

Emulsion Chipsealing: Generating Conscious Capital

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INTRODUCTION

Proponents of management theory have observed that society and business tends to undergo changing management fads that typically have a 10 year cycle. Prior to the 1960's, businesses focussed on manufacturing efficiency and scientific management principles. The 1960's saw the rise of quality management theories and a decade later the focus shifted into the age of marketing during the 1970's. Financial management reigned throughout the 1980's. This was superseded by human resource management theory in the 1990's before the business world became distracted by digital media and communication during the 2000's. Slowly evolving during the last 50 years and emerging throughout the 2010's is the idea of conscious capitalism, which is becoming a driving force for current policy decisions and business management.

Conscious capitalism is a business strategy that recognises the importance of values-based economics as a measure of success. It merges corporate social responsibility with fiscal stewardship and is embodied in the triple bottom line accounting principles. Successful businesses are recognised as achieving positive results simultaneously in the areas of people, planet and profit. Conscious capitalism is recognisable in the "green" movement, fair trade practices and "ethical" investment strategies. It is also a philosophy that is embodied in the theme of the SaferRoads Conference 2017: "Safe and Sustainable Road Surfaces."

Health and Safety at Work Act (2015)

Against this backdrop of conscious capitalism, the current societal context of valuing people in the workplace has led to the introduction of the Health and Safety at Work Act, 2015 (HSWA) in NZ. There has been renewed impetus for New Zealand business managers to ensure the safety of their staff. This legislation requires the effective identification and management of health and safety risks and puts the onus on individuals to ensure compliance. Prosecution can result in serious penalties for individuals and organisations failing to comply with the legislation.

Legislation such as the Health and Safety at Work Act (2015) places obligations on those who create risk and are best placed to manage it. It requires all participants in the process including both suppliers and clients to ensure health and safety as far as is 'reasonably practicable'.

"A guiding principle of HSWA is that workers and other persons should be given the highest level of protection against harm to their health, safety, and welfare from work risks as is reasonably practicable. ...

... When used in this context, something is reasonably practicable if it is reasonably able to be done to ensure health and safety, having weighed up and considered all relevant matters, including:

- *How likely are any hazards or risks to occur?*
- *How severe could the harm that might result from the hazard or risk be?*

- What a person knows or ought to reasonably know about the risk and the ways of eliminating or minimising it (e.g. by removing the source of the risk or using control measures such as isolation or physical controls to minimise it).
- What measures exist to eliminate or minimise the risk (control measures)?
- How available and suitable is the control measure(s)?

Lastly weigh up the cost:

- What is the cost of eliminating or minimising the risk?
- Is the cost grossly disproportionate to the risk?" (Worksafe New Zealand, 2016).

Table 1: Maximum penalties for failure to comply with HSWA (2015) (after Worksafe New Zealand, 2016).

	Individual (Worker)	Manager in charge of business undertaking	Organisation
Reckless conduct that exposes an individual to a risk of serious injury, illness or death.	5 years prison or, \$300,000 fine, or both	5 years prison or, \$600,000 fine, or both	\$3.0 million fine
Failure to comply with duty that exposes an individual to a risk of serious injury, illness or death.	\$150,000 fine	\$300,000 fine	\$1.5 million fine
Failure to comply with a duty.	\$50,000 fine	\$100,000 fine	\$500,000 fine

Safer Roads and Maintenance Chipsealing

Most road safety discussions tend to focus on the user experiences as impacted by road surface condition, operating conditions, vehicle condition and safety, driver ability, experience and training and of course other factors that affect the driver's ability to safely operate a vehicle. When asked the question, "who is the road user?" the more obvious responses are "drivers", "cyclists" and "pedestrians". However, there is another cohort who are often overlooked: the maintenance teams who are responsible for ensuring that the road corridor remains safe to operate in are a significant road user group.

Throughout the year in NZ, thousands of maintenance contractors typically spend a large proportion of their working day operating in hazardous environments within the road corridor. They handle hazardous materials in close proximity to thousands of vehicles moving at speeds that have the potential to cause serious harm or fatality.

Chipsealing is the primary pavement surfacing option used in many territories around the world including NZ, for maintaining the safety of road surfaces. It is one of the more cost-effective and sustainable treatment options available to the roading engineer. Because cost is always an important consideration, NZ has historically preferred the least cost chipsealing option, which has been with cutback bitumen. Cutback bitumen is very effective and the lowest cost binder for construction of chipseals. It is also highly dangerous to use, can be flammable or explosive if mishandled, is energy intensive and has a significant environmental impact. In light of society's and business' increasing desire to be good corporate citizens, application of emulsified bitumen for chipsealing is slowly gaining a greater, albeit still minor, market share at the expense of cutback bitumen.

Road Controlling Authority's (RCAs) exert significant influence on the health and safety risks for maintenance crews engaged in chipsealing operations in the choice of products that they allow to be used on their networks. There is no dispute that emulsified bitumen is safer to use than cutback bitumen and has a relatively small impact upon the environment. However, widespread adoption of

emulsified bitumen in NZ continues to be hindered by the perceived greater cost; a stance that is becoming increasingly indefensible.

