is approximately 5% by weight[4].

Bitumen is a thermoplastic, dark brown to black in colour, and solid or viscous liquid at room temperature, produced by the distillation of crude oil, but which also occurs in natural deposits (Anon. 2015). It is also a viscoelastic material. At high temperatures and/or when subject to slow or stationary traffic it behaves as a viscous material. At low temperatures and/or when subject to high speed traffic, it behaves like an elastic solid and can be susceptible to cracking. Curing of bitumen in asphalt takes place both during heating, as the bitumen is mixed with aggregate, and slowly throughout the lifetime of the asphalt (Honarmand et al. 2019).

Both the amount of traffic and its speed impact the life of asphalt pavements. Consequently, since the late 1980s, some of the bitumen used in asphalt has been modified with polymers (Zhu et al. 2014) to increase the durability of the asphalt (Honarmand et al. 2019). The polymer content in polymer modified bitumen constitutes between 3% and 10% by weight of the bitumen (Porto et al. 2019).

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[3] https://www.asphaltuk.org/uk-asphalt/ (interrogated July 2020)
[4] https://eapa.org/what-is-asphalt/ (interrogated July 2020)

The chemical compatibility of the components of an asphalt mix play a fundamental role in determining behaviour and performance throughout the life of the mix. When a non-bituminous or non-natural aggregate component is added to an asphalt mix, it is important to ensure that this material does not adversely affect the expected life-cycle cost of the project. Therefore, cost, performance and environmental concerns must be carefully deliberated to holistically determine the value-added element of any additives or substitute materials.

Project feasibility and cost-effectiveness are also affected by the availability and supply of waste-derived material that are proposed for use. The introduction of a potentially value-added material can result in a reduction in costs by saving on raw materials (bitumen binder and aggregate) if its performance can be demonstrated to be equal to, or better than, mixes composed solely of virgin material. Alternatively, and in rare instances, higher costs can be tolerated if it can be demonstrated that the design life of an asphalt pavement will be increased; it should be noted that this is very difficult to demonstrate other than through long-term rigorously monitored trials.

Waste-derived materials can be added to bitumen and asphalt in one of two processes:

- ‘Wet’ process in which material is melted into the bitumen. Bitumen plants typically operate at temperatures of >140°C to ensure that the bitumen behaves as a liquid to facilitate transportation and handling (Anon. 2015) as well as to assist optimal coating of the aggregates; any additive must melt below this temperature.
- ‘Dry’ process in which the material is mixed with aggregates prior to the addition of bitumen. Whilst the material may not be required to melt to fulfil its function, it must be tolerant of, and safe at, temperatures of up to 170°C.

In both processes the additive can modify the asphalt mix, making improvements to the properties and behaviours, or extend it by replacing virgin materials.

In this section waste-derived glass, rubber and plastic are investigated as separate materials. However, the similarities between rubber and plastic must be acknowledged as both consist of either thermoplastic or thermoset polymers with chemical additives.

3.1 Glass

Glass cullet has been used as an aggregate in asphalt in the USA since the 1960s, but its use has not grown significantly due to cost and availability. Interest in the use of glass in asphalt (‘Glassphalt’ or ‘Glasphalt’) in the UK started to gather momentum in the early 2000s. This may have been, at least in part, due to the introduction of the Aggregates Levy which applies to virgin aggregates but is not payable on waste-derived alternatives such as glass.

Clearly the high melting temperature of glass (>1000°C) means that it will not melt in either the wet or dry process and is an aggregate replacement. Trials by Lincolnshire County Council in 2001 and 2002 used varying amounts of glass and Recycled Asphalt Planings (RAP) to replace virgin aggregate in 20mm base course recipe mixes. The non-absorbent nature of glass particles means that the binder (bitumen) content could potentially be reduced without impacting on fatigue performance and accordingly filler contents were maintained in order to reduce the potential for deformation. This was further addressed by using crushed rock or crushed slag fine aggregate rather than using natural sand for locations of high traffic and/or stress.

Even when used as an aggregate replacement the non-absorbent nature of the particles meant that the binder content had to be reduced to facilitate handling of the asphalt and the post-compaction air voids value was slightly increased.

However, longer term monitoring found a tendency for the bond between layers to be compromised in contrast to the typical experience that marginal bonds improve over time. Some of the trial sites remain in service and it is reportedly common to encounter a lack of bond when coring 'Glassphalt' material for deflectograph or future works purposes. The trial concluded that that 30% glass (without RAP) was the optimum performance mix. However, the market for waste-derived glass has changed and 'Glassphalt' seems to no longer be marketed.

Concerns regarding the performance of asphalt containing glass include increased susceptibility to stripping and ravelling, the content of deleterious materials in the recovered waste glass, reduced adhesion at the bitumen-glass interface, and potential loss of skid resistance (WRA 2019).

Re-melting cullet back to glass products (closed-loop recycling) is usually the best environmental option and every tonne of glass re-melted saves 246kg of CO_2 emissions as well as decreasing the energy needed to make 'new' glass and reducing reliance on virgin raw materials[5]. British Glass[5] advocates, in line with circular economy principles, that re-melt uses should be prioritised, and glass maintained at its highest material value for as long as possible. While there are some advantages to the use of glass as an aggregate substitute, it is considered that they are outweighed by the disadvantages (Table 1) and 'Glassphalt' is considered to be neither a 'green' nor an economically viable alternative to traditional asphalt.

3.2 Rubber

End of life tyres are often referred to as a 'difficult waste'. Whilst this term has no statutory meaning, it is often used by the waste industry to describe a waste that is problematic. Tyres cannot be easily and economically recycled to produce more tyres because the rubber content is thermoset in nature (i.e. cannot be melted or re-moulded without de-vulcanization) and the disposal of whole and shredded tyres to landfill has been outlawed since 2003 and 2006, respectively, in compliance with EU Landfill Directive requirements.

[5] https://www.britglass.org.uk/ourwork/recycling/ (interrogated July 2020)

Table 1. Advantages and disadvantages of utilization of glass in asphalt mixture (after Tahmoorian et al. 2018). Some of the claims made in the review by Tahmoorian et al. (2018) seem to the authors to be somewhat aspirational and commentary has been added where it seems necessary in square parentheses […].

Advantage	**Description**
Increased road safety	Since the glass particles have low water absorption, the pavement surface gets dry faster after rain. [While the decreased water absorption is not disputed the faster drying seems to be somewhat speculative and the effect of surface water on glass may have a greater detrimental effect on skid resistance that on stone.]
Easier to compact and transport over longer distance	Glass asphalt mixtures hold heat longer compared to conventional asphalt mixtures.
Improved night-time road visibility	Glass asphalt surfaces are more reflective in comparison with conventional asphalt surfaces. [The details of this are somewhat sketchy and it is not clear that any in crease in reflection will give a corresponding increase in the retroreflectivity of the road surface let alone that this would provide a road safety benefit.]
Improved workability	The presence of long and flat particles will positively affect the workability of asphalt mixtures. [Such particles will not meet general aggregate standards and as noted below would likely cause a decrease in skid resistance.]
Improved resistance to thermal cracking	The small inflation coefficient of glass improves the thermal cracking resistance
Disadvantage	**Description**
Reduced road safety[a]	High amount of large size glass particles causes a decrease in skid resistance. [Large particles are not defined and in general would not be desirable from a performance perspective.] The angularity and friction angle of glass particles provides inadequate transverse stability, particularly at braking or start-up.
Increased bitumen bleeding	Low bitumen absorption and density may cause a bleeding problem.
Increased stripping	The smooth surface of glass particles reduces the adhesion of asphalt film to the crushed glass, which may cause stripping of the asphalt mixture.
Sensitive to water damage	The high silica content in glass particles will make asphalt mixtures made with glass have more moisture sensitivity depending on the glass particle size or the glass content in the asphalt mixture.
Abrasion of tyres	The presence of long and flat particles (particularly in case of large glass particles size) may result in abrasion of tyres.

[a] The pothole.info project points out that this means that 'Glassphalt' is entirely unsuitable for high speed roads: https://www.pothole.info/2011/07/glassphalt-have-roads-made-with-recycled-glass-changed-pavement/ (interrogated July 2019)

Waste tyres can be recycled to produce new rubber products by either mechanical processing to produce fillers or aggregates or can go through a process of devulcanization. The latter allows remanufacturing and results in a high value product that can melt and be used in the same way as the virgin, non-vulcanized thermoplastic equivalent. Devulcanization[6], whilst preferable from a circular economy perspective, consumes large amounts of energy and chemicals and coupled with equipment costs, it is generally accepted that the processing cost is higher than the value of the product when compared with virgin equivalents.

3.2.1 History of Use

Rubber from end of life tyres has been used as an additive to asphalt for several decades in countries such as the USA, South Africa and Australia although the first experimental use of virgin natural rubber in bitumen dates to the 1840s (Heitzman 1992; WRAP 2008a). The theory behind using tyre rubber in asphalt is to delay surface cracking and ageing (improved durability) and provide additional waterproofing (to prevent water ingress weakening the asphalt) as it is suggested that it reduces air voids that are present in stone mastic asphalts (SMAs), for example. Controlled laboratory experiments demonstrate that asphalt incorporating waste-derived rubber can at least provide similar mechanical performance when compared to conventional materials such as SMA provided that good quality control is exercised (WRAP 2008b). Studies include the addition of natural and synthetic (general purpose) rubber from end of life vehicle tyres, which may or may not be devulcanized and can sometimes be used in combination with virgin natural non-vulcanized rubber.

3.2.2 Types of Tyre Rubber

Rubber components in tyres can vary widely. Passenger vehicles tyres tend to comprise general purpose rubber with a high styrene butadiene content. Those used for trucks are often a blend of general purpose and natural rubber and tyres on vehicles used for predominantly off-road activities (e.g. quarry vehicles) mainly comprise natural rubber due to its excellent fatigue resistance and high strength.

Devulcanized natural rubber crumb from off-road tyres will dissolve in bitumen more readily at lower temperatures than general purpose rubber and can provide low-temperature performance in cold weather. Crumb containing general purpose rubber will require higher blending temperatures and is generally regarded as being more suitable for hot climates (Gursel et al. 2018). Quality control on the type and source of waste rubbers used in an asphalt mix is therefore essential.

[6] Vulcanization is the process by which the rubber is hardened and made thermoset. Vulcanization works by forming cross-links between sections of polymer chain which result in increased rigidity and durability, as well as other changes in the mechanical and electrical properties of the material. Devulcanization reverses this process returning the rubber to a thermoplastic state; both processes are energy intensive.

The type of rubber, chemical additives and manufacturing process, amongst other things, all influence the performance of an asphalt product. In very simple terms:

- Rubber that has been devulcanized is thermoplastic and will melt. The source (natural/general purpose or a mixture) will dictate the temperature at which it will melt and whether it is more suited for use in hot or cold climates.
- Rubber that has been mechanically treated but not devulcanized is thermoset and does not melt. It therefore performs the function of an aggregate. End of life tyre rubber may be considered to be a bitumen modifier as it reacts with bitumen and is thought to improve asphalt performance.

3.2.3 Asphalt Manufacturing Incorporating Rubber

Rubber can be incorporated into an asphalt mix using either a wet or dry process.

In the wet process, crumb rubber (typically 0.15mm to 0.6 mm) is blended with bitumen for a minimum of 45 minutes at elevated temperatures prior to contact with aggregates. Light fractions of bitumen transfer into the rubber making the rubber particles swell, and the bitumen hardens. Porto et al (2019), notes that many studies concluded that while a low rubber content (around 4% of the weight of bitumen) has almost no effect on the performance and mechanical properties of the binder, more than 20% was found to be unsuitable.

In the dry process, ground rubber (typically 0.85mm to 6.4mm) is hot mixed with aggregates prior to the addition of bitumen and the rubber changes from being an inelastic solid (in solid mechanics this is also referred to as a material that exhibits plastic behaviour) to a gel (in part due to the presence of carbon black in tyre rubber), preventing the formation of voids around particles (Lopez-Moro et al. 2013). In the UK, trials have used rubber as a bitumen modifier (see Appendix D).

Research by Rahman et al. (2004; 2010) determined that the wet process produced better interaction and properties than the dry process and that the service life of dry process mixes was inconsistent, varying from two to 20 years. Later research contradicted this and Shen et al. (2015) concluded that if the dry process blending time is sufficient, there is little distinction between the properties of wet and dry process rubberized asphalts.

In both processes, the bitumen undergoes modification.

3.2.4 Factors Affecting Performance

Many factors can influence the performance and mechanical properties of rubberised binders (Porto et al. 2019), including:

- Size and content of rubber additives.
- Chemical structure.
- Particle surface properties.

- Blend production method.
- Temperature.

Bitumen modified with rubber is reported to have high elasticity and no viscous behaviour and makes asphalt pavements more resistant to rutting and cracking than unmodified asphalts; in addition, these asphalt pavements have a longer life and there is reduced traffic noise (Porto et al. 2019). Various researchers suggest that using tyre rubber in an open-graded asphalt mixture could decrease tyre noise by up to almost 50%[7] (Way & Evans 2006).

