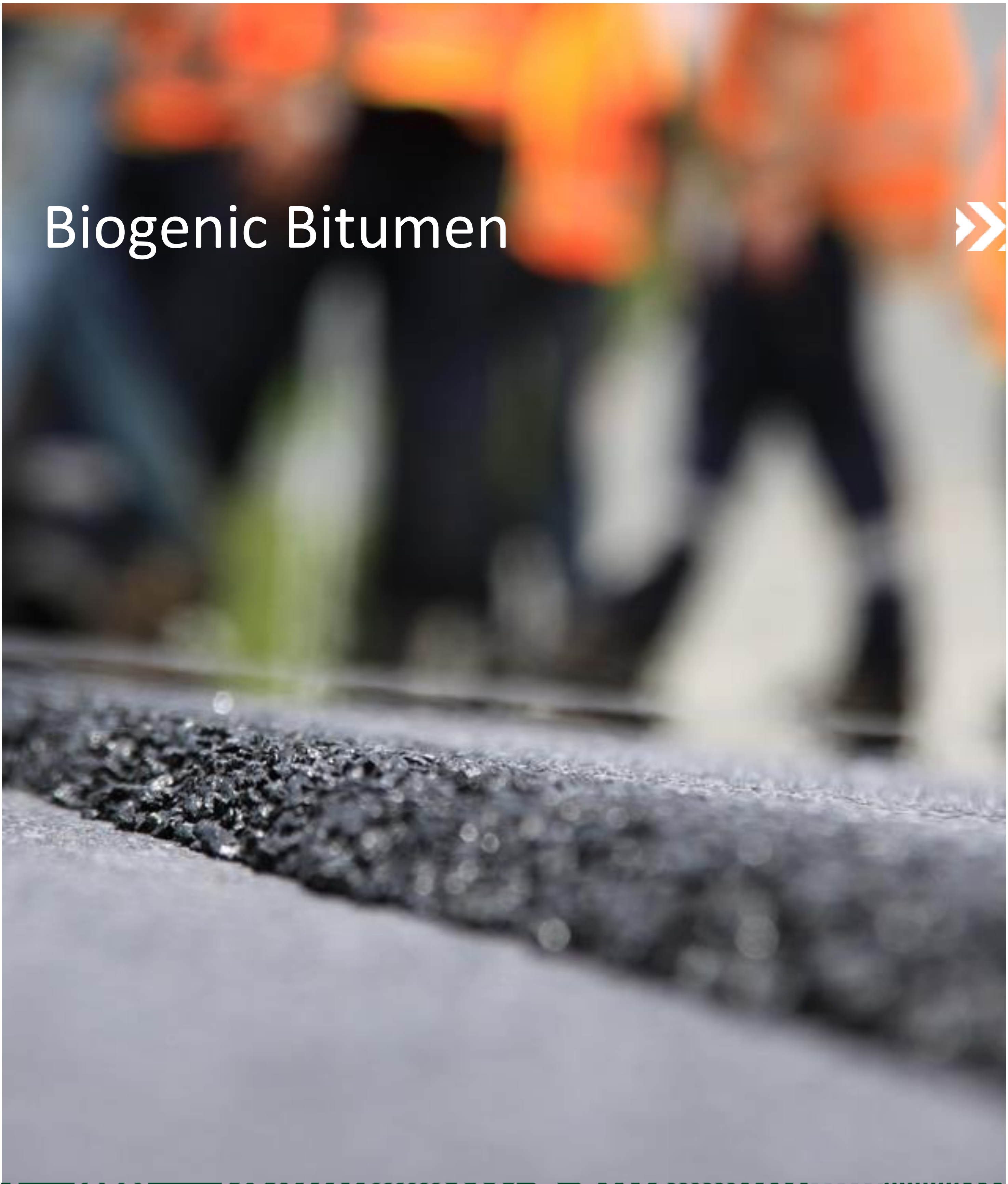
Biogenic Bitumen



Biogenic Bitumen
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HIGGINS

Biogenic Bitumen

Final Report

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Executive Summary

Waka Kotahi NZ Transport Agency Hoe ki angitū Innovation Fund issued a challenge in 2022 for organisations to undertake research projects for investigating how,

> *"we might reduce the environmental impacts of transport infrastructure construction, operation and maintenance activities through accelerating the use of recycled materials and sustainable practices."*

As a part of this challenge, Higgins Contractors Ltd was awarded funding to evaluate candidate materials from non-petroleum, biogenic sources for use as a bitumen extender or replacement. A desk top evaluation assessed commercial and sustainability attributes of the materials whilst laboratory investigations were used to confirm the technical merits of the biogenic bitumens that might be produced.

Increasing concerns regarding climate change and its impacts on society prompted the New Zealand Government to introduce the Climate Change Response (Zero Carbon) Act 2019. This legislation provides a framework for reducing greenhouse gas (GHG) emissions and commits New Zealand to net zero carbon emissions by 2050 or sooner. The New Zealand construction industry has responded by implementing strategies and targets for CO_2 emission reduction. One such initiative is to use biogenic materials as an alternative to fossil fuels for reducing scope 3 CO_2 emissions. Biogenic materials are obtained from or made by life forms, and effectively reduce the impact of CO_2 emissions by sequestering carbon within the material itself, thereby preventing its release to atmosphere.

The publication of Environmental Product Declarations (EPDs) has provided industry with baseline emission factors for materials used in pavement construction. Hot mix asphalt has a typical global warming potential (GWP) of approximately 70 kg CO_2-e/tonne, with an estimated 20 – 35% of that coming from bitumen that is used in the production of asphalt concrete. Estimates of the GWP potential of bitumen vary from 179 – 637 kg CO_2-e/tonne, with a value of 427 kg CO_2-e/tonne being assumed for New Zealand supply. These estimates can be used to benchmark the GWP of biogenic bitumen.

Previous research has identified vegetable oil, tall oil pitch and lignin as being suitable for blending with petroleum bitumen to reduce carbon emissions and produce biogenic bitumen. The performance of these materials has been very promising in several laboratory and full-scale trials that have been conducted in North America, Europe, Australia and New Zealand since the 1990's. Furthermore, the use of vegetable oil, tall oil pitch and lignin are attractive for New Zealand industry because they can all be derived from local resources, thereby reducing New Zealand's reliance on imported materials.

Methodology

The UN Sustainable Development Goals were used as a guideline for assessing the commercial and environmental sustainability of producing biogenic bitumen. The impact that whole-scale adoption of biogenic materials by the roading industry would have on existing supply chains and competing industries was discussed and answers to two specific questions were sought: was the biogenic material available in sufficient quantities to satisfy roading industry demand, and was it available at an

affordable cost. Aspects of environmental sustainability focused on estimating the GWP of alternative materials and the impact that their use would have on climate goals.

The engineering aspects of the biogenic bitumens were assessed by blending vegetable oil, tall oil pitch or lignin in varying proportions with petroleum bitumen in the laboratory. Characterization of the samples was conducted using standard test methods defined by NZTA M1 specification. The properties of the biogenic bitumen were compared to both standard specification parameters and the properties of petroleum bitumen, and inferences to likely engineering performance were drawn.

Key findings

Biogenic bitumen produced from blends of vegetable oil or tall oil pitch, and petroleum bitumen can comply in all respects with the engineering requirements of the NZTA M1 specification for bitumen. The performance properties of these biogenic bitumens are similar to bitumen imported from oil refineries and the in-service performance is expected to be indistinguishable. Good compatibility and ease of handling was observed for blends of bitumen and vegetable oil, or tall oil pitch. No operational problems are expected. It has been noted that current specifications require bitumen to be derived from crude petroleum oil, which will need to be amended before biogenic bitumen can be supplied under the NZTA M1 specification.

While lignin-based biogenic bitumen appears to have good technical merit, some operational problems were identified when blending lignin and bitumen. It is apparent that the lignin used in this study is not very compatible with bitumen commonly used in New Zealand. Lignin forms a two-phase system with bitumen and is subject to settlement and segregation issues, which can have an adverse operational impact and affect consistency of performance. Furthermore, the raw lignin that was supplied contained residual water that caused foaming reactions during blending with hot bitumen. Objectionable odours were also emitted from the hot samples. If the incompatibility can be overcome, it is most likely that lignin will be an excellent base for producing biogenic bitumen that complies with New Zealand specifications. These safety and environmental nuisance concerns will need to be actively managed when producing lignin-based biogenic bitumen.

An assessment of the commercial sustainability of using biogenic materials for roading purposes identified some supply constraints that will require resolution, especially for locally produced material. For example, domestically produced tall oil pitch is currently only available in limited quantities equating to less than 1% of New Zealand's bitumen demand. There is insufficient tall oil pitch being produced in New Zealand. And although lignin is produced in abundant quantities by the NZ forestry industry, none is available in a form that is suitable for use in asphalt and bitumen applications. Furthermore, and while abundant quantities of tallow are produced in New Zealand, the country is a net importer of vegetable oils.

It is expected that biogenic bitumen will incur a slight cost penalty compared to petroleum bitumen (estimated at up to 12% based on current prices). However, this increase is not considered unreasonable or unaffordable. The asphalt industry will also need to compete with the food industry for vegetable oil. Demand for vegetable oil in the food industry tends to attract prices that may be higher than the construction industry is willing (or able) to pay.

