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EVALUATION OF THE PROPERTIES OF RUBBER-AGGREGATE PAVEMENTS FOR USE IN MULTI-USER PATHS AND TRACKS

BY

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Abstract

Growth in cycling and the associated infrastructure in the UK is set to continue. New cycle paths are often constructed on existing multi-user paths and tracks which have previously been surfaced with soft or loose materials. This has sometimes led to conflict because the different groups of users have differing surfacing requirements and needs; with equestrians and runners generally preferring soft tracks and walkers and cyclists generally preferring firm surfaces.

In an attempt to find a solution, rubber-aggregate pavements have recently been trialled by some highway authorities in England in a very small number of cases.

However, there is no published literature on rubber-aggregate pavements and the scientific literature is silent on the engineering, environmental, social and economic properties of the new paving material.

This research evaluates the engineering, environmental, social and economic properties of rubber-aggregate pavements, and makes comparisons with conventional asphalt pavements, for use in multi-user paths and tracks using a case study in East Lancashire, U.K.

Laboratory and on-site tests were carried out, and were complemented by a desk based life cycle assessment of carbon emissions; community satisfaction questionnaire a revised cost-benefit analysis.

Compared to conventional asphalt pavements, the research demonstrates that rubber-aggregate surfaces show less deformation and are more durable; together with having superior drainage properties and better resistance to skidding and ice formation. The elastic properties of rubber and the high void spacing in the material are key factors in this performance.

Carbon equivalent emissions over the life cycle of rubber-aggregate pavements are substantially less than for asphalt pavements. Levels of community satisfaction are high, including among equestrians who are least satisfied with conventional asphalt. Construction costs are slightly less per linear metre compared to asphalt pavements with edgings.

Based on the findings of the case study, highway authorities are likely to find the engineering and environmental properties of rubber-aggregate pavements acceptable. The levels of community satisfaction and competitive construction costs compared to asphalt will also be of interest.

Following on from the findings of this research, opportunities for further are suggested.

Contents

List of Figures

List of Tables

List of Plates

List of Equations

List of Abbreviations and Acronyms

ITS- Indirect Tensile Strength

ELSCN- East Lancashire Strategic Cycle Network

PROW- Public Rights of Way

EC- Embodied Carbon

DEFRA- Department for Environment, Food and Rural Affairs

WRAP- Waste and Resource Action Plan

HMA- Hot Mix Asphalt

ASTM- American Society of Testing Materials

CBA- Cost Benefit Analysis

WLC- Whole Life Cost

$KgCO_2e$- Kilograms of Carbon Dioxide Equivalent

GPa- Gigapascals

KPI-Key Performance Indicator (relating to the environmental evaluation)

1 INTRODUCTION

“Not everyone’s idea of improvement is the same”

(Lund, 2018)

The quote from Lund (2018) recognises the varying surface requirements of equestrians, cyclists, runners and walkers on multi-user paths and tracks, which are often competing and can occasionally result in community tension and conflict. Lund (2018) also recognises the different but important needs of highway authorities on such routes.

In an attempt to find surface solutions that meet the needs of all users, a very small number of highway authorities in England have begun to trial new rubber-aggregate pavements constructed from crumb rubber, aggregate and polyurethane binder (rubber-aggregate pavements).

This research seeks to evaluate the rubber-aggregate paving materials using a case study in East Lancashire, U.K.

An extensive literature review as part of this study has concluded there is no published research on rubber-aggregate pavements, and the scientific literature is silent on the engineering, environmental, social and economic properties of the surfacing material. The literature is also generally weak on pavements in multi-user paths and tracks.

In light of the literature silence, and given this research was the first of its kind, a broad study of the properties of the surfacing material was carried out.

Inevitably this meant the research covered a range of engineering, environmental, social and economic topics to ensure the paving material had the benefit of a rounded evaluation.

In turn, this broad study may provide a suitable foundation to inform future targeted research on specific topics.

1.1 Can Rubber-Aggregate Pavements on Multi-Use Paths and Tracks Satisfy All Users and the Requirements of Highway Authorities?

The length and number of multi-user paths and tracks in England has grown substantially over the last 20 years, fuelled by growing public demand for leisure and alternative commuting opportunities (Sustrans, 2018).

In recent years, the benefits of cycling and the role of dedicated infrastructure in realising those benefits has been acknowledged (Department for Transport, 2017).

In England, the Department for Transport has published a Cycling and Walking Investment Strategy, with an allocation of £1.2bn to encourage cycling and an *"ambition to make cycling and walking a natural choice for shorter journeys"* (Department for Transport, 2017).

This funding has been focused on the development of new cycle infrastructure and upgrading of existing infrastructure. The Strategy forms parts of the government's plan to increase levels of cycling and acknowledges the benefits, including improved heath and air quality, and reduced traffic.

On the strategic network, Highways England published its Cycling Strategy in 2016, acknowledging the role of the network in supporting the needs of cyclists and *"creating routes that are attractive, safe and separate from traffic to encourage people of all abilities to cycle"* (Highways England, 2016).

As a result of this investment, new cycling infrastructure is planned in different parts of England to implement both Strategies, including the construction of new surfaces on routes that were previously unbound and unsealed, including bridleways, dismantled railways and greenways (Department for Transport, 2017).

However, such significant investment in cycling is not without challenges.

For many years, equestrians have campaigned against the upgrade of routes from soft to hard surfaces, particularly when beaten earth or stone tracks have been re-surfaced with asphalt (Lund, 2018; Barth, 2015; Jenkins, 2014). Equestrians argue that horseshoes slip on asphalt surfaces creating a safety hazard. The British Horse Society (2016) say their preferred surface is short, firm, well-drained turf. Runners also prefer softer surfaces (Bloom, 2015; van der Worp, et al., 2015).

Conversely, Sustrans (2012) prefer a bound, firm surface for cyclists, either dense bitumen macadam or hot rolled asphalt. Unbound surfaces are generally not acceptable from the cyclists' point of view, and local highway authorities have concerns about durability, maintenance and ongoing costs (Lancashire County Council, 2019b).

The varying surface requirements of the different groups of users has often been a source of tension; and has occasionally resulted in protest campaigns and conflict, drawing in local politicians and the media as both sides press their case to highway authorities over plans to upgrade a community route (Pendlebury, 2016).

In an attempt to find a solution, rubber-aggregate pavements have been trialled recently by some highway authorities in England in a very small number of cases (Lund, 2018; KBI, 2018).

In light of the infancy of the material, and very limited use of such pavements, there are questions about the long term durability of the rubber-aggregate paving material (Lancashire County Council, 2019b; Bury Metropolitan Borough Council, 2019).

In engineering terms, the most significant load on the surface of multi-user paths and tracks will come from horses and riders that can weigh between 500kg and 700kg (British Horse Society, 2016). Engineering pressures also come from drainage and climate extremes, especially in steep sided valleys.

From the perspective of the different groups of users, there remain questions about satisfaction and acceptability that need further investigation in light of the purely anecdotal feedback to date on rubber-aggregate pavements. And from the perspective of local highway authorities, there are questions about costs, durability, maintenance, and environmental performance (Bury Metropolitan Borough Council, 2019; Lancashire County Council, 2019b).

In summary, two key questions guided the research:

1. Can the properties of rubber-aggregate materials used to surface multi-user paths and tracks satisfy the requirements of all groups of users?
2. Can the properties of rubber-aggregate materials used to surface multi-user paths and tracks satisfy the requirements of local highway authorities in terms of cost, engineering and environmental performance?

The research used a case study of the East Lancashire Strategic Cycle Network (ELSCN) in the U.K to evaluate the engineering, environmental, social and economic properties of rubber-aggregate pavement for use in multi-user paths and tracks to help answer these questions.

1.2 Aims and Objectives

The aim of the research was to:

Evaluate the properties of rubber-aggregate pavements for use in multi-user paths and tracks.

Research Objectives:
The aim was delivered through the following research objectives:

Using a case study of the East Lancashire Strategic Cycle Network, undertake a broad investigation to:

1. **Evaluate the engineering properties of rubber-aggregate paving materials for use in multi-user paths and tracks, and compare with conventional asphalt paving materials.**

2. **Evaluate the environmental properties of rubber-aggregate paving materials for use in multi-user paths and tracks, and compare with conventional asphalt paving materials.**

3. **Evaluate the social properties of rubber-aggregate paving materials for use in multi-user paths and tracks, and compare with conventional asphalt paving materials.**

4. **Evaluate the economic properties of rubber-aggregate paving materials for use in multi-user paths and tracks, and compare with conventional asphalt paving materials.**

5. **Evaluate the feasibility of using rubber-aggregate as an alternative to conventional asphalt for paving multi-user paths and tracks from the perspective of highway authorities.**

1.3 Study Scope and Limitations

Scope:

This research is limited to the study of rubber-aggregate pavements only, but in view of the absence of published research the study also draws on some of the findings in the published literature on rubber-asphalt pavements.

This research has a wide scope and undertakes a broad study into the engineering, environmental, social and economic properties of rubber-aggregate pavements.

The geographic study area is confined to East Lancashire, with the engineering tests confined to the Britannia Greenway and Helmshore sections of the ELSCN (see Figure 5.1 for locations and see section 5.1 for more information on the case study area), and the social evaluation was confined to the Britannia Greenway section. The environmental evaluation investigated a 1km stretch of the Britannia Greenway; one section paved with asphalt and one section paved with rubber-aggregate.

The research has evaluated new rubber-aggregate material together with material that was 16 months old at the time of the study. No older material exists which conforms to the rubber-aggregate specification in section 5.2. The study took place between December 2018 and March 2019.

This research has confined itself to multi-user paths and tracks only; vehicle carriageways were out of scope.

Limitations:

The research approach is set out in Chapter Five, and this describes the advantages and disadvantages of different research approaches and techniques. The chapter also sets out some criteria which have been used to guide the selection of appropriate research methods.

In turn a number of limitations to the research emerged and these are summarized below, meaning the results in Chapter Seven and the discussion in chapter 8 must be interpreted with some caution in light of the limitations:

Research Design. This research is designed around a case study (see section 5.1) where a rubber-aggregate pavement was being deployed at the time of the research. This raises a number of limitations, not least the difficulty of making generalisations about rubber-aggregate pavements based on the findings of a single rubber-aggregate paving material (with the product name Nu-flex, developed by the Nu-phalt Group). The chemical composition of the polyurethane in binder in Nu-flex is unknown and remains commercially confidential. Nevertheless, this may have bearing on the properties of the rubber-aggregate pavement in the case study, meaning any assumptions about other rubber-aggregate pavements may be problematic. Despite this limitation it should be recognized there is a very small number of types of rubber-aggregate pavement in use, with just two suppliers in the U.K identified by this research (Nu-phalt Group Limited and KBI). It is also acknowledged the specification of the pavement is uncomplicated with just three ingredients: aggregate, crumb rubber and a polyurethane binder (see section 5.2 for Nu-flex specification) meaning there is limited scope for substantial variation in different types of rubber-aggregate pavement that may emerge in the future.

Literature. The scientific literature is silent on the properties of rubber-aggregate pavements meaning the theoretical foundations for the research is limited. In turn this also limits any comparative evaluations and validation of the results from this study. Nevertheless, a body of research exists in relation to rubber-asphalt pavements and whilst the material is different, there are sufficient similarities between the two materials meaning the published research on such pavements provides a framework for limited comparison.

Community Questionnaire. The community questionnaire used in this research attempted to gather the views of regular users from different groups (rather than the wider population) of the new rubber-aggregate pavement on the 1 kilometre Britannia Greenway section of the ELSCN (explained more section 5.1). However, the population of regular users of the Britannia Greenway is unknown, meaning the size of a statistically valid sample of that population is also unknown. However, some 87 users responded to the questionnaire and no group of users was underrepresented, giving reasonable credibility to the results.

Secondary Data. Some of the engineering, environmental and economic evaluations relied heavily on secondary data to support meaningful comparisons. This raises a risk around accuracy of the sources selected for comparison and evaluation. This risk was mitigated by using data from credible published sources, including government agencies and as a published in peer reviewed scientific journals.

Test Procedures. There is a diverse range of laboratory and onsite test methods which could be used to evaluate pavement engineering properties. There is a risk that different methods might yield different results when testing the same sample. This risk was mitigated by only selecting test procedures that had been accredited by international test bodies (e.g. British Standards, American Society for Testing Materials).

1.4 Report Structure.

This dissertation contains eight chapters in addition to this introduction.

Chapter Two sets out a literature survey of multi-user paths and tracks in England, and the surfacing requirements of different groups (equestrians, cyclists, runners and walkers). Maintenance regimes of multi-user paths and tracks are also discussed in Chapter Two.

Chapters Three and Four set out the findings of literature reviews of the engineering, environmental, social and economic properties of conventional paving materials (asphalt) and rubber-asphalt pavements respectively. The research gap is identified at the end of Chapter Four in section 4.6.

Chapter Five describes the research approach used in this study. The case study of the East Lancashire Strategic Cycle Network is introduced in section 5.1, and the rubber-aggregate pavement used in this case study is introduced in full in section 5.2. Chapter Five also describes the selection criteria for the test methods used in this research, along with the advantages and disadvantages of each test.

Chapter Six sets out a description of the methods used to evaluate the engineering, environmental, social and economic properties of the rubber-aggregate pavement in the case study.

Chapter Seven presents the finding of this research, with a summary section at the end of the chapter setting out the results which are discussed in Chapter Eight.

Chapter Eight analyses and discusses the results of the research. Explanations of how the results affect different groups of users and the local highway authority are provided.

The final chapter of this research, Chapter Nine, concludes the study’s findings and suggest opportunities for further research.

2 MULTI-USER PATHS AND TRACKS

In England a 'multi user path or tack' is shared use route which is available for use by any combination of walkers, equestrians, runners and cyclists of all abilities.

Multi user paths and tracks provide routes for commuting and leisure. They are typically used by the following groups of people:

- Walkers (a range of walking abilities, including people who have difficulty walking)
- Parents with push chairs and toddlers
- Disabled people using wheelchairs and mobility scooters.
- Dog walkers
- Runners
- horse-riders
- pedal cyclists (children, novice adults and sports cyclists)

(Countryside Agency, 2005; British Horse Society, 2016; Sustrans, 2012)

Multi user paths and tracks are an important resource for cyclists, walkers and other users. They represent a means of encouraging more sustainable travel, fostering healthy lifestyles, generating income for local communities and increasing recreational opportunities for residents and visitors alike. (Davis & Weston, 2014).

Multi user paths and tracks can be privately owned but public use is permitted (e.g. a path owned by the National Trust or a local wildlife trust). Or they can be publically owned (e.g. by a local council) and public use is permitted.

Such 'permissive routes' may be supported by a formal agreement as to the length of time for which the permission is granted, and which user groups may use the route. The majority of canal towpaths in England are not rights of way, but full and open access is provided to the public subject to the right to close them for operational reasons as necessary (Countryside Agency, 2005).

Multi user paths and tracks can also have the benefit of full legal protection through designation as a 'public right of way'. It is this class of path and track that forms the majority of multi user routes in England (Riddall & Trevelyan, 2007).

2.1 Public Rights of Way in England

Public Rights of Way (PROW) in England are specific paths and tracks were legal rights have been secured in law to allow the public to follow prescribed routes for the purpose of access and connectivity (Riddall & Trevelyan, 2007). They provide a wide range of social and economic benefits to the public. In urban areas they provide networks of mobility and interaction for people at the community level, helping to reduce reliance on motorised transport, as well as providing opportunities for recreation.

PROWs include routes such as footpaths, bridleways, restricted byways and byways open to all traffic. They are an important way of encouraging people to engage in informal enjoyment of urban and rural areas, with beneficial consequences for health and welfare (Riddall & Trevelyan, 2007).

In England and Wales, local councils with Highway Authority responsibilities must maintain PROWs. Legislation under sections 60–62 of the Countryside and Rights of Way Act 2000, also requires highway authorities to develop proposals to improve and manage their networks to meet the needs of the public (Riddall & Trevelyan, 2007). From a user perspective, the design and maintenance of PROWs must meet local needs if they are to enjoy community support (Lindsay, 1999; Conine, et al., 2004).

Two key concerns exist for highway authorities in managing PROWs. The first concern relates to the financial pressure of maintaining routes over many years. The second area of concern relates to the aim of satisfying the needs of different users, which can be opposing. This is an ongoing area of concern, which can result in conflict between different groups of users (Lund, 2018).

2.2 Surfacing Needs of Different User Groups

Details of users' requirements for route surfaces are described as follows (Countryside Agency, 2000):

- Utility and leisure walkers: hard, all weather surfaces
- Recreational walkers: surfaces in keeping with the character of the route
- Utility and leisure cyclists: smooth well maintained surfaces
- Recreational cyclists: hard surfaces are preferred, except by mountain bikers
- Horse-riders: soft surfaces free of small loose stones and chippings, including glass

For many routes, a single surface type will be applied, which is often a compromise between the differing needs of the different user groups and trip types. Advice from the Countryside Agency (2005) has been that the surfacing selection should meet the common requirements across user groups as closely as possible. This common denominator approach can, and frequently does, lead to conflict between different groups of users (Lund, 2018; Pendlebury, 2016). In simple terms, most equestrians prefer a soft and unbound surface while most cyclists prefer a hard and bound surface (British Horse Society, 2016; Sustrans, 2012).

Indeed Sustrans (2012) advise that:

"Path surfaces suitable for cyclists may not be suitable to equestrians – dust paths tend to get chewed up by horses, and while cyclists normally prefer a smoother surface, horses fare better with more grip and surface texture."

This fundamental difference of requirements occasionally results in conflict that can also draw in local politicians and the media. Local councils as Highway Authorities are often left in the middle, attempting to mediate a consensus. (Pendlebury, 2016; Barth, 2015; Jenkins, 2014)

In East Lancashire Lund (2018) says that for commuting routes, cyclists generally require a smooth surface which they can use all year round no matter what the weather; and local highway authorities require a route they can keep clean and in a good state of repair at low cost.

Such routes will also be used by pedestrians for getting to work, school and the local shops or simply for recreation (Sustrans, 2012; Lund, 2018). Again there is a desire for a good quality surface which will remain clean and usable all year round. Also amongst the pedestrian users are people using various wheelchairs, mobility vehicles, push chairs, micro scooters, and so on (Lund, 2018).

Lund (2018) says that based on the requirements of cyclists and pedestrians, it was proposed that asphalt was a reasonable surface to use for the bulk of the emerging ELSCN, a large multi user route in England.

Local Equestrians said that asphalt was too hard and does not offer enough grip. Equestrians prefer short firm well drained turf, vegetated paths on a firm base such as grassed over forest roads using crushed stone (British Horse Society, 2016), crushed stone, however, was not acceptable from the cyclists' point of view and, given the highway authority's experience of using it, there were concerns about its durability and the ability to maintain it (Lund, 2018).

Equestrians users established a campaign of protest that featured a "don't tarmac our bridleways" online Facebook group and a protest ride inviting the local media and politicians (Pendlebury, 2016). The key concern for equestrians is the ‘slipperiness’ of asphalt surfaces for horses.

Surfaces can be slippery for two reasons (Surrey County Council, 2009):

- they are intrinsically slippery for certain users - typically with negative textures
- they become polished through use - particular from wheel wear

A positive texture is where aggregate protrudes from the surface of the material, generally having been laid separately. There is air around the stones except where they are fixed to the surface. This provides a good level of grip for all users.

Negative texture is where the aggregate is mixed in with the binder. There is no clear stone protruding from the surface, and any voids to channel away water are actually contained within the surface. This affords good grip to rubber tyres, but poor grip to steel horseshoes. Surrey County Council (2009) advice that negative textures should be avoided where there is equestrian use.

Similar community conflicts to the Lancashire case have occurred in different parts of England. Barth (2015) reports the South Downs National Park and Hampshire County Council’s upgrade of the permissive bridleway along the Old Meon Valley disused railway line into a multi-use track resulted in equestrians setting up a campaign in opposition.

In Surrey, Jenkins (2014) reported conflict between equestrians and cyclists who clashed over a new bike trail that in parts runs alongside a bridleway. Hessell (2014) reported a path surface in East Bierley renewed by Kirklees Council was the source of conflict between equestrians and other users.

Hopper et al (2005) surveyed and analysed the views of a range of users groups via ongoing monitoring of a trial site along a bridleway in Nottingham which was constructed from various mixtures of bitumen and rubber granules (rubber-asphalt, not rubber-aggregate).

The feedback obtained from all user groups was generally positive. Pedestrians represent the largest user group and their perception of the bridleway was generally very positive, with a similar pattern of response from cyclists. There were a lower number of respondents from equestrians and they tended to prefer the bitumen/rubber mixture that had the most deformation under pressure.

Conflict between different groups of users of multi-use paths and tracks is not limited to England, though the situation is likely to be amplified because of the density of population in relation to the available network. In Sweden, Elgåker et al (2012) reports that on the question of whether horse riding damaged the small road system, the majority (55%) of landowners say that the roads were affected in a negative or very negative way.

2.2.1 Surface Types Used in Multi-User Paths and Tracks

The choice of surface materials and construction specifications is critical to the long-term integrity and appeal of routes for pedestrians, cyclists and equestrians. All require a good quality surface with an even profile and a smooth macro texture to provide a comfortable surface to travel on, but a harsh micro texture to provide sufficient skid resistance when wet (Department for Transport, 2005).

The Department for Transport (2005) advise that the following issues should be considered when selecting an appropriate surface for pedestrians, cyclists and equestrians:

- type of use (volume and combination of users)
- skid resistance
- strength and durability, from the anticipated loading
- construction: rigid or flexible, pre-formed or in situ – often dependent upon the above and ease of construction
- visual appearance – often dependent upon the local context and character
- capital and routine maintenance costs

Table 8/1 of the Department for Transport (2005) guidance outlines a range of bound and unbound surfaces, which includes an adequacy score relating to their appropriateness for use by different pedestrians, cyclists and equestrians. The Department for Transport advise that surface selection should be made on a case-by case basis and agreed with the appropriate user groups and the overseeing organisation. Table 8/1 is reproduced in Appendix B.

Importantly, the Department for Transport (2005) guidance advises that equestrian routes have traditionally been 'beaten earth' (dirt tracks) or redundant/little used macadam or bituminous carriageways (asphaltic surface courses). Bituminous surfaces can polish under normal wear and tear, which may provide an unsatisfactory surface for horses. Where routes have a high frequency of use, a formal sub-base and wearing course may be required.

The selection of equestrian surfacing also has a direct impact upon the speed at which the equestrian can ride, which in turn can raise safety and perception concerns for other users on multi-use paths and tracks (Lancashire County Council, 2019b). Short grass or woodchip surfaces lend themselves to a fast trot/canter by horses, whereas asphalt surfaces are only suitable for walking or a slow trot (Department for Transport, 2005).

Perhaps the most significant aspect of Table 8/1 from the Department for Transport, (2005) as far as this research is concerned is the absence of any reference to rubber-aggregate surfaces.

2.3 Maintenance of Multi-User Paths and Tracks

2.3.1 Principle of Whole Life Costing

The primary purpose of a Whole Life Costing is to quantify the long-term economic implications of initial pavement decisions (Hicks & Epps, 2000).

Transport for the West Midlands (2017) advise that a progressive asset management policy for highway infrastructure takes a strategic approach to the design, implementation and future management and maintenance of any scheme which considers the WLC of the assets that it accrues.

The multi-national consultancy group Atkins (2011) prepared guidance to provide local highway authorities with a consistent process for undertaking Whole Life Costing in order to evaluate different maintenance options for specific schemes. An important aspect of the guidance is that Whole life costing relies on accurate estimation of works costs.

Crucially Atkins (2011) advises that the lifecycle of an asset or treatment will determine the timing of future maintenance interventions. The use of realistic, achievable lifecycles is of prime importance in Whole Life Costing. They should be determined locally and be based on a number of factors including: performance history; material type; specification (including construction practices and workmanship); local environment; demand (such as traffic levels and energy consumption and therefore not necessarily applicable to all assets).

2.3.2 Maintenance of Multi-User Paths and Tracks

Atkinson et al (2006) carried out research of highway authorities in England to produce guidance on the whole life value of footways and cycle tracks; indicating the relative Whole Life Cost (WLC) and advantages and disadvantages of various construction types and maintenance treatments.

Information on construction and maintenance costs was obtained from a number of local authorities and showed that there were large regional variations in costs. Average costs and typical maintenance regimes were used to model the WLC for different types of footway.

Importantly, Atkinson et al (2006) found that there was little data available on the costs of constructing and maintaining cycle tracks so they could not be included in the modelling. Given the substantial budget reductions of highway authorities since the research was carried out (Clark, 2018) it is likely that data availability on cycle tracks maintenance has not improved.

Sustrans (2012) indicate that although unbound surfaces are the most economical to construct, evidence suggests their cost is at least 40% higher than a bound surface during a 50 year life cycle of the path.

The purpose of maintenance is to keep the route in a condition suitable for its intended use throughout its length, or to prevent impact on the surrounding landscape (Levik, 2005).

Effective maintenance can also prevent major deterioration occurring and minimise the extent over which repairs are needed. There is a series of options for the management of multi-user paths and tracks (Countryside Agency, 2005). These options are as follows:

- Do nothing or do little – (without compromising the safety of users) for example, minimum intervention may be appropriate for a route in poor condition if alternative routes in good condition are being promoted to take the traffic.
- Restrict access – for example, prevent access to protect a route through an ecologically sensitive environment.
- Reactive maintenance, which addresses problems as they manifest, such as pothole repair.
- Planned maintenance, carrying out routine tasks which prevent problems occurring, such as clearing drains to prevent water ponding on the route.
- Upgrade – Placing a surfacing on a route with poor natural ground material that cannot support the traffic.

Table 2.1 sets out a review as part of this research of seven of the largest upper tier highway authorities in England, and reveals that none carry out planned maintenance of the surfaces of multi-user paths and tracks. Rather, problems are often initially reported by users directly to the relevant authority or through the parish or district council. Given the large size and resources of these authorities compared to others in England, and given the economic importance of the PROW network to some of them, it is not unreasonable to conclude that most highway authorities in England are similar and do not carry out planned maintenance of multi-user paths and tracks surfaces, but carry out reactive maintenance.

Reactive maintenance identifies and corrects problems when these issues are highlighted by concerned users. Immediate or full repairs are not always possible and temporary repairs may be undertaken. ‘Quick fixes’, such as redressing a surface layer, may provide effective maintenance in some instances, but if a repair is required every few years - for example, as a result of regular surface erosion - then more robust surfaces may be appropriate (Lancashire County Council, 2015).

It is suggested that in England typically only 30% of maintenance costs for multi-user paths and tracks relate solely to the surface (Countryside Agency, 2005). It is important to recognise that the multi-user paths and tracks in the Agency’s report refer to all types of surface, many of which are unbound and will require more maintenance than bound surfaces. So the proportion of maintenance costs spent on robust surfaces (e.g., bound and sealed surfaces involving asphalt, aggregate or rubber) will be significantly less.

Table 2.1-Local authorities’ maintenance policies on multi-user paths and tracks

Local authority	Network size (km)	Maintenance policy	Source
Lancashire County Council	5,500	Reactive and not planned, and the County Council relies on members of the public reporting problems. Regular clearance of undergrowth.	Lancashire County Council, 2019b
Kent County Council	6,900	Reactive, responding to issues raised by users, landowners and other interested parties.	Kent County Council,2017
Devon County Council	5000	Investigates reports received by users. No planned maintenance of surfaces.	Devon County Council,2019
Wilshire County Council	6,000	Surface defects reported by public are prioritised for action. No planned maintenance. However there is an annual growth clearance programme.	Wiltshire County Council,2019
Hampshire County Council	4200	No planned maintenance of PROW surfaces .However may introduce one if it can	Hampshire County Council,2015

		identify a strategic network of paths and tracks as a sub-section of its network.	
Essex County Council	6,200	No planned maintenance of PROW surfaces. Surface problems are a reactive problem.	Essex County Council,2019
Dorset County Council	4,800	Investigate reports from public, and carry out appropriate work. No planned maintenance or inspections.	Dorset County Council,2019

Paths for All (2011) advise that maintenance of multi-user paths and tracks should be a primary consideration from the outset of any path development or improvements programme. In particular, initial capital investments should provide robust and sustainable path infrastructure, which requires minimum longer-term maintenance, especially as funding for capital works is often more readily available than revenue funding for routine maintenance. And importantly, whole-life costs of paths, including future maintenance costs, should be assessed and funding commitments secured from the outset of path projects. However, no guidance is offered about the whole-life costs of different surface options, or about maintenance strategies.

Advice on cycle route maintenance in the UK is provided in LTN 2/08 Cycle Infrastructure Design and Application Guide AG26 'Footway and Cycle Route Design, Construction and Maintenance Guide' (U.K Roads Board, 2003).

Advice is also provided in Well Maintained Highways – a Code of Practice for Highway Maintenance Management (U.K Roads Board, 2012).

Both documents advise that un-swept routes and overhanging vegetation can create trip or skid hazards, and can reduce the effective width of the route. Advice is provided for practitioners in relation to designing routes that facilitate ease of maintenance for vegetation management, litter collection and sweeping. Surface maintenance (of bound surfaces) is given little attention. This is because in practice the loads presented by pedestrians and/or cyclists are minimal in comparison with vehicular traffic (U.K Roads Liaison Group, 2018a), meaning the need for surface repairs is rare.

2.3.3 Inspection of Cycleways

The UK Roads Liaison Group (2018b) suggests that highway authorities generally follow the provisions of *Well Managed Highway Infrastructure* (and the predecessor document *Well Maintained Highways (UK Roads Liaison Group, 2013*) for inspecting cycleways.

It should be noted the inspection frequencies (as opposed to maintenance schedules) set out in Table 2.2 mainly relate to cycleways associated with vehicle carriageways, and cannot be easily translated to multi-user paths and tracks, which is the subject of this research. Nevertheless, the inspection frequencies for the last type of cycleway ('cycle trails, leisure routes through open spaces' - which most closely reflects multi-user paths and tracks in terms of access and topography) serve to demonstrate the low levels of inspection for this type of route.