Despite these benefits, Porto et al. (2019) reported that rubber modified asphalts are not common for paving applications. This is because the technological (and economic) properties of these asphalts are almost immediately deteriorated by the rubber polymers due to their hardening properties, as follows:

- The rigidity of the modified binder is increased at low temperatures resulting in increased thermal sensitivity.
- The cost of the rubber additive tends to increase the cost of the asphalt.
- The effectiveness of rubber (as a thermosetting plastic) is usually due to the relatively large quantities in bitumen (more than 10% by weight).

Porto et al. (2019) also reports that the thermodynamic instability of the wet process mix induces a phase separation (or sedimentation) under the influence of gravity. It cannot tolerate being transported over long distances as it has a tendency to separate. Separation has also been observed with asphalts produced using the dry mix process, with rubber particles sinking to the bottom of the mix. Separation can also occur with conventional asphalts, so travel time is always a consideration but not perceived to be a major problem in Scotland.

3.2.5 In-situ Trials

There is a considerable amount of published research comparing the performance and mechanical properties of asphalts containing different types, sizes and amounts of rubber. There is consensus that outcomes greatly depend on the application method (dry or wet process – although Shen et al. (2015) suggest that differences in performance can be minimised by extending the dry process blending time), the characteristics of the base binder, together with the climate where it is being laid and the travel time of the material. For this reason, in situ trials carried out in the UK and in particular Scotland are more relevant to this study than those undertaken overseas. Information on UK trials can be found in Appendix D.

[7] http://www.rubberpavements.org/faq (interrogated July 2019): note that the Rubber Pavements Association website while still accessible appears to indicate that the Association is no longer active.

3.3 Plastics

3.3.1 Plastics and Plastic Recycling

Plastics are widely-used and their versatility has enabled significant innovation and industrial progress. Popular estimates suggest that up to 20 times more plastics are used now than 50 years ago in the UK. As a consequence the amount of plastic discarded is significant and issues surrounding the distribution of microplastics in the aquatic and soil environments have come to the forefront of public attention in recent years.

There are seven main types of plastic each of which is used to create different primary and waste-derived products (Figure 3).

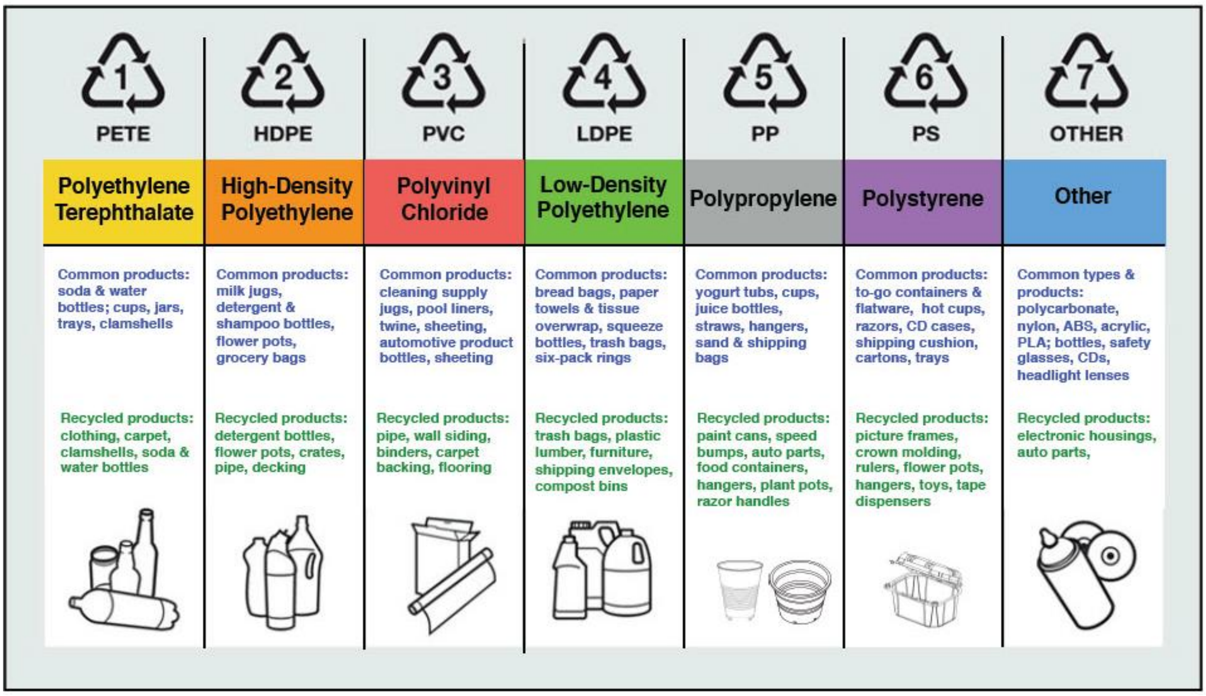

Figure 3. Types of plastic resin, their chemical types, identification codes, and their primary and secondary uses.

All plastics are theoretically recyclable although due to a shortfall in processing capacity and a lack of financial incentives, this does not always happen in the UK. The Waste & Resource Action Programme (WRAP) introduced The UK Plastics Pact[8] in 2019, which is set to transform the way plastics are manufactured, used and managed at their end of life with key targets for substantive change by 2022 and 2025. Publicly Available Specification (PAS 510) is being developed in support of the Plastic Pact, with the aim of preventing nano and microplastic pollution, and is expected to be available in mid-2021 (BSI 2021). It is expected to focus on 'using, processing, handling, storing or transport of plastic pellets, flakes and powders' and could be an important tool for companies to demonstrate good practice in pellet loss prevention measures across the supply chain. It will introduce measures to prevent the emission of such materials to the environment.

[8] www.wrap.org.uk/content/the-uk-plastics-pact-roadmap-2025 (interrogated July 2020)

Irrespective of this Anon (2019a) reported that in 2018, 78% of plastic packaging was recovered. Examples of the types of plastic that can be recycled in Scotland for the purpose of remanufacturing can be found at a specialist site in Dumfries operated by Plastic Technology Services Ltd[9].

Plastics exhibit one of two different types of behaviour:

- Thermoset materials can burn but not melt and cannot be used in the remanufacturing of similar products. They can, however, still be reused or recycled. One example of such recycling is polyurethane foam being used as carpet underlay.
- Thermoplastics melt and can therefore be used to remanufacture new plastic products. Whether they are or not is not covered by this research, but in principal all thermoplastics can be remanufactured and are 100% recyclable[10].

There is also a perception that different thermoplastics cannot be recycled together. This is because they do not always mix when melted together (they can be immiscible). To address this, researchers have identified chemical additives, sometimes referred to as compatibilizers, that facilitate mixing (Lin et al. 2020).

3.3.2 Technical Aspects of Plastic Recycling

The use of waste-derived plastics as an asphalt additive has generated a great deal of interest in recent years, not least due to the abundance and high cost of managing this waste stream. As with rubber, plastics in the form of pellets or shreds can be added to the binder prior to mixing with aggregate (wet process) or to hot aggregate prior to the addition of the binder (dry process). Whilst researchers appear to favour the wet process, there are associated practical and cost issues in that storage of plastic modified binder requires continuous agitation to avoid phase separation which renders the bitumen mix unusable and from which the mix cannot be recovered. The dry process, although it requires prolonged mixing to ensure that a homogeneous mix is achieved, is more common in the UK.

If plastic is to be added to an asphalt mix, it is important to understand that although plastics can be differentiated into broad categories, there is a very wide variety of different types, each with its own chemical composition and mechanical characteristics. Co-mingled waste plastics can therefore perform differently when utilised in an asphalt manufacturing process depending on the ratios of the different plastic types and their compatibility. Bearing this in mind, the source type, or provenance, and consistency of waste-derived plastic used as an asphalt additive is particularly important, whether the material is designed to be a bitumen enhancer or as a partial replacement.

The strength of the bond developed between the bitumen and aggregate is one of the key factors in the performance of a pavement. One of the challenges with using waste-derived plastic as an aggregate replacement in asphalt is the potential weakening of the bonding between the aggregate and bitumen. Guru et al. (2014) reported that, when aggregate was

[9] https://www.ptsltd-uk.com/ (interrogated July 2020)
[10] https://www.bpf.co.uk/sustainability/plastics_recycling.aspx (interrogated July 2020)

replaced with polyethylene terephthalate (PET), the resistance to moisture damage decreased but the resistance to permanent deformation, Marshall stability, stiffness and fatigue life of the asphalt mix all increased.

Jafar (2016) suggested that the reason for the weakening of the bond between the bitumen and plastic was due to the high stability and inert nature of the plastic surface. The recommended treatment to overcome the issue was to introduce a strong oxidising agent (dichromate/sulphuric acid solution) to activate the plastic surface. This would introduce an active ionic functional group, which would then react further in the presence of a cross-linking agent such as polyethyleneimine.

Although chemical treatment of plastic addresses the bitumen adhesion problem, the feasibility of using waste plastic still needs to be driven by good economics. Quoting Jafar (2016), 'it is not economical to use these materials as alternative aggregates unless their use adds sufficient value to the bituminous product, so that the cost of the materials can be justified'.

It should be noted, that currently there are no waste-derived plastic products that are marketed as meeting the standards for use as an aggregate substitute in asphalt in the UK. Manufactured (artificial) aggregates that can be used must be "clean, hard and durable and shall comply with BS EN 13043:2002 and be CE marked and have a declared performance …" (MCHW 1, Clause 901(3)). The intention is that the aggregate should be uncontaminated and stable both mechanically and chemically throughout the design life of the asphalt mix.

Chin & Damen (2019) noted the use of waste printer toner cartridges, which are comprised of a mixture of different plastics, to modify the binder in hot mix asphalt. Trials found that the high-temperature resistance to permanent deformation was improved but that cracking was increased and there was a negative effect on stiffness and issues related to the stability of the mix during storage (Yildirim et al. 2003). In contrast, work by Sharp et al. (2017) on a different toner cartridge modified asphalt suggested an 11% decrease in modulus, a 30% increase in fatigue life and a 50% reduction in cracking relative to a conventional control mix.

Dahlat & Wahhab (2017) examined the use of high density polyethylene (HDPE), low density polyethylene (LDPE) and polypropylene (PP) asphalt modifiers and found that all three increased the resilient modulus compared to an unmodified mix. They also highlighted the issue of oxidation of the bitumen at temperatures needed to melt some plastics while noting that HDPE improved rutting performance, but that none of the waste-derived plastic-modified mixes met American Association of State Highway and Transportation Officials (AASHTO) requirements for elastic recovery.

Some types of plastic such as high density polyethylene (HDPE: e.g. milk bottles and single use shopping bags) and polyethylene terephthalate (PET/PETE: e.g. drink bottles) have been reported as being unsuitable for use as binder extenders or modifiers as the melting points are around 270°C and 260°C, respectively (White 2019; White & Reid 2019). These temperatures are considerably in excess of typical bituminous binder and asphalt production and storage temperatures, which would mean that such materials would not melt and thus form an integral part of the binder mix. Nurfazilah (2012) reported that the use of higher temperatures in a bitumen plant causes increased and potentially hazardous emissions to the atmosphere, promotes subsequent increased oxidation and earlier hardening of the placed surfacing, as well as causing poorer aggregate adhesion and thus potentially poorer durability and shorter life.

3.3.3 In-situ Demonstrations and Trials

The examples given in Section 3.3.2 clearly demonstrate disagreement on the performance of asphalts modified with waste-derived plastic and it should be noted that the majority of experiments incorporating such additives were undertaken in laboratories rather than being full-scale performance trials. As with rubber however, research indicates that the performance and mechanical properties of asphalt modified with waste-derived plastic will be dependent on:

- Size and content of plastic additives.
- Chemical structure.
- Particle surface properties.
- Blend production method.
- Temperature.

For this reason, in-situ demonstrations carried out in the UK and in particular Scotland, using UK-derived plastic waste are more relevant to this study than those undertaken overseas.

A company in Southern Scotland is currently producing three plastic products for use as an asphalt additive. Whilst the composition of these additives is described as being 'proprietary information' they are described (based on MacRebur[11]) as follows:

- MR6 is a complex arrangement of polymers designed for the extension and enhancement of bituminous binder for asphalt used in road surfaces. Initially provided in pellet form, but to facilitate melting [in the asphalt mix], this product is now produced as shreds.
- MR8 is a blend of polymers designed for the extension of bituminous binder for asphalt used in road surfaces. This product is supplied as shreds.
- MR10 contains a block co-polymer designed for the extension and enhancement of bituminous binder for asphalt used in road surfaces. This product is provided in pellet form.

In MacRebur's 'Technical Data Change in form of products' it is stated that, "The shredded form of MR6 and MR 8 are not melted, extruded and cut into pellets". White & Reid (2018) however, state that "… melting allows removal of contaminants by filtration …", so it is therefore reasonable to assume that these products may contain varying proportions of a range of contaminants. Whilst the impact of contaminants on bitumen/asphalt performance

[11] https://www.macrebur.com/the-product (interrogated July 2020)

is unknown, it is accepted that small quantities are inevitable and are permissible when recycling road planings, so it is debatable whether contaminants associated with waste-derived plastic additives used in small quantities, would have any significant impacts.