Utilisation of triple bottom line accounting principles allows the true cost of chipsealing with cutback or emulsified bitumen to be assessed. It is possible to attribute a financial value to the health, safety, environmental and quality considerations that utilisation of cutback or emulsified bitumen provide to the chipsealing operation.

FINANCIAL COSTS

Typical unit costs for chipsealing in NZ are in the order of \$4.00 to \$6.00 /m². Material costs contribute 50 – 70% of the cost of a chipseal, with the bitumen accounting for the majority of this. Hence, this is often seen as the single largest cost factor to control. However, other factors such as seal type, contract size, crew productivity and site location relative to resources are also significant determinants of unit cost. Chipseals constructed using cutback bitumen are currently 10 – 15% less expensive than emulsified bitumen because of the higher cost of emulsion (Olsen, 2014; Ball 2005). The higher cost is partially because emulsification introduces an additional processing step, but mainly because it is seen as a specialty product for applications where use of cutback is less suitable. As production volumes of emulsion increase and it becomes more of a commodity product, it is expected that the cost differential between cutback and emulsified bitumen will decrease.

Cost of aggregate is identical for both cutback and emulsified chipseals. It includes not only the material cost, but also transport, QA, and stockpile losses. The choice of binder type will not significantly affect the aggregate cost. Similarly, experience indicates that productivity is similar for both cutback and emulsion operations. The type of binder used does not tend to dictate productivity. Rather it is site conditions, seal type, traffic management, crew resourcing and distance to stockpiles that tends to determine daily productivity. There is usually no difference in costs associated with seal designs, project management and other ancillary costs.

Table 2: Hypothetical cost contribution of various components of chipsealing for a large network.

	Cutback Bitumen (\$ /m²)	Emulsified Bitumen (\$ /m²)
Bitumen	\$1.717	\$2.314
Aggregate	\$0.993	\$0.993
Equipment and Labour	\$1.000	\$1.000
Project Management / Overheads	\$0.100	\$0.100
Profitability	\$0.200	\$0.200
Total Cost	\$4.010	\$4.608

HEALTH AND SAFETY COSTS

Although cutback bitumens are intuitively regarded as being more dangerous to handle and apply than emulsions, it was not until Olsen (2014) undertook a study that directly compared cutback against emulsion use that quantitative injury data could be obtained. Olsen (2014) reviewed NZ accident compensation claims that related to incidents involving bitumen, cutback bitumen and emulsified bitumen. The study involved roading contractors responsible for 90% of NZ chipsealing and used data from a 5 year period from 2009 to 2013. The conclusion from this study was that although the overall incident frequency is similar for both cutback and emulsified bitumen, the likelihood of serious harm from cutback bitumen incidents are much greater. The overall incident rate was in fact slightly lower for emulsion because there are some accidents that will not occur if emulsion is used, namely fire and explosion hazards caused by kerosene vapour.

Table 3: Accident frequency rate per 100,000 tonnes of bitumen sprayed (adapted from Olsen, 2014).

	Cutback Bitumen	Emulsified Bitumen
Fatalities	0.2	0.0
Serious Harm (non-fatal)	8.7	0.0
Minor harm and near miss	2.8	10.6
Total Incident Rate	11.7	10.6

The incident frequency data was obtained from industry safety databases and accident compensation claims. Data for fatalities and serious harm is expected to be reasonably correct because it is a legal requirement to report these injuries. Minor harm and environmental injuries that do not result in lost time injuries or medical treatment injuries are likely to be under reported as many near misses are probably not recorded.

NZTA (2016) uses a “value of statistical life” (VSL) approach to estimate the economic cost of accidents in NZ. The VSL is an economic tool used to estimate the willingness of society to pay to prevent injury and death. It is the economic value placed on life and varies depending upon the country. NZ adopted a VOSL of \$4.06 million in 2015, up from \$3.85 million in 2013, \$3.35 million in 2008 and \$2.00 million in 1991. MOT (2016) estimated that the average social cost per fatality as a result of road crashes was \$4.09 million at June 2015 prices. Non-fatal, but serious injuries were estimated to have average social costs of \$430,400 and minor injuries cost \$23,000.

Table 4: Typical costs per road crash for different injury types (adapted from NZTA, 2016).

	50 km/h	100 km/h
Fatalities	\$4,600,000	\$4,850,000
Serious Injury (non-fatal)	\$475,000	\$525,000
Minor Injury	\$28,000	\$30,000

For the purpose of this study, the injury costs estimated in Table 4 were averaged to give typical injury costs of:

- Fatality = \$4,700,000
- Serious Harm = \$500,000
- Minor Harm = \$29,000

This data is used to estimate a health and safety cost associated with the use of cutback and emulsified bitumen for chipsealing (Table 5). Given that approximately 100,000 tonnes of bitumen is used annually for chipsealing, the health and safety cost to NZ society of using cutback bitumen is in the order of \$5.37 million per annum. By comparison, emulsified bitumens generate a health and safety risk 17 times lower (6%) at approximately \$307,400.