Table 2.2- Typical inspection frequencies for cycleways

Cycleway Type	***Typical Inspection Frequency***
Cycle lane forming part of the carriageway, commonly a strip adjacent to the nearside kerb. Cycle gaps at road closure point (no entry to traffic, but allowing cycle access)	At the same frequency as the associated carriageway.
Cycle track - a highway route for cyclists not contiguous with the public footway or carriageway	6 months
Shared cycle/pedestrian paths, either segregated by a white line or other physical segregation, or un-segregated	At the same frequency as the associated footway
Cycle provision on carriageway, other than a marked cycle lane or marked cycle provision, where cycle flows are significant.	At the same frequency as the associated carriageway.
Cycle trails, leisure routes through open spaces. These are not necessarily the responsibility of the Highway Authority, but may be maintained by an authority under other powers or duties.	1 year

(U.K Roads Liaison Group, 2016)

In summary, the advice from the UK Roads Board (2003, 2012) and the UK Roads Liaison Group (2013, 2016, 2018a, 2018b) is that inspection frequencies for multi-user paths and tracks in open spaces is low. In turn, this provides further evidence that planned maintenance of bound surfaces (as opposed to litter and vegetation maintenance) of multi-user paths and tracks in off-carriageway locations is likely to be very low or absent.

3 PROPERTIES OF CONVENTIONAL PAVING MATERIALS

3.1 Engineering Properties

Most multi-user paths and tracks are generally not paved (Lancashire County Council, 2019b). To make a multi-user path more accessible to all, the local highway authority may decide the pave the path. As can be seen from Plate 5.1 in section 5, if a path is not paved it can become inaccessible to most users.

The properties identified in this section provide a foundation for comparing rubber-aggregate pavements with conventional asphalt pavements. It should be noted the asphalt properties vary significantly dependent upon the make-up of the asphalt.

The optimal binder (bitumen) content of asphalt is important, and affects it's properties. An asphalt mixture with too much binder can lead to pavement rutting and bleeding, whereas having a mixture with too little binder can lead to pavement durability problems (Kowalski, et al., 2010). A mix design must be undertaken to assess the optimum binder content. Optimal binder content is beyond the scope of this study and will not be discussed, however it is touched upon in some areas of this research.

Skid resistance of paving materials is dependent upon the surface microtexture and macrotexture (Corley-lay, 1998). The microtexture of a surface is the deviation of an aggregate from a true planar surface, with the macrotexture defined as the deviation of a pavement surface from a true planar surface (Fontes, et al., 2006). Microtexture and Macrotexture can be further explained by Figure 3.1. Thus the skid resistance of a pavement is dependent upon the aggregate grade and type used. A study by Ahammed and Tighe (2011) measured the texture depths of 5 different asphalt mixes; two types of hot laid asphalt, one polymer modified asphalt, one stone mastic asphalt and one Superpave (Superior performance asphalt pavement). Texture depths (macrotexture) was measured respectively as; 0.87mm, 0.76mm, 0.92mm, 1.75mm and 0.91mm.

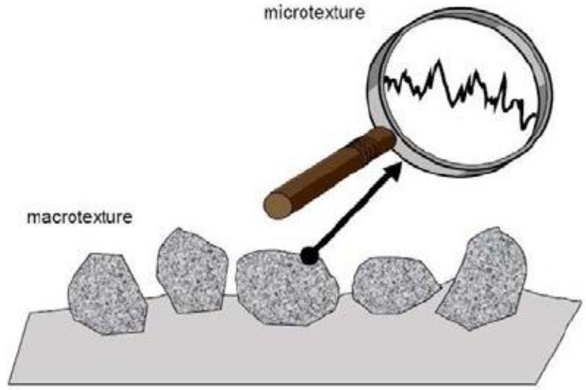


Figure 3.1-Macrotexture and microtexture schematic

(Crow, 2003)

Part of this research has sought to measure the strength (indirect tensile strength -ITS) of rubber-aggregate and compare the findings with typical ITS values for conventional asphalt. The challenge has been to identify representative ITS values for asphalt from the scientific literature because of the broad range of factors that affect ITS.

The ITS of a pavement is the amount of load the material can withstand before failure. A high ITS value indicates good resistance to cracking, and ITS measurements of a pavement is affected by temperature and loading rate (Li & Molenaar, 2012).

ITS of asphalt is affected by various aggregate properties (Al-Suhaibani, 1995). Maximum aggregate sizing within an asphalt mix affects the mix strength (Brown & Bassett, 1989). Furthermore the type of bitumen and content affects the strength of asphalt (Pszczola & Szydlowski, 2018). In summary, the ITS of asphalt depends on the material make-up, and consequently there is no single value for the ITS of asphalt.

Brown and Basset (1989) measured the ITS of asphalt mixes containing varying maximum aggregate sizes. The ITS of an asphalt sample with a maximum aggregate size of 20mm was found by Brown and Basset (1989) be 0.77 N/mm^2. This is relevant to multi-user paths and tracks where the maximum aggregate size is often 20mm (Department for Transport, 2005) and in this is the case in the area of the case study (Lancashire County Council, 2019b). Moreover this is supported by the research of Shunyashree et al (2013) who found the ITS of conventional asphalt to be 0.81 N/mm^2. Research by Halim et al (2001) measured the ITS of three different asphalt mixes. One of the mixes measured by Halim et al (2001) was a conventional asphalt concrete, and the ITS was measured as 1.12 N/mm^2 (it should be noted the loading rate is not stated in the research by Halim et al (2001) and the loading rate can be a factor in ITS measurement).

Studies have shown that using reclaimed asphalt can change the ITS of asphalt, however this is beyond the scope of this thesis which focuses on conventional asphalt in comparison to rubber aggregate pavements.

Stiffness is defined as the ability of a material to resist permanent deformation when a force is applied. A study by Abbas Al-Jumaili (2016) measured the stiffness of conventional asphalt to be 2.21 kN/mm. The study evaluated properties of porous asphalt mixes, with a control mix used for comparison.

A study by Gardete et al (2005) measured the permanent deformation of asphalt specimens, with the maximum aggregate size approximately 20mm. The cyclic compression test was carried out to EN 12697-25, with 3600 loading cycles and a maximum axial stress of 150kpa. The loading was haversine. Table 3.1 shows the permanent deformation and creep rate of varying bitumen contents.

Table 3.1-Deformation and creep rate of conventional asphalt

Bitumen content by weight (%)	Cumulative permanent deformation (mm)	Creep rate (µstrain/cycle)
3.7	0.643	0.339
4.2	0.710	0.400
4.7	0.725	0.515

(Gardete, et al., 2005)

Dołżycki & Judycki (2008) performed a cyclic loading test on mixtures of modified AC20 (maximum aggregate size 20mm) asphalt, a control mixture was used for comparison. The control mixture yielded the percentage strain of 4.3%. The test was carried out to BS EN 12697-25.

A study by Nejad et al (2015) measured the cumulative axial strain of asphalt mixes containing varying amounts of Precipitated Calcium Carbonate. The study also used a control sample of conventional asphalt for comparison. A repeated stress of 100kpa was applied for 2000 cycles at 40 degrees Celsius. The cumulative axial strain after 2000 cycles for the control was 12000µm/m (0.12m/m).

A study by Subhy et al (2017) measured the cumulative axial strain after 3600 cycles of asphalt mixes containing rubber. The control mix's cumulative axial strain was 2.8% (yielding a permanent deformation of 1.12mm), this control mix was conventional asphalt with granite aggregate and no rubber. The test was carried out with an axial stress of 100kpa and at 50 degrees Celsius.

A study by Golalipour et al (2012) measured the permanent deformation of asphalt mixes with varying aggregate gradation (particle size distribution). The maximum aggregate size used was 19mm and three different gradations were investigated. A repeated load test was carried out on 3 samples of each gradation. The test was carried out to BS DD 226 (now replaced by BS EN 12697-25). Each sample was subject to a repeated axial load of 100kpa with a square waveform loading (block pulse loading). 1800 loading cycles were run. Table 3.2 shows the cumulative axial strain and permanent deformation of the varying gradations.

Table 3.2- Permanent deformation of varying aggregate gradations

Aggregate gradation	Cumulative axial strain (%)	Permanent deformation(mm)
Upper gradation band	1.251	1.8750
Middle gradation band	1.592	2.3858
Lower gradation band	2.167	3.2478

(Golalipour, et al., 2012)

3.2 Environmental Properties

Asphalt is used to pave ninety-five percent of roads in the United Kingdom, with over 200 million tonnes of asphalt produced per annum in the U.K alone (Asphalt Industry Alliance, 2019). With the average Embodied Carbon (EC) of virgin asphalt weighing 132kgCO_2 equivalent per ton (Gibson, 2011) equating to 26.400 billion kgCO_2 equivalents per year (assuming all asphalt is virgin). This figure clearly indicates the need for an asphalt alternative with reduced EC content, or a way to reduce the EC of asphalt. Greenhouse gas emissions relating to asphalt are often inconsistent with each other for example an inventory of carbon and energy produced by Hammond & Jones (2011) stated the EC of asphalt to be dependent on the binder (bitumen) content by mass. The EC ranged from 66 kgCO_2e/ton to 86kgCO_2e/ton with 4% to 8% bitumen content respectively. These EC values are average values, and take into account the raw materials extraction and emissions involving producing the asphalt, (transport to site, laying and end of life disposal). The values reported by Hammond & Jones (2011) were produced for DEFRA so are more likely to representative. Values reported by Gibson (2011) were values for a specific asphalt planet, whereas the values reported by Hammond & Jones (2011) are mean values.

An asphalt pavement is made up of both the subbase and the surface course (the asphalt layer). The subbase can consists of limestone and clean stone, however does vary. The asphalt surface course consists of two aggregates bound together by bitumen. Typically asphalt pavements consists of 95% aggregate bound with 5% bitumen by weight (Speight, 2016). Carbon emissions associated with asphalt pavements are a combination of the emissions relating to the following:

- Extraction of raw materials (including sub-base materials and edgings)

- Production of asphaltic surface course
- Transportation of pavement constituents to site
- Emissions associated with laying
- End of life disposal emissions

Asphalt pavements require edgings (or a kerb) for ridged support. Edgings come in many forms; timber, brick, cobbles, road kerbs (Paving expert, 2019). The emissions associated with the edging are dependent upon the edging material.

Transportation emissions are dependent upon the distance travelled, vehicle use and the load the vehicle is carrying. The U.K Department for Environment, Food and Rural Affairs (DEFRA) regularly publishes standard emission values for vehicles, which will be used later in this study to investigated emissions relating to paving materials.

A paver is required to lay asphalt pavements. A standard value for emissions relating to laying and compacting of 4.6 kgCO_2e/ton of asphalt is given by the Transport Research Laboratory (2011).

Once an asphalt pavement is decommissioned it must be disposed in stockpile or landfill. Emissions associated with asphalt decomposition make up a vital part of the life cycle assessment. A value of 1.277 kgCO_2e/ton of asphalt is given by DEFRA (2018).

3.3 Economic Properties

The economics of conventional asphalt often depends on the prevailing global cost of oil. Oil products contribute to more than 50% of asphalt construction and rehabilitation costs (Mirzadeh, et al., 2014). Bitumen is made by refining crude oil, hence oil prices are a large driver of bitumen and hence asphalt costs. With increasing global oil prices, asphalt costs are set to increase.

Pavements require constant maintenance. In October 2018 £420 million was allocated to local authorities to tackle potholes on roads. 95% of the U.K highways are paved with asphalt (Asphalt Industry Alliance, 2018) hence this budget is relevant to almost only potholes on asphalt pavements. A lack of maintenance, especially drainage, can lead to premature failure (Nicholls, et al., 2008). Maintenance of pavements is performed to restore the surface characteristics or prevent further deterioration of the structural layer (Merrill, 2005). Conversations with local highway authorities (Lancashire County Council, 2019b) confirmed that the only sort of maintenance performed on multi-user paths and tracks is ‘minor maintenance’; pothole repairs, removal of debris, cutting of trees. Planned costs of filling potholes are approximately 16% lower than reactive filling on potholes on roads. With planned costing £47 per pothole and reactive costing £56 (Asphalt Industry Alliance, 2018).

3.4 Social Properties

Section 2.2 of this research sets out the varying preferences for surface courses in pavements from the perspective of different groups of users. It concludes that pedestrians, cyclists and equestrians have very different requirements. Equestrians and runners generally prefer soft surfaces; whilst walkers and cyclists tend to prefer firm surfaces.

Asphalt provides a firm surface and is not favoured by equestrians because it is perceived to be slippery to steel horse shoes (Surrey County Council, 2009). Community conflict has sometimes resulted when a previously unmade track or bridleway has been surfaced with asphalt (Lund, 2018; Pendlebury, 2016; Barth, 2015; Jenkins, 2014).

4 PROPERTIES OF RUBBER-ASPHALT PAVEMENTS

Asphalt containing rubber has long been used in transport infrastructure in various locations throughout the world. One of the first uses of rubber in asphalt was in 1964, placed at the Sky Harbour Airport in Phoenix (Brown, n.d.). Various researchers suggest rubber and asphalt or bitumen mixes (using recycled car tyres) have environmental benefits; but the properties of such mixes are tailored to suit different environments or circumstances (Subhy, et al., 2017).

4.1 Engineering Properties

4.1.1 Resilience and Stiffness of Rubber-Asphalt Pavements

A study undertaken at the Budapest University of Technology and Economics (Kisgyörgy, et al., 2016) set out to analyse the elastic modulus of asphalt containing chemically stabilized rubber bitumen. The study concluded that the addition of rubber to asphalt mixes increased the permanent deformation resistance of asphalt. The study further concluded asphalt mixes containing rubber had significantly increased fatigue life. Further literature also supports Kisgyörgy et al (2016) stating that the addition of granulated rubber to hot modified asphalt increases the fatigue life and provides a reduction in permanent deformation (Roberts, et al., 1989).

Rutting is the phenomenon of permanent deformation of a pavement. Rutting of a pavement is due to movement of the aggregate and binder (Liley, 2018). Fontes et al (2010) set out to analyse the rutting resistance of asphalt rubber mixtures (produced by the wet process-explained in section 4.2) compared to conventional asphalt. To measure the rutting resistance two tests were conducted: the ‘Repeated Simple Shear Test at Constant Height’ and the ‘Accelerated Pavement Testing Simulator Test’ (wheel tracking). The study concluded that rutting resistance significantly increased when using the asphalt rubber binder compared to conventional asphalt.

Research by Rahman (2004) set out to characterize the engineering properties of rubberized asphalt using the dry process. The material tested comprised of crumb rubber (produced from the dry process-explained in section 4.2) aggregate and bitumen. When the rubber crumb bitumen mixture was compared to conventional asphalt, the stiffness modulus reduced significantly. Furthermore the fatigue resistance of the rubber bitumen mixture was far superior to that of conventional asphalt. The durability of the rubber bitumen mixture was also compared against conventional asphalt. The rubber bitumen mixture was found to be more susceptible to damage from moisture, yielding a lower stiffness modulus (calculated from the ‘Indirect Tensile Stiffness Modulus Test’). The rubber bitumen mixture also had a reduced fatigue life compared to conventional asphalt when subject to moisture. (Rahman, 2004).

Saberian et al (2018) set out to analyse the permanent deformation of pavements comprising of unbound fine rubber crumb, recycled concrete aggregate and crush rock compacted together. The main aim of the study was to assess the feasibility of using a mixture of crumb rubber and recycled concrete aggregate in the bases and subbases of pavements. Both fine and course crumb rubber where used together with the recycled concrete aggregate, incorporating up to 10% recycled rubber and 50% reclaimed asphalt pavement increase toughness. Saberian et al (2018) concluded that rubber (in crumbed or granular form) can be mixed with recycled concrete aggregate to form a suitable base or subbase. However this is not the case when mixing rubber with crushed rock, which resulted in greater deformation when loaded. (Saberian, et al., 2018).

Fakhri & Amoosoltani (2017) studied the effects of using reclaimed asphalt pavement and crumb rubber on the properties of roller compacted concrete pavement. The flexural and compressive strength of the concrete incorporating both waste materials was tested. Their analysis showed that energy absorbency of the rolled compact concrete pavement increased, thus enhancing the life of the pavement. Benazzouk et al (2007) evaluated the concrete mixes with varying rubber contents. The rubber crumb addition showed an increase in flexural strength; however a compressive strength decrease was reported.

Farhan et al (2015) investigated replacing different percentages of natural aggregate with crumb rubber. The mixture of natural aggregate and crumb rubber was bound with Portland cement and water. They concluded that both stiffness and flexural strength decreased due to the addition of rubber; however the cracking pattern improved.

The use of recycled rubber tyres in pavements has been common practice from the California Department of Transportation (Caltrans) since the 1970s (Holikatti, et al., 2014). In 2004, a field study was conducted to compare the in-situ performance of rubber modified asphalt with conventional dense grade asphalt mix (Cook, et al., 2006). A comprehensive review of Caltrans use of recycled rubber tyres in asphalt mixes concluded that rubberized asphalt mixes have a higher durability and provide an extended pavement service life (Holikatti, et al., 2014). The ‘Ravendale’ project undertaken by Caltrans in 1983. The project involved laying 13 different section of rubberized asphalt, all of different rubber composition made from both the dry and wet process. The section containing dry process rubber was not overlaid for over 19 years (Khalili, et al., 2016).

4.1.2 Skid Resistance of Rubber-Asphalt Pavements

Skid resistance is defined as the force produced when a tyre is unable to rotate skids along a surface (Highways Research Board, 1972). It is common knowledge that more traffic accidents occur on highways that have surfaces with a low skid resistance (Asi, 2007). Pereira & Pais (2014) compared the skid resistance of conventional asphalt, and asphalt with 20% rubber content (terminal blend). The study concluded that asphalt mixtures with rubber had an increased resistance to skidding. Furthermore Pereria & Pais (2014) are supported by a further study on the skid resistance of rubber asphalt, which states that asphalt containing recycled tyre rubber modified with bitumen (wet process) has a higher skid resistance than conventional asphalt (Antunes, et al., 2005).

4.1.3 Freeze Thaw of Rubber-Asphalt Pavements

Water ingress into the pores of bituminous mixes and subsequent freezing causes degradation and reduces pavements service life (Badeli, et al., 2016). Water infiltration in bituminous mixes combined with the variation of positive and negative ambient temperatures deteriorate the adhesive bond between aggregates and binder, which is one of the major distresses that occur in bituminous pavements (Xu, et al., 2016). Crumb rubber used in asphalt binder has been shown to increase the resistance of asphalt to low temperature cracking (Shu & Huang, 2014). Previous research indicates that crumb rubber provides freeze-thaw resistance when added to concrete (Richardson, et al., 2016). The findings of Richardson et al (2016) are supported by other research into the free thaw resistance of the addition of rubber to concrete, where the freeze thaw resistance is increased by adding rubber as an aggregate replacement (Jevtić, et al., 2012).

Hegazi (2014) conducted a study to assess the feasibility of using rubberized asphalt for surfacing highways in Ontario, Canada. The aim of the study was to assess the performance of rubberized asphalt in cold weather, and compare the cold weather performance with conventional Hot Mix Asphalt (HMA). Rubberized asphalt performed better in relation to thermal cracking (Hegazi, 2014).

4.2 Environmental Properties of Rubber-Asphalt Pavements

When tyres are decommissioned they become a waste product (Hegazi, 2014). The European Union Landfill Directive has banned landfill of tyres, hence making use of a previous waste product even more important in the U.K. Waste and Resource Action Programme (WRAP) state that recycled tyres are usually shredded down into crumb rubber (WRAP, 2019), as opposed to reused tyres which are either remoulded or kept whole and used in structures (e.g. landfill bases, coastal defences). Crumb rubber is a form of recycled rubber consisting of ground pieces of varying size made from decommissioned tyres.

Two of the most common technologies for producing crumb rubber are ambient grinding and cryogenic processing (Scrap Tire News, 2019). Ambient grinding produces a more irregular shape with a higher surface area. (Plemons, 2013). In ambient grinding the constituents of a tyre (rubber, steel and textiles) are separated out, then passed through a shredder (Way, et al., 2011). Cryogenic processing of decommissioned tyres involves freezing (often with liquid nitrogen) and breaking tyres up. (Randy & West, 1998; Reschner, 2006).

The use of recycled crumb rubber in asphalt helps to resolve the problem of disposal of waste tyres, and offers energy savings, and reduces the environmental impact compared to landfill disposal. However, rubber asphalt is more viscous and requires an increased mixing temperature and increased mixing time which consumes more energy (Wang, et al., 2018). Saberi et al (2017) set out to analyse the performance of asphalt pavement with the addition of three additives: crumb rubber, reclaimed asphalt pavement and 'Sasobit' (a synthetic hard wax). The study concluded that the use of rubberized asphalt with high reclaimed asphalt pavement content and Sasobit provides a practical way of dealing with waste tyres and reducing waste disposal. Wang et al (2018) conclude the use of rubberized asphalt should be used due to the greenhouse gas emissions savings, and savings in raw materials and energy. Furthermore the emissions of carbon monoxide and methane are significantly lower for rubberized asphalt than conventional asphalt (Wang, et al., 2018). Bartolozzi et al (2012) indicated a 33% reduction in overall energy consumption and carbon emissions. Farina et al (2014) conducted a life cycle assessment of rubberized asphalt, with rubber from both the wet and dry processes. It was concluded from the study that rubber asphalt produced from the wet process leads to benefits including but not limited to; energy saving, environmental impact reductions, and human health improvements. However the rubber asphalt produced using rubber from the dry process did not produce the same results, with no significant difference in environmental benefits when compared to conventional asphalt. Bartolozzi et al (2011) on the life cycle of a rubberized asphalt road in Lamia, Greece concluded that the global life cycle environmental impacts are approximately 35% less for rubber asphalt than conventional asphalt.

Research by WRAP has led to guidelines for the use of rubber asphalt (WRAP, 2009). Having identified the engineering benefits of rubber asphalt from use in other countries and trailed in the U.K. WRAP are now encouraging local authorities throughout the United Kingdom to use rubberized asphalt when upgrading and performing maintenance on their PROW (LocalGov, 2008).

4.3 Social Properties of Rubber-Asphalt Pavements

Paje et al (2010) set out to characterize the acoustics of rubber-asphalt in comparison to conventional asphalt. The rubber-asphalt managed to reduce the noise caused by tyre pavement interaction. This is further supported by Vazquez et al (2016), who found that noise is reduced with the addition of crumb rubber to asphalt. However Vazquez et al (2016) also concluded the benefits of noise reduction decreased over time.

Hooper et al (2005) conducted in Nottingham set out to investigate the feasibility of using rubber (from post-consumer tyres) in asphalt to pave PROW. The paper used different rubber incorporated into three different aspects of the surface; subbase, surface dressing and a sandwich layer. These three surfaces where constructed within close proximity of each other along with a conventional asphalt surface to allow for comparison. A user satisfaction survey accompanied the hard engineering test, where users were asked to select an adjective which best described the surface. The study also compared the stiffness of the four surfaces. The users described the surfaces that contain rubber to have more “give” in them, which was preferential to many users especially runners.

4.4 Economic Properties of Rubber-Asphalt Pavements

Hicks and Epps (2000) carried out a comparative evaluation of the life cycle cost for hot-mix structural overlays, non-structural surface courses, and chip seals containing conventional (or polymer-modified) binders with similar applications containing asphalt rubber binders. The life cycle cost analyses researched by them was limited to wet processed crumb rubber asphalt binder.

Their findings indicate asphalt rubber is cost effective in many of the applications used by local agencies in Arizona and California. However, the authors stress that the estimated lives of different surfaces are based on interviews and on engineering judgment. Changes in the life estimates could therefore affect the final conclusions. It is clear from the work of Hicks and Epps (2000) that the estimates of construction costs and the type of maintenance strategy adopted fundamental affects the estimate of the WLC.

Importantly, the research of Hicks and Epps (2000) was restricted to pavements carrying vehicular traffic. Multi-user paths and tracks, which are subject to very different pressures and forces, were not considered.

McQilllen et al (1988) report the benefits of adding rubber to the mix include increased skid resistance under icy conditions, improved flexibility and crack resistance, elimination of a solid waste, and reduced traffic noise. Their cost comparison (over 30 years ago) of the economics of the rubber-modified system with that of the conventional pavement shows that the rubber-modified surfacing is cost-effective. This conclusion is based on an analysis of life-cycle costs. Like the Hicks and Epps (2000) study, McQuillen et al (1988) only studied pavements carrying vehicular traffic, and did not research multi-user routes. The research only considered rubber asphalt mixes.

Wang et al (2018) summarize recent research findings on warm mix rubberized asphalt concrete. Warm rubberized asphalt concrete has higher initial costs in comparison to conventional Hot Mix Asphalt (HMA), which they say is one of the main concerns of contractors when utilizing this technology. However, the authors suggest warm rubberized asphalt concrete is believed to have long-term benefits, such as improved durability and lower maintenance costs, which they say will be more cost-effective than conventional HMA in a life-cycle manner. Wang et al (2018) drew on research that considered vehicle pavements.

Souliman et al (2016) carried out a laboratory testing program for fatigue performance on three gap-graded mixtures: unmodified, asphalt rubber and polymer-modified. Their analysis showed that the asphalt rubber and polymer-modified asphalt mixtures exhibited significantly higher cost-effectiveness compared to unmodified HMA mixture. Although asphalt rubber and polymer-modification increases the cost of the material, the analysis showed that they are more cost effective than the unmodified mixture. The fatigue testing related to speeds and forces associated with vehicles.

Jiang et al (2018) carried out a review of eco-friendly functional road materials. For permeable asphalt concrete, the authors found in long-term use, with repeated wheel load and the aging of asphalt binder, the accumulation of particles and contaminants on the pavement surface caused pore clogging, which shortens the pavements service life. To tackle the problem of pore clogging, some research institutions have developed a special maintenance truck for permeable asphalt pavement to maintain the permeability function of the pavement. Inevitably this increases the WLC significantly. Such a problem might also occur in rubber aggregate mixtures, depending on the size of void spaces.

4.5 Summary of Current Knowledge

To summarize, the use of rubber-asphalt enhances key engineering properties such as: fatigue life, rutting resistance, flexural strength and skid resistance. Furthermore, the use of rubber-asphalt has environmental benefits and helps contribute to a circular economy by re-using waste. The use of rubber-asphalt reduces the overall carbon footprint of highways by reducing energy demands. Rubber-asphalt has been used in locations throughout the world, with positive results.

4.6 Identification of Knowledge Gap

Rubber-asphalt has been used in highways throughout the world. Highways are subject to different loads and the surface requirements of a highway are very different to a multi-user path or track. The only research conducted into the use of rubber in multi-user paths or tracks is from Nottingham (Hooper, et al., 2005). This study did not take into account the skid resistance, drainage properties, and environmental implications or undertake any form of life cycle assessment.

Furthermore this study looked at using rubber in asphalt, which is considerably different to the new rubber-aggregate and binder mixes. In addition to this, the rubber was used in different layers of the surface (subbase, surface dressing, and sandwich layer), not throughout the material.

The literature is silent on the use of rubber-aggregate mixes and their use in pavements.

There are no examples of WLC evaluations of multi-user pavements in the scientific literature. Atkinson's comprehensive research in 2006 revealed a complete absence of data on the whole life and maintenance costs of cycle tracks. The situation on data availability is unlikely to have improved since then.

In summary, the scientific and professional literature is silent on:

- The properties (engineering, environmental, economic, and social) of pavements constructed of rubber, aggregate and polyurethane binder; particularly in multi-user paths and tracks.

5 RESEARCH APPROACH

This chapter sets out the approach used in the research.

Research approaches in general can use a range of techniques such as primary data collection through laboratory testing or on-site testing, modelling and estimation, secondary data analysis, literature analysis, opinion survey or case study research.

Given the wide range of approaches and methods that are potentially available, criteria were identified for the selection of approaches and methods used in this research.

Section 5.3 sets out the method selection criteria.

Section 5.4 sets out the justification for the approaches and methods selected, taking account of the opportunities and needs of the research, together with the criteria in section 5.3.

5.1 Case Study Used in the Research

The use of rubber-aggregate pavements (as opposed to rubber-asphalt pavements) is new.

There is very little use of rubber-aggregate pavements in multi-user paths and tracks in England (Lund, 2018). The scientific literature was found not to contain research on the material, following an extensive literature review as part of this study. This study found that at the time of the research, just two manufacturers of rubber-aggregate pavements existed in the U.K (Nu-Phalt Group Limited, manufacturing ‘Nu-flex’; and KBI U.K Limited manufacturing ‘Flexipave’), and the material has been deployed in a very small number of cases.

Given the pioneering nature of the material, and in light of the very small number of sites in the U.K where rubber-aggregate pavements have been used in multi-user paths and tracks (Lancashire County Council, 2019b; KBI, 2018; Lund, 2018), it was necessary to evaluate the material through a single case study of the ELSCN which was under construction at the time of the research. A map of the ELSCN is shown in Figure 5.1.

The ELSCN was selected as a case study for the following reasons:

- The network contained several different sections that were paved at the same time with conventional asphalt or with rubber-aggregate, allowing comparison of pavements of the same age (16 months old at the time of the research).

- The network also contained pavements of different ages. Some asphalt and rubber-aggregate was laid new at the time of the research; and some 16 months before the research commenced. This allowed an investigation of fresh material, and a comparison with older material.

- The network was used by a significant number of equestrians, cyclists, runners and walkers. Moreover, there was a history of community disagreement over the type of surface material (Lund, 2018). This provided a good opportunity to investigate the social implications of using different types of pavement.

- Co-operation of the local highway authority (Lancashire County Council) and the pavement supplier (Nu-phalt Group Limited) was available. Information was made available about pavement specifications, costs and maintenance regimes; and samples of the rubber-aggregate material were made available for laboratory testing.