Whilst information on the exact types of plastic used, or their relative proportions, in the aforementioned products is not publicly available, it can be ascertained from MacRebur research (White 2019) that neither plastic bottles nor bags are used in their products. A statement on the landing page of the MacRebur website states that their "… products are made from non-recyclable waste plastics that were destined for landfill or incineration …"[12]. It is assumed therefore that, as all plastics are theoretically recyclable, those referred to are not currently recycled in the UK due to a shortfall in processing capacity, logistics, technology issues or cost.

It is also assumed that the feedstock is co-mingled plastic waste. A video on the MacRebur website[13] refers to agricultural waste plastic (LDPE silage wrap) together with household and commercial plastic waste, being used in its MR6 and MR8 products that contain "… a complex blend of polymers …" and a "… blend of polymers …" respectively. Potential immiscibility[14] is addressed through the use of "MacRebur activators (which) are added to the chosen waste plastics in order to make sure the plastics fully mix in and melt with the remaining bitumen in an asphalt mix making sure there are no lumps of plastic left in the asphalt".[15] As the production of MR6 and MR8 does not involve melting, these activators must be applied to the surface of the plastics in either powder or liquid form; asphalt manufacturers using these products are not advised about the need for compatibilizer additives, so it is assumed that they are added by MacRebur. To ensure these activators remain integral with the product, storage and processing arrangements at asphalt plants must be discussed with the supplier and the products should be accompanied by Safety Data Sheets identifying the properties of the additives as also referred to in Section 6.

UK trials and demonstration projects have been, and are currently in the process of being, undertaken (e.g. Anon. 2019b) in for example Cumbria, Enfield and Coventry. However, data and information relating to these trials, whether detailed or otherwise, has proven very difficult to obtain. This situation is characterised by the lack of pre-, during or post-construction performance testing, including the extraction of cores. At present the information available suggests that the work undertaken with waste-derived plastic in asphalt constitutes demonstrations rather than formal trials of technical performance. Issues related to the requirements of formal trials are detailed further in Section 6. To date all known demonstrations of waste-derived plastic in road surfacings in Scotland have been using the dry process and no evidence is available to suggest that a formal design process has been undertaken to optimise the performance of the final mix.

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[12] https://www.macrebur.com/ (interrogated July 2020)

[13] Available directly from: https://www.youtube.com/watch?v=cHWYoDKYnQo&feature=emb_title (interrogated July 2020)

[14] The inability of two or more materials to mix.

[15] https://www.macrebur.com/pdfs/product/MacRebur_MicroPlastics_Leaflet_v3.pdf (interrogated July 2020)

An international study concluded that a lot of research remained to be done on the implementation of the technology associated with the use of waste-derived plastic in asphalt, not least to address concerns related to performance (WRA 2019). In addition, the New Zealand Product Stewardship Council expressed significant reservations regarding the use of plastic in roads.[16]

Information on UK trials can be found in Appendix D.

3.3.4 Modular Plastic Roads

In the Netherlands, a new plastic road concept is being trialled and marketed. The PlasticRoad[17] is prefabricated and features a hollow space that can be used for various purposes such as water storage and attenuation, utility cables and pipes, geothermal systems for ensuring roads remain ice and snow free, generating energy, and so on. The road is made predominantly from waste-derived plastic, is expected to last two to three times longer than conventional surfaces and could reportedly reduce construction time by up to 70%. It is proposed that these new types of road could be in use on an industrial scale from 2021. Realistically, the potential for the use of this road system in Scotland is likely to be limited to new housing developments and new commercial/retail parks. In addition, concerns regarding the abrasion of the surface by traffic to produce micro-plastics that could enter the environment would have to be fully-addressed through trials and analysis prior to widespread adoption.

3.4 Health and Safety Considerations

Health and Safety in the UK is controlled by the Health and Safety Executive (HSE) and under the primary legislation enacted as the Health and Safety at Work etc. Act 1974 (HSWA)[18]. The HSWA places obligations on all employers in the UK, including asphalt manufacturers, to treat the health, safety and wellbeing of their staff, their product users and the public as a priority. Manufacturers are alert to any issues raised, share information nationally and internationally and respond rapidly and decisively to deal with relevant issues through short-term campaigns and longer-term initiatives. The goal of www.safequarry.com, for example, is stated as being to "… ensure that by facilitating the sharing of information and learning from the experience of others within the industry, we will achieve a safer environment for all those involved, employees, contractors, suppliers, customers and members of the public."

3.4.1 Glass

Respirable crystalline silica sand used to manufacture glass is linked to silicosis, however, during the glass manufacturing process it is converted to amorphous silica, which is non-hazardous. Dust from waste-derived glass products can be an irritant, but it is not linked to

[16] https://www.nzpsc.nz/putting-plastic-packaging-waste-into-roads-is-not-recycling/ (interrogated July 2020)
[17] https://www.plasticroad.eu/en/ (interrogated July 2020)
[18] https://www.legislation.gov.uk/ukpga/1974/37 (interrogated July 2020)

silicosis and if used in asphalt products requires no additional health and safety precautions to be taken.

3.4.2 Rubber

A study in Sweden (Xu et al. 2018) found that there were no increased risks to asphalt workers from crumb rubber modified asphalt when compared to conventional asphalts. The Institute for Safety, Compensation and Recovery Research (ISCRR) in Australia came to similar conclusions in their March 2019 report (Moo et al. 2019).

Fume emissions have also been studied extensively in a number of paving projects in the US since 1989. Separate studies undertaken by the National Institute for Occupational Safety and Health (NIOSH) and the Federal Highways Administration (FHWA) determined that the use of rubberized asphalt does not appear to increase health risks to paving personnel, however there were some reports of an objectionable odour (Lo Presti 2013).

3.4.3 Plastics

Plastics may contain additives such as fillers, pigments, fire retardants and stabilisers, depending upon product requirements. Plastic fumes, produced when the material is heated during processing, can include respiratory sensitizers, irritants and carcinogens.

In order to prevent fume production, residence time (time in flue) and temperature control parameters are critical. The HSE Plastics Processing Sheet No 13 (Revision 1)[19] specifically states that safety data sheets obtained from the supplier/distributer should identify:

- The particular plastic formulation.
- Correct processing temperature.
- Degradation products.
- Any additives and their possible effects on fume production.

Chin & Damen (2019) concluded the research on occupational health and safety was inconclusive with respect to plastic modified asphalt and that more research was required. They did acknowledge that some laboratory work had been done in this area on MacRebur products; White (2019) described a fuming generation evaluation test that was developed to analyse binder samples modified with and without waste-derived plastics. These tests were undertaken at temperatures between 100°C and 200°C to reflect material processing to laying conditions. White concluded that the risk to human health is no greater for MacRebur products than that for unmodified bitumen.

It should be noted that, in the absence of recognised test methods for asphalt fume analysis, the White (2019) testing was undertaken by a specialist UKAS accredited laboratory to ISO/IEC 17025 (British Standards Institution, BSI, 2017) standards. Worker health and safety is a critical issue and more research is needed to verify or otherwise these findings, although it

[19] https://www.hse.gov.uk/pUbns/ppis13.pdf (interrogated July 2020)

should be noted that data from large cohorts over significant time periods for specific effects may be required to inform Regulation.

3.5 Life Cycle Assessment

Life Cycle Assessment (LCA) is an important tool to allow the comparison of the carbon budget of different materials, products and processes. The boundaries, or the extent of the life cycle considered, determine whether a comparison of different LCAs is valid. Ideally boundaries that consider the full life cycle, usually called cradle-to-grave, are used.

However, while agreed national and international datasets increasingly make comparisons between discrete life cycle stages easier, when the results are reported in such detail, uncertainties in actions required in the later stages of a life cycle, typically the operation, maintenance and disposal stages, can make full comparisons difficult. This often causes the boundaries of the study to be narrowed and, in determining LCA of fibre reinforced concrete, Tuladhar & Yin (2019) took a cradle-to-gate (pre-construction) approach, while Leal et al. (2020) took a cradle-to-site (end of construction) approach to the LCA of slope repair techniques.

To make valid comparisons between different LCAs single, independent LCAs covering multiple materials or processes tend to be more useful (Wayman et al. 2011a, 2011b). Comparative LCA would be a worthwhile exercise if, in future, different materials are to be tested on the road network through the protocol outlined in Section 6. The work of Wayman et al. (2011a, 2011b) which has been updated would provide a useful tool for such an exercise updated (Reeves et al 2020; Wayman et al. 2020a, 2020b).

A comparative LCA study of hot-mix and warm-mix asphalts including mixes with RAP, crumb rubber and waste plastic was conducted by Pratico et al. (2020). The boundaries of their study appear to be cradle-to-grave, including a maintenance and disposal component, and the results indicate that using recycled materials generally generates less CO_2-equivalent emissions than extracting, processing and using primary materials. Indeed, RAP and warm-mix asphalt were the most favourable option with the use of RAP in warm-mix, unsurprisingly, the most favourable option. However, these results do need to be treated with some caution as the amounts of RAP assumed in the mixes was in the range 30% to 45%, which is significantly higher than the maximum 20% typically used in the UK.

Adding waste-derived plastic pellets to bitumen has been shown to increase carbon emissions compared to virgin bitumen by up to around 3% depending on the amount added (Santos et al. 2021). Their work also showed that carbon emissions for virgin plastic modified binder were, to some extent, dependent upon the type of plastic used while there was no differentiation between the waste-derived plastic type strongly suggesting that the latter material was mixed and potentially subject to variable performance. The increased carbon emissions of virgin plastic asphalt modifiers compared to waste-derived plastic asphalt modifiers were between 2.5% and 5% for a 2% replacement of material, rising to between 10% and 18% for an 8% replacement.

Santos et al. (2021) also examined the effect on carbon emissions of replacing virgin aggregate with waste-derived plastic pellets in asphalt mixes intended for pavement surfacings and found that the increase was around 19% for the replacement of 2.5% material, rising to around 40% for the replacement of 5%[20]. It should be noted however, that in the UK, certain standards must be met before potential waste-derived plastic can be used as an aggregate replacement in asphalt and to date, none are marketed as meeting the relevant criteria.

Unsurprisingly, there is increasing interest in warm-mix asphalts (Anon. 2019c), particularly in relation to their reduced cooling time (reducing construction times and road user disruption), reduced emission of fumes, and carbon savings due to the (at least 20°C) lower processing temperature. Carbon savings however, are only realised if there is adequate demand as the carbon benefits are lost if asphalt plants have to constantly lower and subsequently raise their temperature. All three waste-derived materials addressed in this report can purportedly be used in warm mixes, but whereas this is clearly not an issue with glass and there is evidence for the use of rubber, none has been identified for the plastic product.

The results of a wide-ranging LCA (Wayman et al. 2012) indicate that recycling a relatively low level of 15% RAP in the bound courses is significantly more environmentally beneficial than warm mixing, particularly if the additives used to facilitate warm mixing are included in the analysis. The combination of RAP in warm-mix asphalt was not included in the study.

3.6 Material Costs

The cost and production capacity of waste-derived materials compared to the virgin materials that they are proposed to replace has a fundamental effect on the viability of recycling.

Bitumen and aggregate prices are difficult to obtain due to the constraints imposed by competition law. The authors have used non-specific discussions with their contacts in the road pavement construction industry to obtain generalised bitumen and aggregate prices. Bitumen prices fluctuate on a traded market and are expected to fluctuate between about £250 and £500 per tonne over a period of a few years with the typical price (average or median) expected to be around £400 per tonne.

The costs of asphalt are complicated by the fact that when it is produced in a quarry where the aggregate used is extracted, haulage costs are minimised. Production outside mineral extraction sites may be higher. The costs are further complicated by the vagaries of economy of scale and fixed base costs (for example, the order of magnitude of the fixed cost is more or less the same for a blast regardless of the amount of aggregate to be produced). However, working from more visible costs of uncoated aggregates for unbound layers, such as Type 1

[20] Santos et al. (2021) also considered replacing 10% and 20% of the aggregate with plastic. However, as this potentially corresponds to up to 60% plastic by volume these figures are not considered relevant in the context of the current study as they would almost constitute a disposal activity and is clearly pointing towards a rather different approach that involves replacing all of the rock aggregate with plastic or, indeed, creating an entirely plastic road (see Section 3.3.4).

(MCHW 1, Clause 803), the production price plus profit of single-sized coated aggregate would be expected to be around £10 to £15 per tonne.

The use of glass cullet in asphalt is referred to as down-cycling within the UK glass industry that champions closed-loop recycling and there is no reason why glass cannot be recycled 100% and in perpetuity[21]. Data from the Waste & Resource Action Programme (WRAP) for 2018/19 suggest glass container prices vary between £8/tonne and £23/tonne[22], clearly showing costs vary between being price comparable with and higher than virgin aggregates, with significant cost volatility. This supports closed-loop recycling within the glass industry while predicating against the use of glass in asphalt.

Waste rubber sells locally in the Central Belt of Scotland for between around £250 and £460 per tonne depending upon the size. These prices clearly predicate against its potential use as an aggregate replacement, unless significant performance enhancement of the asphalt it is used in can be proven. The cost of rubber is broadly comparable with that of bitumen and accordingly its use to extend and/or modify bitumen might well prove to be an appropriate use subject to technical and environmental issues.