Table 5: Estimated annual health and safety cost associated with using cutback and emulsified bitumen for chipsealing.

	Cutback Bitumen	Emulsified Bitumen
Fatalities	\$940,000	\$0
Serious Harm (non-fatal)	\$4,350,000	\$0
Minor harm and near miss	\$81,200	\$307,400
Total Incident Rate	\$5,371,200	\$307,400

Vercoe et al (2006) used a similar approach to that employed here, but in the absence of quantitative data had to make assumptions about the incident frequency. The social cost of fatality (VSL) was also estimated as being much lower at \$2.5 million. The conclusion was that cutback bitumen accidents

cost 5 times more than emulsion accidents due to the severity of the consequences, which is absent when emulsion is used.

QUALITY COSTS

Before attempting to ascertain any difference in chip seal quality that might arise as a result of using cutback or emulsified binders, it is important to firstly understand how chipseals perform. This information is critical in understanding how choice of cutback or emulsified binder could reduce the risk associated with certain types of seal failure and thereby improve the whole of life cost of a seal.

Chipseal performance and failure modes have been discussed by numerous researchers including Ball and Patrick (2005), Gransberg and James (2005), Transit NZ (2005) and Kim et al (2017). The function of chipseals is to protect the underlying pavement from water ingress and to provide a safe, skid resistant wearing surface. Failure modes are therefore related to these two functional requirements and can usually be categorised as:

- Low skid resistance as a result of
 - Texture loss through aggregate embedment, binder rise and flushing
 - Binder tracking and bleeding
 - Aggregate polishing
- Loss of aggregate
 - Age related scabbing and ravelling
 - Moisture induced adhesion loss
- Cracking of the binder film

A review of seals undertaken in New Zealand during the 2002/2003 season found that there is a large variation in lives obtained and is dependent on seal type and traffic volumes (Ball and Patrick, 2005). The average life expectancy for a typical seal Grade 3 (14 mm) single coat or a Grade 4/6 (10/5 mm) two coat, trafficked by approximately 5,000 vehicles per day was around 9 years. However, 15% of seals fail after 3 years with the same proportion lasting longer than 14 years. Another review was undertaken by Towler et al (2010) for the 2008/2009 season and similar results and trends were observed.

The failure modes reported during the 2002/2003 season are given in Figure 1. This analysis also compared the relative proportion of failures that occurred early in life (less than 2 years after application) to all failures that were reported, regardless of age. The most common failure mechanisms for seals lasting longer than 2 years are cracking (14%), loss of texture (18%), low friction (9%) and shoving (7%). Of all the seals undertaken during this period, 47% did not have a reason recorded for why resealing occurred. Therefore the proportions of each failure mode could be much greater than what is reported here. In the absence of more complete data it is assumed that the relative proportions of each failure mode reported above would be the best case scenario.

Considering all the failure modes, chip seals that fail early are more likely to fail by scabbing (~3.5 times as likely, ~7%) or low friction (~2 times, 17%) than what would be expected in seals that last longer than 2 years. Low friction is usually an aggregate related issue, but in many instances where the early failure reason was historically recorded as "Low Friction," it was because fresh binder has tracked over the chipseal surface, or sealing over a flushed seal has resulted in flushing rapidly progressing into the new seal. The relatively high incidence of scabbing is more likely to be due to late season sealing or a low application rate of bitumen. It is commonly a result of poor adhesion in early life failures and results in aggregate being stripped from the chipseal. These early types of failures not only require replacement of the surface much sooner than expected, they also increase the likelihood that subsequent seals do not attain their default service lives, which significantly increases the whole of life cost of the pavement.