The ELSCN is mostly located in Rossendale Valley, which includes steep sided valleys of the River Irwell and its tributaries which dissect the moorland of Rossendale Hills. The area receives very high levels of rainfall which can result in flash floods from the steep hillside (Slater, et al., 2017; Holton, 2012). In the valley bottom, which is spatially constrained, urban settlements compete for space with rivers, roads, railways and limited green space. This complex geography, topography and climate result in harsh conditions and human pressures which must be matched by robust engineering solutions when designing pavements.

Several multi-user paths and tracks on the ELSCN have been previously washed out and became unusable to most people (Lancashire County Council, 2019b). Plate 5.1 shows the Britannia Greenway before the route was upgraded using a rubber-aggregate pavement. The onsite tests were conducted on the Britannia Greenway section of the ELSCN (where both rubber-aggregate and asphalt was laid 16 months before the research commenced) and on the Helmshore section of the ELSCN (where rubber-aggregate was laid afresh during the research). Figure 5.1 shows the locations of the Britannia Greenway and Helmshore sections of the ELSCN.

(Lancashire County Council, 2019b)

Plate 5.1- Britannia Greenway before being paved with rubber-aggregate material

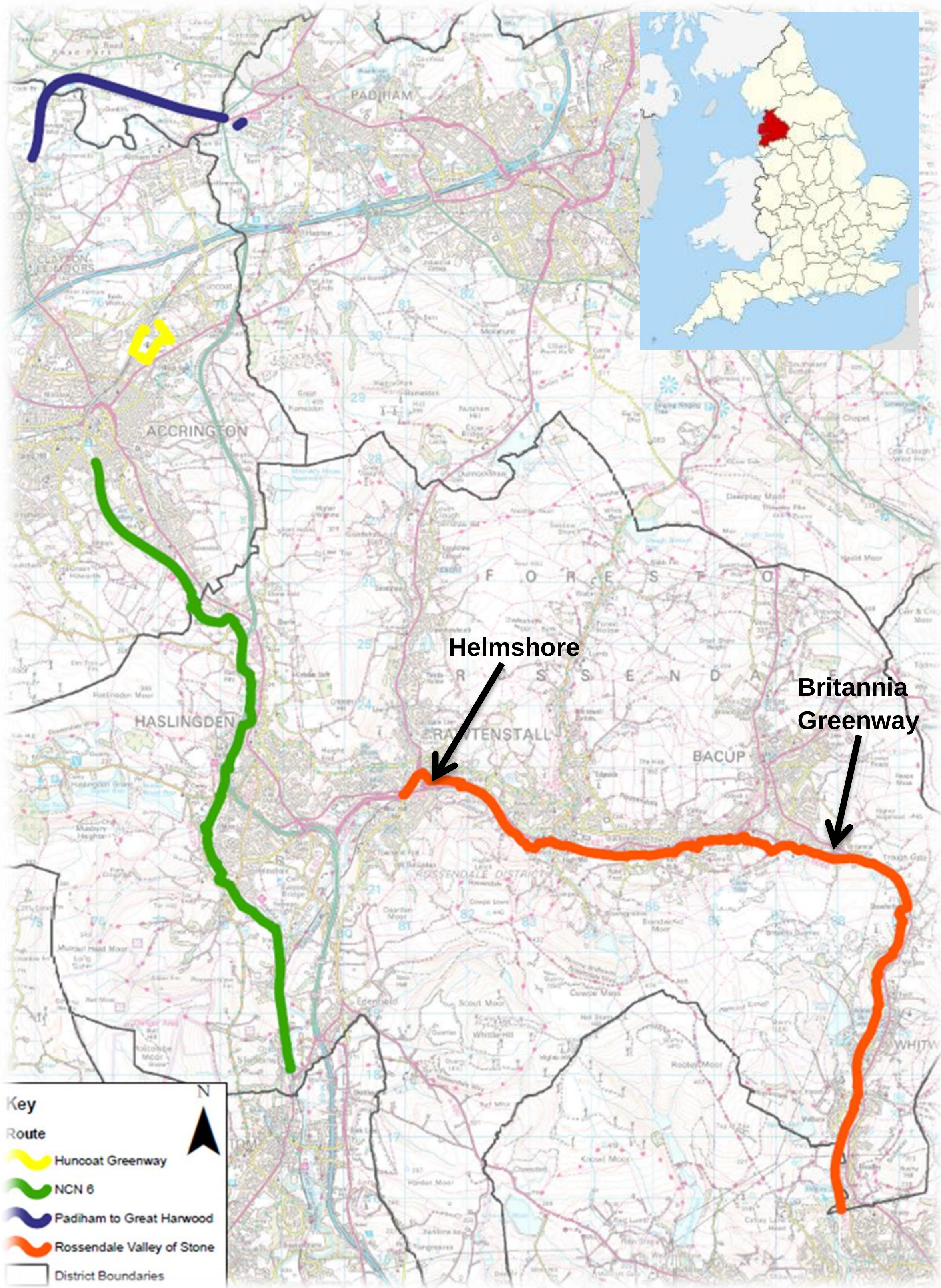


Figure 5.1- Map of the ELSCN (adapted from Lancashire County Council, 2019a)

5.2 Rubber-Aggregate Used in this Research

The rubber-aggregate material evaluated in the case study has the product name 'Nu-flex' and is supplied by the Nu-phalt Group Limited.

The asphalt used to pave the areas testing in the case study was 60mm 20AC binder to clause 906 (MCHW, 2017). Asphalt specification for the Britannia Greenway provided by Lancashire County Council (Lancashire County Council, 2019b).

Nu-flex is:

- 40% Styrene Butadiene Rubber granulate crumb
- 40% Hardstone Aggregate
- 20% Binder: polyurethane (minimum content greater than 10% of the mixture)
- Air void content between 20%-30%

(Lancashire County Council, 2019b)

Plate 5.2 shows a section of Nu-flex laid on the Britannia Greenway, and Plate 5.3 shows a close up profile of Nu-flex, taken by the author.

(Lancashire County Council, 2019b)

Plate 5.2- Britannia Greenway after being paved with Nu-flex

Plate 5.3-Nu-flex cross section

5.3 Research Method Selection Criteria

Given the wide range of testing methods potentially available, several criteria were identified and used to guide the selection of approaches and testing methods for the research. The criteria were:

1. **Repeatability.** This means a method can be repeated in the research. For repeatability to be established, the following conditions must be in place: the same location; the same measurement procedure; the same observer; the same measuring instrument, used under the same conditions; and repetition over a short period of time.
2. **Reproducibility.** Reproducibility refers to the degree of agreement between the results of experiments conducted by different individuals, at different locations, with different instruments. Put simply, it measures an ability of other researchers to replicate the findings of this research.
3. **Reliability.** Refers to the ability of a test to produce consistent results. Established international standards for a test give a good indication of reliability.
4. **Sensitivity.** Refers to the ability of a test to detect small changes in absolute values; and to support the ability to make comparative evaluations between different materials under test. Sensitivity also refers to the ability of a test to measure the property under investigation.
5. **Availability.** Equipment availability, particularly of complex laboratory equipment, is an important limiting factor.
6. **Accessibility.** The ease of use of equipment and its associated methodology, especially for field tests, is a key consideration.

5.4 Research Method Rationale

This section sets out a justification for the selection of approaches and methods used in the research. It describes some of the advantages and disadvantages of different approaches and methods, and sets out the conclusions of an assessment against the method selection criteria.

5.4.1 Engineering Evaluations

The research approach taken for the engineering evaluation was a combination of primary data collection from tests in the laboratory and on-site.

Primary data collection was necessary because of the absence in the scientific literature of published data on the engineering properties of rubber-aggregate. Laboratory tests were selected because of the need for reliability, repeatability, and reproducibility when testing new samples.

On-site tests were chosen because of the need to either test materials in-situ (taking account of the local conditions); the need to test materials that had been in place for a period of time; or the need to observe live conditions.

Five engineering properties were evaluated in this research:

- Strength and Stiffness
- Skid Resistance
- Drainage
- Durability
- Ice Formation

The properties were selected for evaluation based on the surfacing needs and requirements of users of multi-use paths and tracks (set out in 2.2), and the requirements of highway authorities (set out in section 2.3.2).

5.4.1.1 Strength and Stiffness Tests

The strength of a material is its ability to withstand load without failure. The stiffness of a material is a measure of a materials ability to return to its original shape after an applied load.

The Indirect Tensile Strength (ITS) test was chosen to measure the strength of rubber-aggregate paving materials. Reviews carried out by this research on British Standard tests on bituminous mixes demonstrated the ITS test was the only strength test for bituminous mixes that could be conducted in a controlled laboratory environment. Moreover, Kennedy and Hudson (1968) concluded the ITS test had the greatest potential for evaluating the strength of highway materials. It also complies with the method selection criteria set out in section5.3, particularly reliability, repeatability, and reproducibility.

Stiffness was calculated from the load displacement values obtained in the ITS test. Several stiffness tests for paving materials are available. A controlled constant rate of load (as opposed to cyclic loading) was chosen because this is more representative of the maximum load a multi-user path or track may experience (i.e. from a horse). Furthermore the amount of 'give' in the surface was measured, given the preference of runners for surface flexibility. It complies with the test selection criteria section 5.3, and was deemed the most suitable. The use of a light weight deflectometer was considered and dismissed. A light weight deflectometer is a mobile piece of equipment that allows stiffness be measured in-situ. It was not deemed suitable as the equipment was not readily available and required some specialist training.

5.4.1.2 Skid Resistance

Skid resistance is the force produced when a tyre is unable to rotate and skids along a surface (Highways Research Board, 1972). It is a function of the microtexture and the macrotexture of the surface as stated in section 3.1. It is most relevant to cyclists in a multi-user path and track context.

It is usually quantified by a friction factor or skid number (Pavement Interactive, 2019b). However, a friction factor is a function of both the surface course and the tyre.

Many skid resistance tests involve driving a large vehicle over a pavement and applying the vehicle's breaking system. An example of a large scale skid resistance test is the Locked Wheel Test, which is resource intensive and difficult to perform since it involves a vehicle travelling at speed. Furthermore, the test is more applicable to motor vehicles on a carriageway, which travel at much higher speeds than a pedal cycle (Mataei, et al., 2016).

Given these complexities, a simpler test was sought involving macrotexture measurements. Five popular methods where identified by surveying literature for macrotexture measuring: Sand Patch Test, Laser Profiler, Laser Texture Scanner, Circular Texture Meter, and X-ray Computed Tomography (CT) scanning.

The only method that complies with all the test selection criteria set out in section 5.3 is the Sand Patch Test. It has the advantage of being simple to use, and future researchers can reproduce the test quickly, simply and cost-effectively; and use the results in this research as a comparison. Moreover the texture depths measured using laser profiler, laser texture scanner, circular texture meter and CT scanning all yield similar results to the Sand Patch Test (Sezen & Fisco, 2013).

5.4.1.3 Drainage Tests
Drainage is an important property of a multi-user path or track. Wet surfaces increase the potential for skidding. Water pooling on the surface can also form ice in cold periods creating a hazard for users.

The American Society of Testing Materials (ASTM) 1201 Infiltration Test was chosen to assess the drainage capability of paving materials because it is simple, and can be replicated easily by other researchers, allowing comparison with the results of this study.

Measuring the hydraulic conductivity (function of drainage) of rubber-aggregate pavements was considered, using either the Constant Head or Falling Head test. However, the laboratory equipment was not readily available so the test did not meet the test selection criteria set out in section 5.3.

The ASTM c1701 Infiltration Test has the added advantage of being an in-situ test that takes account of field conditions, thus allowing comparison of different aged rubber-aggregate pavements. The ASTM c1701 infiltration test complies with the selection criteria set out in section 5.3.

5.4.1.4 Durability Tests
Durability or resilience is an essential design criterion for pavements.

AECOM (2016) describes 12 methods of testing the durability of high friction surfacing. However many of the methods were unavailable for this research; or were impractical because of resource or time constraints.

Measuring a paving material's resistance to permanent deformation can be achieved by: Static Creep Tests, Repeated Load Tests, Dynamic Modulus Tests or Simulative Tests (for example wheel-tracking device tests). A Static Creep Test was dismissed as it does not correlate well with in-situ pavement performance (Pavement Interactive, 2019a). A wheel-tracking test was deemed inappropriate as it is less relevant to loading conditions experienced by multi-user tracks and paths. It is more appropriate for measuring motor vehicles loading conditions.

A Repeated Load Test was deemed the most appropriate test because the results correlate well with the in-situ performance of pavements (Pavement Interactive, 2019a). The Repeated Load test (BS EN 12697-25:2016) can also be compared with other published results in the scientific literature.

Two loading conditions are suggested: 'block pulse loading' and 'haversine' loading. Block pulse loading is preferred because haversine loading does not allow the asphalt mixture to undergo constant loading (Roy, et al., 2016). The Repeated Load Test complies with all the method selection criteria set out in section 5.3.

5.4.1.5 Ice Formation

The formation of ice on multi-user paths and track can be hazardous and increases the risk of in injury to users of the route. The perception that ice may be present can also discourage use of routes.

It is therefore important to test the potential for the formation of ice on rubber-aggregate and asphalt surfaces.

Given the unique local circumstances that might lead to the formation of ice such as local topography, a micro-climate and local drainage condition, the importance of onsite observations was recognized from the outset. Visual observations on-site at times when local weather conditions could lead to the formation of ice is an acceptable method of assessing the potential for ice formation. It aslo complies with the selection criteria set out in section 5.3.

5.4.2 Environmental Evaluation

There is an absence of published research on the environmental performance of rubber-aggregate materials, meaning comparison of the pavement in the case study with the environmental performance of other pavements was not possible.

Field data collection was not logistically possible because of the dispersed nature of the different production processes involved in the raw ingredients of rubber-aggregate pavements.

It was therefore concluded that a combined modelling and literature review approach should be used to estimate the environmental performance of rubber-aggregate and asphalt pavements.

A life cycle assessment was used to model the carbon emissions. This was underpinned by a review of the literature to identify the different phases in the life of pavement production, together with appropriate emission factors for each phase.

The U.K Department for Environment, Food and Rural Affairs (DEFRA) sets out 22 key performance indicators (KPIs), in relation to the environment. Five of the 22 KPIs relate to construction projects: greenhouse gases; water abstraction; acid rain and smog precursors; and waste (DEFRA, 2006). The five KPIs were considered for evaluation in this research.

Water abstraction was not considered to be an appropriate indicator because very little water is required for the construction of pavements.

Acid rain and smog precursors result from the emissions of: Sulphur dioxide, nitrous oxide ammonia and carbon monoxide (DEFRA, 2006). Acidic gases and particulate emissions have been regulated over many years in the U.K (DEFRA, 2019). Conversely the management of greenhouse gas emissions is a more recent phenomenon and is regulated through activities such as emissions trading schemes, for example the Greenhouse Gas Emissions Trading Scheme Regulations 2012 (U.K Government, 2012). Moreover international efforts to reduce carbon emissions have taken center stage locally, nationally and internationally, meaning that a body of published scientific research is widely available on various emission factors that could be used to inform the assessment. For these reasons, it was deemed more important to evaluate carbon emissions than acid rain and smog precursors.

Waste disposal and re-cycling are a sub-set of an embodied carbon assessment.

In light of these factors it was considered most appropriate to evaluate the carbon emissions associated with the life cycle of paving materials as an indicator of environmental performance.

5.4.3 Social Evaluation.

A range of techniques potentially offer a way to assess community satisfaction. These include: focus group investigation, public meetings, a community questionnaire or interviews with key stakeholders.

A focus group or public meeting might not result in a fair representation of all the user groups; and the results are qualitative making it difficult to correlate the findings with the results of engineering tests in this research.

Similarly, interviews with key stakeholders would not offer quantitative data. Moreover, some key stakeholders may skew the results because of their strong preferences and their desire to advance the priorities of their group. Managing discussions with individuals in a focus group can be difficult (Putit & Buncuan, 2010).

A community questionnaire was deemed the most appropriate survey technique, because the results can be representative of all users. Furthermore, a questionnaire provides quantitative data which can be correlated with the results of the engineering tests. In addition, a community questionnaire allows for structured questions, fixing the range of topics under discussion and making the organization and analysis of the resulting data manageable. Finally, a questionnaire can be reproduced by other researchers; and the results of this research can be compared with other research.

5.4.4 Economic Evaluation

Several research approaches were potentially available to evaluate the economic performance of rubber-aggregate and asphalt pavements.

Whole life costing of a transport asset takes into account the design, construction and future maintenance costs. It relies on an accurate estimation of maintenance costs, including maintenance schedules (Atkins, 2011). But maintenance cost data was not available for rubber-aggregate pavements because of the infancy of the material; and because of the lack of available data on the cost of maintaining multi-use paths and tracks generally, including reliable maintenance schedules (Atkinson et al, 2006; U.K Roads Liaison Group, 2018a). Conversely, construction cost data was available for both paving materials. For these reasons, whole life costing was not used; and a comparison of construction costs only was made.

Cost Benefit Analysis (CBA) is another research approach that was considered. CBA is a technique used to compare the total cost of a project with its benefits. It often seeks to monetise the costs and benefits. This enables the calculation of the net cost or benefit associated with the project (Watkins, 2019). It is an approach used by funding bodies to assess projects, and was used in the case study when the project sponsors originally applied for funds to construct the scheme (ELSCN) based on an assumption the routes would be constructed from asphalt only.

Given the availability of construction cost data, and the availability of the original CBA in the case study, it was recognised that a useful method of research would be to recalculate the CBA using the construction costs of a rubber aggregate pavement only; and to compare the result with the original CBA for an asphalt pavement.

6 RESEARCH METHODS

This chapter sets out the methods used in the research for evaluating the engineering, environmental, social and economic properties of rubber-aggregate and asphalt pavements, with reference to the case study described in section 5.1.

6.1 Engineering Evaluation

6.1.1 Strength and Stiffness

The ITS test was carried out in accordance with British Standard BS EN 12697-23. The test was carried out in the laboratories of the School of Civil Engineering at the University of Leeds. Four samples of Nu-flex (manufactured to the specification as set out in section 5.2), size 100mm diameter by 40mm thickness, were loaded on the Instrom machine diametrically (as shown in Plate 6.1) at a rate of 50mm/minute. The load was applied until failure. The peak load at fracture was recorded. The ITS of Nu-flex was calculated using equation 6.1 from BS EN 12697 (British Standards, 2017). . The load displacement relationship was plotted, from which the stiffness of Nu-flex was also calculated.

$$ITS = \frac{2P}{\pi \mathrm{DH}}$$

Equation 6.1-ITS of a cylindrical specimen

P= Peak load at fracture
D=Diameter of the specimen
H=Height of the specimen

Plate 6.1-ITS and stiffness test set up on Instrom machine

6.1.2 Skid Resistance

The Sand Patch test was conducted on one section of the East Lancashire Strategic Cycle Network (the Britannia Greenway section that was paved with Nu-flex and asphalt 16 months before the test).

The surface was first cleared of any debris. A measuring cylinder containing 35mL of kiln dried sand was poured into a conical shape and spread evenly by hand using a puck. Spreading was stopped once the resulting circle was approximately one grain thick. Four measurements of the resulting circle's diameter were taken and recorded in millimetres. The test was conducted at 12 different locations, 6 paved with asphalt and 6 paved with Nu-flex. The texture depth was then calculated from Equation 6.2, (Vic Roads, 2012). Plate 6.2 shows the sand patch test set up.

Plate 6.2-Sand patch test

$$T = \frac{4V}{\pi d^2}$$

Equation 6.2-Texture depth from sand path test

T= texture depth
V=Volume
d=Diameter of spread sand

6.1.3 Drainage

Infiltration rates of paving materials were measured at locations on the Britannia Greenway and at Helmshore, which are both sections of the East Lancashire Strategic Cycle Network (see Figure 5.1) using the ASTM c1701 Infiltration Test.

Water was sourced from a neighbouring stream in both locations. An infiltration ring of 200m diameter was sealed onto the surface of the pavement (Nu-flex or asphalt) using plumber's putty. Water was poured into the infiltration ring at a regular rate to maintain a constant head of 10mm depth.

On the Britannia Greenway, the Infiltration Test was carried out at five different locations paved with Nu-flex, repeating three times in each. The test was also carried out on five locations paved with asphalt. The Nu-flex and asphalt pavements were 16 months old at the time of the test. The infiltration rate was calculated using Equation 6.3, obtained from the ASTM c1701 standrad (ASTM, 2018).

In addition, the Infiltration Test was carried out on a section of the rubber-aggregate pavement on the Britannia Greenway that was heavily covered with leaf litter (in an attempt to represent an older surface that may be subject to several years of wear). The surface was cleared of leaf litter and the test was repeated. This was done to investigate how surface debris affects the drainage properties of a rubber-aggregate pavement.

The Infiltration Test was also carried at Helmshore on a section surfaced with Nu-flex just one week before the testing.

Plate 6.3 shows the setup of the infiltration test.

Plate 6.3-Infiltration test set up

$$I = \frac{KM}{D^2 t}$$

Equation 6.3-Infiltration rate of paving materials

I= Infiltration rate
K= Equation constant
M=Mass of water
D= Diameter of infiltration ring
t= Infiltration time

6.1.4 Durability

A Cyclic Compressive Test was carried out in accordance with British Standard BS EN 12697-25:2016 by Pavement Testing Services (PTS) Limited in Preston, Lancashire because of broken equipment in the laboratory of the School of Civil Engineering at the University of Leeds. Exact instruction was given to PTS to ensure the test was carried out in the accordance with BS EN 12697-25:2016.

Test specimens of 150mm diameter and 60mm thickness were used, manufactured to the specification set out in section 5.2. Block pulse loading was deployed. The sample was placed coaxially between the two loading plates. Two strain gauges where placed onto the loading plate. A pre-load of 10 kilopascals was applied for a 120 second period. An axial stress of 100 kilopascals was applied to the specimen, with load duration of 1 second. 3600 pulse load cycles were applied at a rate of 1 hertz.

6.1.5 Ice Formation

Site visits where made to the Britannia Greenway section of the case study area on 4, 22 and 28 January 2019. The weather forecast was checked prior to visiting to ensure sub-zero temperatures. Visual observation were made and photographs taken over a 30 minute period along sections of the track paved with Nu-flex, and on sections paved with asphalt.

6.2 Environmental Evaluation

The greenhouse gases emitted during the life cycle of rubber-aggregate and ashaplt paving materials were assessed by calculating the carbon dioxide equivalent (CO_2e). Carbon dioxide equivalent quantifies the amount of carbon dioxide which would have the equivalent global warming impact of a gas. (Brande, 2012). The ‘cradle to grave’ boundary was used in this research. The cradle to grave boundary considers all activities: starting from raw materials extraction and ending at the disposal of the material (Circular Ecology, 2018). The stages considered for the life cycle analysis were:

- Extraction of raw materials (including sub-base materials)
- Processing or raw materials to produce the pavement
- Transportation to site
- Laying emissions
- End of life disposal

Two pavements (one rubber-aggregate and one asphalt) of 1km length on the Britannia Greenway were used for the life cycle assessment. The equivalent carbon emissions were quantified. Quantities of materials (both course and sub-base) were calculated using schematics provided by both the contractor Nu-Phalt (the supplier of Nu-flex) and the local highway authority (Lancashire County Council). The schematic used to calculate volumes of the rubber-aggregate pavement and subbase is shown in Figure 6.1, with the schematic used to calculate volumes of asphalt being shown in Figure 6.2. Relative densities were used to calculate the mass of each material from the known volume; these density values were taken from literature and are shown in the comments section of Appendix A. However, the density of the rubber-aggregate pavement in the case study was calculated by weighing a known volume in the School of Civil Engineering's laboratories at Leeds University.

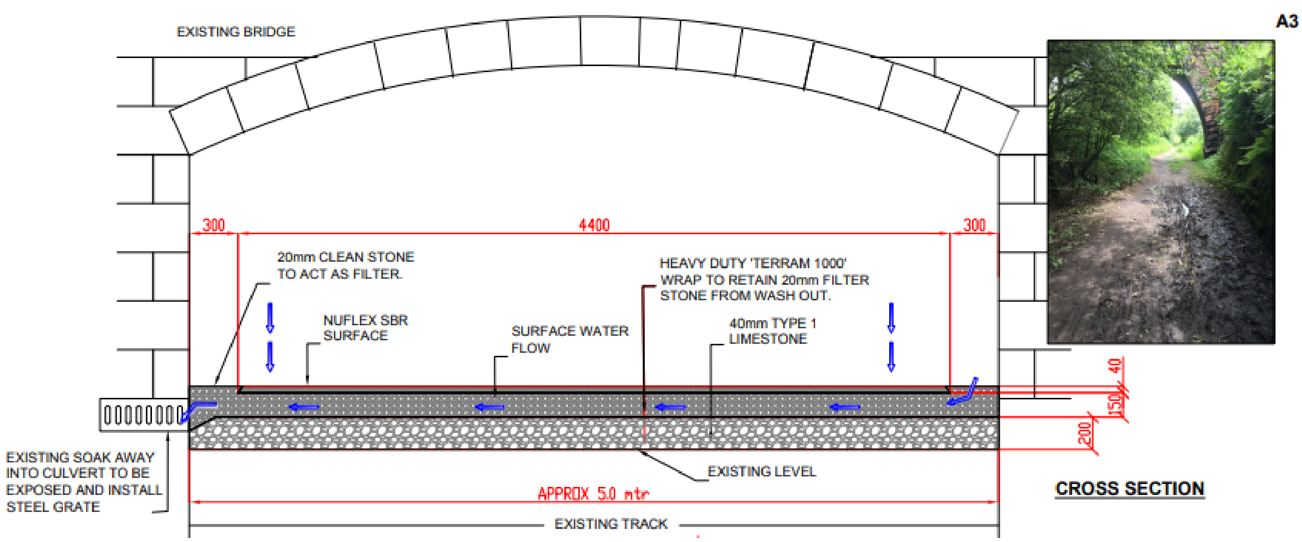


Figure 6.1- Nu-Flex schematic used for life cycle assessment

(Nu-phalt Group Limited, 2019)

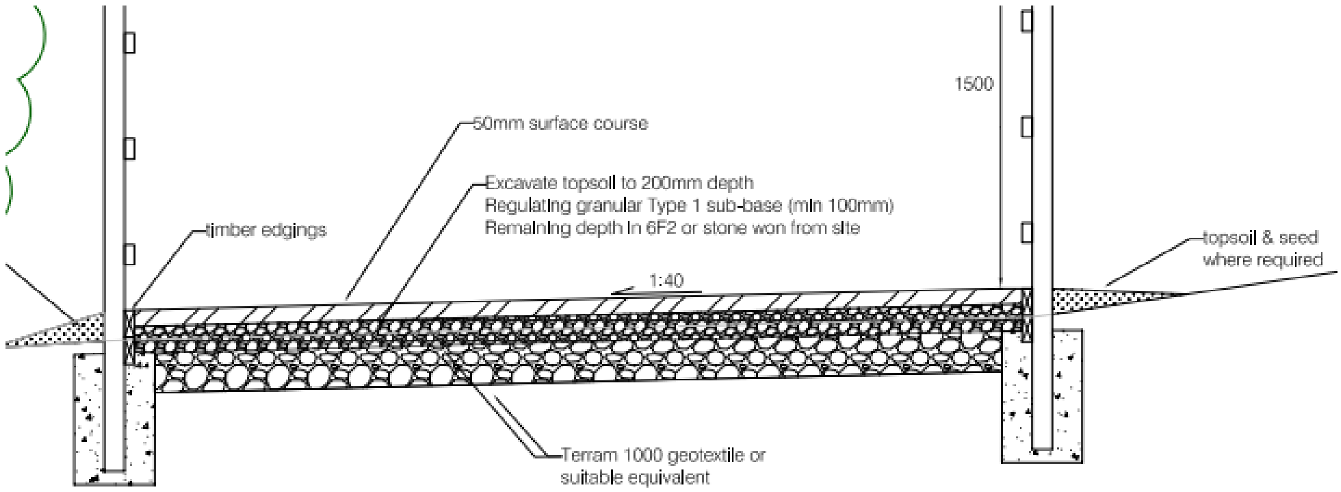


Figure 6.2-Asphalt schematic used for life cycle assessment

(Lancashire County Council, 2019b)

A literature review was undertaken to identify appropriate emission factors used in the assessments. A full inventory of emission factors used to assess the equivalent carbon emissions is at Appendix A, together with the literature sources.

All calculations were carried out in Microsoft excel, a full workbook can be found in Appendix F (all references for values used are in Appendix A)

The following assumptions were made for the life cycle assessment:

- All raw materials for the rubber-aggregate and asphalt pavements where processed at the extracted site, resulting in no transport emissions from quarry to plants (this is common practice).
- Where no information was available on suppliers, the closest supplier to the case study site was used (distances and supplier can be found in Appendix D)
- The aggregates used in the rubber-aggregate pavement and asphalt come from the same source.
- A 50% utilization factor for all vehicles, kgCO_2e per km where calculated in accordance with *'Further guidance on the calculation of whole life greenhouse gas emissions generated by asphalt'* (Transport Research Laboratory, 2011).

6.3 Social Evaluation

An online questionnaire was carried out to investigate the views of different groups of users on the use of rubber-aggregate and asphalt materials in the area of the case study.

The questionnaire was promoted via social media and the secretaries of equestrian, cycling, walking and running clubs in the area. The questionnaire opened on 1st February and closed on 31st March 2019.

Each respondent was asked to state the dominant use they identified with (eg, cyclist, runner, walker or equestrian).

Questions were asked relating to perceptions of the surfaces in the case study. The survey was completed on *Survey Monkey*. The survey can be found at: https://www.surveymonkey.co.uk/r/8CCVD5K.

6.4 Economic Evaluation

Data was obtained from the supplier of the rubber-aggregate pavement in the case study for the cost per linear metre of constructing a hypothetical 1.5km path with either rubber-aggregate or asphalt. The supplier's data was cross checked with the invoiced costs to the highway authority in the case study area to ensure its representativeness.

For the Cost Benefit Analysis (CBA), the original CBA documentation used to support the scheme in the case study was obtained from the highway authority.