WRAP[23] reports the prices of waste plastics in the range £50 to £490 per tonne in July 2019, with prices generally having seen strong growth in recent years. Specific prices included:

- Clear PET bottles, £222.50 per tonne.
- Coloured PET bottles, £50 per tonne.
- Natural HDPE bottles, £490 per tonne.
- Mixed HDPE bottles, £385 per tonne.
- Mixed polymer bottles, £115 per tonne.
- LDPE 98:2 film, £275 per tonne.

These compare to average virgin plastic prices for the first half of 2019 for LDPE of £1,193 per tonne, HDPE of £1,220 per tonne and PET £1,084 per tonne. These prices make a clear case for the plastics industry's stated preference of closed-loop recycling and make open-loop recycling less attractive unless a definitive and significant performance advantage can be obtained and effective solutions to environmental issues, including those related to end of life waste, can be found. It is of course noted that the price of virgin plastics is linked directly to the volatile oil market.

Notwithstanding this, none of the plastics appear to be cost-competitive with aggregates used in road surfacings and only some are cost competitive with bitumen. PET may be one exception to this but it is also important to note that it is resistant to solvents and this is likely to introduce problems with miscibility of the plastic and bitumen. Mixed polymer bottles would not be an option as the proportion of different materials will vary with time rendering any form of quality control, let alone factory production control, impossible.

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[21] https://www.britglass.org.uk/our-work/recycling (interrogated July 2020)
[22] http://www.wrap.org.uk/content/recovered-glass-container-prices-0 (interrogated July 2020)
[23] http://www.wrap.org.uk/content/plastic (interrogated July 2020)

Certainly for plastics closed-loop recycling appears to be the most reasonable route to recycling and there are emerging techniques, processes and markets that raise the prospect of genuinely upcycling[24] such materials including as energy storage products (Mirjalili et al. 2020).

It is important to note that the prices in this section are the most robust and accurate available but that regional variations and temporal fluctuation in material prices are inevitable. It is also clear that poor quality materials may be available at prices lower than those presented here. For plastics in particular it is understood that the residual ‘sweepings’ from waste processing plants may be cheaper but that the material constituents are highly variable and maybe unsuited for a high value application such as asphalt.

[24] Upcycling refers to a recycling process in which the secondary application has a higher utility than the primary application; a hypothetical application might be one in which a pavement foundation layer is recycled in bound pavement layers (Winter 2002).

4 EMISSIONS TO THE ENVIRONMENT AND RECYCLABILITY

4.1 Noise

The use of tyre rubber in open-graded mixture binder has been reported to reduce tyre noise by up to 50% (Way & Evans 2006) (see Section 3.2.1). Although the traffic noise reducing properties of rubber modified asphalt are not disputed in any of the published documents reviewed, most do not detail the mechanism for the noise reduction.

4.2 Particle Emission Potential

The issue of plastic contamination of the marine environment was brought to the attention of the public in David Attenborough's documentary series 'Blue Planet II', aired in the UK in December 2017. Since then, there has been significant pressure to prevent, or at least curb, the release of microplastics into the water environment.

The relevance to road construction and use is the potential for plastic debris from roads to enter the water environment through surface water runoff. The term plastic includes materials consisting of thermoplastic polymers and thermoset polymers with chemical additives. It includes rubber from tyre wear and also particles from road markings and asphalt modified with rubber or plastic. As polymer modified bitumen is a potential source of microplastics that can be released into the water environment through road use (Andersson-Sköld et al. 2020) it is important to establish whether the different modifiers enhance the properties and qualities of the binder/asphalt or if they are simply a mechanism of disposing of a problematic waste stream.

Particles released to the environment as a result of road surface wear may become airborne or carried in surface water. Whilst bitumen is not classified as an environmental or health hazard according to the EU classification and labelling system, some of the chemicals used in Polymer Modified Binders (PMBs) are known to be hazardous to the environment and human health. Notwithstanding this, there are limited studies about the extent to which these substances are released from PMBs as microplastics. In addition, the physical and chemical properties and composition of the different microplastics will affect their behaviour in the environment and to date there has been no research on this issue. In recognition of this, Andersson-Sköld et al. (2020) conclude that research is required on the presence, exposure, effects and risks of microplastics in road wear particles.

From a 'green' procurement perspective, it is worth noting that waste legislation and regulation take a precautionary approach when it comes to the management of wastes. That is, that unless the impacts of an activity are known and can be adequately managed, it should not be allowed to proceed. Rubber and plastic asphalt additives manufactured from waste generated within the UK are however, generally considered to be fully-recovered waste by environmental regulators so are not subject to waste regulatory controls when used in asphalt manufacture. As the potential impact these materials have on the environment when released as a result of road wear is as yet unknown, it would be pertinent for procurement policies to consider whether a precautionary approach should be taken or whether the performance and cost benefits outweigh the potential risk. It is recognised that those making the decision on performance and cost benefits may not always be in the best position to make the decision on the potential environmental risk.

Following an assessment of the health and environmental risks posed by intentionally added microplastics the European Chemicals Agency (ECHA) has concluded that an EU-wide restriction would be justified[25]. If approved it is expected that the ban would extend to the use of tyre-derived rubber infill in sports surfaces[26], and there seems to be no particular reason why this would not extend to rubber and plastic added to road surfacing materials.

4.3 Water Pollution Potential

One study in the US examined the impact of leachate from in-situ crumb rubber asphalt on surface water and groundwater (Azizian et al. 2003). Benzothiazole, aluminium and mercury were of particular concern initially, with concentrations of 0.54mg/l, 1.81mg/l and 0.116mg/l respectively. At these levels, these contaminants are considered to be potentially harmful. However, it was concluded that due to degradation and soil sorption, they were unlikely to be transported to nearby soils or groundwater. This research did not specify the asphalt manufacturing process nor the source of rubber and taking into consideration that Scotland's climate and soils differ to those of the US (Oregon), this study is not considered to be particularly relevant. Accordingly, similar research would need to be undertaken in Scotland to ascertain whether leachate from rubber modified asphalt is likely to impact on the water environment.

To date, no similar research has been identified for asphalt modified with waste-derived plastic additives.

4.4 Recyclability of Rubber and Plastic Modified Asphalt

It is unsurprising that recycling asphalt pavements as bound, rather than unbound, pavements and in surface, rather than base, courses, is preferential from an environmental perspective. The reuse of asphalt in surface courses is particularly relevant as there is likely to be a decline in new road construction in the future and therefore less opportunity to use the asphalt in base layers. The potential to recycle road planings from waste-derived rubber or plastic modified asphalts in the bound layers remains uncertain and such materials could be used unbound on tracks, increasing the potential for microplastic release to the environment, or would be landfilled if their reuse in surface course mixes were not feasible.

Mollenhauer et al. (2012) researched opportunities to increase the rate of recycled asphalt pavement (RAP) in new asphalt courses and suggested that the substitution of virgin materials with 15% RAP is significantly more environmentally beneficial than virgin aggregate warm mix asphalt.

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[25] https://echa.europa.eu/-/echa-proposes-to-restrict-intentionally-added-microplastics#:~:text=ECHA%20has%20submitted%20a%20restriction,thousand%20tonnes%20over%2020%20years (interrogated July 2020)

[26] https://scraptirenews.com/2020/07/06/crumb-rubber-infill-facing-ban-in-europe/ (interrogated July 2020)

It must be established whether asphalts containing waste-derived materials are recyclable, and if they are:

- Can this be done in the same way as traditional asphalts?
- Is more energy and/or chemical additives required?
- Will recycling impact on reuse performance?
- Does their recycling require additional health and safety precautions?

Despite the widespread use of rubberised asphalt in the US over several decades, there is relatively little published literature on the use of reclaimed rubberized asphalt pavement in new asphalt mixes. That which is available tends to be laboratory-based research such as Shen et al. (2006), rather than field trials.

In California, where rubber modified asphalt is relatively common, forming up to 35% of new asphalt laid annually, Alavi et al. (2016) note that RAP from mixed conventional and rubberised stockpiles is used in small quantities (< 15% by weight) as a replacement for virgin aggregate, sometimes referred to as ‘black rock’, in conventional dense-graded asphalt mixes and ‘this generally did not result in any problems’. The properties of the aged RAP binders were not taken into account in new mix designs due to the quantity used.

Alavi et al. (2016) examined whether virgin binders could be altered by the addition of aged binders and hence affect pavement performance. It was concluded that adding RAP milled from rubberized asphalt pavement will generally result in better rutting performance than asphalt mixes without RAP, but there was diminished cracking performance at both high and low temperatures. This concurs with work undertaken by Huang et al. (2015) which questioned whether even RAP from non-rubberized roads should be considered as an inert aggregate replacement (black rock) at any percentage due to the poor understanding of the interaction between new and aged binders.

Mollenhauer et al. (2012) assessed opportunities to increase the rate of reclaimed asphalt paving in new asphalt courses. Whilst the research undertaken covered RAP containing PMBs, it did not include those containing waste-derived rubber or plastic. It did, however, suggest that the same principles could theoretically apply.

When RAP is reused in new hot-mix asphalt the binder associated with the RAP (usually highly aged) is softened during RAP heating and/or mixing with virgin aggregates and new binder. To ensure the compatibility of the two binders, the aged RAP binder must be characterised (Mollenhauer et al. 2012) and the blend mix adapted accordingly. As the aged binder may affect the flexibility of the mix, rejuvenator agents may also be added. However, it was noted that aged and new binders did not always fully mix, resulting in double-coating (new over old binder). One method of addressing this would be to use a solvent to extract the aged binder prior to mixing with the new binder (Alavi et al 2016). However, Alavi et al. note that rubberised binders cannot be chemically extracted from aged RAP as the rubber separates from the aged binder during the process. The rubber is also thermoset and it is therefore reasonable to assume that it will not mix with new binders through heating alone and would therefore simply be coated. No information on the effect this has on overall asphalt performance has been identified.

From the available research it may be deduced that there is uncertainty whether incorporating RAP containing rubber will have a positive, neutral or negative impact on asphalt performance.

It is inferred by Alavi et al. (2016) that this lack of research may be a reflection of concerns that reusing RAP containing rubber may lead to reduced demand for end-of-life tyre rubber within the US, so support for the process has not been generated.

Whilst there would appear to be little concern about using RAP containing rubber modifiers in small quantities (<15%) in new surface course material, more research, particularly field trials, on multiple recycling and reuse of this material as a virgin aggregate replacement and in quantities of 15% or greater, is required to confirm that the performance is acceptable.

To date, no known studies have been conducted on the future reuse of waste-derived plastic modified road surfaces probably as a consequence of there being no aged plastic pavements upon which to undertake research. Whilst it may be possible to treat this RAP as 'black rock' when used in small quantities in new surfacing, as indicated by Huang et al. (2015), it should not be assumed that the black rock is inert. More research is needed on the quality, durability and structural performance of new asphalt containing this type of RAP, the potential for multiple recycling and the effect of reuse on process emissions.

4.5 Critical Raw Materials

The European Commission has created a list of critical raw materials for the European Union[27], which is reviewed and updated regularly. The list identifies raw materials of high importance to the EU economy, which are also high risk due to their supply chain, the governance in the country of origin and trade aspects. Essentially, the list has been drawn up so that the materials on it can be prioritised for recycling and recovery in order to reduce reliance on unstable markets outside the EU.

Natural rubber was added to the list in 2017; closed-loop recycling is therefore the preferred option for tyres composed of natural rubber and should ideally not be considered for use in asphalt.

[27] https://ec.europa.eu/growth/sectors/raw-materials/specific-interest/critical_en (interrogated July 2020)

5 OTHER OPPORTUNITIES

While this report focusses primarily on the use of waste-derived materials in road surfacings this section explores opportunities to use such materials in other elements of road infrastructure. There are many areas of road construction that illustrate the industry's commitment to the reuse and recycling of its waste materials. The industry has long facilitated the reuse of earthworks materials, the volumes of which can number in the 100s of thousand cubic metres on larger construction sites. Closer to the theme of this report asphalt planings have, in the preceding 25 years or so, progressed from being rarely recycled in public roads to being a material that is routinely recycled in both bound and unbound layers.

5.1 Pavement Foundation and Earthworks

Tyre shreds and plastic have potential applications in road foundations (Huang et al. 2007). The properties and behaviours of tyre shreds indicate that they might be a useful addition in lower pavement layers due to their light weight/low density, higher hydraulic conductivity and increased shear strength (particularly at large strains). The low thermal conductivity and insulating properties may also render advantages from a winter service perspective as outlined by Winter et al. (2005, 2006) and can help to reduce the depth of frost penetration (Huang et al. 2007).

Contaminant leaching potential, principally heavy metals, associated with tyre shreds is however, a concern (see also Section 5.4). Mohajerani et al. (2020) conclude that due to variations in the environments in which tyre shreds are used, more research is required to establish whether there will be any significant impacts on ground and surface water quality.

In addition, work on polymeric fibre reinforced soil (Seddon et al. 2018) indicated that there were significant difficulties in effectively and economically mixing these synthetic fibres with natural materials using both in-situ and ex-situ processes. This was partly due to the nature of the plant used and the soil type but also a build-up of static electricity was suspected to cause the fibres to clump together during mixing, negating the potential benefits of the reinforcing function. Clumping of fibres was observed at two of the three trial sites inspected by Seddon et al. (2018) and suspected at the third although excavation to confirm this was not possible.