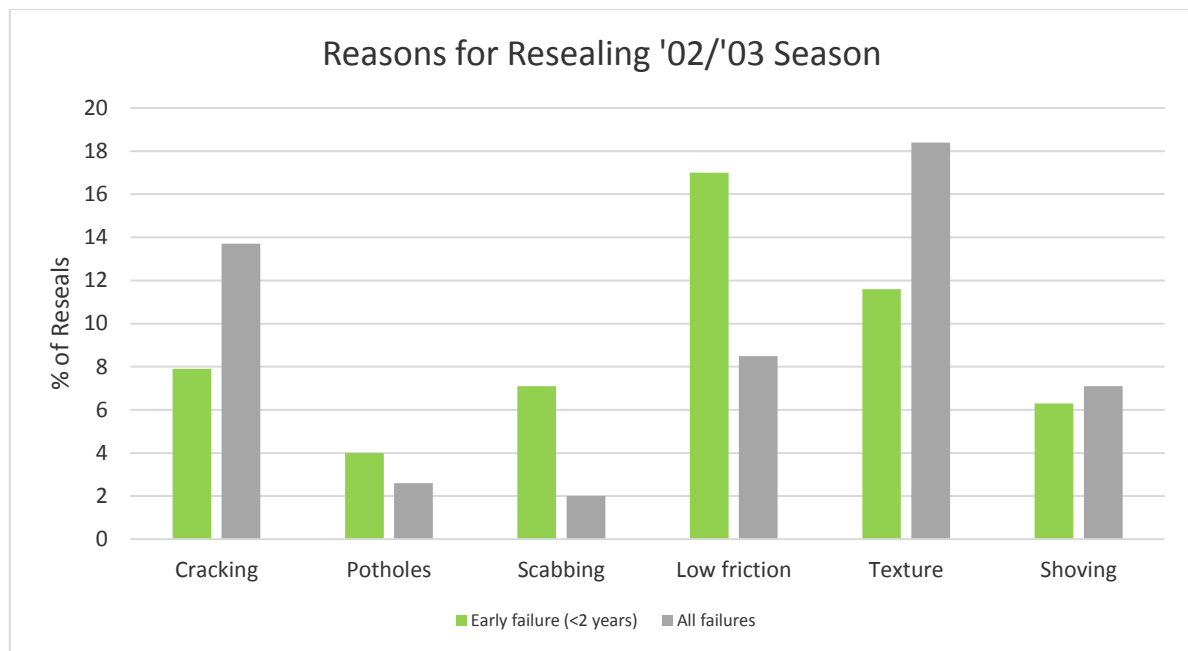


Figure 1: Reasons sites were resealed during 2003/2003 season (after Ball and Patrick, 2005).

Cracking, Shoving and Potholes

In the context of the current discussion, cracking, shoving and potholing is more a function of pavement performance rather than whether the chipseal binder was applied as an emulsion or cutback bitumen. It is generally acknowledged though that polymer modified binders tend to display superior cracking resistance than unmodified binders.

Low Texture and Skid Resistance

Similarly, the choice to use cutback or emulsified bitumen will not usually influence the skid resistance of the chipseal. Skid resistance tends to be determined by aggregate properties such as polishing resistance, chip size and shape, and resistance to abrasion and degradation under traffic loads. However, recent research by Bagshaw (2014) concluded that, regardless of design, actual binder application rates for emulsified bitumen tended to be slightly lower than application rates for cutback bitumen. Also, chipseals constructed using emulsified bitumen had higher cohesive strengths compared to those constructed from cutback bitumen. These two factors tend to suggest that chipseals constructed from emulsified bitumen are less likely to display chip roll-over and binder tracking or, bleeding and texture loss through binder rise and flushing processes, all of which can adversely affect skid resistance.

Gransberg and Carlisle (2005) reported on differences in performance in chipseals constructed using crumb rubber modified (CRM) bitumen and polymer modified emulsions. The chipseals constructed using polymer modified emulsion showed a lower rate of texture loss and were more cost effective than the chipseals constructed using hot CRM bitumen. The emulsified bitumen chipseals had a texture 0.5 mm greater than the hot applied bitumen after 2 years. On this basis, the emulsified bitumen chipseal would be expected to last 2 – 3 years longer.

Scabbing and Stripping

Scabbing can be separated into two failure modes: scabbing and stripping. Early life failure as a result of poor adhesion of the binder to aggregate is often referred to as “stripping”. Scabbing that occurs

later in life is more commonly related to the oxidation and durability of the binder. There is some research to indicate that emulsification reduces the ageing effects of oxidation (Zhao et al, 2012). If this is the case then it could be expected that age related scabbing failures will occur even later in chipseal life, leading to an overall increased in the average seal life.

Emulsified bitumen displays superior adhesion compared to cutback bitumen. The lower viscosity of the bitumen emulsion allows it to easily wet the aggregate allowing for much better early adhesion and reducing the likelihood of stripping. This is especially important during cooler weather when cutback bitumen viscosity effects and moisture content of aggregate stockpiles can affect the ability for cutback bitumen to adhere to the aggregate (Gransberg and James, 2005; Transit NZ, 2005).

The adhesive qualities of emulsions are also the reason that the majority to polymer modified chipseals are constructed using emulsion in NZ. The viscous nature of PMB inhibits good aggregate wetting and the risk of early stripping failure is unacceptably high under conditions experienced in NZ. Early seal failures as a result of stripping are substantially reduced when emulsified bitumen is used. An example of this is that some contractors have experienced rework costs amounting to approximately 2.5% of the contract value when using cutback. The cost of rework dropped by 80% to around 0.5% when they started using emulsified bitumen, largely because of a reduction in early life stripping failures.

Another illustration of the improved adhesion that bitumen emulsion offers can be seen in the change in behaviour of sealing crews when switching from cutback bitumen to emulsion. Figure 2 shows the proportion of monthly bitumen volumes from a contract that previously sprayed 100% hot cutback bitumen compared to the volumes sprayed when the contract converted to 100% bitumen emulsion.