Both tall oil pitch and lignin are also used as low cost, carbon neutral biomass fuel for energy production within the processes that generate them. Diversion of these materials into the roading industry will require those industries that produce them to incur additional costs because they will be forced to procure energy from external parties. Unless an alternative biomass derived fuel can be substituted, the diversion of these products will adversely impact the GWP of production from these industries and increase New Zealand's overall CO_2 emission profile.

That said, there are sufficient quantities of vegetable oil, tall oil pitch and lignin available on the global market. Importation of these materials will alleviate local supply constraints and could facilitate widespread adoption. Despite the high levels of CO_2 that can be emitted during production and transport of imported vegetable oil, tall oil pitch and lignin, their embodied carbon allows significant reductions in the estimated GWP compared to petroleum derived bitumen sources. Inclusion of 21 – 24% of these biogenic materials into the bitumen will be sufficient to attain carbon neutrality. Higher proportions could create a biogenic bitumen with net-negative GWP.

Conclusion and Recommendations

The in-service performance of biogenic bitumen is likely to be indistinguishable from that of petroleum bitumen. A laboratory assessment has demonstrated that biogenic bitumen can comply with the engineering properties of existing NZTA specifications. Some operational and commercial supply constraints have been identified but these could likely be overcome. A minor cost impact with using biogenic bitumen is expected, however this is not currently seen as unreasonable or unaffordable. Furthermore, it has been demonstrated that vegetable oil, tall oil pitch and lignin possess significant potential for producing carbon neutral, biogenic bitumen. Adoption of biogenic bitumen will assist New Zealand industry with achieving both its carbon zero aspirations and sustainable development goals.

Demonstration trials of biogenic bitumen that is produced from blends with vegetable oil or tall oil pitch can be conducted as a next step to give both the construction industry and road controlling authorities the confidence that the performance of these materials is satisfactory. Smallscale demonstration trials could utilize locally produced material without adversely impacting existing supply chains or markets.

Further investigation is required to understand the handling performance of lignin when blended with bitumen. While lignin holds immense promise, significant challenges with segregation, moisture and odour have been observed and will need to be managed before widespread adoption of this material is recommended for the industry.

Contents

Introduction

Climate change has been identified as a significant risk to society and is influencing the way we live, decisions we make and expectations we have. Based on current predictions, New Zealand is likely to experience rising sea levels, higher temperatures and more severe floods, droughts, and other extreme weather events.

The New Zealand Government has responded at a national level by passing the Climate Change Response (Zero Carbon) Act 2019, which commits New Zealand to net zero carbon emissions by 2050 or sooner. The 'zero carbon act' provides a framework where New Zealand can implement policies and allow the country to prepare for the effects of climate change.

The legislation has resulted in the introduction of four key actions:

1. set a new domestic greenhouse gas emissions reduction target for New Zealand to reduce net emissions of all greenhouse gases (except biogenic methane) to zero by 2050
2. establish a system of emissions budgets to act as stepping stones towards the long-term target
3. require the Government to develop and implement policies for climate change adaptation and mitigation
4. establish a new, independent Climate Change Commission to provide expert advice and monitoring to help keep successive governments on track to meeting long-term goals.

As a result of legislative changes, many organizations within New Zealand have committed to reductions in carbon emissions. For example, Fletcher Building, New Zealand's largest construction company, has committed to a 30% reduction in scope 1 (direct) and scope 2 (indirect) emissions by 2030. The target is verified by the Science-Based Targets initiative (SBTi), a recognized international third-party verification body, and in line with the goals set in the Paris agreement. Achievement of this carbon reduction target will require assessment of how, and with what plant and fleet, construction operations are undertaken. This means looking at alternatives to fossil fuels, investment in efficient equipment and processes, and procurement of low carbon raw materials.

Scope 1 emissions cover direct emissions from controlled sources. Within the pavement construction sector, this includes combustion of fossil fuels for plant heating and operation of transportation and construction machinery. Scope 2 emissions are indirect emissions from the generation of purchased electricity. Finally, scope 3 emissions are all other indirect emissions that occur throughout the organisation's supply chain including sources that they do not own or control. Examples of scope 3 emissions are the embodied carbon associated with purchasing plant and equipment used for construction, production of materials that it purchases for construction such as bitumen, aggregate and cement, and the emissions associated with freight of purchased items to New Zealand.

Mitigating against climate change will require a proactive approach to looking at how we produce our roading material, how we construct our roads, and the type of material with which we construct our roads to reduce the overall carbon footprint of construction.

Biogenic Materials for Bitumen and Asphalt Production

The term biogenic refers to a product obtained from or made by life forms. Although by extension, petroleum bitumen has its origin as a 'biogenic' material because it is derived from pre-Cretaceous marine life, it is specifically excluded because petroleum is considered a non-renewable resource over the relatively short timeframes considered when calculating global warming potential (GWP). Materials of interest for developing biogenic bitumen for pavement construction must be renewable, being able to regenerate within the 20-to-100-year timeframes that GWP is typically assessed.

Biogenic materials contribute to a reduction in GWP because of the sequestered embodied carbon that is used to make up the material. This sequestered carbon is unavailable for release to the atmosphere and therefore cannot contribute to climate change. Some energy is unavoidably expended in harvesting, transporting, and processing the biogenic material so that it is in a form that can be used by industry. Nonetheless, sequestered carbon content usually exceeds the processing emissions resulting in a net negative embodied carbon. For example, Puma Energy (2022) claim that the biogenic material used in its bitumen products has a "negative global warming potential of 2.8t CO_2 per tonne of biogenic material." This is likely to be the total biogenic carbon stored in the material without accounting for emissions expended during harvesting, processing, transport, and blending. When used with petroleum bitumen blends the GWP of a 160/220 penetration grade bitumen that contains this biogenic material reduces by 158 kg CO_2-e/tonne (35%) to 287 kg CO_2-e /tonne (Puma Energy, 2023).

Embodied Carbon of Pavement Materials

The embodied carbon of materials that are typically used in pavement construction are becoming relatively well defined, although there is the expected variation depending upon source and composition (Table 1). Recent years have seen a plethora of activity within New Zealand with the publication of numerous Environmental Product Declarations (EPDs), and tools and methodology for estimating the global warming potential of pavement materials and structures (Golden Bay, 2019; ISC, 2019; Firth, 2020; Bearsley and Gallagher, 2021; Higgins, 2023; Winstone, 2023).

Aggregates are naturally occurring materials and do not require energy intensive processes for extraction, crushing and screening. Their GWP is relatively low compared to synthetic aggregates such as slag and calcined bauxite, that are produced by heating to extreme temperatures. Similarly, cement and lime production require calcination and the expenditure of significant amount of energy. It is noteworthy that cement production in NZ has a lower GWP than that recognized by ISC (2019) because the manufacturer uses electricity from renewable sources, and tire derived fuel and woody biomass for heat generation.

Asphalt has a global warming potential in the order of 54 – 133 kg CO_2-e/tonne (Higgins, 2023), most of which is contributed by combustion of fuel for direct -fire process heat, and the bitumen type and content of the mixture. A typical GWP of 70 kg CO_2-e/tonne can be assumed which leads to an estimated 85,000 tonnes CO_2-e emitted from asphalt production annually in New Zealand. Bitumen contributes 20 – 35% of the GWP of asphalt, making it an obvious point source to target for reduction initiatives.

Table 1: GWP of Pavement Construction Materials.

Material	Units	NZ Typical Value	Typical Range	Source
Aggregates (Crushed Natural)	kg CO_2-e/tonne	4	3 - 5	Winstone (2023)
Aggregates (Crushed Slag)	kg CO_2-e/tonne	18	18 - 145	ISC (2019)
Hot Mix Asphalt	kg CO_2-e/tonne	70	54 - 133	Higgins (2023)
Bitumen	kg CO_2-e/tonne	427	179 - 637	Asphalt Institute (2019) ISC (2019) Eurobitume (2020) Puma Energy (2023)
Cement	kg CO_2-e/tonne	732	732 - 962	Golden Bay (2019) ISC (2019)
Lime	kg CO_2-e/tonne	837	837	ISC (2019)
Concrete	kg CO_2-e/m^3	260	185 - 474	Firth (2020)
Steel	kg CO_2-e/tonne	1850	1230 - 2800	ISC (2019)
Timber	kg CO_2-e/tonne	-1540		ISC (2019)

Estimates of GWP for bitumen vary widely. While Eurobitume (2020) calculates GWP of bitumen in a 95% certainty range of 179 – 255 kg CO_2-e/tonne for European Bitumen, Asphalt Institute (2019) calculated a more extreme value of 637 kg CO_2-e/kg for USA. ISC (2019) assumes GWP equals 397 kg CO_2-e /tonne of bitumen for Australia and NZ. Puma Energy (2023) uses a GWP of 445 kg CO_2-e/kg for UK paving grade bitumen and estimates by the authors suggest that GWP for bitumen supplied in NZ is in the order of 427 +/- 10% depending on the source and supply route. Transport of bitumen to New Zealand contributes a significant proportion to the GWP because of the considerable distance from supply points.