It was also recognised that the potential to reuse road foundation materials containing plastic or rubber at end of life was both uncertain and problematic from both a technical point of view and from a waste management perspective due to it being a composite of different materials. As both road foundation and earthworks materials are processed and placed at ambient temperatures any improvement in the properties from the addition of plastic would rely on long polymeric fibres to provide the desired reinforcement (e.g. Seddon et al. 2018).

These issues combined with concerns associated with plastic and tyre particles being released into the environment and end of life legacy issues led to a strong recommendation that the use of polymeric (and rubber) reinforced soil and aggregate be ceased. While earthworks and foundations tend to last longer than pavements, the technical issues surrounding end of life are similar; however, the greater volumes of such materials and the fact that they have less value than those associated with bound pavement layers mean that less resource and energy can be justified in any associated recycling processes. Comments seemingly supporting the use of plastic in the lower layers of roads, as they are not subject to abrasion meaning that microplastics are not released to into the environment, rather miss the point that end of life issues remain extremely problematic[28].

As noted in Section 4.4, there is the potential to use RAP (including that modified with waste-derived materials) in road foundations. However, as Mollenhauer et al. (2012) observe, there is likely to be a decline in new road construction. From a practical point of view, the opportunity to use RAP in foundation layers is likely to become limited and, from an environmental perspective, the use of RAP in surface courses is preferable.

Significant strides were made towards the use of tyre bales in road foundations and other related road asset-based applications (Winter et al. 2005, 2006) and a Publicly Available Specification (PAS 108) was produced to specify the production of tyre bales for use in construction (BSI 2007; Simm et al. 2008), including the all-important Factory Production Control (see Section 6). Soon after that date the proliferation of those seeking to exploit legitimate avenues for recycling tyres as bales without following the provisions of PAS 108 led the UK Environmental Regulators to tighten the controls on the volume of tyre bale production, storage and use leading to many legitimate operators deciding that the market was no longer viable.

5.2 Bound Lower Pavement Layers

Similar arguments can be applied to the lower bound layers of pavements as are made for pavement surfacings, pavement foundations and earthwork materials, particularly in the context of end of life and the potential to recycle. While the value of such materials is greater than for foundation materials and earthworks, the difficulties of effectively recycling the materials without emitting plastic and rubber to the environment remain significantly challenging.

5.3 Footpath, Cycleway and Car Park Surfacings

The bound surfacings of footpaths, dedicated cycleways and car parks typically incur significantly less wear than those of roads suggesting that the release of waste-derived materials to the environment will be less during the in-service period. However, the choice of surfacing materials for these areas is generally based on cost and in some cases, longevity. Performance properties such as skid resistance, noise reduction, resistance to cracking and rutting are not as relevant and as these areas are not usually constructed to the same standards as roads (attention to surface material quality and consistent thickness, base layer stability, drainage considerations, and so on) their design is appropriate to the intended use.

The potential for waste-derived materials such as rubber and plastic to be released to the environment as a result of surface degradation remains and their use in unbound footpaths,

[28] http://www.htma.info/about-the-htma/news_detail.plastics-use-in-highways.html (interrogated July 2020)

dedicated cycleways and car park surfacings should not be permitted. For footpath and cycleway surfaces in particular, maintenance will generate relatively small amounts of waste making it difficult to manage, and tempting to use in unbound form.

If the surface being maintained is asphaltic, its incorporation in new asphalt mixes should not be problematic from a technical point of view. However, on the basis that enhanced pavement performance is not a consideration in these situations, it must be concluded that the use of waste-derived materials in these environments, whether in bound or unbound form, is a means of linear landfill.

5.4 Drainage

Drainage components, including those for Sustainable Urban Drainage Systems (SUDS), are often made from plastic. In particular, plastic 'milk crate' type spacers are used to create subsurface attenuation voids. There are concerns regarding the emission of plastics to the environment that relate to both virgin and waste-derived materials. The suitability of such units containing waste-derived materials, and potentially virgin materials in the future, will depend on an assessment of their likely degradation in the situation in which they are being used and consequently the environmental regulator may permit their use in some but not necessarily all drainage projects.

Plastic kerb blocks incorporating drainage channels are viewed similarly although there are additional considerations, particularly those issues surrounding cutting, material composition and UV degradation, as covered in Section 5.5.

Whole tyres and tyre bales can and have been used successfully in drainage (Hylands & Shulman 2003; Winter et al. 2006; Simm et al. 2008). Concerns have been expressed regarding the release of heavy metals from tyres and these have been found to be largely within acceptable limits for whole tyres and tyre bales as leaching occurs from only the first 2mm or so depth from the surface of the tyre (Collins et al. 1995, 2002; Simm et al. 2004). With a much greater surface area the conclusion for tyre shred, chip and crumb is that the leaching of heavy metals from such products used in a drainage environment would generally be expected to be unacceptable.

5.5 Street Furniture, Signs, Barriers and Traffic Cones

There are clear opportunities for plastic to be recycled for use in street furniture, such as bollards, warning reflectors, road signs, barriers, cones and seating and to some extent this is already the case. Passively safe columns made of fibreglass-reinforced plastic designed to BS EN 12767 (BSI 2019) are also used by some local authorities.

Trials by Doncaster Council of kerbs that are claimed to be made from plastic bottle tops and closures have resulted in their adoption for use in future projects[29] and similar trials are

[29] https://www.letsrecycle.com/news/latest-news/cumbria-doncaster-participate-plastic-road-initiatives/ (interrogated July 2020)

underway in Wokingham[30]. As the blocks are made from a potentially uniform waste source, recyclability at the end of life is more assured than if they were composed of several plastic polymer types. However, the manufacturer's literature suggests that 182 bottles caps and closures are incorporated into each kerb, which appears to be inconsistent with the seemingly greater 955mm×255mm×125mm kerb dimensions[31]. Notwithstanding this the blocks are lighter than traditional concrete, reducing risks associated with handling-related musculoskeletal injuries.

However, while cutting the plastic kerbs with a handsaw will eliminate the airborne respirable crystalline silica dust potentially associated with cutting concrete blocks, it will produce microplastics; both have potential health and safety impacts while the microplastics also have an environmental impact and must be captured and dealt with effectively, preferably by being returned to the manufacturer for reincorporation into future products. The potential for such units to degrade under the action of UV-light also needs to be considered.

5.6 Environmental Barriers

Other alternative applications for waste-derived plastic and rubber include environmental barriers. Typically, these are noise barriers constructed using waste-derived plastic and tyre-derived rubber material and have been widely researched (e.g. Joynt 2005; Watts & Morgan 2005; Morgan et al. 2015). Noise barriers constructed from waste-derived plastic have been available since the early-2000s, and it is understood that at least one form of such structure is undergoing trial on the Highways England Strategic Road Network in northern England[32].

Additionally, the use of plastic barriers and tunnel lining tiles to absorb pollutants, particularly NO_2[33], has been suggested (Anon. 2019d) and further trials and research by those interested in potentially bringing such products to market may be appropriate.

As with all such products particular attention would need to be paid to ensuring in-service durability, including resistance to the deleterious effects of UV-light on material stability, and end of life applications.

5.7 Closed-loop Recycling

It seems clear that if plastic components such as those described in Sections 5.4 to 5.6 are to be used in road construction, operation and maintenance then every effort should be made to ensure that manufacturers operate an efficient, closed-loop recycling process with product design and composition being targeted to facilitate end of life recycling. Ideally this should be operated within the supply chain (e.g. recycling of material from end of life traffic cones as

[30] https://www.wokingham.co.uk/plastic-eco-friendly-kerbs-part-of-new-cycleway/ (interrogated July 2020)
[31] https://www.durakerb.co.uk/wp-content/uploads/Durakerb-Technical-Brochure-04.pdf (interrogated July 2020)
[32] https://airqualitynews.com/2017/08/02/10613/ (interrogated July 2020)
[33] https://www.thisismoney.co.uk/money/cars/article-8565023/Five-ways-UK-motorways-set-change-coming-years.html (interrogated July 2020)

new traffic cones) but a broader approach may also be acceptable provided that recycling of end of life materials is ensured.

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6 INTRODUCING INNOVATIVE MATERIALS TO THE ROAD NETWORK

The Scottish road network is one of the largest and most visible community assets. It is used for an estimated two million private vehicle journeys and a further one million bus journeys daily (Anon. 2020) and is fundamental to the economic and social wellbeing of Scotland. Asset owners are charged with the care of the nation's infrastructure and to ensure that it is available, and in a suitable condition, for those who wish and need to use it in pursuit of business, education, leisure, health and other pursuits. It is particularly important that the infrastructure is constructed and maintained in a safe condition.

6.1 Product and Design Standards and Construction and Maintenance Specifications

Standards and specifications are published documents that define, or specify, the required quality, performance, compatibility and compliance of a particular asset or component thereof.

In the UK, the design of road infrastructure is governed by the standards contained in the Design Manual for Roads and Bridges[34] (DMRB), including the National Application Annexes of the four nations that constitute the UK, while for construction the Manual of Contract Documents for Highway Works[35] (MCHW), which includes the Specification for Highways Works, is used. These standards and specifications call up detailed content from European and International, including product and other, standards where necessary. It is important to note that these standards and specifications are intended for use on the strategic, or trunk, road and motorway networks in the UK rather than for more lightly trafficked roads that usually fall under the jurisdiction of local authorities.

However, not all such roads are lightly trafficked and local authorities typically use these standards and specifications for highly-trafficked roads albeit that there may be more latitude to depart from these standards and specifications at the discretion of the roads authority (Anon. 2017). For lightly-trafficked local authority roads designers refer to DMRB and MCHW for detailed technical guidance or specification on technical aspects (Anon. 2017) while following the key principles of Designing Streets (Anon. 2010).

6.2 Current Materials

Often standards and specifications define allowable products, materials and processes that are suitable for use. If a particular material or product-type is not mentioned, then it is considered not to be permitted. Standards and specifications form an important safeguard for the road construction and maintenance industry and, more particularly, its customers. Such standards and specifications rely on knowledge of the in-service performance of materials. They enable asset owners to ensure that designs are appropriate and that the methods and materials used to implement those designs will achieve both best value and the

[34] https://www.standardsforhighways.co.uk/dmrb/ (interrogated July 2020)
[35] https://www.standardsforhighways.co.uk/ha/standards/mchw/index.htm (interrogated July 2020)

required performance, even when it is not possible to measure long-term performance at the time of construction.

Currently, the MCHW 1 (Clause 901.2) permits the use in asphalt mixes up to 1% [by mass] of other materials (Class X) including wood, plastic and metal, as contaminants within recycled coarse aggregate or recycled concrete aggregate, but this would not apply to virgin aggregate substitutes.

Clause 902.2 states that "Other recycled materials shall only be used in bituminous mixtures with the approval of the Overseeing Organisation"; thus effectively allowing the possibility that a Departure from Standards might be permitted provided that the performance of the alternative mix can be adequately demonstrated and that it complies with the "… requirements of all the relevant clauses in [the MCHW 1 900] Series."

Stone mastic asphalt surface course (TS2010) (Clause 942TS) is essentially a method, or recipe, specification that is based on trialling and subsequent type approval of individual mixtures and potentially allows the use of waste-derived rubber, and/or waste-derived plastic, in PMBs. However, it should be noted that this was not the intention of TS2010 and the need for mixture specific trials to be conducted and evaluated in accordance with Anon. (2018) remains for such materials (McHale et al. 2011).

Typically, materials used in the construction of road pavements are detailed in European and/or International standards that are administered by the British Standards Institution in the UK. Such standards require a robust, independently-audited quality control process, usually in the form of a Factory Production Control (FPC) (e.g. Simm et al. 2008), to be implemented and used by manufacturers. BS EN 13108[36] details the standards applicable to bituminous mixtures and material specifications with which the material must comply. These standards are revised regularly and evidence of compliance with the most recent versions, including test results, should always be sought.

6.3 Future Materials

Before any new or innovative material can be used on the trunk road network it needs to be approved, and in order for that to happen robust, independently-audited technical evidence demonstrating that the material meets the performance requirements of existing standards and specifications is required.

This process will usually include laboratory tests to demonstrate material properties and behaviours are within acceptable limits, full-scale trials to demonstrate constructability and trials on live roads to demonstrate longer-term performance. In order to ensure the veracity of the results of such activities the work would normally be expected to be undertaken, or at least audited, by organisations independent of the manufacturers and suppliers.

[36] BS EN 13108 comprises up to 31 individual parts (documents) parts and these are not referenced here but the latest versions can be accessed from https://www.bsigroup.com/en-GB/standards/ (interrogated July 2020)

Using this process, and working with the innovators, it is possible to develop a draft standard and to undertake in-service monitoring of applications, the results of which can be used to refine the standard. This iterative process continues until it is possible to bring the new process or material into more routine use and broadly reflects the process used by Transport Scotland to introduce the TS2010 material and associated specification (McHale et al. 2011; Sanders et al. 2017; McHale & Martin 2017, 2019). However, it is important to note that this process of refinement continues throughout the life of the product-type or process as it is further developed and greater knowledge is gained; a good example of such long-term evolution of specifications is given by Parsons (1992).