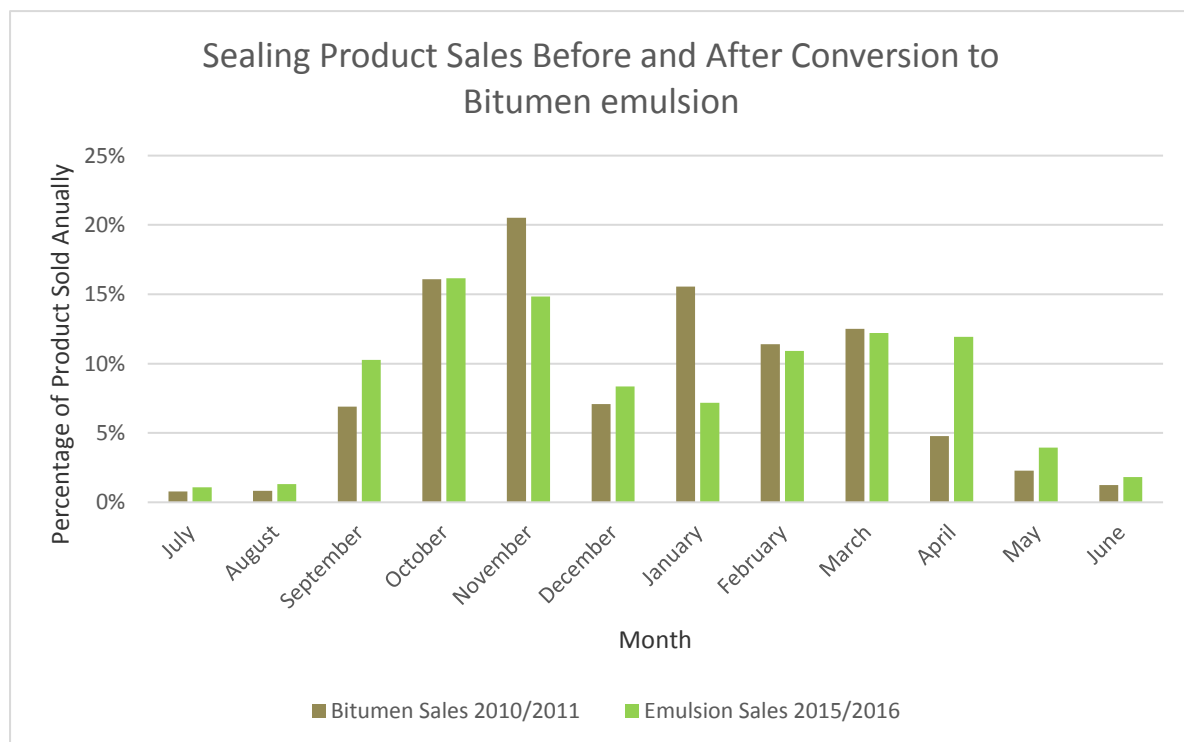


Figure 2: Bitumen sales from a contract that converted from hot cutback bitumen to bitumen emulsion

In New Zealand the sealing season for hot cutback bitumen ends on 31st March as through experience, the risk associated with stripping using hot cutback bitumen becomes too great due to the cooling climate. Bitumen sales volumes reduce dramatically after March when using hot cutback bitumen whereas bitumen emulsion sales remain at the same level as what was experienced during

summer. A similar situation exists in September where hot cutback bitumen sales are lower than bitumen emulsion sales. In both cases it can be seen that the improved adhesion of bitumen emulsion allows crews to seal in colder conditions where the risk of stripping when using hot cutback bitumen would be too great.

Overall Performance

Both Bagshaw (2014) and Wanty (2014) examining NZTA's RAMM database and attempted to determine if there was any differences in chipseal service life depending upon whether cutback or emulsified bitumen was used. Both studies were inconclusive. This finding is likely related to the different applications that cutback and emulsified bitumen is used in NZ rather than any lack of difference in performance. Wanty (2014) reported that some regions showed similar or increased life with emulsion use (increase of 7 years), whereas others showed shorter lives (reduction of 6 years). Confidence in the analysis was hampered by size of the data sets available for emulsion chipseals.

Bagshaw's (2014) analysis shows that emulsified bitumens tend to be used in multicoat applications and a higher proportion of emulsified binders (47%) are polymer modified compared to hot applied PMBs (7%). Only approximately 7% of emulsified bitumen chipseals were constructed as single coat seals whereas 44% of cutback bitumen chipseals were single coats. This data indicates that emulsions tend to be used in speciality applications, or in higher stress applications in NZ, where cutback bitumen would present an increased risk of failure. Bagshaw (2014) also observed that residual binder application rates for emulsified bitumen tended to be approximately 4% lower than if cutback bitumen was used. This reduction in application rate will tend to increase texture by 0.05 – 0.10 mm, and consequently is expected to increase the service life of seals that would normally failure through low texture.