There exists a substantial body of knowledge and existing technologies that allows reduction in scope 1 and 2 emissions within the asphalt and bitumen industry. Recycled asphalt pavement (RAP) is commonly used in asphalt production and there is an emerging use of biofuels and warm mix technology in New Zealand. Bitumen emulsion technology provides a convenient and affordable route for low emission cold-mix asphalt production and chip seal construction. These initiatives reduce non-renewable energy demand, and consequently scope 1 and 2 emissions. A reduction in scope 3 emissions can be achieved by procurement of raw materials and equipment that contain a low embodied carbon.

Performance Review of Biogenic Bitumen and Asphalt

Investigation of biogenic materials for production of low carbon pavement materials is becoming increasingly commonplace (Gaudenzi et al, 2023a). A recent review commissioned by Waka Kotahi has identified several options for reducing the embodied carbon of bitumen (van den Kerkhof and Herrington, 2022). The recommendations are derived from prior published research and include use of biogenic materials as a recognized way of reducing the embodied carbon of bitumen. The biogenic materials that have received the most attention in NZ are tall oil pitch, lignin, and vegetable oil. These materials can be produced domestically, are recognized as potential substitutes for bitumen and will be a focus of this investigation.

del Barco Carrion et al (2017) researched the performance of biogenic bitumen commercially available in Europe. One of these binders was produced from 100% renewable resources, the other was a patented bio-bitumen called Biophalt®. Their conclusion was that while some biogenic materials may respond differently from bitumen, it is also possible to select and blend biogenic material to give high performance in asphalt materials as assessed using standardized engineering tests. Urquhart and Malone (2013) assessed the performance of two commercially available bio-bitumens that are predominantly composed of plant-based material: Vegecol and Floraphalte. The performance assessment indicated that they complied with the Australian and NZ specifications for bitumen and could reasonably be assumed to perform as well as petroleum bitumen.

Vegetable oils have found application as bitumen extenders and have successfully been used in pavements (Bailey and Zoorob, 2012). They show good compatibility with bitumen and produce biogenic blends with bitumen that show improved ageing resistance and similar rheological characteristics to petroleum bitumen. Bailey and Zoorob (2012) report that the performance of pavements constructed with binders that contain vegetable oil is similar if not better than pavements made from petroleum bitumen. Addition of vegetable oil softens the bitumen and for this reason simple blends tend to limit oil content to less than 10%.

Urquhart and Malone (2013) reinforced the earlier work of others (Mazuch, 1993; Ball et al, 1993; Herrington et al, 1996; Bearsley and Haverkamp, 2007a and 2007b) who identified tall oil pitch as a very promising material for use as a bitumen extender. Tall oil pitch can effectively act as a bitumen substitute and has been investigated at concentrations up to 32% with no adverse effect on performance. The proportion of tall oil pitch that can be added to bitumen is limited by stiffness of the bitumen and the softening effect that tall oil pitch has. Recent studies by Lu et al (2020) and Gaudenzi et al (2021) confirmed previous findings.

Early investigations by Terrel et al (1980) concluded that lignin had technical and commercial potential as a bitumen additive although lignin compatibility was recognized as a potential issue. The lignin source and processing route contribute to affinity with, or lack thereof, with bitumen. Kraft lignin from pulp mills is abundant and contains a high proportion of sulfonated functional groups compared to lignin recovered using the Organosolv™ process that is more typical of production from biorefineries. Lignin has a high proportion of hydroxyl groups compared to bitumen and van Vliet et al (2016) observed that compatibility of Organosolv™ lignin with bitumen was good at 10% addition, but incompatibility occurred in blends containing 25% lignin. Compatibility with bitumen improved upon reaction with epoxides, which blocked the hydroxyl groups and increased the lignin hydrophobicity.

Kalampokis et al (2022) observed that lignin has a stiffening effect on bitumen and storage stable blends containing up to 15% Kraft lignin could be produced under the mixing conditions employed. Kalampokis et al (2022) does however note that their findings are contrary to other researchers who observed separation between bitumen and lignin upon hot static storage. Increasing heterogeneity of lignin and bitumen mixtures was also reported by Gaudenzi (2023a) once concentrations exceeded 10%.

Gaudenzi et al (2022, 2023b), van Vliet et al (2016) and Kalampokis et al (2022) all observed that lignin had beneficial increases in complex modulus, stiffness and elastic properties of bitumen and asphalt mixtures. Lignin reduces temperature susceptibility and imparts an anti-ageing effect on asphalt mixtures, but there is some contradictory evidence that thermal and fatigue cracking resistance may be compromised slightly. This could be caused by the higher stiffness achieved with lignin modified asphalt, which increases the stress generated within the asphalt sample under controlled strain testing. The research is inconclusive. A comprehensive review by Gaudenzi et al (2023a) noted beneficial effects on mechanical and adhesive properties of bitumen and asphalt by adding lignin. Numerous road trials of lignin modified asphalt were also reviewed and it was noted that performance was very good.

Climate Change Impact

It is generally agreed that incorporation of biogenic materials into bitumen and asphalt will reduce the estimated GWP. Gaudenzi (2023a) reviewed numerous life cycle assessments (LCA) of lignin modified asphalt. The overall conclusion was that lignin reduced GWP of asphalt anywhere from 5 to 75% depending on how the lignin was used, its quantity, production and recovery processes, and assumptions and allocations made in the energy calculations. Moretti et al (2022) presented LCA case studies that estimated a potential asphalt GWP reduction between 25 and 70% (up to 43 kg CO_2-e /tonne) when using bio-refined lignin at 50% of the bitumen content. This is more promising than the modest reduction of 5% in an Australian study that was reported in literature reviewed by Moretti et al (2021).

Lu et al (2020) suggested that tall oil pitch modified bitumens could form the basis for a carbon neutral bio-bitumen. However, the GWP of bitumen assumed in the study was much lower than values that are applicable to NZ. Although the proportions of materials required to achieve carbon neutrality under NZ conditions will differ, the approach followed by Lu et al (2020) has merit.

Determination of embodied carbon of biogenic materials should be treated with caution depending on the allocation method used in the calculations. For example, the sequestered carbon of 1 kg of rapeseed oil is calculated to be 2.85 kg CO_2-e/kg. Alcock et al (2022) cautions that the emissions associated with cultivation and production vary widely with an average value of 1.21 kg CO_2-e/kg for rapeseed oil. This value increases to 3.50 kg CO_2-e/kg when land use considerations are accounted for, which implies the whole-of-life GWP of canola oil would be in the order of 0.65 kg CO_2-e/kg. That being the case, the production of vegetable oil could conceivably contribute to global warming, despite the biogenic carbon sequestered by the crops and oil.

Likewise, the sequestered carbon content of lignin is estimated to be 2.47 kg CO_2-e/kg. Hermansson et al (2020) reviewed 10 allocation methods and determined that climate impact of 1 kg of lignin ranged from 0.0 – 4.0 kg CO_2-e/kg, with likely values between 0.18 and 0.64 kg CO_2-e/kg, depending on assumptions made. Recovery of lignin is energy intensive and at its extreme could result in net positive emissions profile. Hermansson et al (2020) estimated that the GHG emission associated with Kraft lignin production for sale as a stand-alone product (e.g., for use in roading) was 0.47 kg CO_2-e/kg. Recovery of lignin that was produced by Dutch biorefineries generated between 0.21 and 1.96 kg CO_2-e /kg of lignin depending on the refining process and energy sources used (Moretti et al, 2022). The biorefinery lignin was compared to Kraft lignin sources that has GWP in the range 0.6 – 2.4 kg CO_2-e/kg. The proportion of energy produced from black liquor or other biomass in a Kraft pulp mill has a considerable influence over the emissions associated with production.

Table 2: Emissions attributed to production of materials that can be used to manufacture biogenic bitumen.

Material	Units	Typical Value	Range	Source
Kraft Lignin	kg CO_2-e/kg	0.47	0.18 – 0.64	Hermansson et al (2020)
Kraft Lignin	kg CO_2-e/kg	0.7	0.6 – 2.4	Moretti et al (2022)
Biorefinery Lignin	kg CO_2-e/kg	1.12	0.21 – 1.96	Moretti et al (2021, 2022)
Organosolv Lignin	kg CO_2-e/kg	1.85	1.4 – 2.1	Moretti et al (2021)
Tall Oil Pitch	kg CO_2-e/kg	1.17	0.74 – 1.47	Cashman et al (2015)
Palm Oil	kg CO_2-e/kg	1.42	0.49 – 2.55	Alcock et al (2022)
Soyabean Oil	kg CO_2-e/kg	1.18	0.67 – 4.65	Alcock et al (2022)
Rapeseed Oil	kg CO_2-e/kg	1.14	0.76 – 2.63	Alcock et al (2022)
Sunflower Oil	kg CO_2-e/kg	1.09	0.64 – 3.02	Alcock et al (2022)

An estimate of biogenic and embodied carbon has been made for the materials used in this investigation (Table 3). Biogenic carbon was estimated from chemical composition, while carbon emission values for cultivation and processing were obtained from literature. Estimates of transport emissions assumed all materials were imported from a market 12,000km distant. An emission factor of 0.020 kg CO_2-e/tonne.km was applied for all materials because it was assumed that they would all need to be imported in shipping containers. They all have a similar net negative embodied carbon of 1.47 to 1.76 kg CO2-e/kg. As such, use of these materials in biogenic bitumen will reduce scope 3 carbon emissions.