In addition to the technical requirements related to performance it is important to establish whether any waste-derived materials to be used are considered to be fully recovered waste. If they are not, their use may be subject to waste regulatory controls. Whilst it is the courts that make the final judgement on whether a material is fully-recovered waste or not, if the manufacturer and environmental regulator are in agreement, then legal intervention is unnecessary. It is also important to remember that SEPA may take a different view to other UK environmental regulators on whether a waste is fully-recovered and the material status should be checked with the regulator in whose area it is to be used. SEPA guidance on determining full waste recovery can be accessed on its website[37].

Any additional health and safety issues associated with the manufacture, handling and use of innovative products must also be considered.

6.4 Protocol for Material Introduction

The roads industry in Scotland has an enviable record of both innovation and recycling and it is, from client to contractor, keen to encourage sustainable development.

There are two strands to the acceptance of a new material, product or process for use in Scotland's road pavements: technical and environmental. A protocol for the initial evaluation of such materials, to be managed by the Transport Scotland Pavement Forum (TSPF), is proposed in order to give the manufacturers of new and innovative materials rapid access to a preliminary consideration on the potential future of a new process or material.

This preliminary protocol is based on a traffic light system, scoring a number of factors related to cost, technical efficacy, environmental impact, and health and safety as either 'green', 'amber' or 'red' as set out in Table 2. It is intended that this scoring table should form the basis of a governance system to be developed and evolved to provide initial feedback for those intending to promote innovative materials and processes to those responsible for procuring roads construction and maintenance goods and services. The intention is to give an absolute assessment of one or more materials or technologies rather than necessarily to facilitate a comparison of the purely technical state of development as is the case for the Highways England Technology Readiness Level scheme (Sanders 2016) and which is generally most effective in a comparative setting. It is acknowledged that a protocol is in development

[37] https://www.sepa.org.uk/media/154077/is_it_waste.pdf (interrogated July 2020)

by Highways England in association with the Mineral Products Association but that its use in Scotland will be effectively prevented by the differences between the English and Scottish legislative and regulatory environments.

Table 2. Preliminary evaluation protocol for new and innovative systems and materials for road pavements.

Factor	Description	Score
Whole Life Cost (WLC)	Lower WLC	Green
	WLC neutral	Amber
	Higher WLC	Red
Technical: Manufacturing and construction	Integrates easily with existing manufacturing and construction systems	Green
	Likely to create minor difficulties during manufacturing and construction (e.g. minor modifications to batching plant to address process emissions, material handling/storage pre and post production)	Amber
	Likely to create major difficulties during manufacturing and construction (e.g. major modifications to batching plant and/or difficult to work)	Red
Technical: Material behaviour and performance	Yields a demonstrable improvement in at least one performance or behaviour parameter (e.g. durability, ease of use, ease of installation, …)	Green
	Likely to be behaviour and performance neutral	Amber
	Likely to have an adverse effect on behaviour and performance	Red
Technical: Factory Production Control (FPC)	FPC in-place and independently-audited	Green
	FPC in-development	Amber
	No FPC	Red
Environment: Emissions and CO_2 use	Yields a demonstrable environmental benefit (e.g. reduced noise and/or CO_2 use)	Green
	Possible but unlikely to occur or can be satisfactorily managed	Amber
	Significant additional emissions or CO_2 use	Red
	High risk emissions (e.g. containing hazardous materials, those likely to have long term effects or with unknown consequences)	Red
Environment: End of life waste reuse or recycling	Certainty of end of life waste reuse or recycling	Green
	Lack of certainty or clarity as to the end of life waste reuse or recycling	Amber
	No clear potential route to end of life waste reuse or recycling	Red
Human health & safety	Promotes a safer working environment and/or wider human health and safety benefits	Green
	No known or suspected issues, or minor issues that can be effectively eliminated and COSHH available	Amber
	Significant issues that cannot be effectively eliminated or no COSHH	Red

The primary aim of any such governance process must be to ensure that the same rigorous standards and processes are applied to new and innovative materials as are applied to standard materials. This will help road authorities to meet the obligations placed on them by government and society. The intention is that a single ‘Red’ score would generally rule out the material or process for use on the road network. One or more ‘Amber’ scores would require further investigation which may deliver a potential route to use or rule out the material or process.

It is intended that those materials and processes that pass this initial test would next be subject to independently conducted and audited testing and trial as specified by the TSPF, normally at the expense of the manufacturer or supplier of the material or process. Trials are expected to be preceded by laboratory testing to inform the design of the in-situ trial and one or more control sections will be required. Where possible trials of different materials of processes will be combined with a view to reducing the financial burden of the manufacturer or supplier; this shall be entirely at the discretion of the TSPF. It is further expected that tests, evaluations and inspections shall be conducted during construction and thereafter, at intervals specified by the TSPF, in order to assess long term performance.

This trial process will require the full disclosure of the material(s) and/or process(es) in order that the tests and trials can be designed, specified, conducted, analysed and interpreted to the benefit of all parties. Non-disclosure may be allowable if the material complies with a recognised, audited industry specification that allows confidence in the material or product. It is expected that the results will be published in an open, accessible and peer-reviewed format. This information is also essential for assessments of human health and safety and environmental issues. The minimum required is an assessment under the Control of Substances Hazardous to Health Regulations 2002 (often referred to as COSHH) (see HSE 2012, 2013, 2020). It is also important that throughout this process the materials to be evaluated are maintained in a consistent form if a valid and acceptable outcome is to result; it will be tempting to make adjustments and further innovations but these introduce inconsistency and prevent an evaluation being completed successfully.

Any waste-derived product or material approval by the TSPF using the Protocol will be specific to that proposed by a specific company and to the detailed constituents of that product or material. Approvals will not be applicable to generic products, materials or processes (e.g. rubber in asphalt) regardless of the way in which they are used.

In parallel, if proposals involve the use of waste, there is a requirement to enter into dialogue with SEPA to ascertain what waste regulatory controls will apply. This would also be expected where wastes that are purported to be fully recovered are to be used, if they are not identical to their virgin equivalent. It is expected that SEPA and TSPF would mutually consult and that a negative decision by either would render an overall negative decision on the future use of the new and innovative material.

Enquiries should initially be submitted to the Transport Scotland Pavement Forum care of the Head of Materials and Standards Branch at Transport Scotland and SEPA’s National Operations Waste Unit.

In the longer term, consideration should be given to comparative LCA of any materials or processes implemented on the road network through this process. It is, of course, essential that the comparative LCA includes one or more established materials or processes in order to ensure that a valid comparison can be made.

7 DISCUSSION

In this report the use of waste-derived glass, rubber and plastic in road surfacings is examined from the viewpoint of technical efficacy, waste regulation and environmental impact. In Section 2.4 a series of questions was posed as a means of evaluation of the use of such materials. These questions are now answered for each material in the following paragraphs.

7.1 Glass

Is the waste-derived material a direct substitute for virgin material?

- Yes. The glass is a substitute for aggregate.

Does it enhance the properties and quality of the binder/asphalt?

- Potentially. Improved workability and resistance to thermal cracking of asphalt are reported, but there may also be increased bleeding, stripping and sensitivity to water damage.

Are there any additional health and safety precautions during manufacture and construction to consider?

- No.

Are there any additional environmental impacts associated with the use of asphalts containing the waste-derived material?

- No, but the preference within the glass industry is closed-loop recycling.

Is the use of the material cost-effective for the road industry?

- No.

Can the asphalt subsequently be recycled at the end of life and are special precautions necessary?

- Yes it can be recycled at end of life and no special precautions are necessary.

7.2 Rubber

Is the waste-derived material a direct substitute for virgin material?

- Yes, it can potentially be used as a binder modifier.

Does it enhance the properties and quality of the binder/asphalt?

- Yes. Rubberised asphalt is reported to be more resistant to rutting and cracking, extending the life of the asphalt, as well as reducing tyre noise.

Are there any additional health and safety precautions during manufacture and construction to consider?

- No.

Are there any additional environmental impacts associated with the use of asphalts containing the waste-derived material?

- Yes, there is the potential for the release of nano and microplastics as a result of road wear as well as during planing and processing at the end of the pavement life, albeit that the amounts used, and thus the emissions will be small.

Is the use of the material cost-effective for the road industry?

- No, but it is an inexpensive means of managing a problematic waste when compared with other options for end of life tyres such as closed-loop recycling activities.

Can the asphalt subsequently be recycled at the end of life and are special precautions necessary?

- Yes, but currently in limited quantities. Little is known about the interaction of old (rubberised) binder with new binder and subsequently the impact on long-term performance and pavement longevity.

7.3 Plastics

Is the waste-derived material a direct substitute for virgin material?

- Yes, potentially as a bitumen replacement and is marketed as a binder extender/enhancer depending on the type of plastic but the amounts used are very small. It is also being trialled as an aggregate replacement in some countries, but no waste-derived plastic products marketed for use in asphalt in the UK currently meet the MCHW 1 aggregates criteria.

Does it enhance the properties and quality of the binder/asphalt?

- Unproven, but there is potentially improved resistance to moisture damage, cracking and rutting performance. This is dependent on the type of plastic used and whether it melts fully in the asphalt mix. Some plastics are however, reported to increase moisture damage potential. More work on this is required to provide evidence of benefits and research must clearly identify the type or mixtures of component plastics and their ratios in the material marketed.

Are there any additional health and safety precautions during manufacture and construction to consider?

- Potentially. It has not been possible to obtain details on the ‘activators’ (compatibilizers) used in materials marketed in Scotland, so it is not possible to provide a definitive comment. Further work on fume analysis is also required.

Are there any additional environmental impacts associated with the use of asphalts containing the waste-derived material?

- There is potential for nano and microplastics to be released during road surface wear as well as during planing and processing at the end of pavement life. However, the quantity of waste-derived plastic, and thus the emissions, will be small.

Is the use of the material cost-effective for the road industry?

- Where waste plastic types are separated (either at source or after collection to fulfil product quality criteria) they have more value than co-mingled plastics due to their potential for use in plastic remanufacturing. The costs may therefore be higher than the virgin equivalent it is being used to substitute. This is dependent on waste reprocessing capacity, proximity and demand. For mixed plastic types that have not been separated and therefore have not been through a quality control procedure, the cost may be lower than the virgin equivalent but material performance within an asphalt mix is unlikely to be guaranteed.

Can the asphalt subsequently be recycled at the end of life and are special precautions necessary?

- Potentially, but no evidence is available to demonstrate this and the interaction between aged plastic binders and new binders needs to be investigated. Potential release of nano and microplastics to the environment during reprocessing must also be considered particularly as they have been found in human tissue.

While outside the scope of this report, it is recognised that virgin plastic is used in bitumen mixes, commonly called Polymer Modified Bitumen (PMB). It is important to note that the quality and lack of contaminants in virgin materials are strictly controlled through accepted standards and specifications, and, as the composition is known, miscibility of the plastics is assured.

The potential for the use of waste-derived glass in asphalt is primarily limited by the efforts of the UK glass industry to undertake closed-loop recycling and to maintain the value of the resource. However, for rubber and plastic the situation is rather different. In Figure 2 (Section 2.2) the development of waste-derived material products was illustrated. The position of rubber and glass on this continuum is potentially contentious as some demonstration projects have been undertaken. In the US, the use of waste-derived rubber in asphalt is at the fully-developed stage, whereas in the UK it is still being trialled; waste-derived plastic however, is in the research phase (Figure 4).

7.4 Microplastics in the Environment

The issue of the release of microplastics in the environment is one that is of increasing concern to society globally. Plastic is considered to be a potential marker for the Anthropocene in the future sedimentary record (e.g. Corcoran et al. 2014, 2015, 2017; Bank & Hansson 2019), with Corcoran et al. (2014) having identified 'plastiglomerate' materials formed from waste plastic in the environment and naturally occurring geological materials. Such a significant negative legacy is not considered to be one to which the road construction and maintenance industry should actively seek to contribute.

The contribution of road transport to the problem of plastic in the environment is highlighted by the work of Roychand & Pramanik (2019) who noted significant amounts of tyre wear particles in road dust samples collected from Australian roads. The road transport industry in Europe is responsible for the production of an estimated 500,000 tonnes of particulate matter from tyre wear per annum. Such particulate matter is the second-largest microplastic pollutant in the oceans[38]. While this is not a problem that Scottish, or UK, road authorities have the power or the resources to tackle it is clear that this will need to be addressed by the road transport and vehicle industries in the near future[39].