While much evidence suggests that emulsified bitumen chipseals could last longer than cutback seals, this has yet to be conclusively proven. What is readily apparent though, is that there is a scarcity of research to suggest that cutback bitumen chipseals will outperform emulsified bitumen chipseals. On the balance of probability there is more evidence weighing in favour of better chipseal performance when emulsified binders are used. Better early chip retention as a result of improved adhesion has been proven by experience. Increased scabbing resistance as a result of improved binder durability is likely. A reduction in the rate of texture loss as a result of lower application rates and better cohesive properties of the binder are probable. The improved cohesive properties of emulsified binders are also less likely to cause bleeding and tracking in hot weather, which can reduce skid resistance to unacceptable levels.

Estimating Quality Improvement

An estimate of the failure mode occurrence for chipseals constructed using cutback bitumen was made from the failure mode frequency data in Ball and Patrick (2005) and Towler et al (2010). The frequency of reseals that did not disclose a reason for failure were pro-rated to provide a better estimate of the frequency of each failure mode (Table 6). Assumptions have been made, based on the reviewed research literature, about how the use of emulsified bitumen may influence chipseal life.

Assuming average chipseal lives are in the order of 10 years and that overall annual failure rates could reduce by approximately 8% (based on estimates in Table 6), it is estimated that use of emulsified bitumen for chip sealing, could potentially increase average chipseal lives by 0.5 – 1.0 years through various mechanisms. The benefit that this would bring to NZ society is in the order of \$20 million annually.

Table 6: Estimates of failure mode frequency for cutback bitumen chipseals and life improvement that may be available by using emulsified bitumen ^(a).

Failure Mode	Cutback Bitumen Failure Frequency	Estimated Improvement by Using Emulsion	Estimated Increase in Chipseal Life
Cracking	32.6%	0%	-
Low Texture			
- caused by higher spray rates	2.1%	100%	2.1%
- caused by reflective flushing	3.3%	0%	-
- caused by end of life	36.5%	10%	3.7%
Low Friction			
- caused by polishing	19.9%	0%	-
- caused by bleeding/tracking	1.0%	50%	0.5%
Scabbing			
- caused by poor adhesion	2.0%	80%	1.6%
- caused by aged bitumen	2.7%	10%	0.3%
Total	100%		8.2%

^(a) see Appendix 1 for rationale behind estimates.

ENVIRONMENTAL COSTS

Greenhouse Gas Generation

Several studies have evaluated the environmental impact of using emulsified bitumen compared to hot applied systems. In each case the conclusion is that emulsified bitumen has a lower environmental impact than the hot alternative. Unfortunately few studies have been found that directly compare the environmental impact of chipseals constructed using cutback and emulsified bitumen.

New Zealand Research

Ball (2005) reviewed studies that compared the environmental footprint of cutback and emulsified bitumen. One study estimated that production, heating and transport of cutback bitumen produced 62kg CO₂ per tonne and emulsified bitumen generated 23kg CO₂ per tonne.

Martin and Berry (2012) undertook an environmental assessment for cutback and emulsified bitumen throughout the product life-cycle and concluded that emulsified bitumen generated ~50% of the CO₂ that cutback does. The assessment is summarised in Table 7 and included production, heating, transport and applications factors that influence the generation of CO₂ emissions of emulsion and cutback sprayed in New Zealand.

Cutback bitumen has a higher carbon demand mostly because it contains hydrocarbon diluents that emulsified bitumen does not. Energy demand for distribution of emulsions is usually higher due to the larger volume of product that is transported on a residual bitumen basis.

Differences in heating demand for cutback and emulsion are largely related to production and storage temperatures. Because emulsions are produced, stored and handled at lower temperatures they require less heating energy during storage and use. Estimated heat losses for cutback tanks are in the order of 16 kW as opposed to emulsion that lose a little over 7 kW. Storage and heating of emulsions will consume 65% of the energy of cutback bitumen on a tonne bitumen basis.

The economic cost of greenhouse gas generation as a result of energy consumption is estimated by NZTA (2016) to be \$40 / tonne of CO₂-e emitted. Based on Martin and Berry's (2012) estimates and assuming an annual consumption of 100,000 tonnes of cutback bitumen, the annual cost to NZ of CO₂ emissions from cutback bitumen is \$5.7 million. The cost of CO₂ emissions from emulsified bitumen is \$2.9 million.

Table 7: Product carbon foot print summary per tonne of residual bitumen sprayed (after Martin and Berry, 2012).

	Cutback Bitumen (kg CO₂-e)	Emulsified Bitumen (kg CO₂-e)
Upstream		
Raw material acquisition	438.5	425.1
Core Process		
Production	1.1	4.5
Downstream		
Distribution	50.2	65.1
Operations	905.6	211.3
Maintenance & Disposal	24.4	16.8
Total	1420	723

Other Research

Chehovits and Galehouse (2010) calculated annualised energy consumption and greenhouse gas emission for microsurfacing and emulsion chipseals that were typically 5 – 10 times less than that of hot mix asphalt overlays on a square metre basis.