Table 3: Estimates of embodied carbon of biogenic materials that can be used for producing biogenic bituminous materials.

Emission Source	Units	Vegetable Oil	Tall Oil Pitch	Lignin
Biogenic Carbon	kg CO_2-e/kg	-2.85	-2.92	-2.47
Cultivation & Processing	kg CO_2-e/kg	1.14 [a]	1.17 [b]	0.47 [c]
Transport to Market	kg CO_2-e/kg	0.24	0.24	0.24
Embodied Carbon	**kg CO_2-e/kg**	**-1.47**	**-1.51**	**-1.76**

a. Alcock et al (2022)
b. Cashman S. et al (2015)
c. Hermansson et al (2020)

Experimental

Scope and Objectives

The intent of the investigation was to evaluate candidate materials from non-petroleum, biogenic sources for use as a bitumen extender or replacement. A desk top evaluation assessed commercial and sustainability attributes of the materials. Laboratory investigations were used to confirm the technical merits of the biogenic bitumens that might be produced.

Ideally the biogenic bitumen would have the following benefits:

1. Contain a major proportion of biogenic materials from New Zealand derived sources
2. Provide a low carbon bitumen that will assist NZ in meeting its carbon zero goals
3. Provide a value-added output for by-products from NZ's horticulture and forestry industries
4. Reduce New Zealand's reliance on imported products and global supply dynamics that impact cost and emissions associated with climate change.

Methodology and Materials

Tall oil pitch, lignin and vegetable oil are biogenic materials that have previously been identified as having the best potential for use in bitumen and asphalt pavements. They have an affinity for bitumen, produce blends with similar or improved mechanical properties compared to petroleum derived bitumen, and can be derived from New Zealand's renewable horticulture and forestry industries. A laboratory investigation assessed the rheological properties of biogenic bitumen blends against the NZTA M1 specification for roading bitumen. This specification is the benchmark standard for bitumen used in New Zealand. Observations on the operational feasibility of producing biogenic bitumen were deduced from the laboratory study.

Samples of biogenic bitumen were prepared in the laboratory by blending in low shear conditions at temperatures ranging from 160 to 180°C for 30 to 120 minutes. Characterization of the samples was conducted using standard test methods defined by NZTA M1 specification.

The commercial and environmental sustainability of biogenic bitumen was also investigated by reviewing the potential impacts that the use of these materials in roading might have on existing markets. An assessment of sustainability was made by estimating the GWP of each of the biogenic bitumen blends and the potential contribution they may make to New Zealand's climate change initiatives.

Bitumen

All bitumen used in this investigation was NZTA M1 compliant 60/70 grade bitumen that was supplied by Higgins Bitumen, Napier.

Tall Oil Pitch

> "As in the case of asphalt, [tall oil pitch] is a very complex system containing numerous individual compounds. A typical representative of the fatty acids fraction are C_{18} linear and unsaturated compounds such as linoleic, oleic, and stearic acids. Resin acids are represented by C_{20} abietic acid (rosin) and its homologues. The unsaponifiables and

neutrals contain mostly high fatty alcohols, esters, sterols (β-sitosterol) and terpenes" (Mazuch, 1993).

Tall oil pitch was obtained from Lawter (NZ) Ltd, Mt Maunganui and is sold under the trade name Pinechem 450. It is the residue from processing crude tall oil derived from Kraft pulping of Pinus Radiata softwoods. It is a viscous, resinous product with a characteristic odour and was used as received.

Vegetable Oil

The vegetable oil used in this study was a recycled cooking oil supplied by Direct Fats and Oils Ltd, Napier. The oil is predominately canola oil that is recovered from restaurants, takeaway, and food production facilities. It has been treated such that it is relatively pure and free of moisture and food residues. It was received and used as a free flowing, low viscosity, clear and bright liquid.

Lignin

Lignin is one of the world's most abundant, naturally occurring polymers. Lignin can be found in terrestrial woody plants and grasses and exists in some marine flora. It is important for the formation of cell walls and providing the plant materials with rigidity and structure. Lignin is present in all vascular plants and fulfils a role in the transport of water and nutrients throughout the plant.

In terms of its composition, it is a heterogenous, three dimensional, crosslinked, organic polymer of coniferyl, sinapyl and p-coumaroyl alcohols (Figure 1). It is insoluble in water in its pure form but is solubilized by reaction with strong acids and bases: this is the basis of the Klason, Soda Lignin and Kraft pulping processes. The chemical and mechanical properties of the lignin will depend upon the source material and the recovery method.

Kraft lignin that had been recovered using the LignoBoost® process was obtained from Stora Enso, Helsinki, Finland as a free-flowing granulated material (Table 4). It was used in an as received state. Attempts to use Kraft lignin from a NZ based producer were unsuccessful as no suppliers of commercial quantities were identified. Enquiries were also placed with producers of lignin derived from locally grown grasses and hemp, but indications are that the commercial volumes produced are currently too small (approximately 5 tonnes per annum) to warrant serious investigation.

Table 4: Properties of Lignin

Property	Target
Physical Form	Free Flowing Brown Granules
Lignin Dry Content	94 +/- 6%
Impurities	
- Ash	< 2.5%
- Sulphur	< 3.0%
- Residual Carbohydrates	< 2.0%
pH (40% slurry in water)	2 – 4
Max Particle Size	2.0 mm
Bulk Density	450 – 550 kg/m^3
Average Molecular Weight, M_w	5,500 – 7,500 g/mol

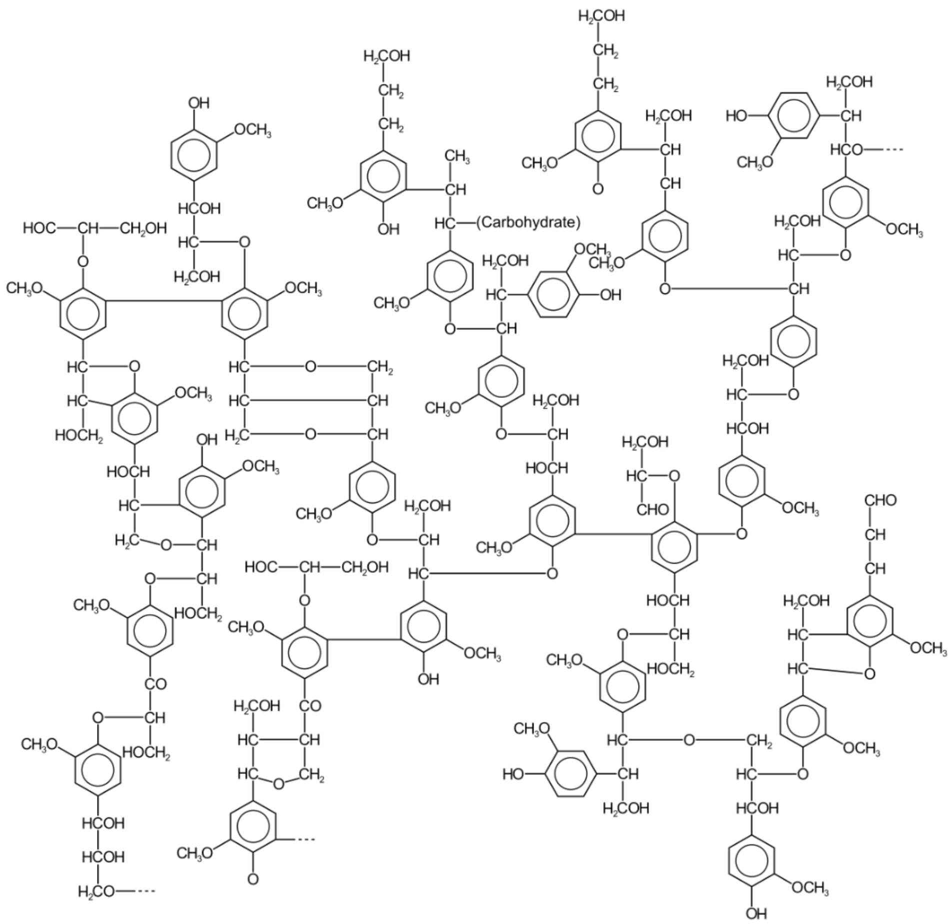

Figure 1: Model structure of softwood lignin according to Wikipedia (2023)

Results and Discussion

Commercial and Supply Chain

Introduction of a new product or process requires an assessment of the commercial feasibility and commercial, ethical, and environmental sustainability of the new development. Whilst it is important to understand if the new development is technically capable of delivering the desired outcome, and that it can be delivered and operated in a safe manner, and in an environmentally sustainable way, it is also important to assess the commercial viability.

Sustainable Development Goals

Exploration of biogenic bitumens for New Zealand's roading sector should take a considered and holistic approach to sustainable development. The United Nations 17 Sustainable Development Goals (SDGs) provides a blueprint for sustainable development in a global context, and aim to balance economic, social, and environmental sustainability with the understanding these goals are interconnected, synergistic, and not separate from one another. Guidance can be taken from the Sustainable Development Goals when assessing the suitability of alternative biogenic bitumen materials.