The original CBA assumed the 23km of new surfacing in the case study area would be constructed with asphalt pavement. The cost part of the original CBA was recalculated with rubber-aggregate replacing asphalt, and using the construction cost data obtained from the supplier.

The estimated benefits in the original CBA (Jacobs, 2015 – see Appendix E) were based on the creation of a cycle track with a hard surface and the expected benefits in modal shift, rather than the type of surface used in the construction. It is therefore difficult to calculate the change in benefits as a result of constructing a rubber-aggregate surface rather than an asphalt surface. Nevertheless, this research attempted to make a qualitative assessment of the change in benefits that might result from a change in surface types.

7 RESULTS

This chapter sets out the results from the tests on the properties of the paving materials investigated: engineering, environmental, social and economic.

7.1 Engineering Evaluation

This section summarises the findings of all engineering evaluation methods discussed in section 6.1.

7.1.1 Strength and Stiffness

Figure 7.1 shows the mean load displacement relationship of four specimens of a rubber-aggregate pavement tested from the case study. During loading it was oberved the rubber-aggregate paving material did not split, but the specimen reduced in size vertically while elongating horizontally, diplaying elastic behavior.

No 'split' occurred during loading of the rubber-aggregate material; the aggregate and rubber seperated in parts. The material was still relatively bound compared to when conventinal asphalt was subject to load until failiure.

The mean strength and stiffness results from the test are shown in Table 7.1 along with the standard deviation deviation and co-efficient of variance.

Table 7.1-Strength stiffness of a rubber-aggregate pavement

Property	Mean	Standard deviation	Co-efficient of variance (%)
ITS (N/mm^2)	1.06	0.02	1
Stiffness (kN/mm^2)	0.15	0.01	4

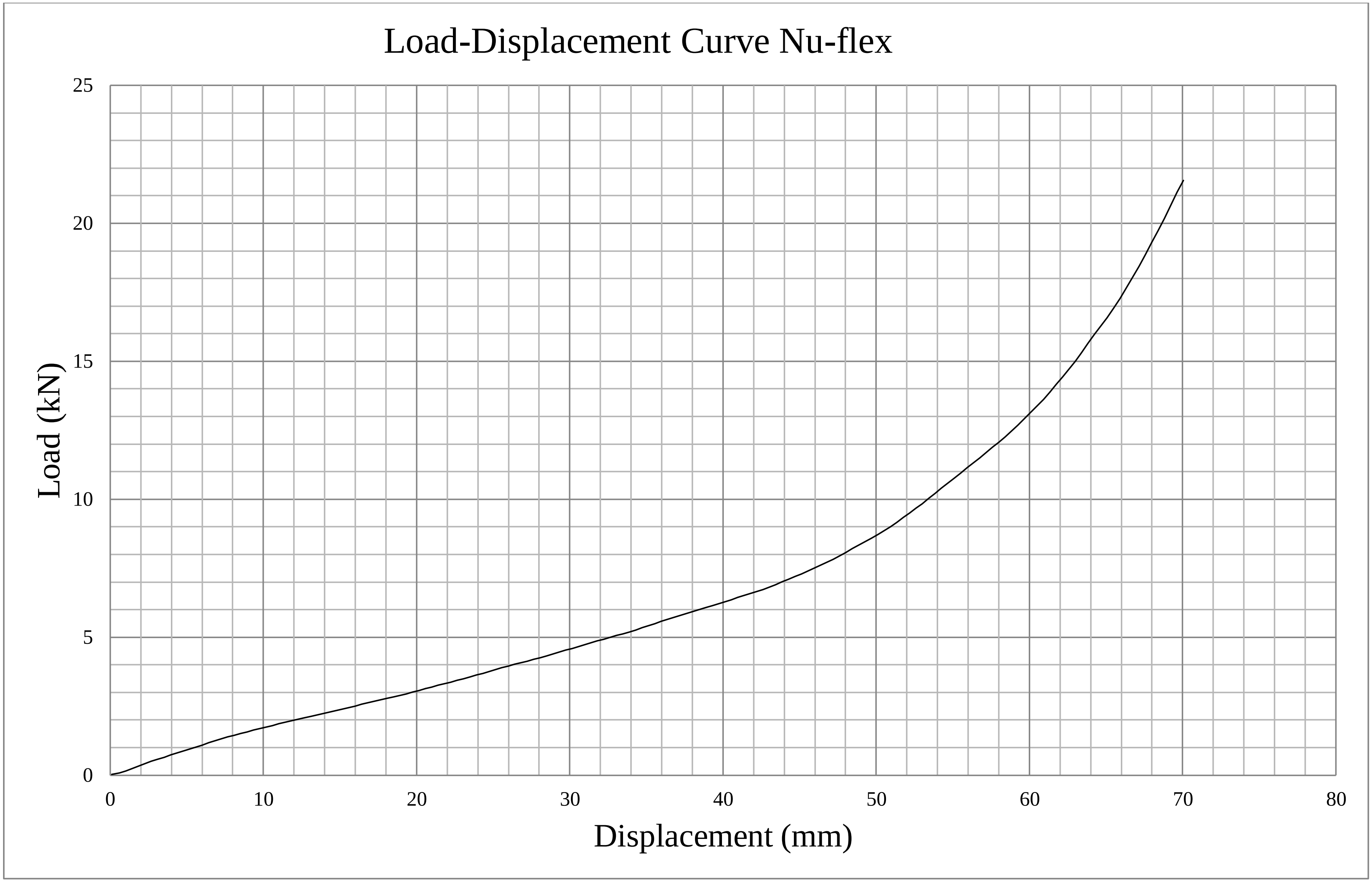


Figure 7.1- Mean load-displacement curve Nu-flex

7.1.2 Skid Resistance

Table 7.2 shows the mean texture depth from the results of testing the pavements on the Britannia Greenway section of the ELSCN in the case study. The standard deviation is also shown.

Table 7.2-Mean texture depth of rubber-aggregate and asphalt pavements

Paving material	Mean texture depth (mm)	Standard deviation (mm)	Co-efficient of variance (%)
Nu-flex	1.98	0.06	3
Asphalt	0.84	0.04	5

7.1.3 Drainage

Table 7.3 shows the mean infiltration rates from the results of testing the paving materials used in the area of the case study.

The tests were conducted on the Britannia Greenway, apart from the test on the freshly laid rubber-aggregate pavement which was carried out at the Helmshore location (Figure 5.1).

Table 7.3-Mean infiltration rates of rubber-aggregate and asphalt pavements in the case study

Paving material and condition	Mean infiltration rate (mm/min)	Standard deviation (mm/min)	Co-efficient of variance (%)
Nu-flex (fresh laid)	840.63	13.31	2
Nu-flex (18 month old)	465.75	20.79	4
Nu-flex (with leaves)	344.84	19.43	6
Nu-flex (swept leaves)	345.00	18.66	5
Asphalt	1.84	0.01	0

7.1.4 Durability

Table 7.4 shows a summary of the results from the cyclic compressive test. The results showed significant variability, as can be seen from the standard deviations in Table 7.4. For that reason all six creep curves are presented (Figures 6.2-6.7 from PTS International (2019)). The variability is discussed in section 8.1.4, and the mean and maximum values are compared to asphalt.

Table 7.4-Cyclic compressive test results

Property	Mean	Standard deviation	Co-efficient of variance (%)
Permeant deformation (mm)	0.59	0.16	27
Cumulative axial strain (%)	0.97	0.26	27
Creep modulus (MPa)	110.57	29.04	26
Creep rate (μm/m/cycle)	0.22	0.07	30

(PTS International, 2019)

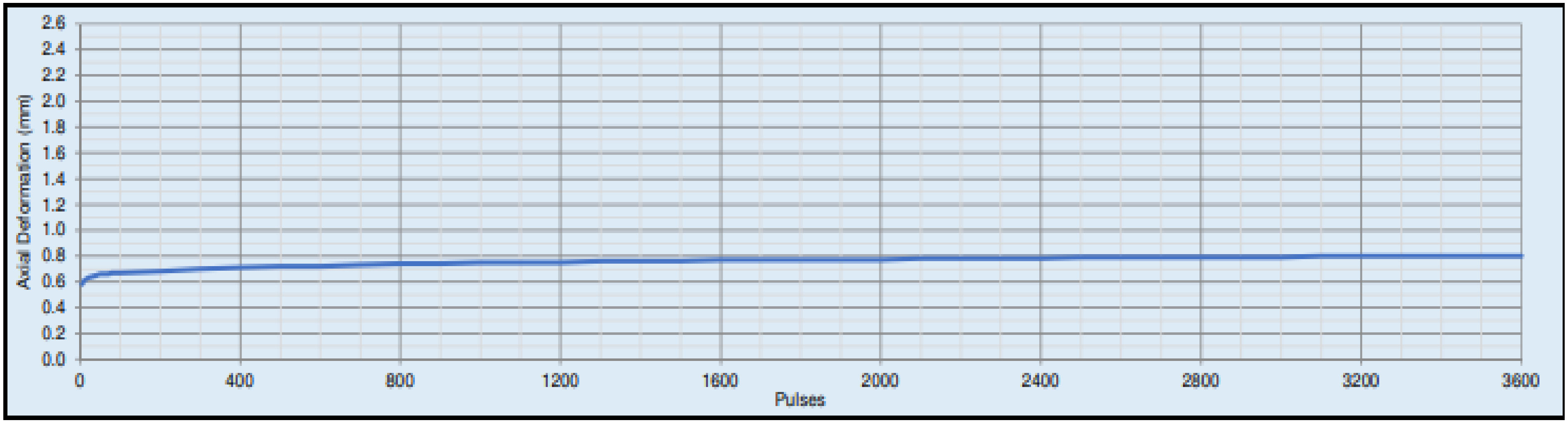


Figure 7.2-Cyclic creep curve sample 1 (PTS International, 2019)

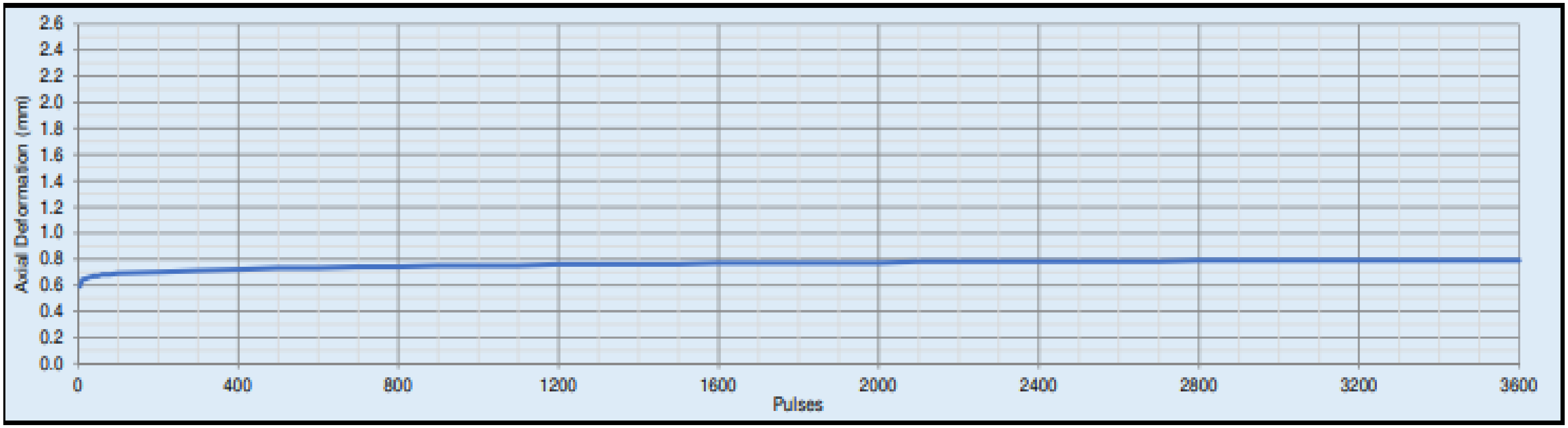


Figure 7.3-Cyclic creep curve sample 2 (PTS International, 2019)

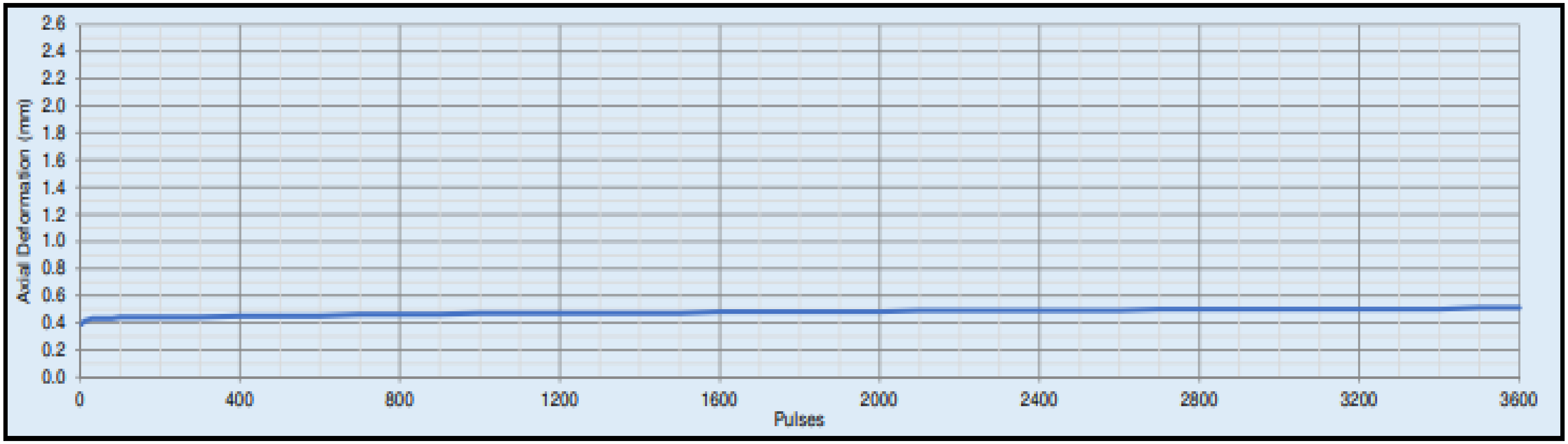


Figure 7.4-Cyclic creep curve sample 3 (PTS International, 2019)

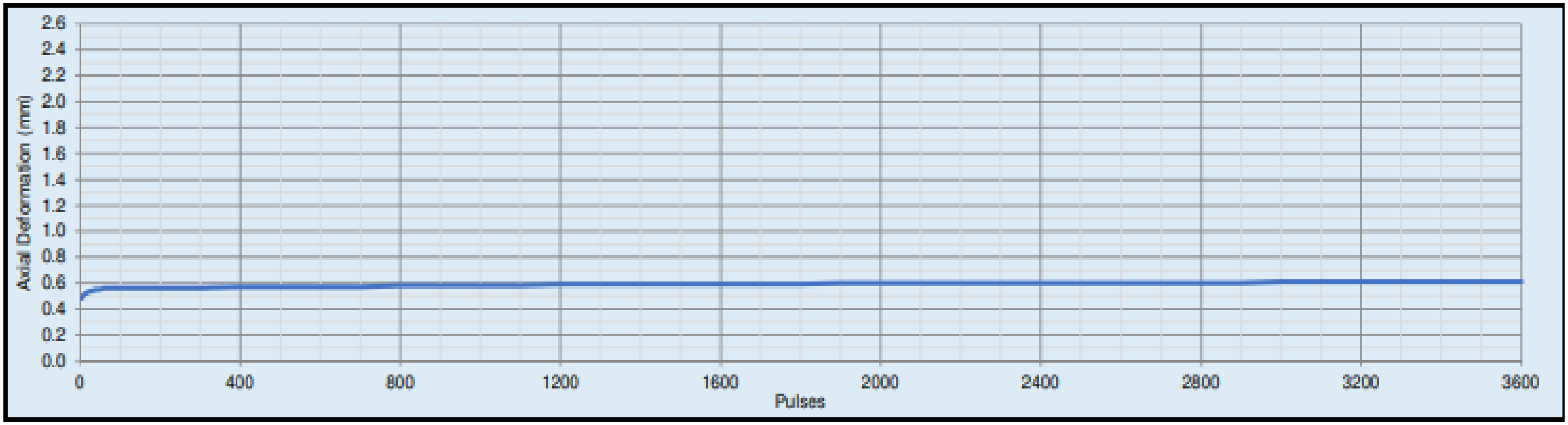


Figure 7.5-Cyclic creep curve sample 4 (PTS International, 2019)

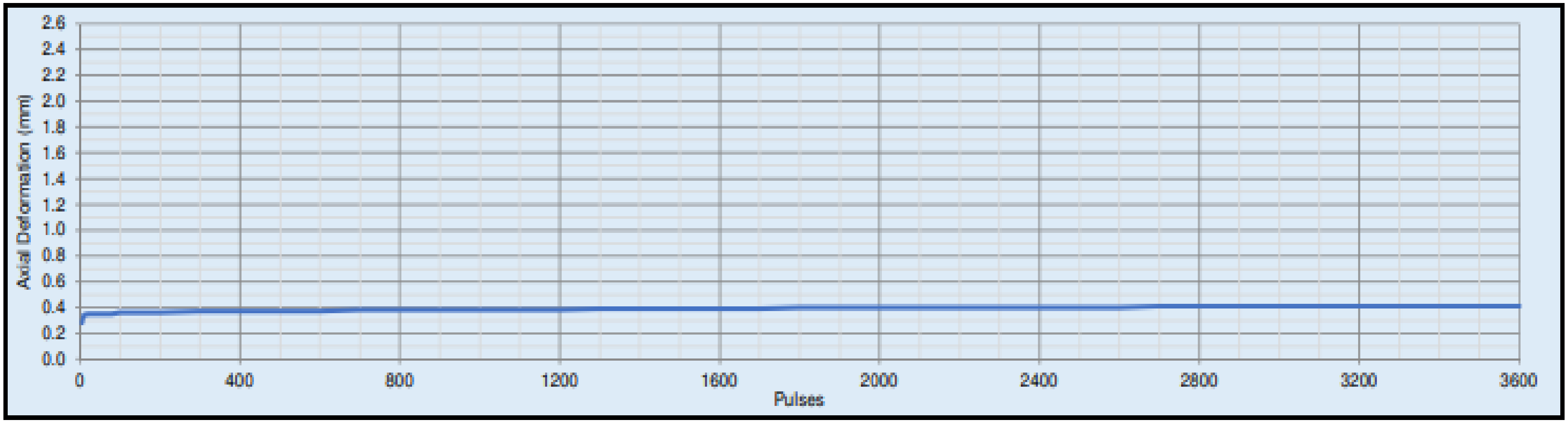


Figure 7.6-Cyclic creep curve sample 5 (PTS International, 2019)

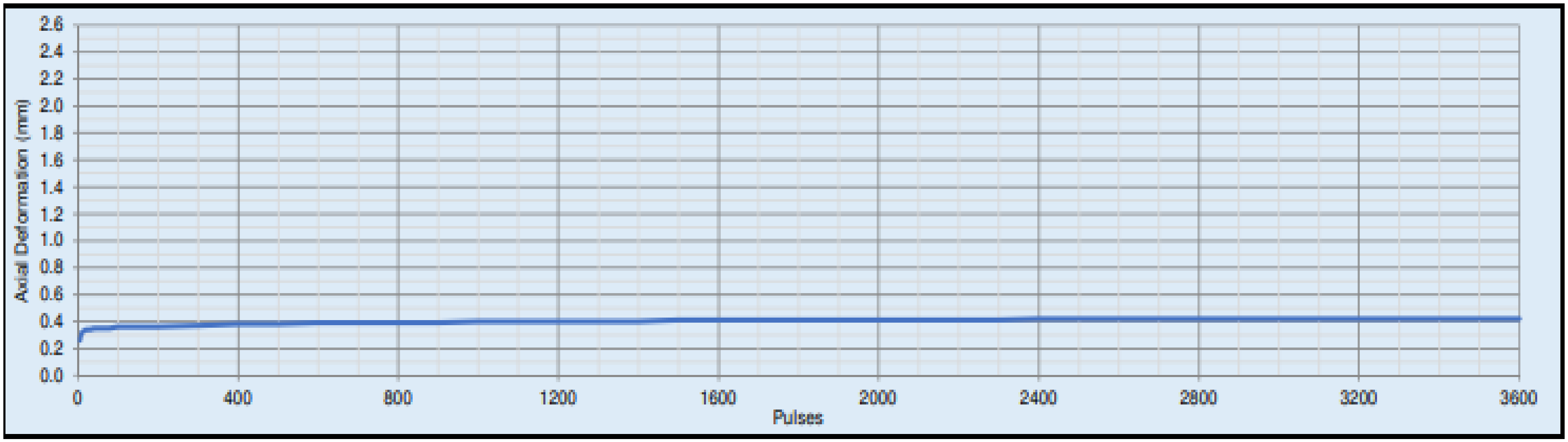


Figure 7.7-Cyclic creep curve sample 6 (PTS International, 2019)

7.1.5 Ice Formation

Plate 7.1 and Plate 7.2 show sections of the Britannia Greenway paved with Nu-flex and asphalt respectively, the images were by both taken by the author on 28th January 2019

Plate 7.1-Brittania Greenway Nu-flex section in sub-zero temperatures showing no ice

Plate 7.2-Britannia Greenway asphalt section in sub-zero temperatures showing ice

7.2 Environmental Evaluation

Table 7.5 shows this study's calculations of the equivalent carbon emissions resulting from paving a one kilometre section of the Britannia Greenway with either a rubber-aggregate pavement (Nu-flex in the case study) or conventional asphalt. Appendix A sets out sources and references used to calculate the values in Table 7.5. Full calculations can be found in Appendix F.

Figure 7.8 shows the emissions from each phase of the life cycle assessment carried out in this study as a percentage of the total emissions for a rubber-aggregate pavement. Figure 7.9 presents the same emissions calculated in this study for conventional asphalt.

Table 7.5-Carbon emissions associated with the construction of rubber-aggregate and asphalt pavements in the case study area.

Emission source	Total emissions from a 1km stretch of rubber-aggregate pavement in the case study area ($kgCO_2e$)	Total emissions from a 1km stretch of a conventional asphalt pavement in the case study area ($kgCO_2e$)
Raw material extraction and processing	172,772.97	56,563.25
Recycling of tyres	-163,038.60	0
Transportation to site	2,167.09	2,831.42
Laying emissions	0*	2635.525
End of life disposal	716.01	716.01
Total	12,617.55	62,746.27

*manual mixing and laying

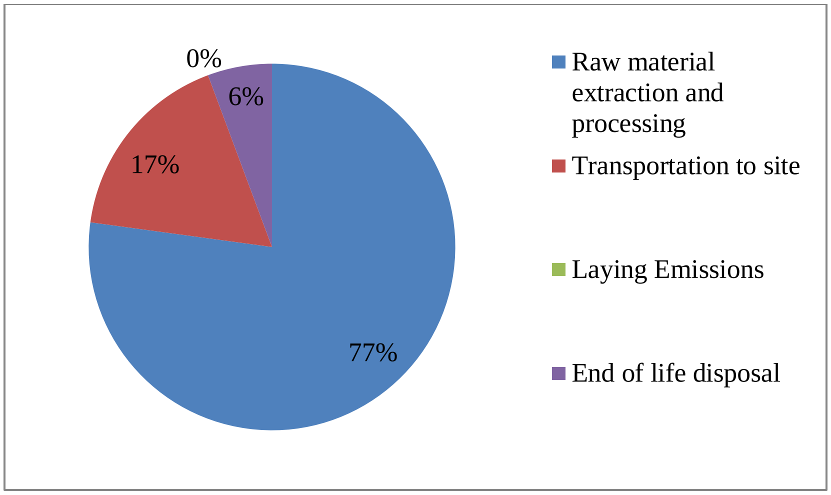


Figure 7.8-Rubber-aggregate pavement: emissions of carbon by phase of life cycle

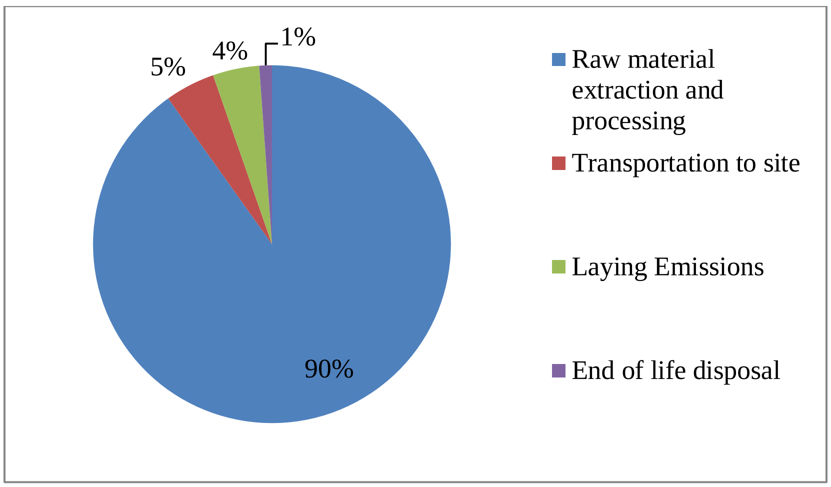


Figure 7.9-Conventional asphalt pavement: emissions of carbon by phase of life cycle

7.3 Social Evaluation

7.3.1 Overall Responses to the Community Questionnaire

Some 87 users responded to the community satisfaction questionnaire. The overall response by user group is shown in Figure 7.10. The highway authority in the case study has confirmed there was good representation of the different groups of users (Lancashire County Council, 2019b). Responses were disaggregated by user group and are set out in sections 7.3.2, 7.3.3, 7.3.4 and 7.3.5. No wheelchair user responses were received. Five users selected *'Other',* these being: reduced mobility walker, parent with pram, 'canicross', 'local who does short walks' and a councillor.

Users were asked to select an adjective which best described the feel of the surface. Figure 7.11 shows the responses, not taking their user group into account. Responses by user group are shown in Figure 7.12, Figure 7.16, Figure 7.20 and Figure 7.24.

Respondents were asked about the amount of water pooling on the rubber-aggregate surface, and how this compared to asphalt: 83% of users said they had never experienced any water pooling, and 15% said they had experienced a small amount of water pooling. One person said they had experienced lots of water, and one further person said they have never used the path in wet conditions.

Respondents were also asked if they had noticed any frost or ice formation on the rubber-aggregate pavement, and how it compared with asphalt. Some 60% of respondents said they had never experienced any ice or frost, and 39% said they had experienced some ice or frost. Only one respondent said they had experienced significant ice or frost levels. Some 72% of respondents said the neighbouring asphalt section had more frost or ice; 23% stated both sections had a similar amount of frost or ice, and 5% said more ice/frost had formed on the rubber-aggregate section.

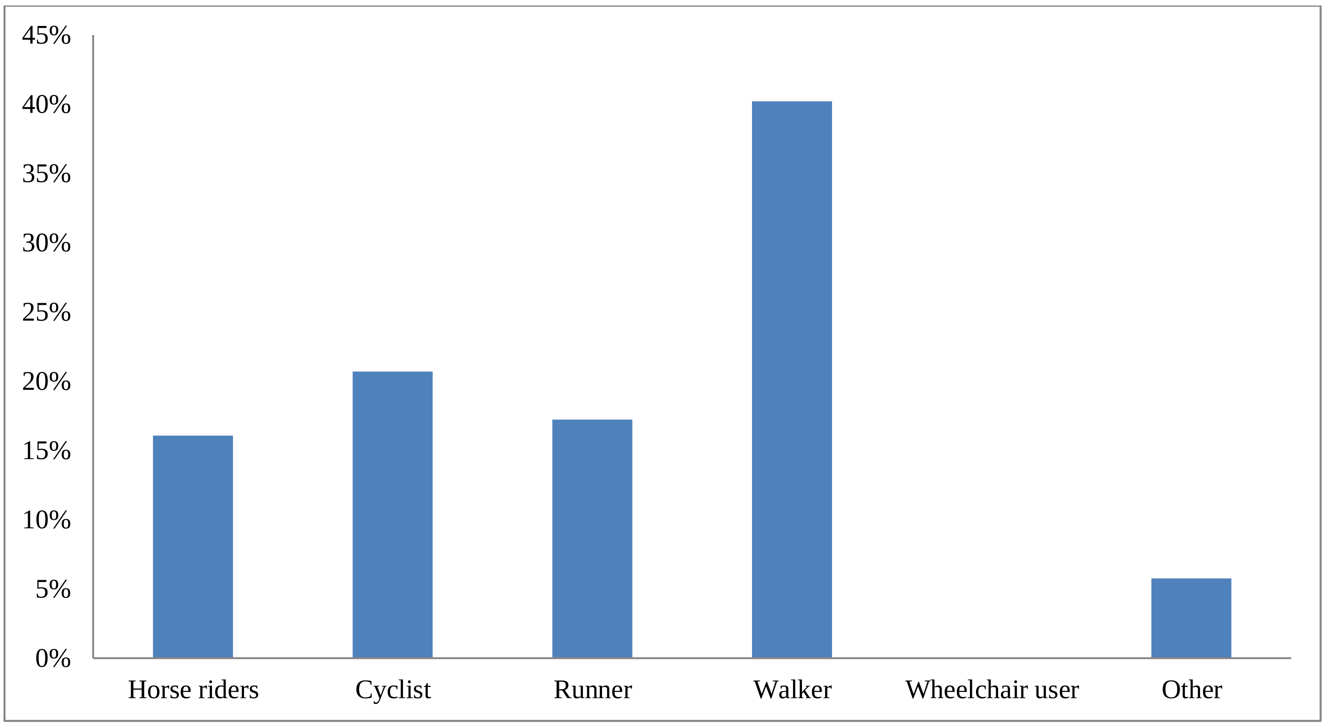


Figure 7.10-Responses to the community questionnaire by user group

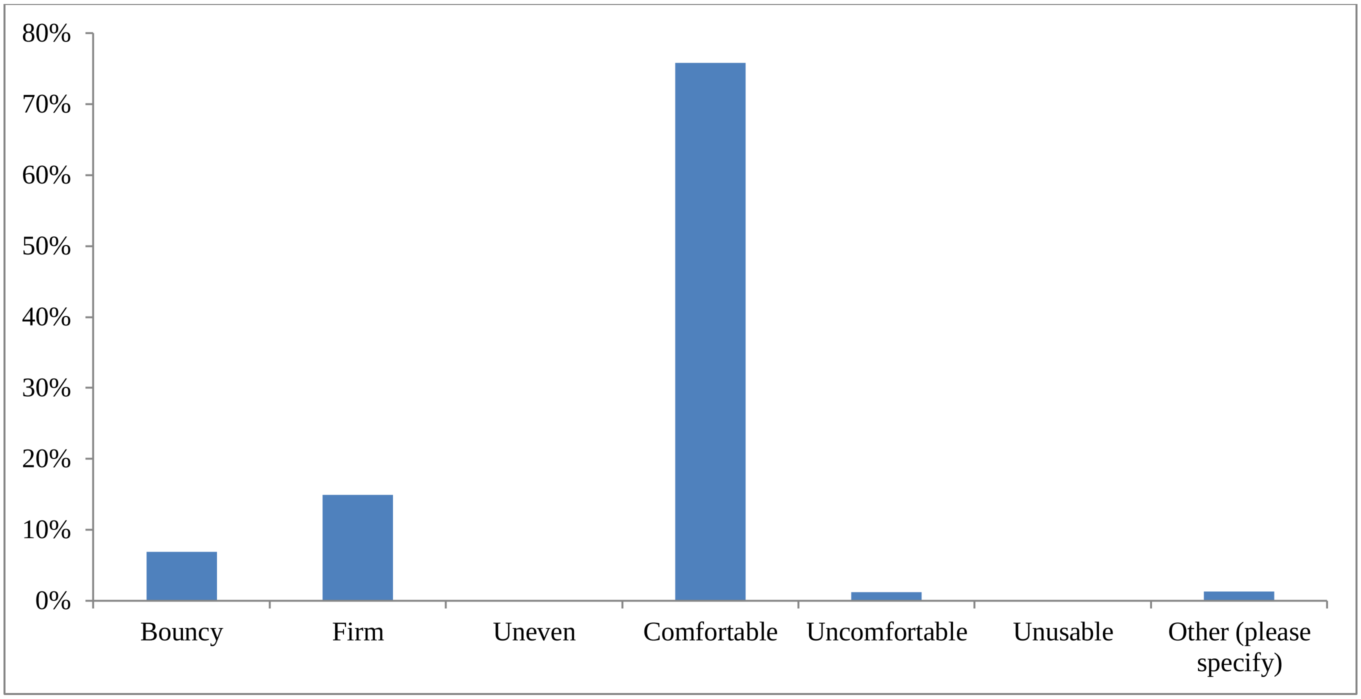


Figure 7.11-Community descriptions of the 'feel' of the rubber-aggregate pavement in the case study

7.3.2 Satisfaction with the Rubber-Aggregate Pavement in the Case Study-Equestrians

This section sets out the responses of equestrians. A total of 14 equestrians responded to the survey.