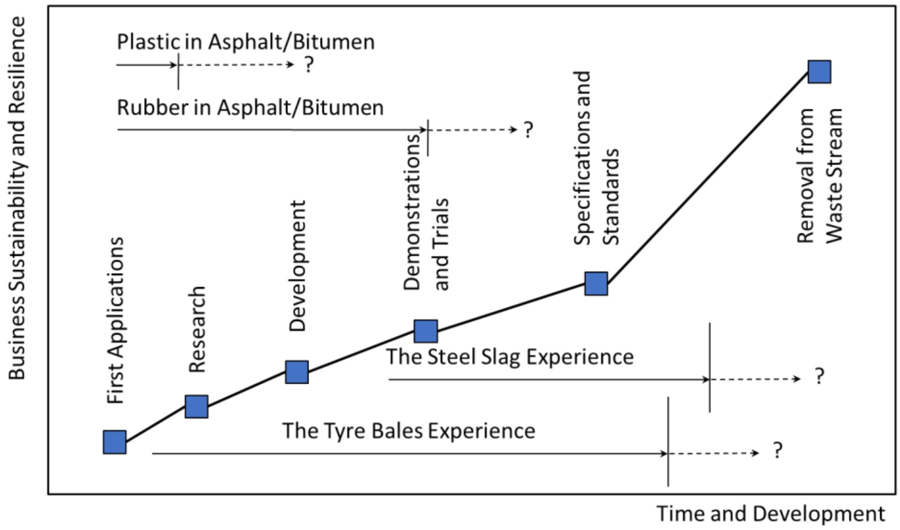

Figure 4. The development of business-based on the production and sale of waste-derived material products showing the progress of waste-derived rubber and plastic in bitumen or asphalt in the UK (adapted from Winter & Gomes Correia 2019).

As if to reinforce this point yet further, recent research (Rolsky et al. 2020) found microplastics in human organs that provide a filtration function, demonstrating the immediacy of the problem of nano and microplastics entering the environment as well as the longer-term impacts. Cingotti & Howard (2020) identify the synthetic chemicals in plastic that are thought to be carcinogenic, neurotoxicants and may cause endocrine disruption in humans and Li et al (2020) report on uptake by plants of microplastics in soils. This means they are entering the human food chain either through direct ingestion of crops or indirectly through ingestion of grazing animals and their products (e.g. meat and dairy products[40]).

The UK Plastics Pact supported by the development of PAS 510, with the aim of introducing measures to prevent the leakage of such materials to the environment, demonstrates the growing commitment to the issue of environmental microplastics in the influential charity sector. Bournemouth Christchurch & Poole Council provide an example of leadership in this area with funding for an Ecohub that will inter alia focus on "… behavioural change with

[38] https://www.gov.uk/government/consultations/air-quality-brake-tyre-and-road-surface-wear-call-for-evidence/outcome/brake-tyre-and-road-surface-wear-call-for-evidence-summary-of-responses (interrogated September 2020)
[39] https://www.theguardian.com/environment/2020/sep/17/device-to-curb-microplastic-emissions-wins-james-dyson-award (interrogated September 2020)
[40] www.ehn.org/plastic-in-farm-soil-and-food-2647384684.html?rebelltitem=4#rebelltitem4 (interrogated September 2020)

visitors taking away a new awareness around plastic use and recycling …"[41], including microplastics in the environment.

The need for further work to allow the use of waste-derived plastic in road construction and an associated governance structure similar to that proposed in Section 6 was highlighted by Chin & Damon (2019) and this has been followed up by an Austroads technical research project[42]. The stated objective of this newly-commissioned research is to develop evidence-based and performance-based specifications to establish a road-grade plastic polymer sourced from recycled plastic manufacturers and material recovery facilities. This reiterates the need for significantly greater understanding and control of such uses of waste-derived plastic compared to that available at present.

In parallel, it is considered essential that Scotland's road authorities need to play their part in controlling the emission of nano and microplastics to the environment by not adopting new materials that have the potential to increase the emission of such materials to the environment.

7.5 Future Use

It is proposed that waste-derived plastic and rubber should not be further used in road surfacing, in bound layers of road construction, at the present time, unless in a trial situation.

It is further proposed that waste-derived plastic and rubber should not be further used in the unbound layers of road construction, including the foundations layer(s), or in earthworks other than as fully-accredited geosynthetic materials.

These statements are based on the current state-of-the-art and its application. While this closes opportunities for such use in the short-term it is fully-accepted that this may change in the future. It is entirely possible that the use of waste-derived rubber and/or plastic could successfully meet the requirements of the protocol described in Section 6. However, in order for that process to commence the following criteria must be met:

- Performance of the modified and/or extended material must be demonstrated to be at least at the level expected of conventional materials. While international research and trials provides helpful background, variations in the composition of waste-derived additives, asphalt mixes and processes and climate mean their relevance to Scottish road construction and maintenance is not assured.
- Issues surrounding the emission of microplastics (and other plastics) to the environment must be satisfactorily addressed, including in the context of planer removal of the material that has reached end of life.
- The end of life recyclability of the material must be demonstrated to be satisfactory including the performance of the recycled material.

[41] https://www.bcpcouncil.gov.uk/News/News-Articles/Environmental-Innovation-Hub-planned-for-Dorset-coast.aspx (interrogated September 2020)
[42] https://austroads.com.au/projects/project?id=APT6305 (interrogated September 2020)

In terms of the development of waste-derived materials use in road construction and maintenance it is important to consider the technical, financial, environmental, and health and safety criteria set-out in Table 2 (Section 6). Taking an honest and open approach to the necessary engagement with the TSPF will make the decision-making process easier and, most likely, lead to more timely decisions on the potential way forward.

8 CONCLUSIONS AND RECOMMENDATIONS

8.1 Conclusions

In recent years the use of waste-derived glass, rubber and plastic in bitumen or asphalt has been promoted with claims of dramatically increased performance and/or as an effective means of dealing with such wastes. In this report the potential use of such materials has been examined from the performance, financial, environmental, health and safety, and, as far as possible, financial perspectives.

The use of glass in road surfacings, or other parts of the road asset, is unlikely to progress further in the context of the strong lead being provided by the UK glass industry towards a system of closed-loop recycling that effectively keeps waste-derived glass within that industry.

The use of waste-derived rubber may increase if the claimed performance benefits of rubberised road surfacings can be proven in the UK, particularly as currently there is a lack of capacity for sustainably treating end of life tyres. However, concerns remain regarding waste-derived material quality control (including the potential for contaminants and the suitability of tyres for processing into asphalt additive materials) and the potential for the release of microplastics during pavement service and at end of life.

The case for waste-derived plastics to improve the performance of bitumen or asphalt is far from proven. There are also concerns around the quality control of mixed waste-derived plastics and this needs to be addressed to prevent batch and ultimately pavement performance variation.

In addition, and as for rubber, there are significant concerns around the release of microplastics to the environment. The Scottish Government has signalled its intention to tackle the microplastic problem and has gone so far as to introduce legislation to prevent the sale of goods such as cosmetics and personal hygiene products which contain plastic microbeads (The Environmental Protection (Microbeads) (Scotland) Regulations 2018). Scotland is also a signatory to the Ellen MacArthur Foundation's New Plastics Economy global commitment to end plastic pollution and it is questionable therefore whether the use of waste-derived plastics in road surfaces is aligned with government policy.

Modular plastic roads made with waste-derived materials have also been trialled, most notably in the Netherlands. These also raise concerns regarding the release of microplastics to the environment, particularly as a result of wear during their service life.

The issue of microplastics is one that is of great concern to society and in isolation would point to a decision to cease the use of waste-derived plastics in road surfacings. In combination with the lack of clear performance benefits from the addition of waste-derived plastics to bitumen or asphalt a decision to not use such materials seems straightforward.

The use of waste-derived rubber or plastics in pavement foundations, earthworks and unbound and bound lower pavement layers is also not recommended due to the same concerns surrounding the release of microplastics at the end of the service life. It is perhaps noteworthy that Highways England ceased the use of fibre reinforced soil in late-2018. For footway, cycleways and car parks, where increased performance is not required, the use of such materials can only be described as a means of linear landfill. This is not intended to include fully-accredited geosynthetic materials that form discrete layers within the structure rather than exist within the mix in a random distribution.

Where there does seem to be some potential to allow for the use of waste-derived plastic in parts of the road asset is where these are non-composite/single-material, quality controlled products. These might include drainage elements, kerbs, street furniture, signs, barriers, traffic cones and environmental barriers. Indeed, the authors are aware of moves within the industry to promote, trial and use such products. Notwithstanding this, there is a need to ensure the control of the potential release of microplastics, particularly if the products may need to be cut during construction. In addition, as with all such products particular attention would need to be paid to ensuring in-service durability, including resistance to the deleterious effects of UV-light on material stability, and end of life applications. Closed-loop recycling of such products is to be encouraged.

Uses of plastic in roads in Scotland to date largely constitute demonstration projects rather than formal trials to assess technical performance. These demonstrations all appear to use the dry process, in which plastics are added to the asphalt mix as a binder extender or enhancer. No evidence is available to suggest that a formal design process has been undertaken to optimise the performance of the final mix.

A protocol for the introduction of innovative materials and processes, including those containing waste-derived materials, to the road network has been proposed. This is tentative and intended as a starting point further development prior to implementation. The protocol considers technical, financial, environmental, and health and safety aspects of innovative materials and processes. The focus is on pavement surfacing materials but it could be extended to encompass other asset features albeit that other disciplines, earthworks for example, would require a rather different approach to the detailed evaluation process.

This work will help Scottish roads authorities to continue to assist and contribute to the delivery of government priorities, including those related to climate change.

8.2 Recommendations

Recommendation 1: Based on the evidence currently available there is, as yet, no viable technical, environmental or economic case for the use (addition or replacement) of waste-derived glass or plastic in asphalt.

Recommendation 2: While the research is further advanced for waste-derived rubber (addition or replacement) than for plastic, the available technical and environmental case for its use in asphalt does not yet fully-support its use. Further research and trials are needed in this area including through the use of the protocol described in Section 6.

Recommendation 3: It is recommended that waste-derived (or virgin) rubber or plastic not be used in unbound pavements layers, including the foundation layer(s), or in earthworks other than as fully-accredited geosynthetic materials.

Recommendation 4: It is recommended that in the future the use of waste-derived materials in road surfacing and other structural and foundation layers should be subject to the scrutiny of the TSPF under the protocol described in Recommendation 6.

Recommendation 5: Opportunities should be sought to use waste-derived materials and products in other non-composite/single material-type, quality controlled products. These might include drainage elements, kerbs, street furniture, signs, barriers, traffic cones and environmental barriers. Such use should be subject to a full evaluation of the technical, financial, environmental, and health and safety efficacy and impacts of the product.

Recommendation 6: A protocol to steer the appropriate and constructive use of waste-derived materials and products in pavements should be introduced.

Recommendation 7: That the protocol in Recommendation 6 be extended to include innovative (non-waste) materials, products and processes that are proposed for use in pavements and innovative (waste-derived and non-waste) materials, products and processes in other elements of the road asset.

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Shaun Millar, Roads Collaboration Programme.

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APPENDIX A: CONSULTATION

A.1 Survey of Local Authorities

All Scottish local authorities were contacted by the Roads Collaboration Programme to ascertain whether or not they had any experience of using recycled (or waste-derived) materials in road surfacing materials. This was followed up with a request for further details using the questionnaire in Appendix B.

Seventeen (53%) questionnaire surveys were returned from the 32 authorities. Question 1 related to the anonymity of the respondent and is not reported here.

Question 2: Has your LA held discussions on using recycled materials in road surfacing?

Of the 17 respondents, 10 (59%) gave either a null or 'no' response to Question 2. Of the remaining seven (100%) that responded 'yes' all (100%) had held discussions on plastic and one (14%) had also held discussions on the use of rubber. For five (71%) the outcome was to go ahead with a trial of which three (60%) are currently planned and two are complete (40%) (two. Or 29%, of the seven respondents did not specify the outcome of their discussions).

The respondent who reported that discussions had been held for both rubber and plastic did not respond to Questions 3 to 9 so the information below is relevant only to the use of plastic.

Question 3: What were the drivers behind the trial objectives?

Of the seven who responded positively to Question 1, five (71%) responded to this question three (60%) stated that the trial objects were to obtain the same performance and one (20%) to obtain enhanced performance compared to conventional asphalt. One (20%) specified 'other' and noted a open-ended curiosity as to the relative performance. One further respondent who did not specify the outcome of their discussions noted that it was felt that there were too many unknowns associated with the use of waste-derived plastic in roads were to great to proceed with a trial.

Question 4: Did the LA workforce lay the waste modified asphalt?

Three (43%) responded to this question with two (67%) reporting that the local authority workforce laid the modified asphalt and that that there were no handling issues. The third respondent (33%) reported that the local authority did not lay the modified asphalt and did not respond on the question of handling issues.

Question 5: Was travel time from the asphalt plant to site a consideration or limitation?

Four (57%) responded to this question and three (75%) reported no consideration or limitation on travel time while the fourth (25%) reported that there were considerations or limitations.

Question 6: Were there any modifications to working practices required when laying the material?

One (14%) responded to this question and the respondent, at pains to point out that the experience was purely anecdotal, noted that Operatives found it stiffer once laid and that it could be trafficked sooner. [It is important to note that increased stiffness can be to the detriment of long-term performance as well as a benefit in terms of allowing earlier trafficking.]

Question 7: Health and safety

Two (29%) responded to this question noted no additional requirements or observations on health and safety issues.

Question 8: Costs

Three (43%) responded to this question were split with one (33%) reporting that the costs were the same but that there was a subsidy and two (67%) reporting higher costs without subsidy. This sems to imply that, independent of any subsidy, costs will be higher for plastic roads.

Question 9: Who takes responsibility for the asphalt should it not perform as expected?

Three (43%) responded to this question with one (33%) stating that responsibility for any lack of performance was taken by the asphalt producer and two (67%) that responsibility was taken by the local authority.