The SDGs that this project directly contributes to are (see also Table 5):

- Goal 9; Build resilient infrastructure, promote inclusive and sustainable industrialization and foster innovation (targets 9.1 and 9.4)
- Goal 11; Make cities and human settlements inclusive, safe, resilient, and sustainable (targets 11.2)
- Goal 12; Ensure sustainable consumption and production patterns (targets 12.2, 12.4, 12.5, 12.6)
- Goal 13; Take urgent action to combat climate change and its impacts (target 13.1).

Table 5: Goals and targets relevant to this study

Goal	Target	Description
9	9.1	Develop quality, reliable, sustainable, and resilient infrastructure, including regional and transborder infrastructure, to support economic development and human well-being, with a focus on affordable and equitable access for all
9	9.4	By 2030, upgrade infrastructure and retrofit industries to make them sustainable, with increased resource-use efficiency and greater adoption of clean and environmentally sound technologies and industrial processes, with all countries acting in accordance with their respective capabilities
11	11.2	By 2030, provide access to safe, affordable, accessible, and sustainable transport systems for all, improving road safety, notably by expanding public transport, with special attention to the needs of those in vulnerable situations, women, children, persons with disabilities and older persons
12	12.2	By 2030, achieve sustainable management and efficient use of natural resources.
12	12.4	By 2020, achieve the environmentally sound management of chemicals and all wastes throughout their life cycle, in accordance with agreed international frameworks, and significantly reduce their release to air, water and soil to minimize their adverse impacts on human health and the environment
12	12.5	By 2030, reduce waste generation through prevention, reduction, recycling, and reuse
12	12.6	Encourage companies, especially large and transnational companies, to adopt sustainable practices and to integrate sustainability information into their reporting cycle
13	13.1	Strengthen resilience and adaptive capacity to climate-related hazards and natural disasters in all countries

The New Zealand road network is a critical piece of infrastructure that enables movement of people and maintains economic activity. Yet it is vulnerable to the impacts of climate change and natural resource availability. While developing bitumen alternatives derived from renewable biogenic sources, a preferred outcome is to ensure that these materials contribute to strengthening the resilience and sustainability of this transport system (goals 9, 11, 13). Integrating whole-of-life, cradle-to-cradle design thinking will enable sustainable management and efficient use of natural resources to ensure we do not compromise the recyclability of pavements (goal 12).

Good commercial practices and the UN Sustainable Development Goals are interconnected: benefits in one, reflect in the other. It is known that some biogenic source material is produced using less sustainable practices. For example, palm oil is readily available at commercially attractive prices, but there have historically been concerns raised regarding deforestation practices used during development of palm plantations. Alcock et al (2022) has cautioned regarding the adverse impact of deforestation on GWP for vegetable oil production. Refining of biogenic materials is energy intensive and those processes that use greater amounts of non-renewable fossil fuels will produce greater carbon emissions. Biogenic material derived from domestic sources is likely to have lower scope 3 GHG emissions than material that is imported from offshore, simply because less transport fuels will be combusted.

Consideration should also be given to the regenerative capacity when selecting a biogenic material source. For example, fast growing softwood plantations, and even grasses, may be a preferred source of lignin rather than a slow growing native hardwood species.

Furthermore, consideration must be given to ethical procurement practices. That is to say, a minimum standard must be met for any labour used within the supply chain. New Zealand has robust and enforceable labour practices for domestic production but has less influence on labour employed offshore for production of imported materials.

Availability and Competing Markets

A critical issue that needs to be resolved before committing significant volumes of biogenic material to the roading market is its commercial value in competing industries. Biogenic materials that naturally lend themselves to roading application are also used in food, chemical, manufacturing and energy industries. To this end a market overview of biogenic sources that could potentially be used to manufacture bitumen alternatives was undertaken, with the intention of identifying potential commercial barriers to adoption.

Bitumen

One of the attractive features of using petroleum bitumen for pavement construction is that it is readily available in large volumes at an acceptable cost. Global production of bitumen is in the order of 100 million tonnes. New Zealand's consumption of bitumen is approximately 160,000 tonnes, which makes NZ a small consumer (0.16%) in a global context. The security of supply for bitumen is hindered by NZ's small market size and its distance to market. It would be advantageous to be able to rely on domestic production of either bitumen, or a suitable alternative.

Vegetable Oils and Tallow

New Zealand is a net importer of vegetable oils, whilst exporting approximately 120,000 tonnes of tallow. Vegetable oils and tallow tend to attract higher value in food, coatings, surfactants, and biofuels applications than if it was redirected into the bitumen market. Any biogenic material that competes with food markets may not be a commercially sustainable proposition for use as a bitumen replacement. Suppliers prefer to commit to these other industries because they are more commercially attractive. An oil recycling industry is currently operating in New Zealand that can supply recycled vegetable oil and tallow of adequate quality for asphalt and bitumen production. The attractive feature of using recycled vegetable oil and recycled tallow is that this product stream does not compete directly with food markets.

Whilst there is sufficient production of virgin tallow in NZ to consider its use in roading applications, vegetable oil does not enjoy the same abundance. Any vegetable oil intended for use with bitumen or asphalt in the roading market will most likely need to be imported.

It must also be considered that not all vegetable oils will be suitable for use as a bitumen extender. Lighter oils are less preferred because of inherent issues with flashpoint, fuming and volatility at high production temperatures. Palm oil, sunflower, safflower, rapeseed, corn, and soya oil have all been used previously in bituminous applications.

Tall oil pitch

Tall oil pitch finds application in the resins industry and as a processing aid for rubber applications. The cost and availability of tall oil pitch will be dictated by these other industries. The Lawter (NZ) Ltd site in Mt Manganui produces approximately 2,000 tonne of tall oil pitch per annum. Half of this is sold as a resinous product and the other half is used as a biofuel for internal process heat requirements.

The tall oil pitch that is produced domestically and is available to the market represents less than 1% of NZ's total bitumen demand volume. Widespread adoption of a bituminous alternative based on tall oil pitch would require importation of significant volumes. Nonetheless, a small amount of domestic tall oil pitch is commercially available for bespoke applications.

Lignin

Approximately 15 – 25% of softwood biomass is lignin. The NZ forestry industry harvests around 10 million tonnes of wood per annum giving a potential supply of approximately 2 million tonnes of lignin. Obviously, this is not all available as feedstock for lignin production. Much of the harvested wood is sold as logs, wood chips and pellets, or used for construction timber. Furthermore, any pulping done using thermo-mechanical processes does not yield a lignin that can be used in bituminous applications.

Lignin is an underdeveloped resource in New Zealand. It can be recovered and sold as a solid fuel, biopolymer, or phenolic resin derivative, or converted into carbon fibres for light weight composite materials (Ryder, 2012; Hermansson et al, 2020). It is estimated that around 250,000 tonnes of lignin is produced in Kraft black liquor in New Zealand per annum. This compares favourably with the estimated 160,000 tonne of bitumen that is imported annually. While there is sufficient lignin produced in New Zealand to be used as the basis of biogenic bitumen for roading applications, it is not available in a form that presents ready use in bitumen and asphalt. Further processing involving energy intensive acidulation, evaporation, separation, and drying processes will be required before lignin can be used in an asphalt plant.

Furthermore, all the lignin contained in the Kraft black liquor tends to be used inside the pulp mill as biomass for heating, accounting for 63% of the mill's energy sources (Ryder, 2012). Extracting this lignin for use in other applications will disrupt the GHG emission profile and economics of pulp and paper manufacture. New Zealand pulp mills currently enjoy an enviable position of having a low GWP profile with Ryder (2012) indicating that emission in the order of 0.35 kg CO_2-e/kg of pulp produced are typical. If an alternative non-renewable fuel is substituted because the lignin is extracted and used for asphalt production, the GWP profile of pulp mills could potentially increase to 0.9 – 1.0 kg CO_2-e/kg of pulp. Carbon emissions from pulp and paper manufacture in the USA range from 0.608 to 1.978 kg CO_2-e/kg of paper and average 0.942 kg CO_2-e/kg (Tomberlin et al, 2020). A higher proportion of fossil fuels are used by US pulp mills (approximately 30%) for energy generation compared to NZ pulp mills (14%).

Commercial quantities are available for import from Finland and Canada where annual plant production capacities can approach 50,000 tonnes per annum of dry lignin. It is anticipated that as pulp and paper mills, and biorefineries seek to optimize returns, they will continue to diversify to produce high quality lignin from the trademarked LignoBoost® LignoForce™ and Organosolv® processes. It is possible that these processes could be established within NZ, if it is seen as commercially attractive to do so.

Cost

The cost of producing biogenic bitumen depends on the material used and the proportion but typically incurs a modest cost increment compared to bitumen produced from petroleum oils. Vegetable oils, lignin and tall oil pitch are all available at costs equal to or slightly higher than bitumen. The cost difference for typical biogenic blends is not disproportionate and is unlikely to be a significant barrier to market adoption.

Table 6: Estimate of cost impact of using biogenic materials for bitumen production.