Figure 7.12 sets out how equestrians describe the 'feel' of the surface; and Figure 7.13 sets out their description of the 'grip' of the rubber-aggregate surface. Figure 7.14 shows how equestrians would prefer a similar path to be paved in the future. Figure 7.15 shows the overall satisfaction of equestrians with the rubber-aggregate pavement.

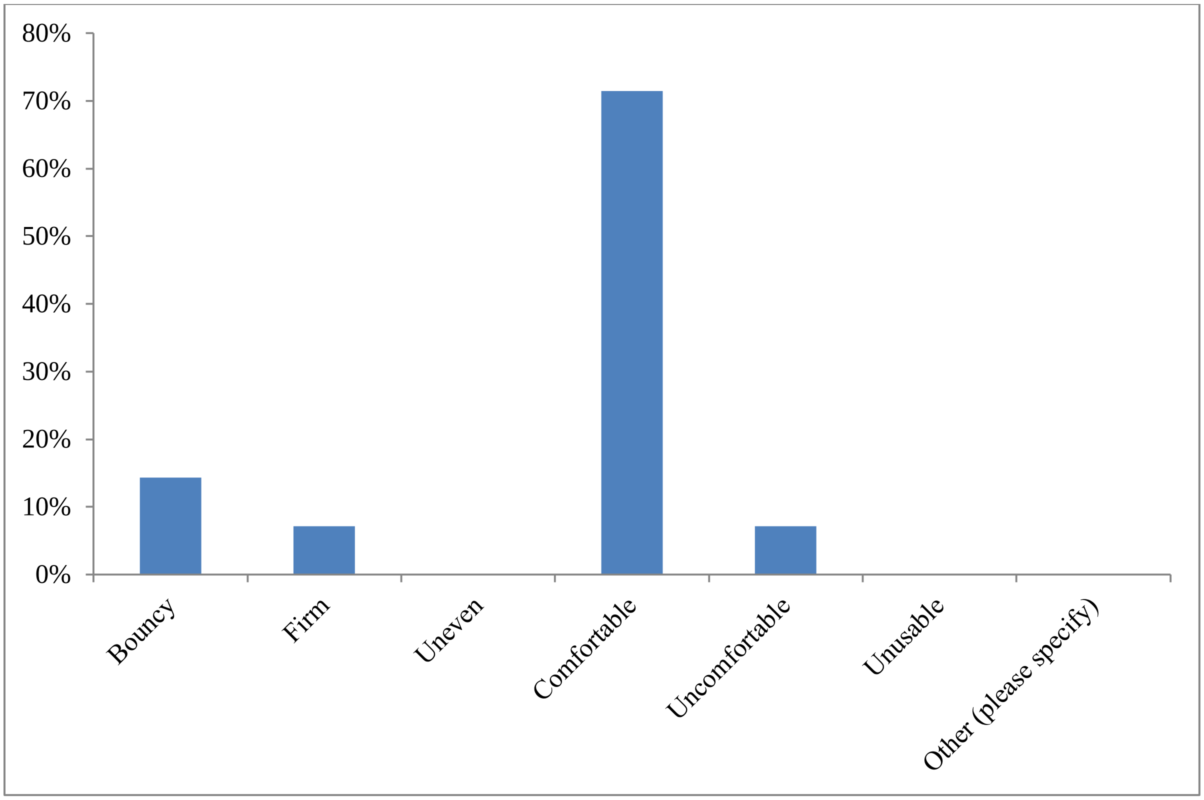


Figure 7.12-Equestrian's description of the 'feel' of the rubber-aggregate pavement in the case study

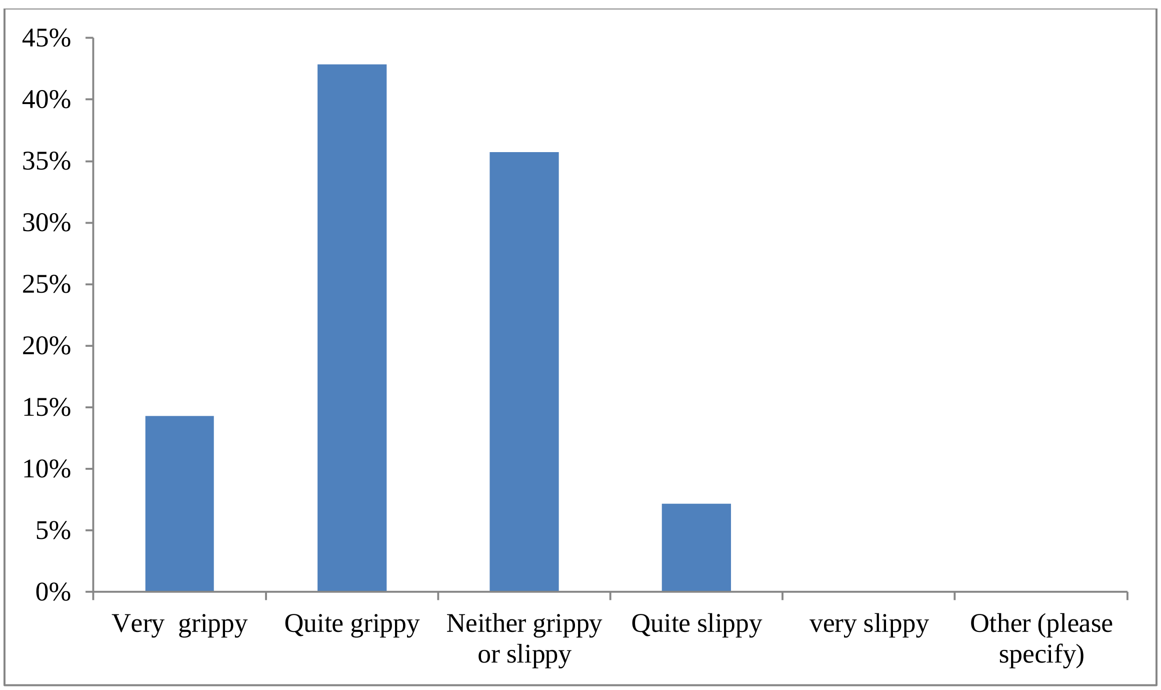


Figure 7.13-Equestrian's description of 'grip' of the rubber-aggregate pavement in the case study

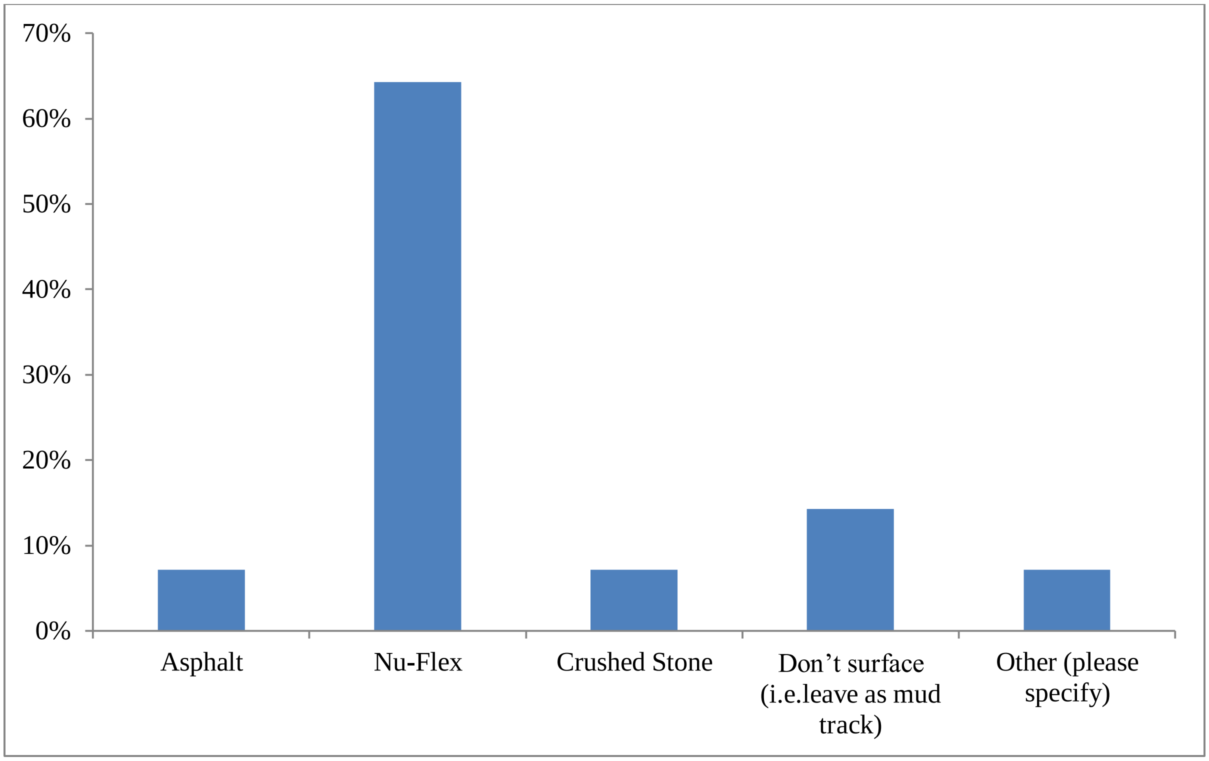


Figure 7.14 –Equestrian’s preference for future pavements

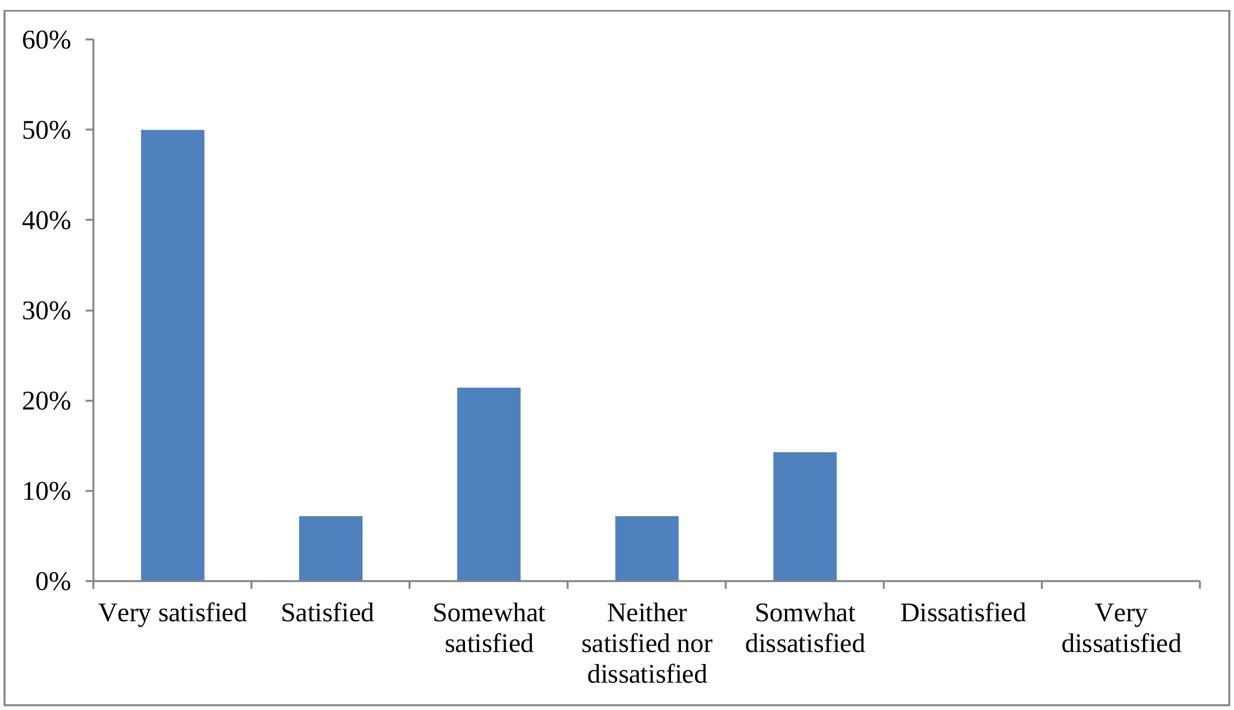


Figure 7.15-Equestrian’s overall satisfaction with the rubber-aggregate pavement in the case study

7.3.3 Satisfaction with the Rubber-Aggregate Pavement in the Case Study-Cyclists

This section sets out the responses of cyclists. A total of 18 cyclists responded to the survey.

Figure 7.16 sets out how cyclists describe the 'feel' of the surface; and Figure 7.17 sets out their description of the 'grip' of the rubber-aggregate surface. Figure 7.18 shows how cyclists would prefer a similar path to be paved in the future. Figure 7.19 shows the overall satisfaction of cyclists with the rubber-aggregate pavement.

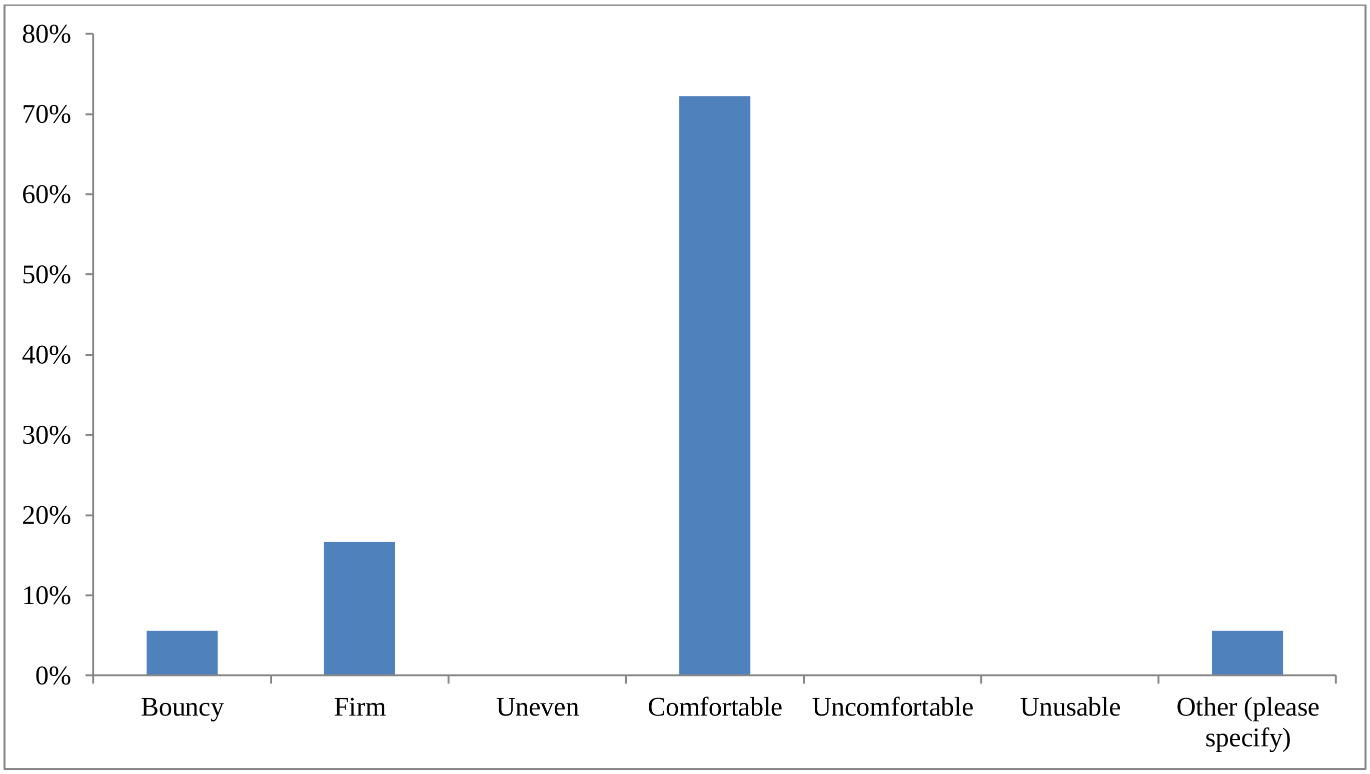


Figure 7.16-Cyclist's description of the 'feel' of the rubber-aggregate pavement in the case study

The *'other'* response was that the rubber-aggregate pavement felt like asphalt.

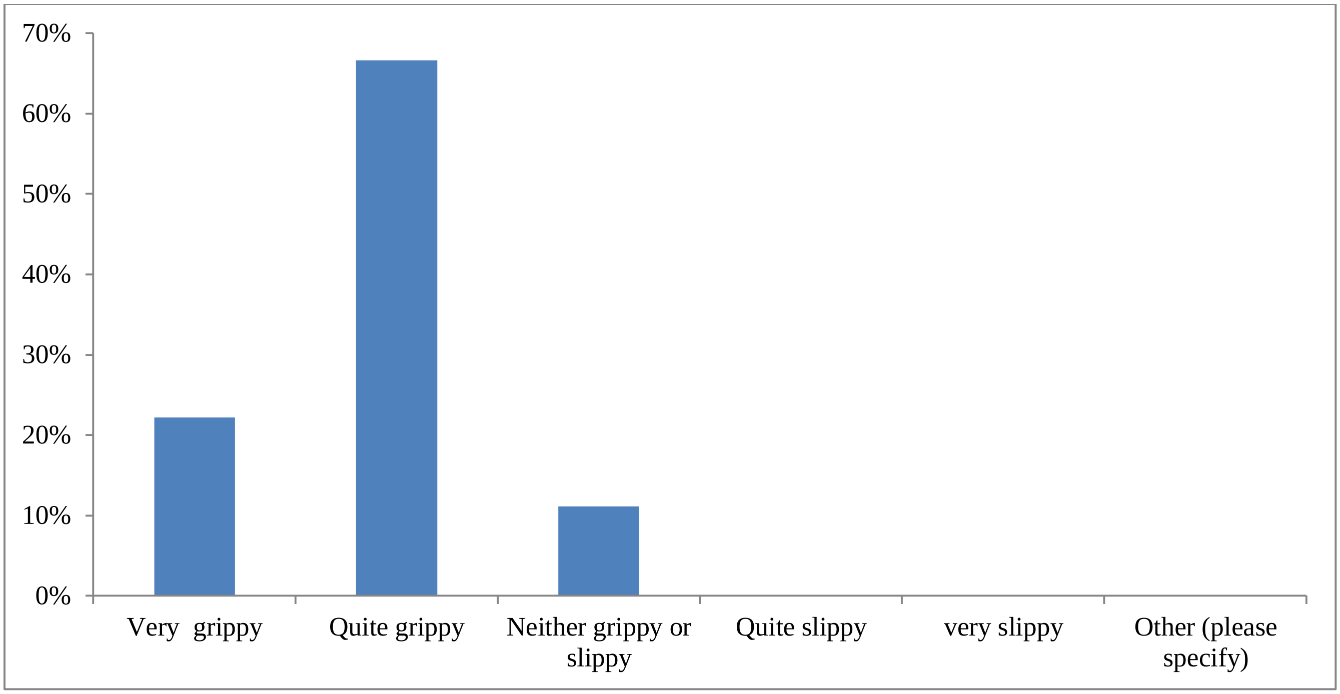


Figure 7.17-Cyclist's description of 'grip' of the rubber-aggregate pavement in the case study

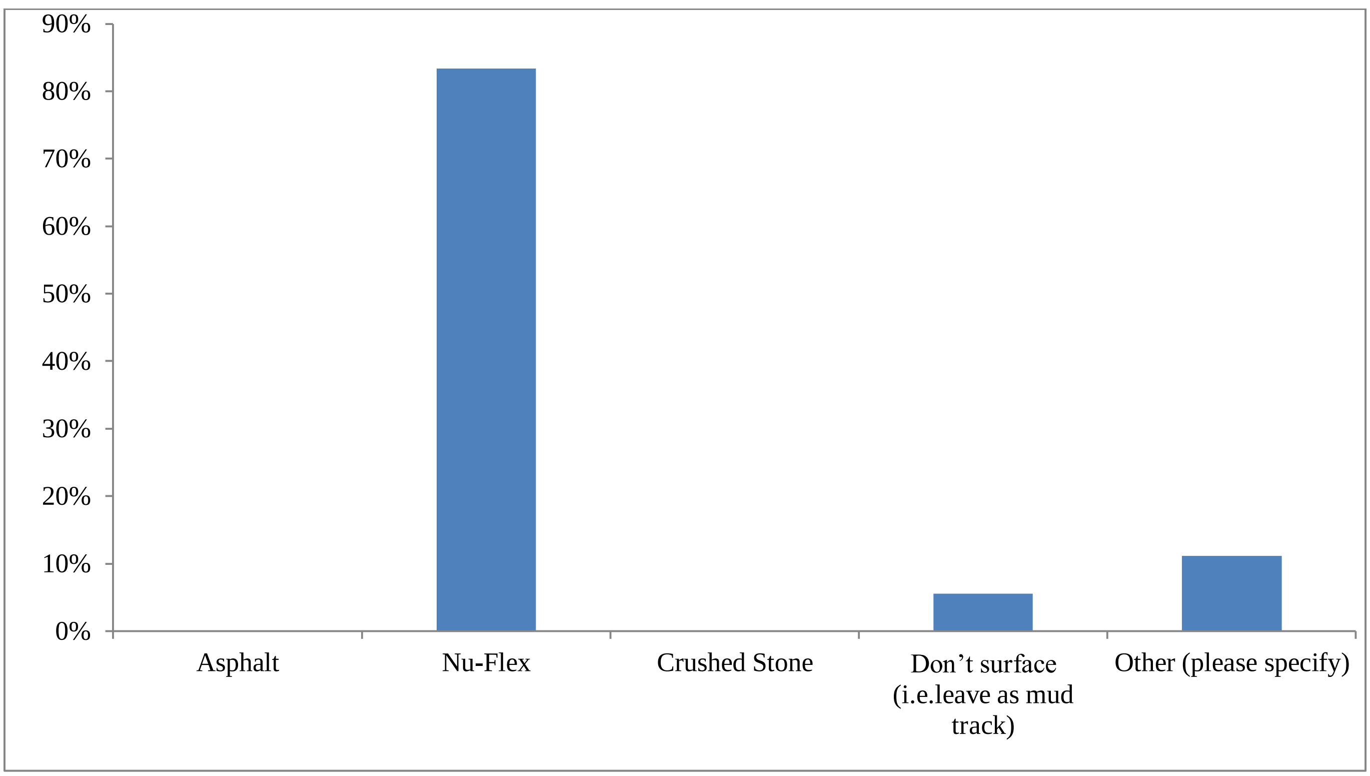


Figure 7.18-Cyclist's preference for future pavements

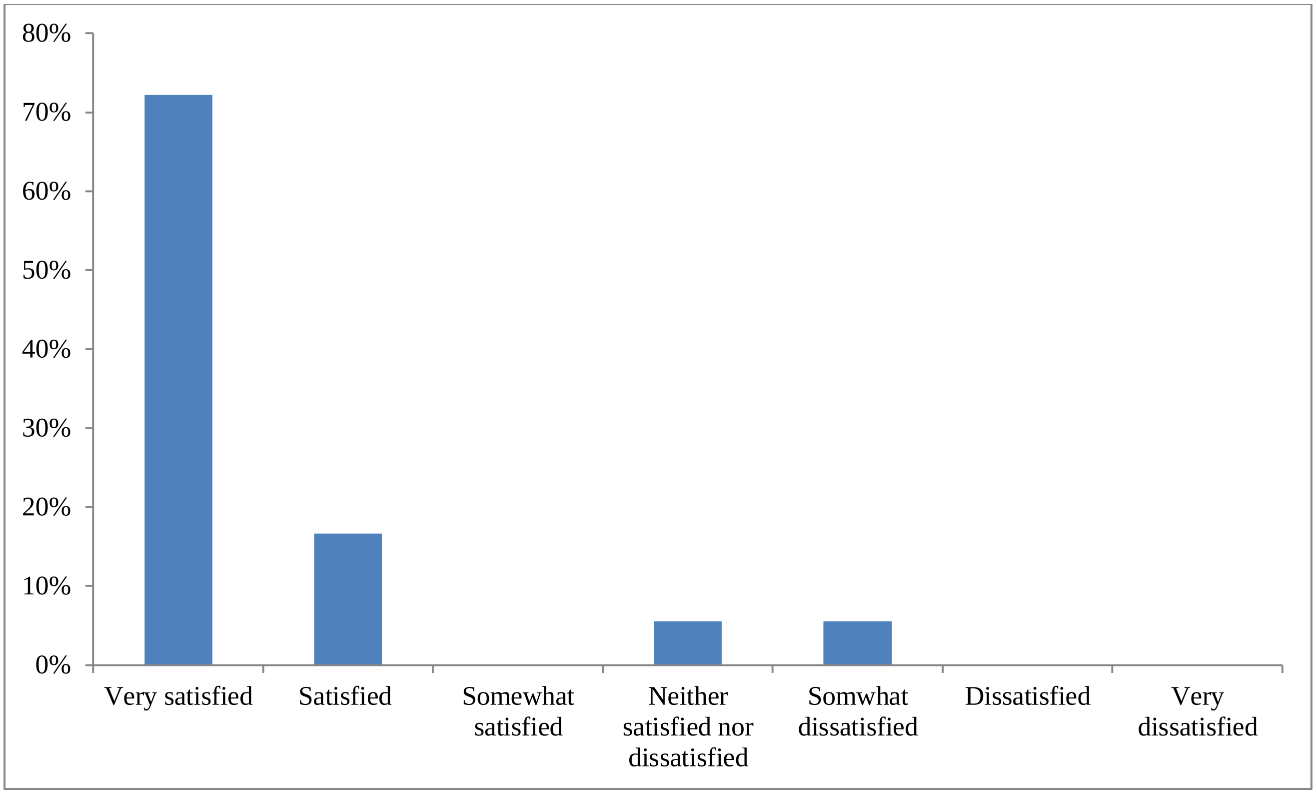


Figure 7.19-Cyclist's overall satisfaction with the rubber-aggregate pavement in the case study

7.3.4 Satisfaction with the Rubber-Aggregate Pavement in the Case Study – Runners

This section sets out the responses of runners. A total of 15 runners responded to the survey.

Figure 7.20 sets out how runners describe the 'feel' of the surface; and Figure 7.21 sets out their description of the 'grip' of the rubber-aggregate surface. Figure 7.22 shows how runners would prefer a similar path to be paved in the future. Figure 7.23 shows the overall satisfaction of runners with the rubber-aggregate pavement.