Question 10: Developer use of asphalt containing waste-derived additives

Fourteen (82%) responded to the question about whether they were aware of developer plans to use so called 'green' asphalt containing waste-derived additives in new roads that the local authority will ultimately have to adopt. Of those 11 (79%) responded 'no' and three (21%) 'yes'. Of the latter one noted that discussions with a local house builder led to a trial despite the local authority expressing reservations about the future adoption of the road that had been selected.

Twelve (71%) response to the question 'Do you have any influence over what material developers use?', with 4 (33%) responding 'no' and 8 (67%) responding 'yes'. Six of those who responded 'yes' also made text comments that centred around the requirement that of developers comply with National Road Development Guide (Anon. 2017), the importance of ensuring that the mix was appropriate for the batching plant, the influence of internal local authority structures and active engagement with developers.

Further comments were also made in the freeform text box at the end. These included the need and desire to await the guidance that is promulgated through this current project and for Scottish local authorities to act in a consistent manner on this issue, including in the context of pressure from developers and others through Elected Members despite concerns of the engineering team. Other comments pointed to the approach that might be taken if approaches were received from developers and set out details of some demonstration projects that had been constructed.

A.2 Wider Consultation

Wider consultation has been undertaken with manufacturers of asphalt and key industry bodies. This has been largely through the vehicle of the Steering Group both through formal meetings and more informal contacts and discussions.

Formal meetings and discussions have also been conducted with the Society of Chief Officers of Transportation in Scotland (SCOTS) Roads Group and informal contacts have been with individual members have also been pursued.

Additional contact and liaison has also been effected with Highways England, Cumbria County Council and Lincolnshire County Council, and ADEPT were represented on the Steering Group.

SEPA were consulted, in particular, on issues related to waste management and associated legislation and regulation.

While the project team reached out to manufacturers of waste-derived rubber and plastic for use in asphalt no responses were received (see Appendix C).

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APPENDIX B: LOCAL AUTHORITY QUESTIONNAIRE

Questionnaire for Scottish Local Authorities – July 2020 **'Green' LA roads in Scotland**

The Scottish Roads Research Board (SRRB) has commissioned a project through the Roads Collaboration Programme to examine and provide guidance on the current and future use of recycled waste materials in road surfacing construction.

For the purpose of this questionnaire, only asphalt containing recycled waste other than reclaimed asphalt planings (RAP) should be considered (e.g. plastic, rubber, glass, etc.).

The objective of this questionnaire is to enable the project team to judge the recent, current and future extent of the use of such materials in road construction, the drivers for such use and trials, and some issues around logistics, working practices, health and safety, costs and liability.

This should also give the team a good steer on the current status of local policy regarding the use of asphalt containing waste-derived additives.

Please answer the questions using the 'Grey' drop down boxes, tick boxes and free text cells.

Question 1 Anonymity

a) Do you want your response to be anonymous, or are you happy to provide contact details should the project team have any queries?

Contact details:

b) Can the final report make reference to your Local Authority or is it preferred that the information is anonymised?

Question 2 Has your LA held discussions on using recycled materials in road surfacing?

a) If the answer is 'yes', what materials have been discussed? Please tick all that apply and provide details of 'Other' materials used below:

- ☐ Plastic
- ☐ Rubber
- ☐ Glass
- ☐ Other

If 'Other' please specify:

b) Was the outcome of these discussions to go ahead with a trial or accept the performance information and utilise the modified asphalt?

c) If 'yes', is the trial(s)/utilisation planned, current or complete?

Question 3 What were the drivers behind the trial objectives? To ascertain whether the performance of the asphalt containing waste-derived materials compared to traditional asphalt was (Please Select):

If 'Other' please specify:

Question 4 Did the LA workforce lay the waste modified asphalt?

a) Were there any handling issues associated with its use?

Question 5 Was travel time from the asphalt plant to site a consideration or limitation?

Question 6 Were there any modifications to working practices required when laying the material?

a) Shorter timeframe for using the asphalt?

b) Observations on workability/ease of use?

If 'yes' please provide details:

Question 6 Were there any modifications to working practices required when laying the material?	
a) Shorter timeframe for using the asphalt?	
b) Observations on workability/ease of use?	
If 'yes' please provide details:	
Question 7 Health and Safety:	
a) Were there any additional H&S requirements for the workforce using the material?	
b) Were there any observations on whether the material was better, worse or the same to use e.g. in terms of fumes?	
If 'yes' please provide details:	
Question 8 Costs:	
a) Was the cost of the material higher, lower or the same as the asphalt you would normally procure?	
b) Was the cost reduced or subsidised to encourage the use/trialling of the asphalt (the project team is aware that some asphalt producers have been requested to absorb additional costs associated with the use of waste-derived additives to encourage trials)?	
Question 9 Who takes responsibility for the asphalt should it not perform as expected?	◯ Local Authority ◯ Asphalt producer ◯ Recycled material provider ◯ Shared (please specify)
If 'Shared' please specify:	
Question 10 Developer use of asphalt containing waste-derived additives:	
a) Are you aware of developer plans to use so called 'green' asphalt containing waste derived additives in new roads that the Local Authority will ultimately have to adopt?	
If 'yes' please provide further details if you are willing and able to do so:	
b) Do you have any influence over what material developers use?	
If 'yes' please provide further details if you are willing and able to do so:	

If you have any further coments please use this box to provide them (please alsp feel free to contine your comments on a separate sheet of paper):

Thank you for your assistance on behalf of the Project Team (Mike Winter and Paula Coopland)

Please return this completed questionaire to:

Shaun Millar at Improvement Service: Shaun.Millar@improvementservice.org.uk

APPENDIX C: INFORMATION REQUESTS FOR MANUFACTURERS

Dear Sirs

We have been commissioned by the Scottish Road Research Board to undertake a study on Recycled Materials in Road Construction & Maintenance. The project summary and web address are given below.

One of the materials and processes that we are keen to evaluate in terms of its potential future use in road surfacings and the lower bound layers is waste-derived glass/rubber/plastic*. While there is a great deal of literature available most is insufficiently specific as to material type, mix, processing, etc to be able make valid comparisons and to draw conclusions. [Where appropriate a note on information already examined and with which the manufacturer is closely linked: e.g. website material.]

We are now seeking further more detailed information on test properties of the bitumen and asphalt mixes with waste-derived glass/rubber/plastic* added as both extender and modifier. The information that we seek relates to laboratory test results, the design of asphalt mixes, and UK-based trials including tests undertaken during and after construction.

We are also seeking information on the quality control processes implemented and full product data safety information.

We hope that you will be able to assist us with this request and allow us to better advise Scottish road authorities how the use of waste-derived glass/rubber/plastic* in asphalt might best be progressed.

Thank you in anticipation

Recycled Materials in Road Construction & Maintenance

(https://www.transport.gov.scot/our-approach/industry-guidance/scottish-road-research-board/#45123)

Collaborative study between all Scottish road authorities and the main material suppliers to undertake a literature review of published research into the use of recycled materials in road construction/ maintenance, collate all current UK trialling and testing of recycled materials in road (and associated) infrastructure, and identify any materials/processes worthy of further consideration and/or research.

Completion expected: Summer 2021

* Deleted as applicable to each manufacturer contacted.

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APPENDIX D: INFORMATION ON UK TRIALS

D.1 Glass

Trials by Lincolnshire County Council (see also Section 3.1) in 2001 and 2002 used varying amounts of glass and RAP to replace virgin aggregate in 20mm base course recipe mixes. The non-absorbent nature of glass particles means that the binder (bitumen) content could potentially be reduced without impacting on fatigue performance and accordingly filler contents were maintained in order to reduce the potential for deformation. This was further addressed by using crushed rock or crushed slag fine aggregate rather than using natural sand for locations of high traffic and/or stress. Visual inspections and routine deflectograph, SCRIM and SCANNER surveys continued until 2010.

Even when used as an aggregate replacement the non-absorbent nature of the particles meant that the binder content had to be reduced to facilitate handling of the asphalt and the post-compaction air voids value was slightly increased.

However, longer term monitoring found a tendency for the bond between layers to be compromised in contrast to the typical experience that marginal bonds improve over time. Some of the trial sites remain in service and it is reportedly common to encounter a lack of bond when coring 'Glassphalt' material for deflectograph or future works purposes. The trial concluded that that 30% glass (without RAP) was the optimum performance mix.

D.1 Rubber

All of the known trials were undertaken using asphalt manufactured using the dry process.

2012

Trial sections of a 14mm and 10mm SMA ground tyre rubber, modified thin surface course, were laid on the A90 in Scotland in April 2012. The 14mm section was replaced in 2019, but it is known to have been affected by bad load ends at the time of laying, so the early demise of the surface was not unexpected. The 10mm trial surface however, is reported to still be performing satisfactorily. The granulated tyre rubber used was not sourced from within the UK.

A 10mm SMA containing 1% ground tyre rubber by weight of asphalt was laid at a compound at Cairneyhill in West Fife after transporting it for 30 miles to determine susceptibility to binder migration during transport. It was noted that the load discharged cleanly to the paver and comments from Contracting operatives were favourable. Again, the granulated tyre rubber used was not sourced from within the UK.

2013

Two trial strips of 10mm SMA containing 0.67% ground tyre rubber by weight of asphalt (sourced from outside the UK) were laid in the presence of Transport Scotland at a compound in Cairneyhill and both were cored for testing. The trial results indicate that the asphalt was within TS2010 trial limits and the strips are reported to be performing well.

Trial strips were also laid on a site in Whitley Bay, North Tyneside. These trial mixes replicated the target compositions used in the Cairneyhill trials, but used the local Northumberland basalt. Granulated tyre rubber sourced from outside the UK and from Suffolk, with a similar particle size distribution, were used to modify the asphalt. Annual site visits have been carried out to monitor performance and it is reported that both of the asphalt surfaces are performing well.

2018

Four site trials within the Coventry City Council area were undertaken using 1% ground tyre rubber by weight of asphalt from Suffolk. 10mm rubber modified SMA has been installed on three sites and a 6mm rubber modified SMA was also produced and laid on a housing estate road and all are reported to be performing well.

2019

In May, 120 tonnes of a 14mm rubber modified SMA containing 1% ground tyre rubber from Suffolk was installed in lane 1 of the M1 near Junction 22 in Leicestershire. Highways England commissioned AECOM to carry out laboratory testing on the asphalt supplied to site. The durability of the surface is being monitored.

In October, 37 tonnes of rubber modified SMA was laid in lane 1 of the M9 between Junctions 8 and 9. Coring and site testing was carried out by independent assessors and wheel tracking testing was carried out by Tarmac. The results showed that the material was within permitted compliance limits and the texture depth of 1.2mm complies with the requirement for high speed roads.

2020

A trial stretch of the A6075 Forest Road, Ollerton, Nottinghamshire was laid in March.

General Observations

The product appears to be highly tolerant to extended travel and storage time. It is reported that during an enforced prolonged delay between manufacture and laying of around four hours, that the mix was still fully homogenous.

It is reported that for every tonne of asphalt produced, potentially one and a half tyres worth of rubber is used and for every mile of road, this could provide an opportunity to use rubber from up to 750 waste tyres.

Tarmac, which undertook the majority of the trials to date, anticipates that rubberised asphalt will be shown to provide at least the same level of safety, grip and rideability performance as conventional asphalt[43].

D.3 Plastic

Whilst waste-derived plastic modified asphalt has been laid at several sites throughout the UK, to date, little independent coring and testing has been undertaken and/or the results are not in the public domain due to commercial constraints. Public information is also lacking on the actual quantities of waste-derived plastic added to the asphalt mixes laid at the different sites and the proportions of different plastics used. It is also apparent there have been product changes since the first demonstrations were undertaken. Due to these potential variables, it is not possible to make comparisons between demonstration sites and the waste-derived plastic suppliers claims can therefore not be substantiated at this time.

Some examples of where waste-derived plastic modified asphalt has been laid can be found in the central belt of Scotland, Dumfriesshire and Ayrshire as well as in Cumbria, Northumbria, the London Borough of Enfield and Coventry. ADEPT 'Live Lab' trails are however, currently being progressed in Cumbria and these will provide independent analysis and performance information.

Demonstrations

200 tonnes of waste-derived plastic modified asphalt were laid near a quarry in Hexham in Cumbria. Core samples were taken and there were no visible signs of plastic. It has not been possible to source information on the plastic product, asphalt design mix or core testing results.

In October 2018 on the A883 (Stirling Street in Denny) a strip of modified hot rolled asphalt was laid adjacent to conventional hot rolled asphalt and in November 2018, panel patching was undertaken at Bankside, Falkirk. No visual differences between the conventional and modified mixes is currently evident. The local authority also advised that the cost of the modified hot rolled asphalt was higher than the conventional asphalt at the time, but the additional cost was borne by the asphalt producer. Due to the relatively short length of time that the pavements have been in place, it is not possible to ascertain whether the potential additional cost of the modified asphalt can be justified by any performance benefits.

[43] http://sustainability-report.tarmac.com/case-studies/rubber-roads-pave-the-way-for-tyre-recycling-as-tarmac-expands-asphalt-range/ (interrogated September 2020)

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