Cost		Bitumen	Vegetable Oil	Tall Oil Pitch	Lignin
Materials (Imported, CIF)	$/tonne	1,500	2,300	1,500	1,700
Typical Biogenic Content of Bitumen Blend	%	-	2 – 10	5 – 25	10 – 33
Infrastructure, transport, storage, processing, and handling	$/tonne	-	100	100	100
Estimated Cost	**$/tonne**	**1,500**	**1,616 – 1,680**	**1,600**	**1,620 – 1,666**
Incremental Cost	$/tonne	0	+116 to +180	+100	+120 to + 166
		0%	+8% to +12%	+7%	+8% to + 11%

Performance Evaluation

Vegetable Oil

All biogenic bitumens blends were assessed against NZTA M1 test criteria (Table 7). Vegetable oil has a good affinity for bitumen and is highly effective as a softening or plasticizing agent. Biogenic bitumen blends that meet the NZTA M1 specification in all respects can be readily produced at low proportions of oil (Table 8). It can be assumed that biogenic bitumen produced from blends of petroleum bitumen and vegetable oil will perform as intended in bitumen surfacing applications. The in-service behaviour is likely to be indistinguishable from petroleum-based bitumen.

Table 7: NZTA M1 specification criteria for penetration graded bitumen.

Property	Method	Temp.	Units	60/70	80/100	130/150	180/200
Original Binder Properties							
Penetration	ASTM D5	25°C	dmm	60 – 70	80 – 100	130 – 150	180 – 200
Dynamic Viscosity	ASTM D2171	60°C	Pa.s	190 min.	115 min.	58 min.	36 min.
Handling Viscosity	ASTM D2170	135°C	mm^2/s	360-850	300-650	190-450	140-350
Density	ASTM D70	25°C	kg/m^3	Report			
Flash Point	ASTM D92		°C	218 minimum			
Solubility in Trichloroethene	ASTM D2042		%	99.5 minimum			
RTFO Properties							
Mass Change	ASTM D2872		%	+/- 1.000			
Retained Penetration	ASTM D5	25°C	%	50 minimum			
Ductility	ASTM D113	25°C	m	0.60 minimum			
PAV Aged Properties							
Durability	NZTA T13	5°C	MPa	Report		100 maximum	

Table 8: Properties of vegetable oil based biogenic bitumen blends.

Property	Temp.	Units	Penetration Grade				
			60/70	80/100	130/150	180/200	180/200
Vegetable Oil		%	0	2	4	6	0
Original Binder Properties							
Penetration	25°C	dmm	65	94	133	182	194
Dynamic Viscosity	60°C	Pa.s	227	141	110	59	46
Handling Viscosity	135°C	mPa.s	422	360	310	257	202
Density	25°C	kg/m^3	1026	1027	1022	1019	1008
Flash Point		°C	355	338	340	344	333
Solubility in Trichloroethene		%	99.9	100.0	99.9	99.9	100.0
RTFO Properties							
Mass Change		%	-0.08	-0.07	-0.05	-0.06	-0.05
Retained Penetration	25°C	%	52	56	55	50	57
Ductility	25°C	m	-	-	>1.0	>1.0	>1.0
PAV Aged Properties							
Durability	5°C	MPa	91	63	36	28	51

The biogenic blends made using vegetable oil did not foam, were visually homogenous and had viscosity (135°C) that would ensure ease of handling. Flash point was unaffected by oil addition and the biogenic bitumen is expected to present no greater flammability risk than that of bitumen. Durability related characteristics such as retained penetration, mass loss after RTFO treatment and the durability test are all within accepted limits. Durability tended to improve with increased oil addition. High in-service temperature behaviour as indicated by viscosity at 60°C shows values higher than specification minimums. Cracking resistance that is assumed by indicators such as penetration and ductility are all within expected limits and are typical of values expected for the specific penetration grade of petroleum bitumen. All indications are that vegetable oil based biogenic bitumen will be less temperature susceptible than petroleum bitumen.

The low temperature properties of the vegetable oil based biogenic bitumen were assessed following a procedure used previously by Bearsley and Bosma (2019). While creep stiffness is not usually assessed in NZ for chipseal grade bitumens, such as 180/200, it was included as a useful indicator of brittle behaviour. The low temperature behaviour of biogenic 180/200 bitumen that was made using vegetable oil performed favorably compared to a reference sample of bitumen that had been obtained from Marathon Refinery, Garyville and used throughout the 2022/23 sealing season in New Zealand (Figure 2). The biogenic bitumen displayed lower creep stiffness at sub-zero temperature and a higher m-value, which is a measure of the rate of stress relaxation. These indicators suggest that biogenic bitumen produced using vegetable oil is less likely to suffer brittle failure in sub-zero, winter conditions. The slightly higher ΔT_c parameter associated with biogenic bitumen indicates that the brittle failure of the vegetable oil blended bitumen will be controlled by its creep stiffness rather than its ability to undergo stress relaxation.

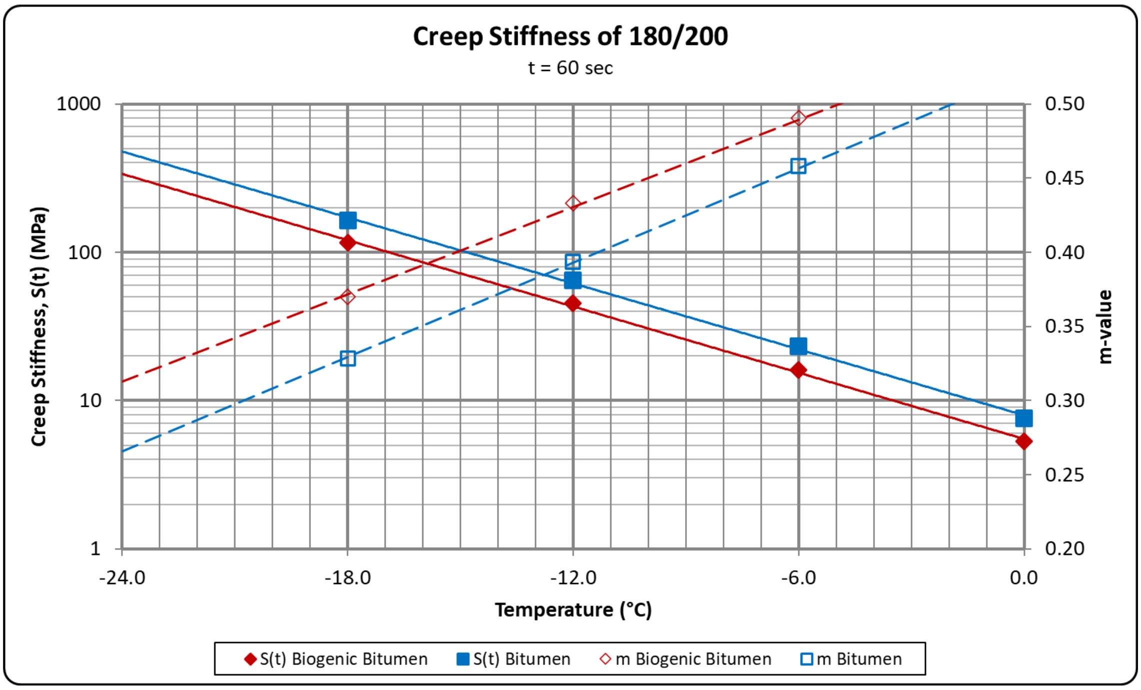

Figure 2: Low temperature properties of 180/200 biogenic bitumen made using vegetable oil.

Lignin

Biogenic bitumen samples were prepared using lignin by blending with a 180/200 grade bitumen that was made by mixing 60/70 with 7% vegetable oil. The lignin blends were relatively easy to blend at low concentrations, but blends containing 20% and 30% lignin were noticeably stiff to mix initially, eventually becoming less viscous as the lignin dispersed in the bitumen. Foaming of the heated bitumen occurred upon addition of lignin because of residual water that was in the lignin. The bitumen blends with lignin all had a characteristic, acrid odour, and a heterogeneous appearance, which indicates that dissolution has not occurred. The lignin and bitumen blend is a two-phase system.

Addition of lignin to bitumen has a stiffening effect as measured by the penetration test, which is consistent with findings reported in the literature (Figure 3). Full characterization of the lignin blends and comparison against NZTA M1 was not undertaken, but results that were available indicate that a complying 130/150 may be achievable by adding 10 – 15% lignin to a 180/200 bitumen (Table 9). However, lignin addition to the 60/70 bitumen and vegetable oil blend did not achieve the expected increase in viscosity that would normally accompany reduction in penetration (Figure 4). The viscosity of the 30% lignin blend fell below the minimum NZTA M1 specification criteria of 115 Pa.s and a complying 80/100 biogenic bitumen grade was not attained.