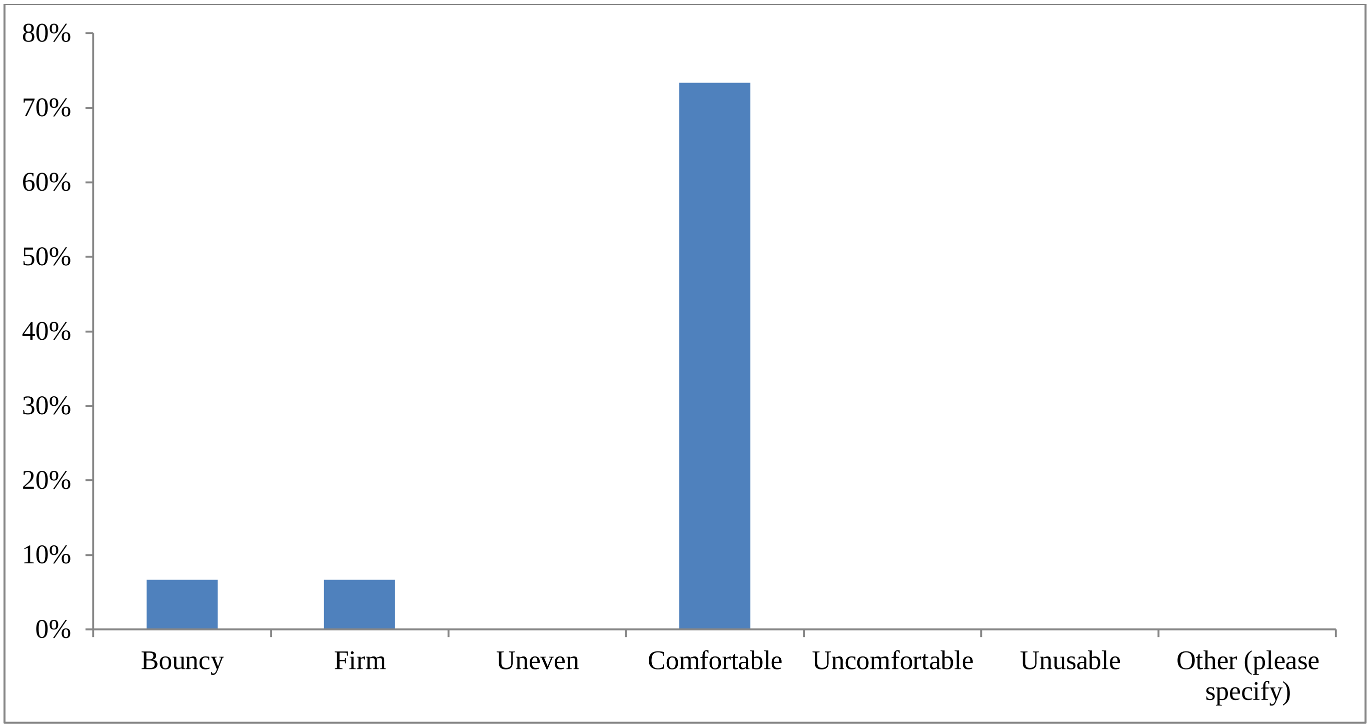


Figure 7.20-Runner's description of the 'feel' of the rubber-aggregate pavement in the case study

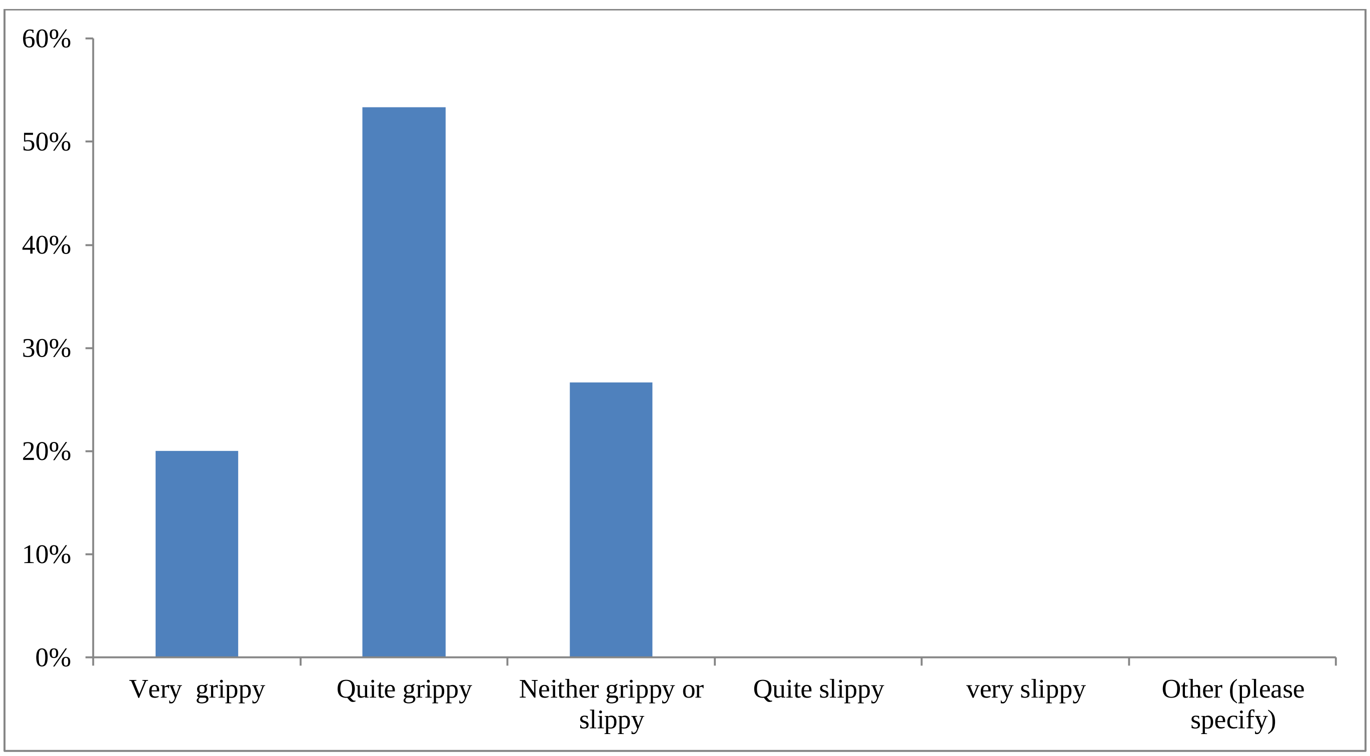


Figure 7.21-Runner's description of 'grip' of the rubber-aggregate pavement in the case study

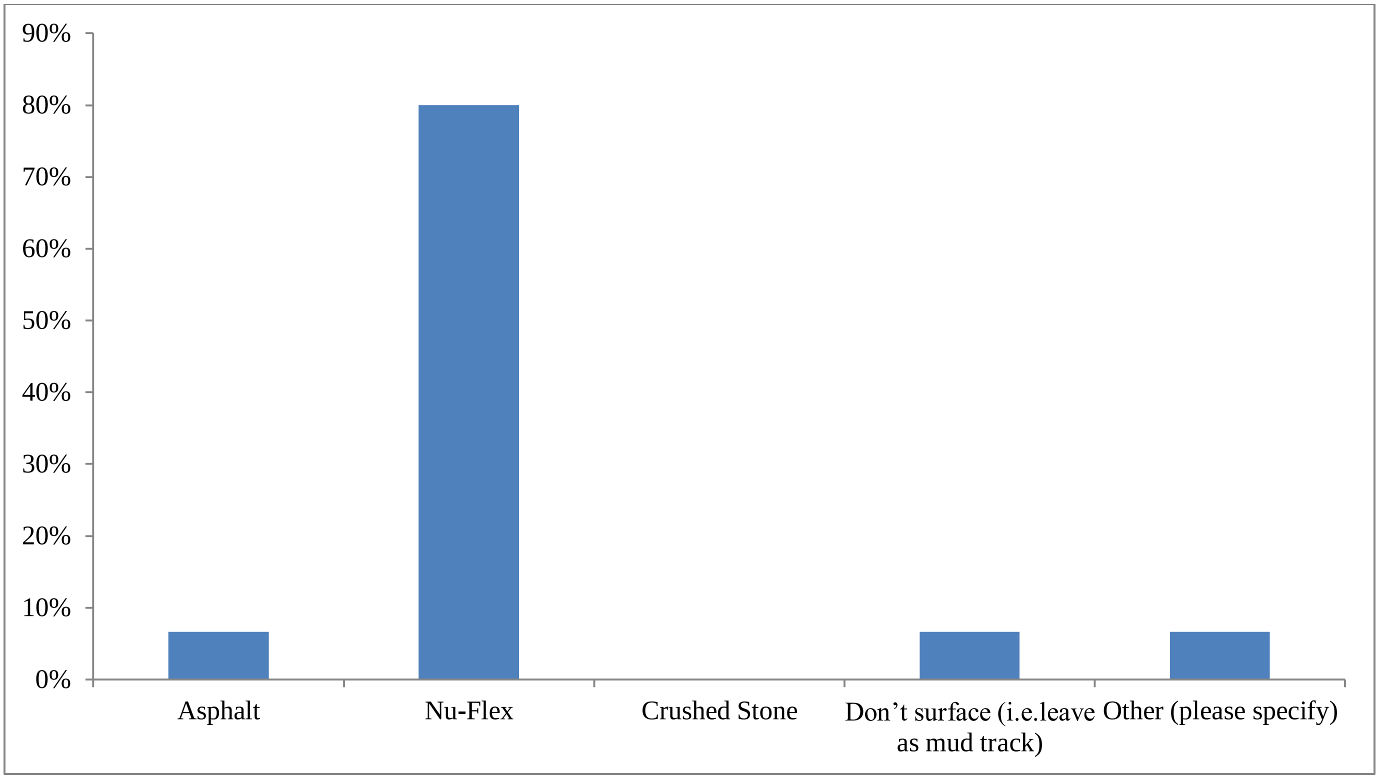


Figure 7.22-Runner's preference for future pavements

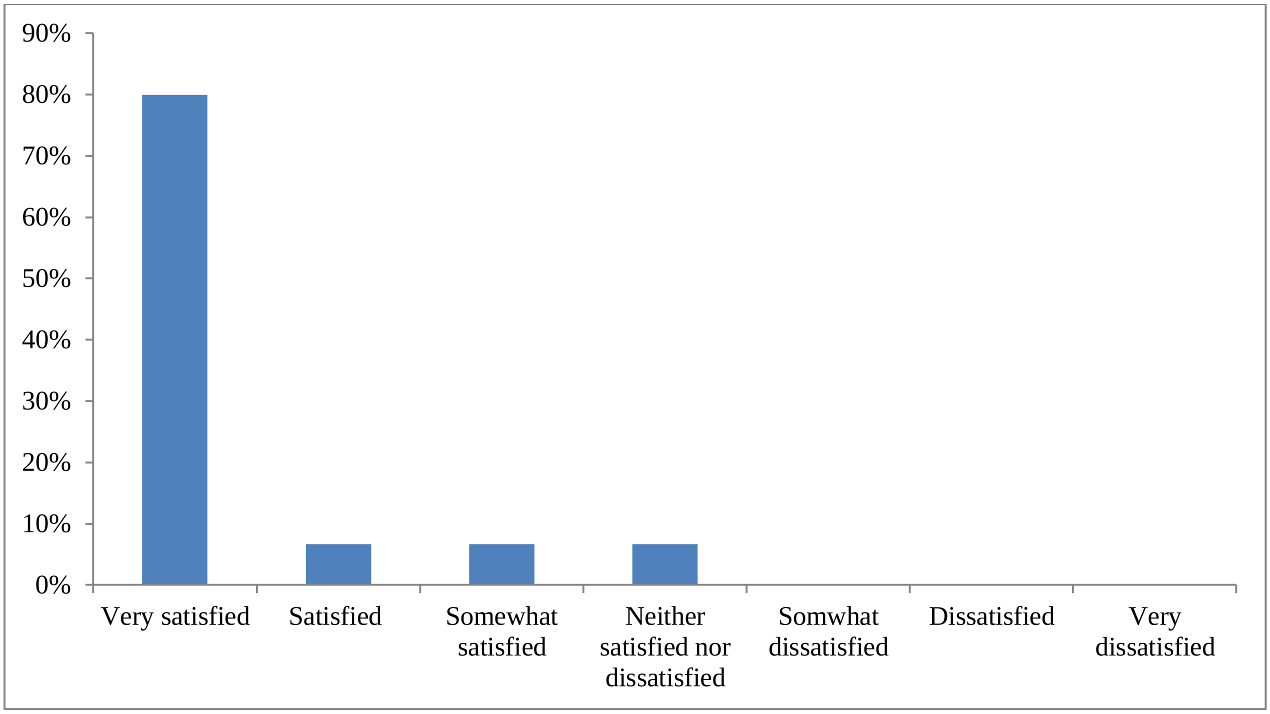


Figure 7.23-Runner's overall satisfaction with the rubber-aggregate pavement in the case study

7.3.5 Satisfaction with the Rubber-Aggregate Pavement in the Case Study-Walkers

This section sets out the responses of walkers. A total of 35 walkers responded to the survey.

Figure 7.24 sets out how walkers describe the 'feel' of the surface; and Figure 7.25 sets out their description of the 'grip' of the rubber-aggregate surface. Figure 7.26 shows how walkers would prefer a similar path to be paved in the future. Figure 7.27 shows the overall satisfaction of walkers with the rubber-aggregate pavement.

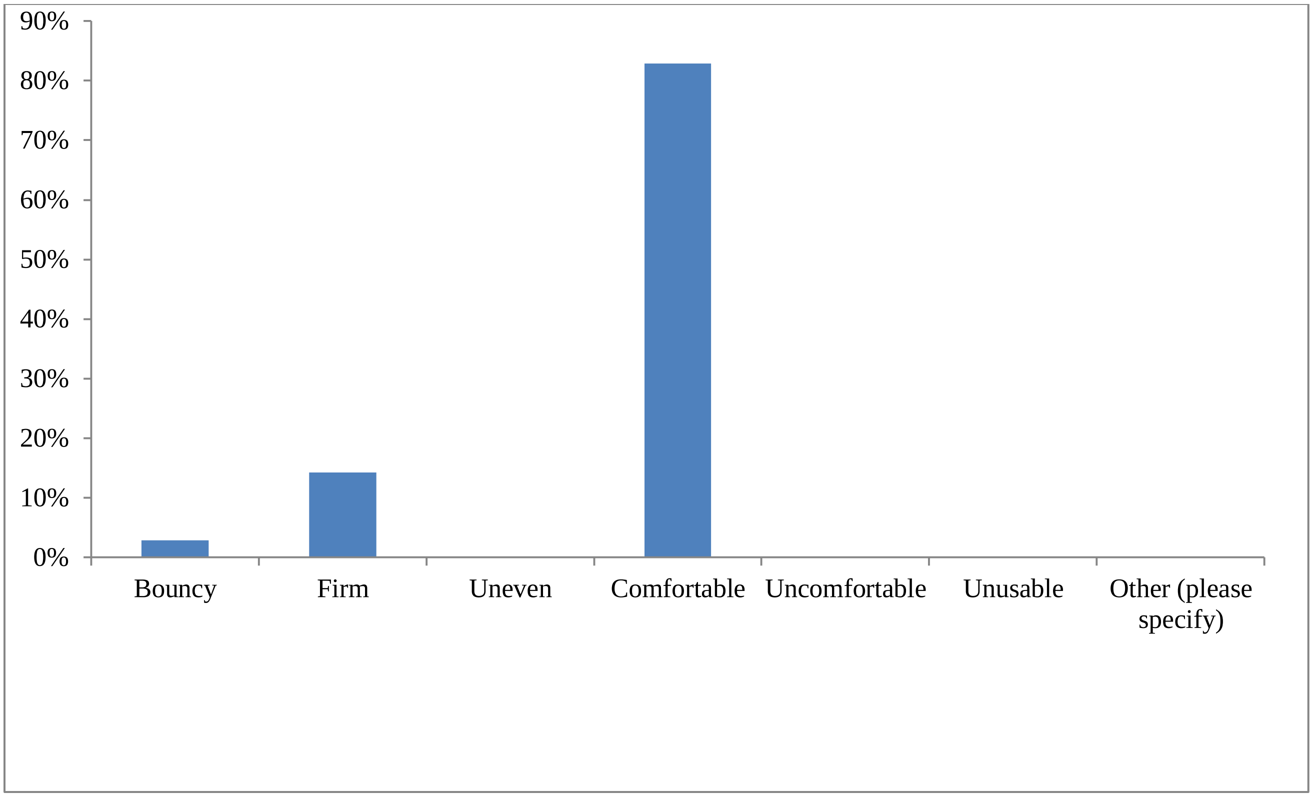


Figure 7.24-Walker's description of the 'feel' of the rubber-aggregate pavement in the case study

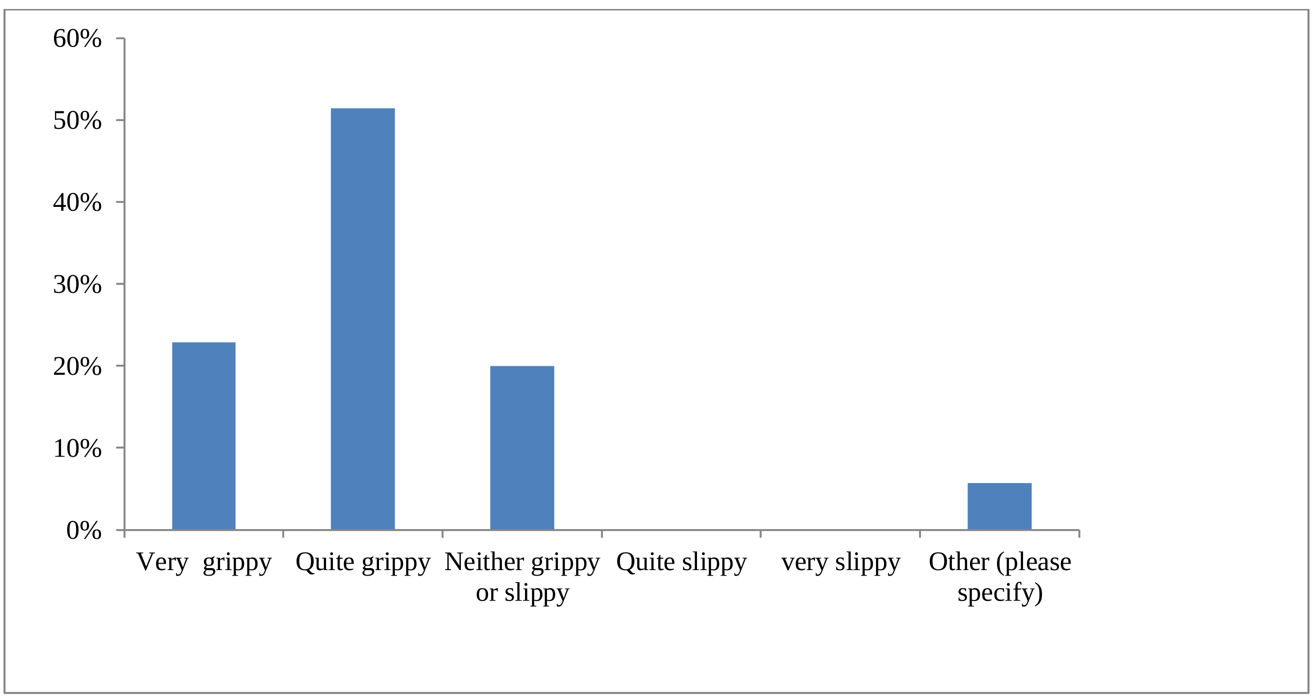


Figure 7.25-Walker's description of 'grip' of the rubber-aggregate pavement in the case study

Other responses related to the type of footwear worn.

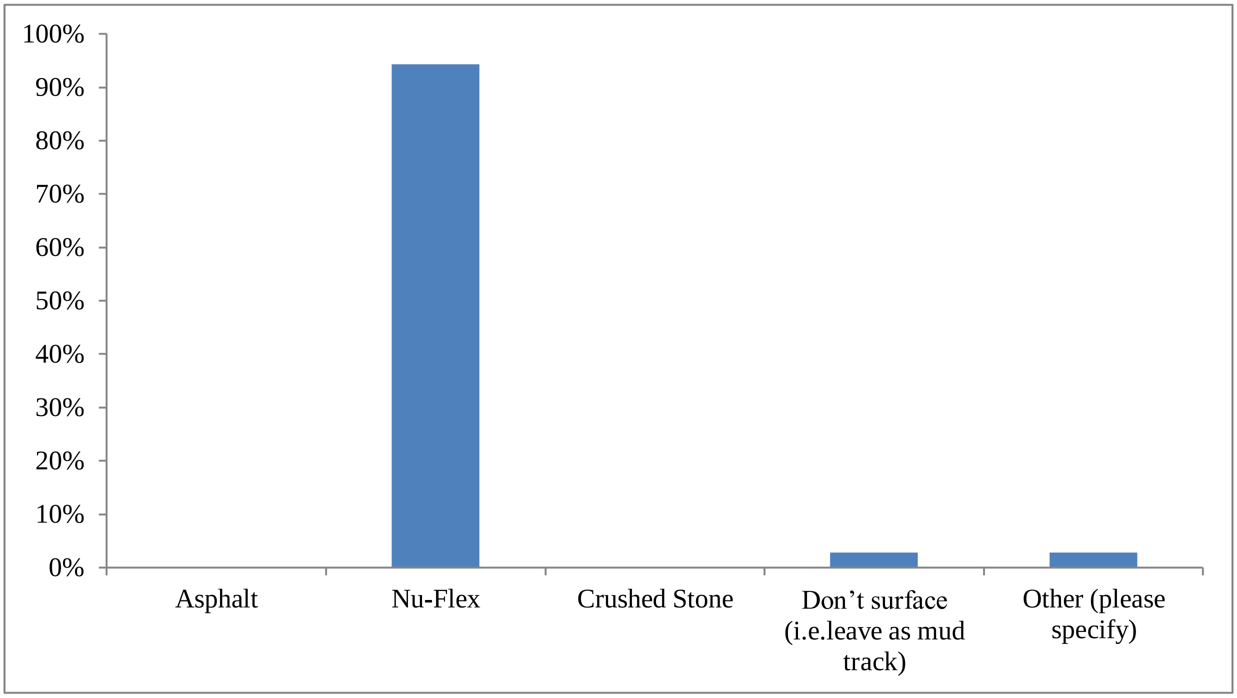


Figure 7.26- Walker’s preference for future pavements

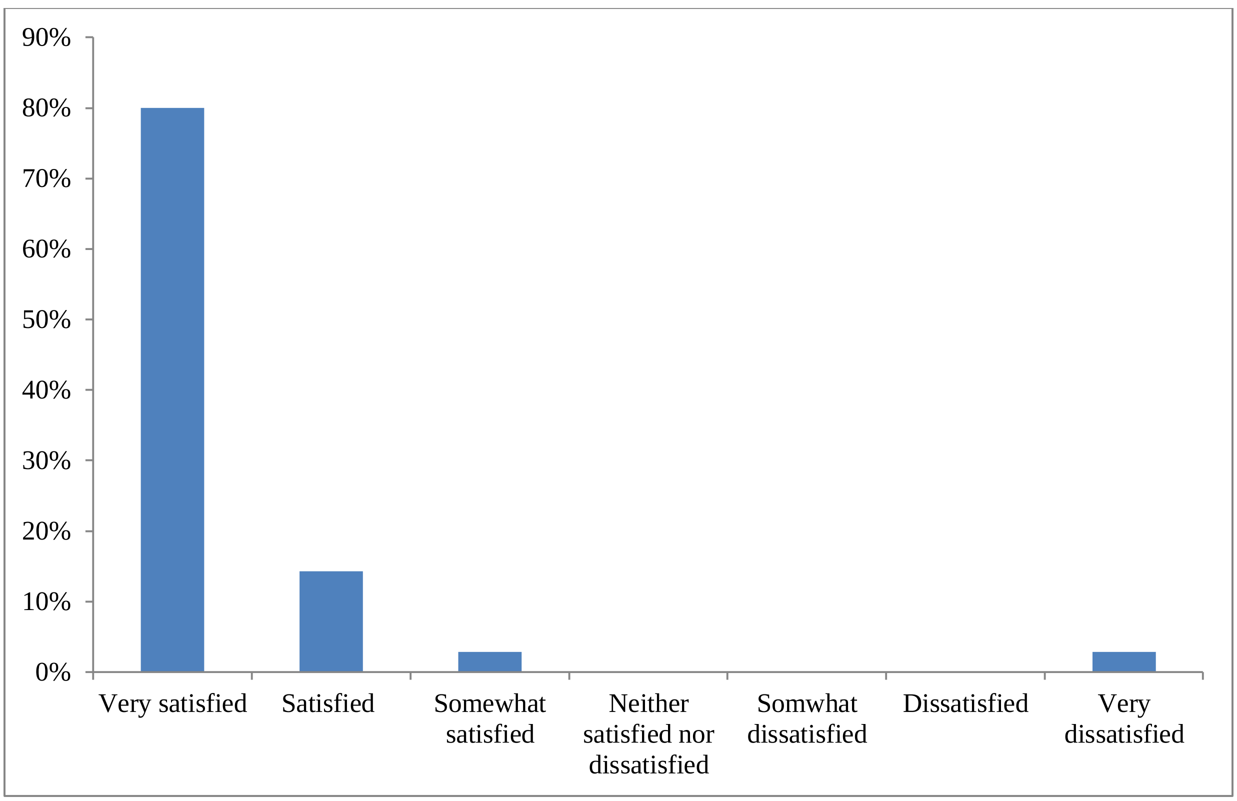


Figure 7.27- Walker’s overall satisfaction with the rubber-aggregate pavement in the case study

7.4 Economic Evaluation

7.4.1 Construction Cost Comparison

Commercially sensitive data on the construction costs per linear metre of asphalt and rubber-aggregate pavements was obtained from the supplier in the case study. The data was converted into standard units (with asphalt with concrete edgings assigned as unity) to allow comparisons capable of publication without compromising the commercial interests of the supplier. Officials from the local highway authority confirmed the data received from the supplier was consistent with invoices for the construction work in the area of the case study (Lancashire County Council, 2019b).

Table 7.6-Unit cost of pavements in the case study

Pavement type	Unit cost
Asphalt with concrete edgings	1.00
Asphalt with timber edgings	0.95
Rubber-aggregate	0.87

(Nu-phalt Group Limited, 2019)

7.4.2 Re-calculation of the Benefit Cost Ratio used in the Case Study

Data from the original CBA used to support the highway authorities business case for the ELSCN is set out in Table 7.7 (Jacobs, 2015), and more detail is set out in Appendix E. Table 7.8 shows the re-calculated BCR, using the costs for rubber-aggregate rather than the cost of asphalt. All other data and assumptions in the original CBA remained the same.

Table 7.7- Original Cost Benefit Analysis of paving the ELSCN with asphalt

Sensitivity	15%	30%	60%
Path Construction Costs	£4,701,890	£4,701,890	£4,701,890
Other Construction Costs	£2,473,269	£2,473,269	£2,473,296
Total Present Value Cost	£7,175,159	£7,175,159	£7,175,159
Present Value of Benefits	£20,021,008	£23,660,390	£29,671,438
Cost-Benefit Ratio	2.79	3.30	4.14

(Jacobs, 2015)

Table 7.8-Revised Cost Benefit Analysis of paving the ELSCN with rubber-aggregate

Sensitivity	15%	30%	60%
Path Construction Costs *	£4,098,600	£4,098,600	£4,098,600
Other Construction Costs	£2,473,269	£2,473,269	£2,473,296
Total Present Value Cost	£6,571,869	£6,571,869	£6,571,869
Present Value of Befits	£20,021,008	£23,660,390	£29,671,438
Benefit cost ratio	3.05	3.60	4.51

**path construction cost is calculated from data provided by the pavement supplier from the case study (see section 7.4.1)*

Adapted from Jacobs (2015)

7.4.3 Health and Physical Activity in the Case Study Area.

The most recent local authority Health Profiles (Public Health England, 2018) was collected. This show the health of the people in Hyndburn, Rossendale and Blackburn (the three local authority areas covered by the cycle network in the case study) is generally worse than the England average and in Blackburn the situation is significantly worse. Relatively high levels of socio-economic deprivation in East Lancashire are linked to poor health outcomes.

Though life expectancy has improved, and some indicators are similar to the national average, life expectancy is significantly below the national average in all three districts. There are also wide social inequalities within East Lancashire and between East Lancashire and nationally (Public Health England, 2018).

Poor life expectancy is driven by relatively high early death rates from heart disease, cancers and respiratory diseases. The number of people recorded with diabetes and mental illness in Hyndburn and Blackburn is also significantly higher than the national average (Public Health England, 2018).

Levels of obesity are high and increasing in East Lancashire. All three districts have higher levels of excess weight in adults and cardiovascular mortality rates, than both the England and the North West average, and in Hyndburn and Blackburn obesity and cardiovascular mortality in the under 75s is significantly higher than the regional average (Public Health England, 2018)

The percentage of physically active adults in all three districts is worse than the regional and national average, and significantly lower in both Hyndburn and Blackburn. The Sport England Active People Survey (2017) found that between 32 to 38% of the adult population of Blackburn, Rossendale and Hyndburn were inactive; this is significantly worse than the England average.

Public Health England (2018) data indicate that for children in East Lancashire schools in Year Six, 31% are classified as obese. The causes of obesity are complex, and include social, economic and environmental factors. However, improving diet and increasing levels of physical activity among adults and children are key objectives in tackling obesity and reducing many of the causes of mortality and morbidity prevalent in East Lancashire (Public Health England, 2018).

7.5 Summary of Results.

This section sets out a summary of the results from the tests and assessments carried out in this research.

Engineering Results.

This research found the Indirect Tensile Strength of the rubber-aggregate pavement in the case study to be 1.06 N/mm^2, with a low stiffness (0.15 kN/mm). Furthermore, the rubber-aggregate pavement in the case study was found to have a high level of resistance to permanent deformation. These values are compared to conventional asphalt in Chapter Eight. Moreover, the rubber-aggregate pavement in the case study showed a higher resistance to skid, better drainage, and less ice formation than conventional asphalt in the case study.

Environmental Results.

The rubber-aggregate pavement in the case study emitted less carbon dioxide equivalent per kilometre than a conventional asphalt pavement over its life cycle. The rubber-aggregate pavement emitted 12,617.55kgCO2e compared to asphalt, which emitted 62,746.27kgCO2e.

Social Results.