Lubbers (2008) compared the cost and eco-efficiency of chipseals constructed using hot applied crumb rubber or SBR or SBS modified bitumen emulsions. The conclusion was that the emulsified bitumen increased costs by only 1.5% compared to the crumb rubber system. Hot applied crumb rubber chipseal was more polluting in terms of smog generation, resource consumption and CO₂ generation, and had a higher impact on health effect scores. However, it must also be noted that the crumb rubber modified chipseal required residual binder application rates that were 28% higher than the emulsified binders and utilised precoated aggregate. These two factors influenced the cost and energy consumption calculations and therefore a direct comparison between hot applied and emulsified systems using the same binder and construction methodology could not be made using this data.

Austrroads (2000) estimates that typically 27.6 kg of non-methane volatile organic carbon (NMVOC) is emitted per tonne of cutback bitumen, which equates to a global warming potential (GWP) of 91 kg CO₂ per tonne of bitumen assuming a conversion factor of 3.3 is used. The study concluded that there is little difference in CO₂ emissions between cutback and emulsions. However, the study is based on Australian data that suggests that emulsions typically contain 2% diluent, transport distances are a significant factor, and that emulsion use will result in a reduction in lane-kms being sealed due to higher product costs. These factors are typically not applicable to the NZ context.

NMVOCs and Particulates

Claims that emulsified bitumen generates less greenhouse gases than cutback bitumen are generally recognised and have not been disputed. However, the economic impact of this is relatively minor when taken in the context of an estimated \$250 million annual chipsealing expenditure. What is not assessed adequately when valuing CO₂ emissions is the effect that smog and particulate emissions from use of cutback bitumen have on health and the environment. An estimated 3 million litres of kerosene is used annually in NZ to produce cutback bitumen. The kerosene is either dispersed as a fine mist during spraying or evaporates from the chipseal over time as non-methane volatile organic carbon (NMVOC), which generates smog. It impacts upon air, water and soil quality and consequently, the health of people and natural eco-systems.

Kerosene is a Class 6.1E hazardous substance that can cause adverse effects to health upon inhalation or aspiration. It is also a Class 9.1B eco-toxic substance and as such the release of an estimated 15,000 – 20,000 litres into the environment on any typical summer's day in NZ is a concern.

Any ordinary commercial activity that attempted to gain resource consent to discharge that quantity of NMVOCs into the atmosphere on a daily basis would usually be challenged by regulatory bodies.

By comparison, accidental release of emulsified bitumen to the environment is estimated to be no more than 100 L per day on average through spillage, accident and runoff, which amounts to 0.6% of the daily emissions from cutback bitumen.

Holland et al (2005) estimates the marginal damage cost of NMVOC emissions in Europe to average between €950 and €2,800 per tonne depending upon the assessment method. This estimate includes effects on human health, agricultural, horticultural and maritime production systems and value of property and cultural heritage as a result of pollution. EnvEcon (2015) adopts an estimated marginal damage value of €875 per tonne of NMVOC emission for all of Ireland. The marginal damage value approximately doubles for population centres with >15,000 people and triples for metropolitan areas.

Using marginal damage values for NMVOC pollutants published by EnvEcon (2015), it is possible to estimate the marginal cost of cutback bitumen chipseals in various regions in NZ (Table 8). Assuming that similar values are applicable for NZ and based on similar population size, climate and mix of agricultural and industrial economy, we can estimate that the economic cost of NMVOC emission from cutback chipsealing in NZ is in the order of NZ\$3.3 million (€2.1 million) annually.

Table 8: Estimated marginal damage costs for NMVOC emissions from cutback bitumen used for chipsealing.

Region	Population	NMVOC Damage Cost	Typical Spray Rate	Chipseal Unit Cost
		NZ \$ / tonne	L /m ²	NZ \$ / m ²
Urban Large		4,250	1.6	0.130
Urban Medium	>15,000	2,460	1.8	0.085
Urban Small	10,000 – 15,000	2,150	2.0	0.082
Small Towns	<10,000	1,625	2.2	0.069
Rural Areas		1,350	2.2	0.057

TRIPLE BOTTOM LINE COST OF CHIPSEALS

Summarising the financial cost of chipsealing along with the marginal costs associated with health and safety, quality and environmental risks allows an estimate to be made of the true cost of chipseals (Table 9). Conscious capital is generated by choosing to invest in products that eliminate or minimise risk factors that would otherwise cause collateral damage to people or the environment (Figure 3).

Table 9: Estimated financial and marginal cost of chipsealing.

	Cutback Bitumen		Emulsified Bitumen	
	per m ²	%	per m ²	%
Financial Cost	\$4.010	85.4	\$4.608	98.3
Health and Safety Cost	\$0.097	2.1	\$0.006	0.1
Environmental Cost	\$0.162	3.5	\$0.052	1.1
Quality Cost	\$0.423	9.0	\$0.023	0.5
TOTAL COST	\$4.692	100.0	\$4.688	100.0

There is no difference in the overall total cost of chipsealing with cutback or emulsified bitumen, despite persistent perceptions to the contrary. There is a marginal cost associated with the use of cutback bitumen for chipsealing that is estimated to be \$0.682 /m². This is typically 11 – 17% of the

financial cost of chipsealing and is estimated to cost NZ society \$37.9 million annually. By comparison, the marginal cost of chipsealing using emulsified bitumen is estimated at \$0.081 /m² and has a financial cost of approximately \$4.5 million. The difference is the conscious capital that can be generated from use of emulsified bitumen: \$33.4 million annually.