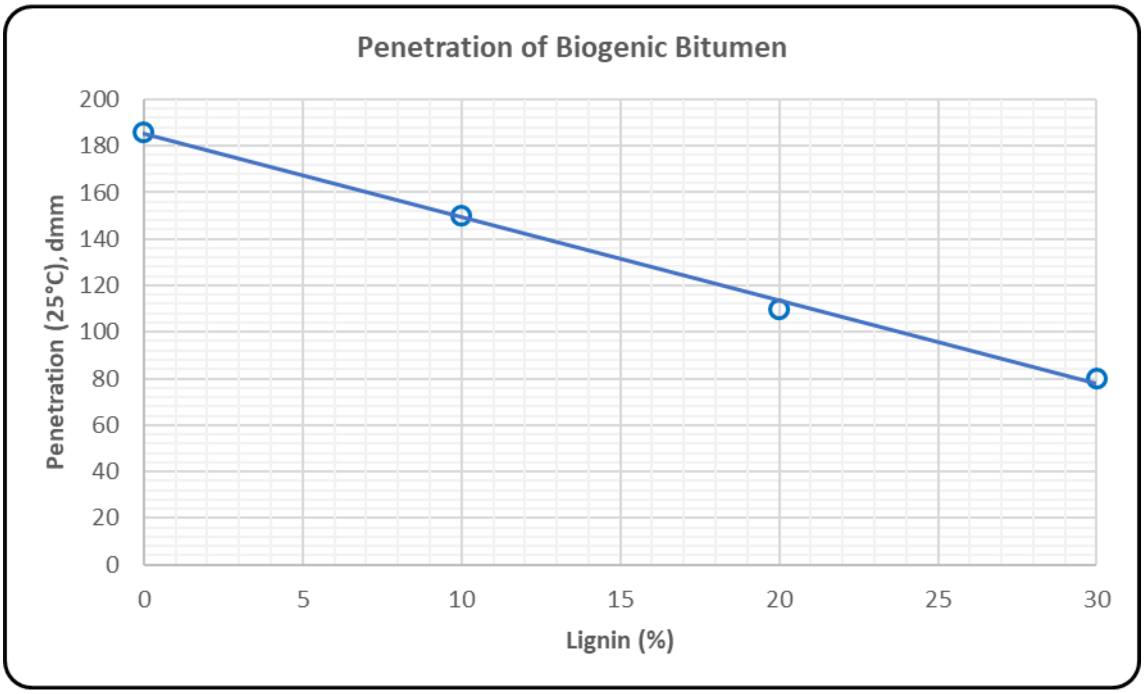

Figure 3: Stiffening effect of lignin on bitumen.

This low viscosity (60°C) result was not expected, especially since the penetration index of the lignin blends indicates a temperature susceptibility that should be no different to that of petroleum bitumen. The viscosity (60°C) of the lignin biogenic bitumen was measured using a dynamic shear rheometer following the procedure of ASTM D7175. A shear rate of 1.0 rad/s was used in each instance. It is also noted that the density for the 80/100 lignin biogenic bitumen was much lower than other blends containing lessor amounts of lignin. Given the difficulty experienced in the laboratory with blending high proportions of lignin with bitumen, the observed heterogenous nature of the samples, it is possible that segregation of lignin from the bitumen has occurred, and the test results obtained for viscosity at 60°C and density at 25°C may not be representative of the blend. The density of the lignin was not directly measured but was inferred as 1.24 kg/m3 by simple linear regression of bitumen density and lignin content. Such a high density relative to bitumen would result in settlement of lignin if the bitumen and lignin were incompatible. Adequate dissolution, reaction or dispersion would be difficult to achieve in this case.

Table 9: Properties of lignin based biogenic bitumen blends.

Property	Temp.	Units	Penetration Grade			
			80/100	**-**	**130/150**	**180/200**
Bitumen 60/70			65.1	74.4	83.7	93.0
Vegetable Oil		%	4.9	5.6	6.3	7.0
Lignin		%	30	20	10	0
Original Binder Properties						
Penetration	25°C	dmm	80	110	150	186
Dynamic Viscosity	60°C	Pa.s	103	93	81	62
Handling Viscosity	135°C	mPa.s	405	335	297	245
Density	25°C	kg/m^3	1026	1061	1046	1017
Complex Modulus	64°C	kPa	-	0.58	0.51	0.39
Phase Angle	64°C	°	-	88.0	88.2	88.4
Softening Point		°C	49.2	45.2	40.6	38.8
Penetration Index			-0.2	-0.4	-1.0	-0.9
PAV Aged Properties						
Durability	5°C	MPa	81	-	-	-

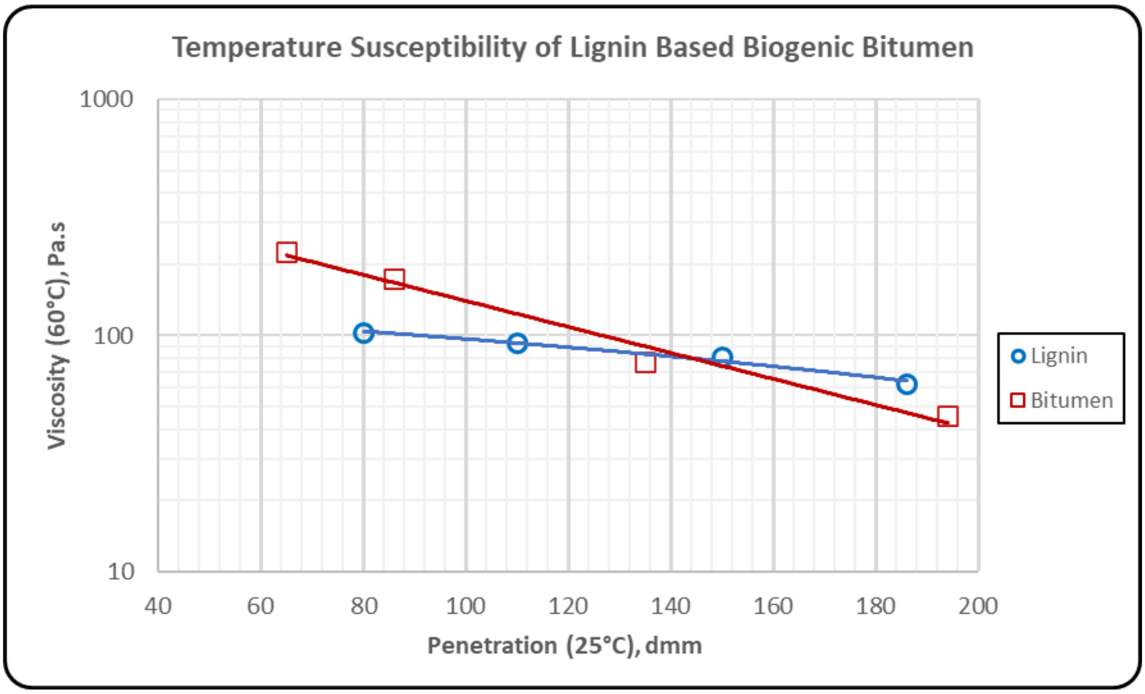

Figure 4: Observed change in temperature susceptibility with lignin based biogenic bitumen.

Further investigation was conducted on lignin and bitumen blends to evaluate the segregation and viscosity effects. Segregation was measured by storing samples undisturbed at 180°C for 48 hours before measuring the complex modulus of the top and bottom portions. Stable, compatible samples should show no difference in complex modulus between top and bottom portions after storage at elevated temperatures. The segregation result in Table 10 indicate that the lignin and bitumen used in this study are incompatible under the mixing regime that has been used. Heterogeneous behaviour is likely to present as handling and processing problems during operation, and potentially as inconsistency in performance.

Table 10: Properties of lignin and bitumen blends.

Property	Temp.	Units	Bitumen Grade					
			60/70	60/70	60/70	80/100	80/100	80/100
Lignin		%	0	10	20	0	10	20
Original Binder Properties								
Penetration	25°C	dmm	64	39	33	86	57	54
Dynamic Viscosity	60°C	Pa.s	375	644	824	174	297	398
Handling Viscosity	135°C	mPa.s	643	841	1290	370	579	850
Density	25°C	kg/m^3	1035	1051	1070	1027	1087	1064
Complex Modulus	64°C	kPa	2.12	3.50	4.43	-	1.67	2.19
Phase Angle	64°C	°	83.4	85.2	85.6	-	86.0	86.1
Softening Point		°C	50.2	54.2	55.6	-	51.2	52.8
Penetration Index			-0.6	-0.8	-0.8	-	-0.6	-0.4
Segregation		%	-	54	127	-	50	110

The penetration index of the blends in Table 10 are consistent with blends prepared from 60/70 and 7% vegetable oil and would denote acceptable temperature susceptibility. Similarly, the viscosity at 60°C of the lignin blends reported in Table 10 is of the expected magnitude given the penetration. Therefore, it may be possible that inclusion of vegetable oil in the blends shown in Table 9 has interacted with the lignin in such a way that it is acting more as an inert filler rather than a part of the bitumen phase. The lack of viscosity build with the initial blending studies remains unexplained. Further investigation is warranted to adequately explain the behaviour of lignin in bitumen.

It is worth noting that lignin based biogenic bitumen has satisfactory long term ageing resistance as measured using the NZTA T13 durability test. A biogenic bitumen containing 30% lignin had a durability of 81 MPa, which satisfies the NZTA M1 criteria.

Tall Oil Pitch

The tall oil pitch mixed readily with the bitumen at 160°C and required minimal blending. No foaming was observed during sample preparation, although a characteristic pine resin odour was noticed. Tall oil pitch characteristically softened the bitumen. Increasing penetration values and decreasing viscosity occurred as the proportion of tall oil pitch increased. An NZTA M1 compliant 80/100 blend was prepared from 60/70 and 15% tall oil pitch (Table 11). There was no change in penetration index as the tall oil pitch proportion increased, implying that tall oil pitch does not affect the temperature susceptibility of the bitumen within the range studied.