The rubber-aggregate pavements in the case study showed high levels of community satisfaction, with all groups of users preferring it to asphalt. Only equestrians showed slightly less satisfaction but the levels were still high compared to asphalt.

Economic Results

The estimated cost of constructing the rubber-aggregate pavement in the case study was lower than the cost of constructing a conventional asphalt pavement with concrete or timber edgings. The lower construction cost yields more value for money, with a higher Benefit to Cost Ratio than conventional asphalt. Furthermore, in the area of the case study the current state of public health and physical activity is low.

8 DISCUSSION

8.1 Engineering Evaluation

The results in Chapter Seven show rubber-aggregate pavements perform better across the five engineering properties that were tested when compared to conventional asphalt pavements: Strength and Stiffness, Skid Resistance, Drainage, Durability and Ice Formation. These are discussed below.

8.1.1 Strength and Stiffness

Section 7.1.1 shows that the rubber-aggregate material tested from the case study has a mean ITS of 1.06N/mm^2. When this is compared to a representative ITS value of 0.77N/mm^2 for conventional asphalt (Brown & Bassett, 1989), it is clear that the rubber-aggregate pavement is able to withstand greater loads.

However, as set out in section 3.1 there is a degree of uncertainty over the identification of a representative ITS value for conventional asphalt used in multi-user paths and tracks, because asphalt can be made from a diverse range of aggregates and bitumen quantities. Nevertheless, the aggregate used in the asphalt that was tested by Brown and Bassett (1989) had a maximum size of 20mm, which is not untypical of asphalts used in multi-user paths and tracks (Department for Transport, 2005) and Appendix B.

Moreover, other researchers have found ITS values for asphalt of 0.81N/mm^2 and 1.12 N/mm^2 (Shunyashree, et al., 2013; Halim, et al., 2001) which are not significantly different from the values used in this research for the comparison. Irrespective, the key question is whether rubber-aggregate pavements are able to withstand the maximum load that can be expected on a multi-user path or track, which is likely to come from a large horse and rider. The maximum mass of a horse is 700kg, with a rider assumed to be 90kg (British Horse Society, 2016). As a worst case scenario, it has been assumed just two hooves are in contact with the pavement simultaneously (i.e. the horse is travelling at speed). This 790kg mass (horse plus rider) translates to a stress of 0.4N/mm^2, which is over 2.5 times less than the ITS of the rubber-aggregate pavement tested in this research. Therefore the rubber-aggregate pavement will not fail in tension.

Interestingly, the ITS decreases when crumb rubber is added to asphalt (Navarro & Gámez, 2012). An asphaltic rubber mix comprises of three main components: aggregates, crumb rubber and bitumen. In contrast a rubber-aggregate material comprises of: aggregates, crumb rubber and a polyurethane binder (see section 5.2). Given this difference, the increase in ITS of a rubber-aggregate pavement is likely to be due to the properties of the polyurethane binder used in Nu-flex, the material tested in the case study. Clearly the polyurethane binder is a key component of the material. It's ingredients and chemistry are commercially sensitive and not in the public domain.

The stiffness of the rubber-aggregate tested in this research is significantly lower than the stiffness values of asphalt recorded in the scientific literature (see section 3.1). From the literature, the stiffness of conventional asphalt was measured to be 2.21kN/mm^2 (Abbas Al-Jumaili, 2016), compared to a stiffness value of 0.15kN/mm^2 measured in this research, calculated from the elastic region of Figure 7.1. During loading the rubber-aggregate samples displayed a high degree of elasticity. Lateral movement was observed with no observations of cracking until the peak load (used to calculate the ITS) was reached. Even after the peak load was reached the rubber-aggregate material did not crack, rather bits of crumb rubber and aggregate broke away from the sample, showing only a small departure from its original shape.

The elastic behaviour of the rubber-aggregate material is clearly due to the high rubber content. The load displacement relationship show in Figure 7.1 is not too dissimilar to the load displacement of rubber, showing a high degree of elasticity. The elastic modulus varies dependant on the type of rubber; however it is always low (Cambridge University Engineering Department, 2003). The elastic modulus of natural rubber is approximately 0.0015GPa (Cambridge University Engineering Department, 2003). The elastic modulus of aggregates (which generally make up 95% of an asphalt pavement) can be up to 0.55GPa (Newcomb, et al., 2002), explaining the lower stiffness of asphalt pavements. Furthermore the findings of this research are supported by other research that state the stiffness of asphalt decreases when rubber is added (Rahman, 2004).

The benefits of a pavement with a lower stiffness are discussed in section 8.3.

8.1.2 Skid Resistance

The skid resistance of a pavement is a function it's macrotexture (Corley-lay, 1998). In this research macrotexture has been measured via the texture depth. The texture depth of the rubber-aggregate pavement was found to be over double that of the asphalt in the area of the case study, thus a rubber-aggregate pavement is more resistant to skidding than conventional asphalt. Furthermore, the rubber-aggregate pavement in the area of the case study has a higher texture depth than values for asphalt pavements from the scientific literature (Ahammed & Tighe, 2011).

Texture depths measured by Ahammed & Tighe (2011) (see section 3.1) for a range of asphalt mixes are all lower than the mean texture depth of the rubber-aggregate pavement in this study meaning they have a lower skid resistance. The stone mastic asphalt measured by Ahammed & Tighe (2011) had the highest mean texture depth (1.75mm). This value is still lower than 1.98mm for the rubber-aggregate pavement measured in this research, however given standard deviations are not reported by

Ahammed & Tighe (2011) there may be standard deviation overlap meaning rubber-aggregate pavements may not have higher texture depths compared to asphalt in all circumstances. But it is not unreasonable to assume the vast majority of rubber-aggregate pavements do have higher texture depths than asphalt pavements, and therefore have better skid resistance in most circumstances, as also demonstrated by the tests in this case study.

The macrotexture of a pavement is dependent upon the aggregate particle arrangement (Magnoni, et al., 2016). A pavement with a high macrotexture provides a space for surface water to drain, thus reducing the slip of the pavement (Stroup-Gardiner, et al., 2001). Moreover, Stroup-Gardiner et al (2001) state one of the main factors affecting macrotexture is the nominal maximum aggregate size, with a higher maximum nominal aggregate size yielding a higher texture depth.

Given the conclusion of the research by Stroup-Gardiner et al (2001), the reason for the high texture depth of the rubber-aggregate pavement in the area of the case study is related to the maximum size of the constituents in the rubber-aggregate pavement. If the aggregates and crumb rubber are smaller, the texture depth of a rubber-aggregate pavement will decrease. Furthermore, the gradation of an asphalt mix influences the macrotexture (Williams, 2008); with gap-graded asphalts having a larger texture depth. If a rubber-aggregate pavement's voids were filled by finer crumb rubber or aggregate (better gradation), then the texture depth would be expected to decrease given the work by Williams (2008), thus decreasing skid resistance.

8.1.3 Drainage

Section 0 shows that 16 month old rubber-aggregate pavement (with a mean infiltration rate of 465.75 mm/min) infiltrates 250 times faster than the same age conventional asphalt (1.84mm/min) in the case study area. In other words, rubber-aggregate drains substantially better than asphalt.

Examining infiltration rates of rubber-aggregate pavements over time shows some reduction in the drainage properties, but the very high infiltration rates were still maintained when compared to asphalt. This is demonstrated in section 0 which shows a fresh rubber-aggregate pavement had an infiltration rate mean of 840.63mm/min, whereas 16 month old rubber-aggregate had a mean infiltration rate of 465.75mm/min. Whilst this is a significant reduction, the mean rate of 465.75mm/min remains very high when compared to asphalt.

A section of the 16 month old rubber-aggregate pavement that was heavily contaminated with leaf litter was also tested. This showed a further reduction of the mean infiltration rate (345.00mm/min). Whilst being the same age as the other pavement under test, the high levels of leaf litter and associated decomposed material in this part of the pavement mean this section is likely to be more representative of a surface several years older. A test before sweeping the surface of debris showed no statistically significant difference in the infiltration rate compared to the pavement once the surface leaf litter had been swept. In other words, decomposed leaf material (rather than surface leaf litter) is a key factor in reducing the drainage properties. Irrespective, the drainage properties of mature rubber-aggregate pavements are still substantially greater than conventional asphalt.

Having established that rubber-aggregate pavements have substantially better drainage properties than conventional asphalt, the next question is why this is the case. Aboufoul & Garcia (2017) state the hydraulic conductivity (how fast water drains, similar to the infiltration rate) of asphalt is related to a pavement's air void content. In turn air void content is a function of aggregate size and gradation (Abdullah & Obaidat, 1998) together with the volume of binder agent. Section 5.2 sets out the typical specification for the Nu-flex rubber-aggregate material used in the case study, which shows Nu-flex has a high air void content (approximately 20% to 30%). The typical air void content for asphalt is approximately 6% (Roy, et al., 2013).

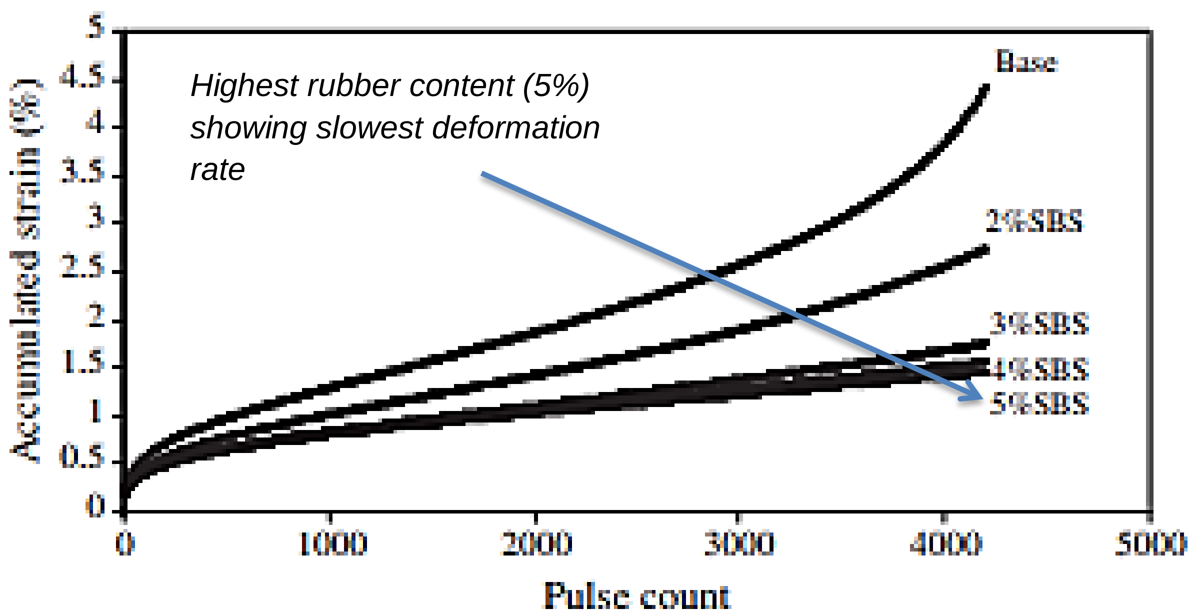
Decomposing leaf litter, silt, or other micro-debris will reduce the air void content over time. However given the very high initial air void content of new rubber-aggregate and given the high infiltration rates of the section tested that had high levels of leaf litter, it is not unreasonable to conclude that the good drainage properties of the rubber-aggregate tested in this case study will be maintained over a period of several years without the need for dedicated cleaning of the pavement.

The good drainage properties of rubber-aggregate and the likelihood of maintaining these over time means the material will be attractive to users and highway authorities, because of its resistance to ice formation (discussed in section 8.1.5) and it's resilience to water damage (see Plate 5.1 and Plate 5.2).

8.1.4 Durability

The results from the cyclic compression test in section 7.1.4 show the range in permanent deformation values obtained from six laboratory tests. The test results as shown in relation to the degree of permanent deformation (as shown in Table 7.4) have a standard deviation of 0.16mm and a co-efficient of variance of 27%. The mean permanent deformation of the rubber-aggregate materials was 0.59mm and the maximum deformation from sample 1 (Figure 7.2) was 0.80mm. The tests were carried out to British Standard BS EN 12697-25 (method A1) by PTS International Laboratory in March 2019. PTS is a UKAS accredited laboratory specialising in advanced asphalt testing. The variation in permanent deformation results might be explained by differences in the rubber-aggregate or binder proportions in the samples, though the samples were supplied from the same batch of material.

Figure 7.2, Figure 7.3, Figure 7.4, Figure 7.5, Figure 7.6, and Figure 7.7 show the creep curve for all six samples tested. All figures are presented to show the variability in test results. All the figures show the most deformation occurs within the first 75 loading pulses. The rate of deformation slows down, with very little deformation occurring after approximately 1600 loading cycles for all six samples tested. The low rate of deformation is unsurprising given other studies have shown adding rubber to asphalt achieves a lower rate of deformation (Kök & Çolak, 2011). Figure 8.1 shows the creep curve for asphalt with varying amounts of crumb rubber added, the rate of deformation clearly peaks off with higher rubber contents. Given the work by Kök & Çolak (2011) and Figures 7.2-7.7, it is clear that the elastic properties of the rubber reduce the rate of deformation or the creep rate.



(Kök & Çolak, 2011)

Figure 8.1-Creep curve for rubberized asphalt with varying rubber content

The lab report (PTS International, 2019) states *"the results achieved in terms of permanent deformation are by far the best I've ever seen for a material"*.

Given this statement, together with the results in Figures 6.2-6.7, it is clear the rubber-aggregate sample (Nu-flex) tested shows high levels of resistance to permanent deformation.

To evaluate the deformation results of the rubber-aggregate test, comparison needs to be made with the results of permeant deformation tests for conventional asphalt by identifying appropriate values in the published scientific literature.

However, there is a broad range of tests for permanent deformation and each test can vary according to the loads, number of load cycles and sample sizes used. In addition the composition of the material under test (in terms of aggregate and bitumen proportions and sizes) will affect test results (Hussan, et al., 2017; Golalipour, et al., 2012).

Nevertheless, despite the wide variability in testing regimes and material composition, two studies (Subhy, et al., 2017; Golalipour, et al., 2012) were identified that potentially allow appropriate comparisons to be made between permanent deformation values for rubber-aggregate and conventional asphalt.

Subhy et al (2017) identified a permanent deformation of 1.12mm for conventional asphalt using a very similar laboratory test to the BS EN 12697-25 method A1(BS DD 226), however there was a 10 degrees Celsius difference between the test conducted by Subhy et al (2017) which as tested at 50 degrees Celsius and the test in this research (40 degrees Celsius). Research by Al-Mosawe (2016) showed a higher testing temperature yields a higher deformation. However it is not known whether the difference from 40 to 50 degrees Celsius makes a significant difference because Al-Mosawe (2016) also tested a number of specimens which varied in aggregate and bitumen content, which showed varying deformation changes, ranging from very little change to significant change. Nevertheless, given this uncertainty the deformation value of Subhy et al (2016) cannot be fully relied upon as a representative value.

Golalipour et al (2012) identified permanent deformations for 3 types of asphalt ranging from 1.875mm to 3.2478mm. The main testing difference to the BS EN 12697-25 A1 used in this research was a 2kpa tangential stress was applied to the sample, and 1800 load cycles were ran (as opposed to 3600 in a BS EN 12697-25 method A1). So half the number of load cycles was performed on the samples by Golalipour et al (2012) compared to the tests in this research. The test carried out by Golalipor et al (2012) is more consistent with the tests in this research.

Comparing the rubber-aggregate values from this study (mean 0.59mm) with conventional asphalt measured by Golaipour et al (2012) (1.875mm to 3.2478mm) shows that significantly less deformation occurs in rubber-aggregate. This also holds true when comparing the asphalt deformation values against the maximum deformation of the six rubber-aggregate samples tested, which was 0.8mm (can be seen from Figure 7.2).

Despite the small differences in testing methodology it is not unreasonable to conclude that the rubber-aggregate (Nu-flex) material tested in this research is significantly more durable than conventional asphalt. Perhaps this isn't surprising given that asphalt containing rubber deforms less than pure asphalt (Fontes, et al., 2010; Farhan, et al., 2015).

Having established that rubber-aggregate pavements (as tested in this case study) shows less deformation under cyclic loading than conventional asphalt, there remains a question as to why this might be the case.

Given the high level of rubber content in Nu-flex (40% by weight), it is reasonable to conclude the rubber provides high levels of elasticity, which in turn provides good recovery from deformation under loading. Research by Lo Presti (2013) and Caltrans (2006) found that rubber increases elasticity when added to asphalt, leading to greater resistance to rutting (permanent deformation) and lower maintenance costs.

Similarly, given the good resistance to permanent deformation of rubber-aggregate it is likely this will result in reduced maintenance costs; which as set out in section 2.3.2 will be attractive to highway authorities.

However, it is acknowledged that the cyclic compression test applies loading forces that are uniaxial, and may not represent the all different loads experienced by pavements in multi-use environments, particularly the loads from horses and their steel shoes.

Figure 8.2 shows typical differences in forces and ground reaction during the different stages of horse propulsion and breaking. The horse limb is loaded differently from hoof landing to lift off, and Peterson et al (2012) divided limb loading movements into four stages as seen in Figure 8.2.

The differing forces and their angle of impact when coupled with a steel horse shoe represent very different loading conditions to that which is provided by the cyclic compression test. The advantage of the cyclic compression test is that it is comparable across a range of pavements and testing regimes, and has the backing of an international testing standard. But it cannot account for the forces described in Figure 8.2, and which may be exacerbated when a horse moves up or down inclines.

The evidence from this study is that the scientific literature is silent on testing methods that reproduce horse shoe load patterns and ground interaction forces on pavements. It may be that the conclusions about the long term durability of rubber-aggregate pavements should be assessed with testing equipment that seeks to replicate the forces in Figure 8.2.

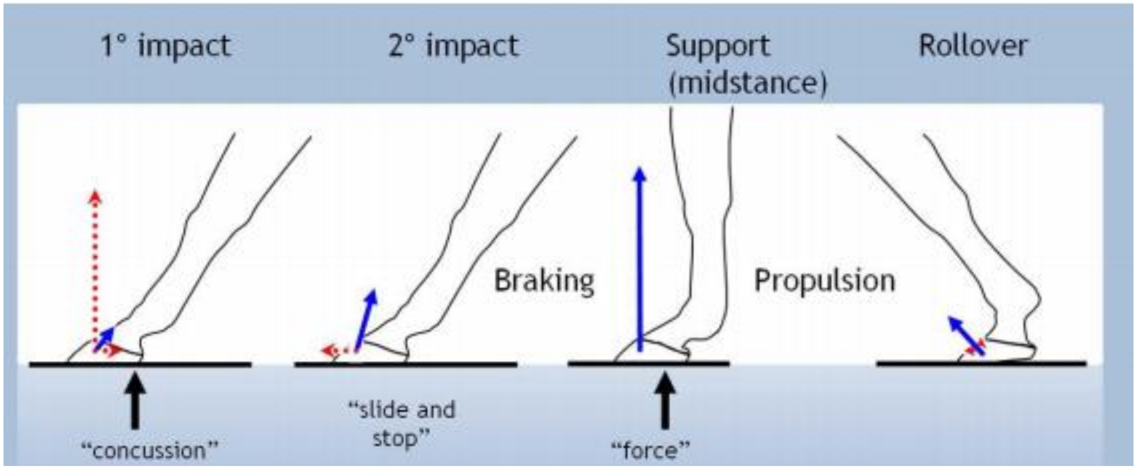


Figure 8.2-Horse foot and ground force interaction

(Peterson, et al., 2012)

This study has selected the resistance to permanent deformation (rutting) as the key indicator of the durability of a rubber-aggregate pavement, because this is a common pressure when of durability is discussed in the scientific literature. However, other pressures such as, long term freezing, extreme heat or ultraviolet radiation can also significantly affect the durability of pavements. These factors were beyond the scope of this study, but might yield a profitable area for further work.

8.1.5 Ice Formation

Plate 7.1 shows no ice formed on the section of rubber-aggregate pavement in comparison to the asphalt pavement on the section of the Britannia Greenway in the case study (Plate 7.2). Moreover this is supported by 72% of questionnaire respondents stating that during cold conditions they observed less ice formation on the rubber-aggregate section in comparison to the asphalt section of the Britannia Greenway.

The reduced level of ice formation on the rubber-aggregate pavement in the area of the case study when compared to the asphalt section is due to the drainage properties of the rubber-aggregate pavement. The surface water does not have time to freeze; as it infiltrates through the rubber-aggregate pavement.

8.2 Environmental Evaluation

This research has shown that rubber-aggregate pavements have demonstrable environmental benefits when compared to asphalt pavements.

The results in Table 7.5 show the construction of rubber-aggregate pavements emit approximately 5 times less carbon dioxide equivalent (CO_2e) compared to conventional asphalt pavements over their life cycle when evaluated in the case study. This is unsurprising given asphalt rubber pavements show life cycle carbon savings (Wang, et al., 2018; Bartolozzi, et al., 2011) when compared to conventional asphalt pavements.

Most of the lower carbon equivalent emissions from the life cycle assessment in the case study can be accounted for by significantly less emissions from the raw material extraction and production processes, which is again five times less than asphalt pavements.

Carbon equivalent emissions from the case study are very similar from the transport of both types of pavement, which is understandable given similar HGVs and similar transport distances were assumed in the life cycle assessment.

Emissions from the end of life disposal of asphalt pavements are provided by DEFRA (2018) but are not provided for rubber-aggregate pavements given the infancy of the material. Nevertheless, given that both have high aggregate content and both contain oil based constituent materials, it is not unreasonable to assume both types of pavement might have similar end of life emissions. Irrespective, end of life emissions for asphalt account for 1% of their total emissions as set out in Figure 7.8, meaning any assumption errors will have a negligible impact on the overall emissions.

Table 7.5 shows the carbon equivalent emissions for the production of rubber-aggregate pavements are high (172,772.97kgCO_2e for 1km in this case study), with the recycling of tyres and the production of crumb rubber being particularly energy intensive. As established in section 4.2, Way et al (2011), Reschner (2006), Plemons (2013) and Randy & West (1998) describe the complex process of crumb rubber production. Utomo et al (2010) conclude the processing energy needed for crumb rubber production is significant. Similarly, the production of the other key component of rubber-aggregate pavements (polyurethane binder) is very energy intensive, and contains tonne for tonne the same amount of energy as coal (ISOPA, 2019).

The high level of carbon emissions for the production of rubber-aggregate pavements in the case study is offset by the significant carbon savings achieved through the recycling of waste tyres (DEFRA, 2012), and avoiding landfill disposal.

In addition to saving carbon emissions, the use of recycled tyres in rubber-aggregate pavements helps with compliance with the European Union Landfill Directive (WRAP, 2019), which banned disposal of tyres to landfill from 2006.

The carbon savings of rubber-aggregate when compared to asphalt in Table 7.5 are based upon a rubber-aggregate pavement depth of 40mm and an asphalt depth of 50mm, which was based of the actual depth in the case study (The Department for Transport (2005) in Appendix B indicates asphalt paths and tracks can have a depth of up to 85mm). However, the U.K's only two suppliers of rubber-aggregate have indicated they typically construct rubber-aggregate pavements to a depth of 35mm and achieve acceptable service performance (Lancashire County Council, 2019b). Clearly a shallower rubber-aggregate pavement would deliver even greater carbon savings.

A conventional asphalt pavement requires edgings (to prevent lateral movement), whereas a rubber-aggregate pavement does not due to its flexible nature (Nu-phalt Group Limited, 2019). Edgings used for the asphalt pavement in the case study are concrete, which is common practice, and make up over 8% of the total emissions. Concrete production is a very carbon intensive process, emitting 107kgCO_2e/ton (DEFRA, 2018). Negating the need for edgings in rubber-aggregate pavements therefore contributes to carbon savings as well as cost savings.

As can be seen in Figure 7.8 and Figure 7.9, raw material extraction and processing is responsible for the majority of carbon emissions. It follows that any changes in the energy intensity of the raw material extraction and production process, for example production plants being supplied by renewable energy, will lead to significant reductions in the overall carbon footprint of either paving option. Similarly any errors in the assumptions used to inform the life cycle assessment may also lead to changes in the calculated carbon emissions. The impact of such potential errors has been minimised through the use of reputable emission factors as set out in Appendix A.

8.3 Social Evaluation

Figure 7.10 shows 87 responses with good representation across all the main groups of users. None of the main groups are underrepresented demonstrating the community questionnaire has successfully addressed the concerns raised in section 5.4.3.

8.3.1 Comfort

Figure 7.11 shows most (76%) respondents described the surface as comfortable. Interestingly, all four of the main user groups described the rubber-aggregate surface in the case study as comfortable (Figures 6.12, 6.16, 6.20, 6.24). This is noteworthy in light of the previous conflicts between runners, walkers, cyclists and equestrians as set out in section 2.2 (Lund, 2018; Pendlebury, 2016; Barth, 2015; Jenkins, 2014).

It appears the rubber-aggregate surface in the case study provides acceptable levels of stiffness for the different groups of users: sufficient softness for equestrians (British Horse Society, 2016) and runners (Bloom, 2015; van der Worp, et al., 2015); but also sufficient firmness for cyclists (Sustrans, 2012).

As discussed in section 8.1.1, the rubber-aggregate pavement in the case study is significantly more flexible than asphalt (based on the engineering stiffness test). The elastic properties of the rubber-aggregate pavement provide acceptable levels of 'give' to satisfy the needs of equestrians and runners.

Conversely the requirements for cyclists to have a firmer surface also appear to be satisfied. It appears the stiffness properties of the rubber-aggregate pavement in the case study have achieved the correct balance between softness and firmness to satisfy the needs of the different groups of users. This is likely to be explained by the material achieving the correct crumb rubber to aggregate ratio, as set out in section 5.2.

8.3.2 Grip

Figures 6.13, 6.17, 2.21, 6.25 show the majority of equestrians, cyclists, runners and walkers believed the rubber-aggregate surface in the case study to be either very 'grippy' or 'quite grippy' (59%, 89%, 73%, 74% respectively). Interestingly, equestrians recorded the rubber-aggregate pavement to have the least grip. However this is a significant improvement on the feeling of 'slipperiness' described by equestrians using asphalt in section 2.2 and by Surrey County Council (2009), Lund (2018) and Pendlebury (2016). Despite fewer equestrians describing the surface as 'grippy' or 'quite grippy' compared to cyclists, there is nevertheless good levels of satisfaction with the grip between groups of users that sometimes disagree about the surface properties of multi-user paths and tracks.

The grip described by users is a function of the friction between the foot and the surface and the skid resistance of the surface (Fontes, et al., 2006). Friction can be influenced by footwear, including steel horse shoes (Surrey County Council, 2009). The high levels of macrotexture (the high texture depth), as measured by this research, of the rubber-aggregate pavement in the case study contributes to the grip described by respondents. Moreover, as described in section 3.1, microtexture also contributes to grip, and some authors (Fontes, et al., 2006) conclude the addition of rubber to pavements increases microtexture, which might contribute to the grip described by users of the rubber-aggregate pavement in the case study.

8.3.3 Satisfaction and Surface Preference

Overall, 86% of respondents are either very satisfied or satisfied with the rubber-aggregate pavement in the case study. However, Figure 6.16, 6.19, 6.23 and 6.27 show varying levels of satisfaction between equestrians, cyclists, runners, and walkers (57%, 89%, 87% and 94% respectively).

Similarly 85% of respondents would prefer the rubber-aggregate pavement in the case study to be used in the construction of future multi-user paths and tracks. However, like the satisfaction levels, there is variation in the preferences of respondents for future surface types. Figures 6.14, 6.18, 6.22, and 6.26 show the variation with 64% of equestrians preferring rubber-aggregate pavements in the future, compared to over 80% for cyclists, runners, and walkers.

From these results it is clear that equestrians are least supportive of the rubber-aggregate pavement in the case study, despite relatively high levels of support compared to the dislike of asphalt pavements as described in section 2.2.

Given that public rights of way legislation confers rights of use on certain multi-user paths and tracks for equestrians and cyclists (as described in section 2.2) it may be the case that equestrians recognise the need to accommodate the surface requirements of other users. The British Horse Society (2016) state their surface preference is well drained turf or vegetated paths on a firm base. Clearly rubber-aggregate pavements do not fit this specification, so it is reasonable to conclude the relatively good support from equestrians for the use of rubber-aggregate pavements in future construction shows that a level of compromise has been made without a compete departure from their requirement for a softer surface.

The high level of support from cyclists, runners and walkers (83%, 80% and 94% respectively) for the use of rubber-aggregate pavements correlates well with the high levels of satisfaction and descriptions of grip, and comfort, together with the low levels of water pooling and ice formation. In turn, the results of the tests into engineering properties identified in section 7.1 undoubtedly underpin the high levels of support from respondents for the rubber-aggregate pavement.

8.4 Economic Evaluation

8.4.1 Construction Cost Comparison

Table 7.6 shows the rubber-aggregate pavement in the case study cost 8% less than asphalt pavements constructed with timber edgings; and 13% less than asphalt pavements with concrete edgings. Rubber-aggregate pavements can be constructed without edgings, unlike asphalt pavements because of their flexibility.

The construction cost data provided by the supplier was validated by checking against the invoices received by the highway authority for the scheme in the case study, and was found to be reasonably representative (Lancashire County Council, 2019b).

One of the key questions posed by this research related to the feasibility of rubber-aggregate pavements being used by highway authorities in multi-use paths and tracks (see section 1.1 and objective 5). Construction costs are a key determinant in the wider use by highway authorities, and this research has demonstrated construction costs are slightly less than the costs of using conventional asphalt pavements which highway authorities use extensively (see Appendix B). Based on this case study, highway authorities can have confidence that the construction cost of rubber-aggregate pavements is competitive.

In terms of maintenance, section 5.4.4 sets out the difficulty in estimating future maintenance costs because of the infancy of rubber-aggregate pavements and the lack of data generally on maintenance regimes for multi-user paths and tracks in England. However, the results of the durability tests in section 7.1.4 show rubber-aggregate pavements are more durable than conventional asphalt pavements according to the case study in this research. It is therefore likely that maintenance costs will be less, and not present any significant differences for highway authorities compared to the cost of maintaining conventional asphalt pavements.