Tall oil pitch did not have any adverse effect on durability of the bitumen as determined using the NZTA T13 durability test. This implies that long term age hardening for tall oil pitch based biogenic bitumen is likely to be similar to petroleum bitumen that has historically proven to have good long-term service performance. The test data indicates that biogenic bitumen can be produced using tall oil pitch and its performance is likely to be indistinguishable from petroleum bitumen. This is consistent with previous research conducted on this subject in New Zealand (Ball et al, 1993; Herrington et al, 1996; Bearsley and Haverkamp, 2007a and 2007b).

Table 11: Properties of tall oil pitch based biogenic bitumen blends.

Property	Temperature	Units	Penetration Grade		
			60/70	80/100	-
Bitumen 60/70		%	100	85	80
Tall Oil Pitch		%	0	15	20
Original Binder Properties					
Penetration	25°C	dmm	65	92	106
Dynamic Viscosity	60°C	Pa.s	227	129	101
Handling Viscosity	135°C	mPa.s	422	323	274
Density	25°C	kg/m^3	1026	1022	1021
Complex Modulus	64°C	kPa	1.45	0.80	0.62
Phase Angle	64°C	°	86.6	88.2	88.6
Softening Point		°C	50.2	46.6	45.2
Penetration Index			-0.5	-0.6	-0.6
PAV Aged Properties					
Durability	5°C	MPa	91	-	84

GWP of Biogenic Bitumen

The global warming potential of the biogenic bitumen blends under investigation have been estimated using the data and assumption in Table 1 and Table 3. Each of the biogenic bitumens have an estimated GWP that is lower than that of the reference petroleum bitumen (Table 12). In fact, the point of carbon neutrality can be estimated using this same data by following the approach taken by Lu et al (2020). Carbon neutrality is estimated as the proportion of biogenic material that has to be added to the bitumen so that the sequestered carbon that is embodied in the biogenic material is equivalent to the carbon emitted throughout the life cycle of the blended bitumen. Because all three biogenic materials have a similar estimated GWP they will achieve carbon neutrality when blended with bitumen at proportions of 21 – 24%. It is apparent from this simple carbon accounting approach that carbon neutrality does not require that biogenic material constitutes a major portion of the bitumen blend. Furthermore, it implies that biogenic materials can assist the New Zealand bitumen and asphalt industry with achieving its carbon zero aspirations.

Table 12: Estimated GWP of biogenic bitumen blends.

		Vegetable Oil	Tall Oil Pitch	Lignin
Bitumen GWP	kg CO_2-e/kg	0.43	0.43	0.43
Biogenic Material GWP	kg CO_2-e/kg	-1.47	-1.51	-1.76
Biogenic Material	%	2 – 6	15 – 20	10 – 30
Processing Emissions	kg CO_2-e/kg	0.02	0.02	0.02
Total GWP	**kg CO_2-e/kg**	**+0.34 to +0.41**	**+0.06 to +0.16**	**-0.21 to +0.23**
GWP Change	%	-4 to -22%	-63 to -86%	-46 to -148%
Proportion of Biogenic Material Required to Achieve Carbon Neutrality	%	24	23	21

Health, Safety and Environmental Considerations

Fumes and Odours

Fume and odour control is becoming an increasing issue for asphalt plants and construction sites. Complaints are becoming more frequent, which is prompting regional authorities to investigate and discuss the issues with asphalt producers. Bitumen has a slight characteristic odour when applied hot, and whilst it is not objectionable, it is noticeable. Strong, acrid, and potentially irritating fumes were observed when adding lignin to hot bitumen during the laboratory investigation. Whilst this is manageable in a laboratory setting, fume and odour control may be required during full-scale production. Further investigation will be required to ascertain the presence and effect of lignin fumes during construction of asphalt pavements.

Similarly, the addition of tall oil pitch to bitumen increased the observance of characteristic and acrid fumes. Fumes were less noticeable when tall oil pitch was added compared to lignin but were stronger than hot bitumen alone. Fumes associated with vegetable oils were no more noticeable than those associated with hot bitumen.

Flammability

Other health and safety factors that need to be considered when selecting biogenic sources as bitumen extenders or replacements are the presence of toxic, flammable, or other dangerous contaminants. All materials considered during this study had a flash point in excess of 218°C, so the presence of flammable or combustible vapours was no more likely than when handling bitumen.

Toxicity

Lignin, tall oil pitch, and vegetable oils are not toxic, and do not contain carcinogenic materials. All three materials have a long history of use in industrial settings with no observed carcinogenic effects. Mazuch (1993) reports that the use of tall oil pitch in bitumen is unlikely to cause any health and safety concerns over and above what is normally experienced when handling conventional bitumen. Emissions of polynuclear aromatic hydrocarbons, phenols, and acetaldehyde from the tall oil pitch modified bitumen are all within the permitted levels as specified by the relevant Canadian authorities. Tall oil and its derivatives have been used for many years without creating any known health and safety problems.

Other Considerations

Even when supplied as a dry powder or granule, lignin contains a minor amount of water. This water caused bitumen to foam when added to hot bitumen. Foaming reactions are a serious safety issue within and around bitumen plants and can cause explosions and permanent injury if not controlled and managed. Careful consideration will be required when adding lignin to bitumen to ensure that any foaming reactions occur in a controlled manner.

Lignin was supplied in granulated form but is also available as a coarse powder. The risk of inhaling respirable dusts is considered low because of the particle size of the material. Production plants that process lignin powder should be designed and operated to minimize the risks associated with combustible dust explosions, respirable particles, and environmental contamination.

Tall oil pitch, lignin or vegetable oils are not known to contain dangerous levels of heavy metal contaminants.

Conclusions and Recommendations

Three biogenic materials have been assessed for their suitability as potential precursors for a biogenic bitumen: recycled vegetable oil and tall oil pitch sourced from New Zealand, and lignin sourced from Finland. The investigation was undertaken within the framework of climate change mitigation and the UN Sustainable Development Goals.

The research centered on vegetable oil, tall oil pitch and lignin because all three have previously been investigated in the international market with promising results, and New Zealand can produce these materials from existing resources and industries. However, some commercial and environmental sustainability constraints have been identified that require resolution before widespread adoption of biogenic bitumen derived from these domestic sources will be possible.

New Zealand is a net importer of vegetable oils. There is insufficient local production of vegetable oil to permit widespread use as the basis of biogenic bitumen. Vegetable oil is also prioritized as a food source, with chemical, biofuels and roading industries being secondary markets. Similarly, there is insufficient tall oil production in New Zealand currently to allow biogenic bitumen based on tall oil pitch to occupy anything other than a niche market. Tall oil pitch is also used as a fuel for process heat, the diversion of which into the roading industry could negatively impact on the GWP of crude tall oil distillation in New Zealand. Abundant quantities of lignin are produced annually in New Zealand, but none is currently available for use as the basis of a biogenic bitumen for roading. All lignin that is extracted during pulp production is used as a fuel for process heat and electricity generation in pulp mills. Diversion of any of this lignin for use in other applications such as pavement surfacing, will negatively impact GWP of pulp production and will likely increase New Zealand's CO_2 emissions.

However, abundant quantities of vegetable oil, tall oil pitch and lignin are available on international markets. Carbon is sequestered in these materials and importation of these materials for use as a biogenic bitumen will reduce New Zealand's overall CO_2 emissions. It will be possible to produce biogenic bitumen that has a net zero or even a negative carbon emissions profile. Furthermore, and while production of biogenic bitumen from these materials is likely to increase the cost of bitumen supply in New Zealand slightly (up to 12%), the cost increase is neither unreasonable, nor unaffordable.

Both tall oil pitch and vegetable oil can easily be blended with bitumen to produce a biogenic bitumen that complies with New Zealand specifications. It is anticipated that biogenic bitumen produced as a blend of these materials with petroleum bitumen will have a performance outcome that is indistinguishable from bitumen that is currently imported from oil refineries. No health and safety, or operational issues have been identified that would impede use of these materials in New Zealand.

Lignin has shown promise in the literature as the basis of biogenic bitumen. While initial investigations were partially successful, further research is required to understand its performance, behaviour, and ability to produce a biogenic bitumen that complies with New Zealand specifications. There are some health and safety concerns regarding its use as a bitumen additive because residual water present in the lignin causes foaming upon addition to hot bitumen. Objectionable odours were also emitted upon blending with hot bitumen, which will need to be mitigated if full scale industrial application were to eventuate. Additionally, there are compatibility issues that could cause operational problems if the lignin is blended with hot bitumen. It may be better suited to a dry-mix process in an asphalt plant.

An aspirational objective of this investigation was to produce a biogenic bitumen that contained a majority proportion of biogenic material. While this has yet to be demonstrated, it is still possible to produce carbon neutral, biogenic bitumen from blends of bitumen and lessor proportions of vegetable oil, tall oil pitch and lignin. These materials have significant potential for assisting New Zealand industry with achieving both its carbon zero aspirations and sustainable development goals.

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