8.4.2 Re-Calculation of the Benefit Cost Ratio used in the Case Study

The original Cost Benefit Analysis for constructing the scheme in the case study was obtained from the highway authority and is summarized in Table 7.7 (Jacobs, 2015).

The original CBA approach followed UK guidance (WebTAG Unit A5.1: Active Mode Appraisal) (Department for Transport, 2014) and growth in demand for the ELSCN was forecast based on observed growth from similar cycle schemes within the locality (SUSTRANs Connect2 Bury scheme showing 15% growth; SUSTRANs Connect2 Padiham scheme showing 30% growth; Preston Guild Wheel showing 60% growth; (Jacobs, 2015)). The original CBA assumed the scheme was surfaced with asphalt only, and was based on construction costs prepared by the highway authority in 2014.

The asphalt surfacing costs in the original CBA were substituted with rubber-aggregate surfacing costs at 2019 prices, provided by the supplier of the rubber-aggregate pavement in the case study, and which are referred to in Table 7.6. The CBA was then revised in order to calculate a new Benefit-Cost Ratio (BCR).

Table 7.7 and Table 7.8 set out the BCRs for asphalt and for rubber-aggregate based on the three the growth scenarios (15%, 30% and 60%) assumed in the original CBA.

Revising the CBA with surfacing costs for rubber-aggregate results in the BCR range increasing from 3.05 to 4.51 dependent upon growth, compared to the range of 2.79 to 4.14 using the original asphalt costs.

Both ranges of BCRs are in the high value for money category (i.e. BCR greater than 2.0) as set out in the WebTAG guidance (Department for Transport, 2014). However it is clear that surfacing the scheme with rubber-aggregate provides a higher BCR than with asphalt, meaning better value for money.

The fact that a rubber-aggregate surfacing provides better value for money overall is not surprising given the slightly lower cost per linear metre of the surface compared to asphalt as set out in Table 7.6; and given the benefits are assumed to be unchanged. However the asphalt costs in the original CBA were based on 2014 prices, whereas the rubber-aggregate costs were based on 2019 prices. Inflationary costs since 2014 mean the cost of surfacing the scheme with asphalt will have increased. In turn this might reduce the BCR for asphalt surfacing if it was calculated on 2019 prices, meaning rubber-aggregate pavements might provide even greater value for money. Conversely the value of the benefits might also have increased due to inflation possibly negating the cost increases. A more detailed scrutiny of the changes in economics is beyond the remit of this study.

The estimated benefits in the original CBA (Jacobs, 2015 – see Appendix E) were based on the creation of a cycle track with a hard surface and the expected benefits in modal shift, rather than the type of surface used in the construction. It is therefore difficult to calculate the change in benefits as a result of constructing a rubber-aggregate surface rather than an asphalt surface.

The original CBA calculated different levels of monetarised benefits according to different estimates of usage or 'growth' (15%, 30% and 60%). Given the strong community preference for rubber-aggregate pavements over asphalt, it is possible the higher levels of growth set out in Appendix E will be realised if rubber-aggregate pavements are used.

The benefits from a cycle scheme accrue because of changes in modal shift from cars to walking and cycling (Department for Transport, 2014). In turn these bring benefits such as reduced car travel, vehicle and noise pollution and accidents. Walking, cycling and running improve health and reduce absenteeism from work (National Institute for Clinical Excellence, 2012); and these benefits were calculated in the original CBA (Appendix E).

However there is a range of other morbidity benefits that were not taken into account in the original CBA and which are particularly relevant in the case study area. Section 7.2.4 sets out the high levels of adult and child illness, obesity and physical inactivity that exist in the local area of the case study. It is likely the scheme in the case study will result in improved benefits that were not captured in the original CBA, and these will be further enhanced by the use of a rubber-aggregate pavement which has a strong community preference. (Wang, et al., 2005; Sæelensminde, 2004; Winters, et al., 2007).

8.5 Code of Good Practice

This section sets out common themes emerging from the discussion of engineering, environmental, social and economic properties (sections 8.1-8.4) that might be addressed through the preparation of a Code of Good Practice for rubber-aggregate pavements.

It has been established the rubber-aggregate pavement in the case study has superior engineering, environmental, social and economic properties when compared to the conventional asphalt pavement. It has also been established that the rubber component of the pavement and in particular it's elastic property contributes to the engineering performance of the pavement.

The rubber content, derived from recycled car tyres, also contributes to the superior environmental performance together with the high levels of community satisfaction with the surface.

However, whilst the specification of the material is undoubtedly important, other factors can also influence the engineering properties of the rubber-aggregate pavement. For example the construction of the sub-base, including the size compaction and aggregate composition could affect the engineering properties. The laying practices and techniques can also affect the engineering properties. The environmental performance could be affected by the raw materials used to produce the crumb rubber as well as the make-up of aggregate and polyurethane binder.

Finally the appropriate deployment or application of the material can influence its performance. The expected loading forces together with local environment conditions should be taken into account to ensure the material is deployed appropriately and can deliver the expected performance. For example the paving material may not be suitable in situations where large numbers of heavy agricultural or forestry vehicles are expected.

Factors such as sub-base construction, laying technique, raw material composition and appropriate application can be codified into industry good practice guidance to ensure consistency of pavement performance, providing surety for suppliers, installers, designers and highway authorities.

This research has identified that no guidance currently exists, and the research and preparation of a Code of Good Practice for rubber-aggregate pavements would be worthy of further work.

8.6 Relative Importance of the Different Properties

Section 1.3 describes the scope of this study as covering engineering, environmental, social and economic properties, because the scientific literature is silent on all aspects of rubber-aggregate pavements. It also describes that this research, because it was the first of its kind, took the opportunity to evaluate the engineering, environmental, social and economic properties of rubber-aggregate pavements to provide a rounded study of the new paving material.

However, having evaluated the different properties, it is appropriate to assess the relative importance or weight that might be attached to the different properties. Clearly, perspective plays a key role in prioritising different properties. For example, engineering durability will be important from the perspective of highway authorities; but environmental performance will be important to the Environment Agency, particularly when managing the end of life disposal of the pavement.

Nevertheless, Table 8.1 sets out the results of an assessment of the relative importance of the different properties. From the decision matrix in Table 8.1 it is clear that the engineering properties are the most important. The importance of engineering relative to other properties is not surprising given the physical properties of the paving material and its construction underpin the properties which are valued by different groups of users (e.g. comfort, grip and drainage), together with some of the properties that will influence the economic viability of the pavement (e.g. cost saving because of a lack of a need for edgings). Engineering also influences environmental performance, for example the ability to install the pavement without the need for energy intensive practices.

Table 8.1- Decision matrix on the relative importance of the properties of rubber-aggregate pavements

Criteria	Engineering Properties	Environmental Properties	Social Properties	Economic Properties
Importance to Highway Authorities	3	2	2	3
Importance to Communities	2	1	3	1
Link to Other Properties	3	1	1	1
Impact on Successful use	3	1	3	1
Resilience	3	1	1	1
Environmental Sustainability	2	3	1	1
Total	16	9	11	8

1- Low importance
2- Medium importance
3- High importance

As the quote from Lund (2018) at the start of this study shows, it is important that the engineering properties of a pavement must be capable of meeting the varying needs of equestrians, cyclists, runners and walkers, as well as the needs of highway authorities.

This research has shown rubber-aggregate pavements are capable of satisfying those needs.

9 CONCLUSIONS

9.1 Conclusions

There has been substantial growth in the number of people cycling and the associated infrastructure in the U.K, and this is set to continue. New cycle paths are often constructed on existing multi-user paths and tracks which have previously been surfaced with soft or loose materials. This has sometimes led to conflict because the different groups of users because of their differing surfacing requirements and needs; with equestrians and runners generally preferring soft tracks and walkers and cyclists generally preferring firm surfaces.

In an attempt to find a solution, rubber-aggregate pavements have been trialled by some highway authorities in England in a very small number of cases.

However, there is no published literature on rubber-aggregate pavements and the scientific literature is silent on the engineering, environmental, social and economic properties of the new paving material.

This research has therefore attempted to evaluate rubber-aggregate paving materials for use in multi-user paths and tracks using a case study in Lancashire, U.K. Given the research was the first of its kind, a broad study of the properties of the surfacing material was carried out. Inevitably this meant the research covered a range of engineering, environmental, social and economic properties to ensure the paving material had the benefit of a rounded evaluation.

The aim of the research was therefore to evaluate the properties of rubber-aggregate pavements for use in multi-user paths and tracks.

Using a case study of the East Lancashire Strategic Cycle Network, the research undertook a broad investigation using the following objectives:

1. Evaluate the engineering properties of rubber-aggregate paving materials for use in multi-user paths and tracks, and compare with conventional asphalt paving materials.

From the case study, the research found:

- Rubber-aggregate paving materials have a higher Indirect Tensile Strength than typical convention asphalt paving materials used in multi-user paths and tracks, and can withstand the loads of the heaviest horses and riders.
- Rubber-aggregate paving materials have a higher degree of elasticity than conventional asphalt paving materials.

- Rubber-aggregate paving materials are more resistant to skidding than conventional asphalt paving materials because the texture depth is more than double that of conventional asphalt.
- Rubber-aggregate pavements drain 250 times faster than the same age conventional asphalt pavements. There was some reduction in the drainage property over time because of silt and decomposed leaf litter filling some of the pavement's voids. However the high initial void content meant the drainage property remained substantially better than conventional asphalt.
- Rubber-aggregate paving materials have higher resistance to permanent deformation, and the long-term deformation properties are better than conventional asphalt. This is because of the rubber content giving the material a high degree of elasticity, making it more durable. The European standard for a cyclic compression test used in this research applied uniaxial loads only, which may not represent the load from horses and their steel shoes. The scientific literature is silent on testing methods that reproduce horse shoe load patterns and ground interaction forces on pavements, and it may be the durability of rubber-aggregate pavements should be assessed with testing equipment that seeks to replicate the forces from horses and their steel shoes.
- In sub-zero temperatures ice was observed on the surface of the conventional asphalt pavement but not on the rubber-aggregate pavement. Similarly, users of the route reported substantially less ice on the rubber-aggregate pavement compared to the asphalt pavement. This is due to the drainage properties, preventing water pooling and freezing.

2. Evaluate the environmental properties of rubber-aggregate paving materials for use in multi-user paths and tracks, and compare with conventional asphalt paving materials.

From the case study, the research found:

- Rubber-aggregate pavements emit significantly less carbon dioxide equivalent compared to conventional asphalt pavements according to the life cycle assessment in this research.
- Most of the lower carbon emissions can be accounted for by significantly less emissions from the raw materials extraction and production process, which is five times less intensive than conventional asphalt pavement.
- However, the production of crumb rubber, together with the production of the polyurethane binder is very carbon intensive. This is offset by the significant carbon savings achieved through the recycling of waste tyres, avoiding landfill disposal.

3. Evaluate the social properties of rubber-aggregate paving materials for use in multi-user paths and tracks, and compare with conventional asphalt paving materials.

From the case study, the research found:

- Very high levels (85%) of satisfaction with the rubber-aggregate pavement and similar levels of support for its use in the future; apart from equestrians where there was slightly lower support (64%) for its future use. Levels of support for conventional asphalt pavements were much lower.
- Despite lower levels of support from equestrians in the future, the level of support for rubber-aggregate pavements is substantially higher than for conventional asphalt surfaces.
- Rubber-aggregate pavements appear to have achieved an acceptable balance of materials, properties and performance to satisfy the needs of all groups of users.

4. Evaluate the economic properties of rubber-aggregate paving materials for use in multi-user paths and tracks, and compare with conventional asphalt paving materials.

From the case study, the research found:

- Constructing a rubber-aggregate pavement costs less (13%) than a conventional asphalt pavement with concrete edgings.
- The original cost benefit analysis for constructing the scheme was revised using the construction costs for rubber-aggregate rather than asphalt. The benefit cost ratio was re-calculated and found to provide even greater value for money than the original analysis because of the lower cost of rubber-aggregate pavements.
- The original cost benefit analysis assumed a hard bound surface (asphalt), and so changing the type of hard bound surface (to rubber-aggregate) is unlikely to yield significantly different benefits. However the community preference for rubber-aggregate over asphalt means more people are likely to use the surface than was assumed in the original cost benefit analysis. In turn, this means the higher levels of growth (usage) modelled in the original cost benefit analysis are more likely to be realised, though quantification is problematic.

5. Evaluate the feasibility of using rubber-aggregate as an alternative to conventional asphalt for paving multi-user paths and tracks from the perspective of highway authorities.

From the case study, the research found:

- Rubber-aggregate pavements have superior strength, drainage and durability properties compared to conventional asphalt, which are important factors in the future maintenance of multi-user paths and tracks by highway authorities.
- Given the infancy of rubber-aggregate paving materials, and the fact that long term maintenance experience is unavailable, the durability results will be particularly important for highway authorities. Similarly, in light of the major path washout problems experienced in the area of the case study, the drainage properties are also important.
- The skid resistance properties, and resistance to ice formation, of rubber-aggregate pavements will be of interest to highway authorities in helping to maintain safety.
- The superior environmental performance of the rubber-aggregate pavement compared to conventional asphalt will be of interest to highway authorities in delivering their carbon management plans.
- High levels of community satisfaction with the rubber-aggregate pavement mean that highway authorities should experience less community conflict over types of surfacing, if rubber-aggregate pavements are used rather than conventional asphalt pavements.
- The slightly lower cost of constructing rubber-aggregate pavements compared to asphalt pavements will benefit highway authority budgets, or improve the prospects of external funding applications.

In light of the achievement of the research objectives, the aim of the research (to evaluate the properties of rubber-aggregate pavements for use in multi-user paths and tracks) has been met.

9.2 Opportunities for Further Research

This research has carried out a broad study of the engineering, environmental, social and economic properties of rubber-aggregate pavements, resulting in a rounded evaluation of the new surfacing material.

In turn, specific and targeted research would be the obvious next step given the absence of published literature on any of the properties. The following may provide worthwhile areas of further investigation:

1. Long term durability of rubber-aggregate pavements in relation to equestrian loading, particularly the impact of various hoof and steel shoe interactions with the pavement surface, including horse speeds and gradients.
2. If rubber-aggregate pavements are deployed more widely by highway authorities, it will be useful undertake a comparative evaluation of several cases in different parts of the U.K.
3. Long term drainage testing, particularly on rubber-aggregate pavements that are subject to heavy leaf litter or silt accumulations and the impact these have on void spacing within the pavement.
4. The long term impact of freeze-thaw on the pavement, together with the impact of ultra-violet radiation on the polyurethane binder.
5. The resilience of the surface to loading from heavy agricultural or forestry machinery using different pavement and sub-base thicknesses.
6. Detailed assessment of carbon equivalent emissions for specific phases of the life cycle of rubber-aggregate pavements, including polyurethane binder production, crumb rubber production and end of life disposal of the pavement.
7. Targeted cost benefit analysis with particular reference to any change in benefits between rubber-aggregate pavements and conventional asphalt pavements on multi-user paths and tracks.
8. Long term assessment of the practices and costs of maintaining rubber-aggregate pavements by highway authorities.
9. Investigation and preparation of a Code of Good Practice for the raw material production, construction, maintenance and appropriate use of rubber-aggregate pavements.

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APPENDIX A- CARBON EMISSION FACTORS

Table A.1- Emission factors used for life cycle assessment

Emission source	Unit	Emissions	Comments
Crumb rubber	$KgCO_2e/ton$	290.7	Adapted from Utomo et al (2010) where the energy breakdown of crumb rubber is stated as 3.06272 MJ/kg, with 60.62% of this energy from electricity and 38.86% from diesel, with the remaining energy coming from a non-carbon intensive process. Transport Research Laboratory *'further guidance on whole life greenhouse gas emissions generated by asphalt'* was used to convert to an equivalent $KgCO_2e/ton$. Full calculations can be found in Appendix C.
Crumb rubber savings	$KgCO_2e/ton$	-1,910	The carbon savings for recycling waste tyres versus landfill (DEFRA, 2012) (U.K Government, 2011). This value quantifies the carbon equivalent that would be emitted if the re-cycling did not occur. (i.e. the tyre was sent to landfill). The total saving in the 1km stretch used for the life cycle assessment was found my multiplying the savings factor by 40% of the total Nu-flex weight in 1km, since Nu-flex is 40% crumb rubber by weight.
Primary aggregate	$KgCO_2e/ton$	3.7	(Mitchel, 2015).
Drying of aggregate	$KgCO_2e/ton$	33.88	Carbon equivalent emission due to heating and drying of aggregate (Gibson, 2011)
Limestone	$KgCO_2e/ton$	2.8	Limestone makes up part of the subbase (Kittipongvises, 2017). Density of 2560 kg/m^3 used for life cycle assessment (Natural-Stone, 2019).
Clean stone	$KgCO_2e/ton$	3.8	(Mineral Products Association Sustainability Site, 2014). Density of 1,520 kg/m^3 used in the life cycle assessment (RF Cafe, 2019).
Polyurethane resin	$KgCO_2e/ton$	3119	An extensive review of the scientific literature revealed that very little

			information is available relating to the carbon emissions associated with polyurethane resin. A value for 'average plastics' was used (DEFRA, 2018) given. The official list of emission factors in the UK does not provide a factor for polyurethane, but emission factors are provided for nine other types of plastic.
Transportation for rubber-aggregate constituents (including sub-base) at 50% laden	$KgCO_2e/km$	0.68567	Standard emissions for HGV's given by DEFRA (2018).
Transportation for rubber-aggregate constituents (including sub-base) at 0% laden	$kgCO_2e/km$	0.8452	Standard emissions for HGV's have been given by DEFRA (2018).
Transportation of asphalt sub-base	$KgCO_2e/km$	Values above (0.68567, 0.8452)	Sub-base is the same for both paving materials, thus values used above have been used to evaluate emission relating to transporting sub-base materials.
Transportation of asphalt	$KgCO_2e/km$	Same as above	
Laying emissions of asphalt	$KgCO_2e/ton$	4.6	(Transport Research Laboratory, 2011).
Laying emissions of rubber-aggregate pavements	$KgCO_2e/ton$	0	Nu-flex is laid cold (this is the case with all rubber-aggregate pavements). The only emissions are from a mixing drum, but this is insignificant in context of the entire project so is discounted.
Asphalt Production	$KgCO_2e/ton$	71	Based on a 5% bitumen content by weight (Hammond & Jones, 2011). Asphalt density used in life cycle assessment was 2,243 kg/m^3 (SI Metric, 2016).
Concrete edgings required for asphalt	$KgCO_2e/ton$	107	Based on standard concrete emissions (Hammond & Jones, 2011). Density of concrete used in the life cycle assessment was 2,400kg/m^3 (Everything

pavement			About Concrete, 2018).
End of life disposal emissions for asphalt	$KgCO_2e/ton$	1.277	Emissions relating to landfilling of asphalt taken from DEFRA (2018).
End of life disposal emissions for rubber-aggregate pavements	$KgCO_2e/ton$	1.277	No information available on landfilling of rubber-aggregate pavement, as the material is in its infancy. An assumption that emissions will be similar to asphalt has been made given that both contain high proportions of aggregate and oil based constituents.

APPENDIX B - DEPARTMENT FOR TRANSPORT (2005) GUIDANCE ON SURFACE TYPE FOR USE IN MULTI-USE PATHS AND TRACKS

Table B.1- Guidance on bound and unbound surfaces

Surface Material	Adequacy (see note a)			Construction Details
	Pedestrians	Cyclists	Equestrians	
Hot rolled asphalt surface course	1	1	3	25mm hot rolled asphalt wearing course (6mm aggregate size) on 60mm bituminous macadam base course on 150mm thick Type 1 sub-base.
Bituminous macadam surface course	1	1	2	25mm dense bitumen macadam wearing course on 60mm bituminous macadam base course on 150mm thick Type 1 sub-base. *
Surface dressing on stone base or bitumen	1	1	2	Single coat gravel 3-6mm size 50mm dense bituminous macadam of 20mm aggregate size on 100-150mm Type 1 granular material*.
Clay pavers	4	3	3	65mm thick on sand on 150mm Type 1 subbase.
Concrete blocks/flags	1	1	3	65mm thick blocks on 30mm sharp sand bed and 150mm Type 1 sub-base*.
In situ concrete	1	2	2	40mm granolithic concrete on 75mm concrete on 150mm Type 1 sub-base. Surface to be textured to

				provide satisfactory skid resistance.
Naturally binding stones and gravels	2	2	2	20mm depth limestone/hoggin (3mm dust) or other such as 50mm depth Breedon Gravel (6mm dust) or75mm depth Coxell Gravel (30mm fines).
Sand	3	4	1	75mm sand on 150mm free draining layer.
Wood chips	2	4	1	Chips laid to a compacted thickness of 225mm on free draining surface layer.
Grassed gravel	1	3	1	150mm surface course of aggregate mixed with 25% topsoil on 150mm aggregate on geotextile sub-base.
Reinforced turf	2	3	1	Rubber bonded fibre/grit sand laid on turf.
Scalping./ballast with quarry waste	2	2	2/3	Max. 40mm size with a high content of quarry waste laid (well compacted) on 150mm Type 1 sub-base**.
Industrial waste products	2	3	1/2	100mm wearing course/150mm base course Graded Fuel Ash/Pulverised Fuel Ash/Colliery Shale/Red Shale (approved by English Nature).
Road planings	1	1	2	Screened recycled road planings***.

Reproduced from Department for Transport (2005).

Notes

a) Adequacy Scale: 1 – Excellent, 2 – Good, 3 – Reasonable and 4 –Inadequate.

b) All gradients should be in line with other DMRB guidance and unbound surfaces should be well compacted.

c) All wearing course depths are typical and require an adequate base course and/or sub-base based upon local BCR values. Local gravel should be used where possible.

d) Unbound surfaces also require an edge restraint in the form of a pre-cast concrete pin-kerb or CCA treated softwood timber peg and edgeboard.

* Only for equestrians for walk or trot. Not to be used on steep slopes.

** By their nature, scalpings will be of variable quality and some varieties will not be suitable for use on riding tracks. Local knowledge is important in the selections of scalpings as a surface material. The surface can also become polished and may become unsuitable for horse riding. Ballast is not always a satisfactory surface for horses as the surface can be kicked up by hooves and can damage the horse’s foot.

*** This material can be inconsistent. Specification should require small and uniform sized particles.

APPENDIX C- ENVIRONMENTAL EVALUATION CONVERSION: CALCULATIONS FOR CRUMB RUBBER

$$Crumb\ Rubber\ CO_2 = Electricity\ CO_2 + Fuel\ CO_2$$

Conversion factors

$$Electricity\ to\ CO_2\ Conversion\ Factor = 0.53936\ (\text{DEFRA}, 2018)$$

$$Fuel\ CO_2\ conversion\ factor\ (GJ\ to\ kWh) = 277.78$$

$$Fuel\ to\ CO_2\ Conversion\ Factor = 0.25011\ (\text{DEFRA}, 2018)$$

Conversion of electricity to KgCO$_2$e/ton

$$Electricty = 60.62\% \times 3.06272\frac{MJ}{kg} = 1.85662\frac{MJ}{kg}$$

$$Electricity = 1.85662\ \times 0.28 = 0.51985\frac{kWh}{kg}$$

$$Electricity\ CO_2 = 0.53936 \times 0.51985 = 0.20804\frac{kgCO_2}{kg\ crumb\ rubber}$$

$$Electricity\ CO_2 = 0.20804 \times 1000 = 208.04\frac{kgCO_2}{ton}$$

Conversion of fuel (diesel) to kgCO$_2$e/ton

$$Fuel\ CO_2 = 38.86\% \times 3.06272\frac{MJ}{kg} = 1.19012\frac{MJ}{kg}$$

$$Fuel\ CO_2 = 0.00119012\frac{GJ}{kg}$$

$$Fuel\ CO_2 = 0.00119012\ \times 277.78 = 0.33059 kWh/kg$$

$$Fuel\ CO_2 = 0.25011 \times 0.33059\frac{kWh}{kg} = 0.08268\frac{kgCO_2}{kg\ crumb\ rubber}$$

$$Fuel\ CO_2 = 0.08268 \times 1000 = 82.68386\frac{kgCO_2}{ton}$$

$$Crumb\ rubber\ CO_2 = 208.04 + 82.68 = 290.72\frac{kgCO_2}{ton}$$

APPENDIX D- ENVIRONMENTAL EVALUATION: CARBON ASSESSMENT DISTANCES TRAVELLED

Table D.1 – Distances assumed for life cycle assessment

Supplier	Distance to site (km)	Comments
Express asphalt	34	Assumed supplier for asphalt. Address: Goose House Ln, Darwen BB3 0EH
Peel Quarry	16	Assumed supplier of clean stone and primary aggregates and limestone Address: 52 Cross Lane, Bury
Hansons Ready Mix Concrete	38	Assumed supplier of concrete edgings Address: Bold St, Preston PR1 7NX
SRC Rubber Products	53	Assumed supplier of crumb rubber Address: Greg St, Stockport SK5 7BS

APPENDIX E- JACOBS (2015) EXTRACT OF ORIGINAL CBA REPORT

Summary of the CBA for the ELSCN produced by Jacobs (2015) for the local highway authority.

Combined	Growth Sensitivity		
	15%	30%[6]	60%[7]
Noise	£68	£82	£105
Local Air Quality	£4	£4	£6
Greenhouse Gases	£363	£440	£564
Journey Quality (Congestion)	£10,412	£12,595	£16,135
Physical Activity - Mortality	£17,958,841	£21,193,487	£26,535,961
Physical Activity - Absenteeism	£225,456	£275,291	£349,390
Infrastructure Maintenance	£61	£73	£94
Accidents	£964	£1,166	£1,494
Economic Efficiency	£1,826,585	£2,179,367	£2,770,399
Wider Public Finances (Indirect Taxation)	-£1,746	-£2,115	-£2,711
Present Value of Benefits (PVB)	£20,021,008	£23,660,390	£29,671,438
Broad Transport Budget	£7,175,159	£7,175,159	£7,175,159
Present Value of Costs (PVC)	£7,175,159	£7,175,159	£7,175,159
Net Present Value (NPV)	£12,845,848	£16,485,231	£22,496,278
Benefit to Cost Ratio (BCR)	**2.79**	**3.30**	**4.14**

(Jacobs, 2015)

APPENDIX F- LIFE CYCLE ASSESSMENT CALCULATIONS

Rubber-Aggregate Life Cycle Calculations

Materials	$kgCO_2$/ton	Volume (m^3) in 1km	Density (kg/m^3)	Mass (kg) in 1km	$KgCO_2$ in 1km
Crumb rubber	290.70			85,360.80	
Primary aggregate	37.78			85,360.80	
Limestone	2.80	1,000.00	2,560.00	2,560,000.00	7,168.00
Plastic resin	3,119.00			42,680.40	
Clean Stone	3.90	750.00	1,520.00	1,140,000.00	4,446.00
Nu-Flex (mixed onsite)	755.19	200.00	1,067.01	213,402.00	161,159.48
Carbon savings	-1910			85,360.80	-163,039.13
					9,734.36

Material Transported	Mass to be transported (kg)	Vehicle Capacity (kg)	Vehicles required	Vehicles used	Distance travelled per vehicle
Crumb rubber	85,360.80	26000	3.283107692	4	53
Primary Aggregate	85360.8	26000	3.283107692	4	16
Limestone	2,560,000.00	26000	98.46153846	99	16
Clean Stone	1140000	26000	43.84615385	44	16

Material Transported	kgCO2/km (50% load)	kgCO2/km (0% load)	Utalisation	Vehicle Type	KgC02 per vehicle
Crumb rubber	0.8452	0.68567	0.5	All HGVs	44.7956
Primary Aggregate	0.8452	0.68567	0.5	All HGVs	13.5232
Limestone	0.8452	0.68567	0.5	All HGVs	13.5232
Clean Stone	0.8452	0.68567	0.5	All HGVs	13.5232

Material Transported	Total kgCO2 from transport
Crumb rubber	179.1824
Primary Aggregate	54.0928
Limestone	1338.7968
Clean Stone	595.0208
Total	2167.0928

Laying impacts	0	kgC02/ton
Laying Impacts 1km	0	kgC02

Total C02 in 1km	12,617.53	kgC02

Asphalt Life Cycle Calculations

Raw Materials	kgCO2/ton	Volume (m3) in 1km	Density (kg/m3)	Mass (kg) in 1km	kgC02 in 1 km
Limestone	2.80	1,000.00	2,560.00	2,560,000.00	7,168.00
Clean stone	3.90	750.00	1,520.00	1,140,000.00	4,446.00
Asphalt	71.00	250.00	2,243.00	560,750.00	39,813.25
Concrete Edgings	107.00	20.00	2,400.00	48,000.00	5,136.00
					56,563.25

Transported Material	Mass Transported (kg)	Vehicle Capacity (kg)	Vehicles Required	Vehicles Used	Distance per vehicle	kgCO2 (50% load)	kgCO2 (0% load)
Asphalt	560,750.00	20000	28.0375	29	34	0.8452	0.68567
Clean stone	2,560,000.00	26000	98.46153846	99	16	0.8452	0.68567
Limestone	1,140,000.00	26000	43.84615385	44	16	0.8452	0.68567
Edgings	48,000.00	26000	1.846153846	2	38	0.8452	0.68567

Transported Material	Utalisation	Vehicle type	kgCO2 per Vehicle	Total kgCO2
Asphalt	0.5	HGV	28.7368	833.3672
Clean stone	0.5		13.5232	1338.7968
Limestone	0.5		13.5232	595.0208
Edgings	0.5		32.1176	64.2352
				2831.42

Laying Impacts	4.7	kgCO2/ton
Laying impacts 1 km	2635.525	kgC02

Landfill per ton	1.277	kgCO2/ton
Landfill for 1km	716.07775	kkgC02

Total kgCO2 in 1km	62,746.27