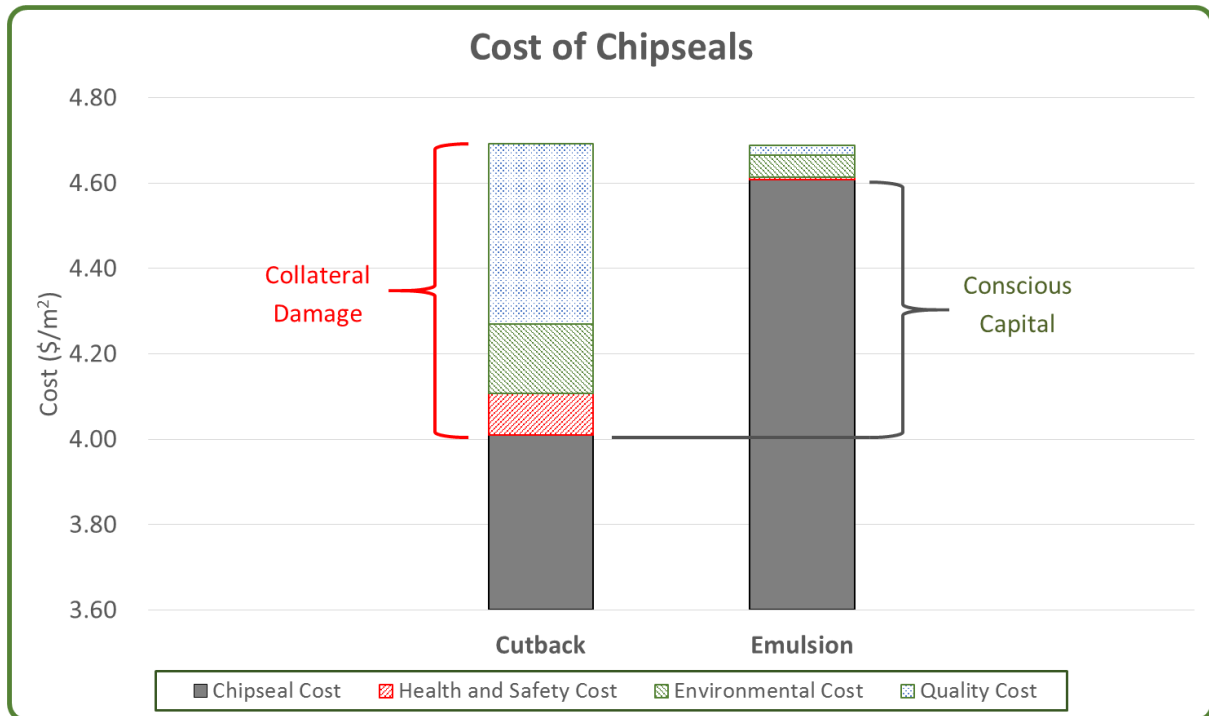


Figure 3: Conscious capital generated from use of emulsified bitumen.

CONCLUSIONS

By using a triple bottom line reporting approach it is possible to more equitably determine the true cost of chipsealing using cutback or emulsified bitumen. This approach enables the asset manager to apportion costs appropriately so that communities exposed to pollution and individual workers exposed to health and safety risks do not have to pay the price for society's benefits. It enables the asset manager to either accept collateral damage to people and the environment or to invest in conscious capital.

While adoption of emulsified bitumen in preference to cutback chipsealing may attract a higher initial financial cost, it has the potential to return benefits that would not otherwise be available:

- Health and safety benefit = \$5.1 million
- Environmental benefit = \$6.1 million
- Quality benefit = \$22.2 million

Marginal damage costs associated with quality, health and safety, and environmental impacts contribute approximately 15% to the cost of chipseals constructed using cutback bitumen. Marginal costs are not valued during the procurement process, but are paid by society in one form or another. Accounting for the marginal damage cost acknowledges that additional benefits are associated with use of emulsions and eliminates the current cost differential with cutback bitumen that is impeding increased use of emulsified bitumen.

Use of emulsified bitumen for chipsealing enables road controlling authorities to reasonably and practicably meet obligations under health and safety legislation. "A guiding principle of HSWA is that

workers and other persons should be given the highest level of protection against harm to their health, safety, and welfare from work risks as is reasonably practicable” (Worksafe, 2016), provided that the cost is not grossly disproportionate to eliminating or minimising the risk. Chipsealing using emulsified bitumen offers a means to eliminate many of the safety risks associated with cutback bitumen, thereby offering workers the highest level of protection at a cost that is proportional to the risk.

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APPENDIX 1 – Calculations for Table 6 Data.

The following data illustrates how estimates in Table 6 of improvements by using emulsion were made.

Table A.1: Reasons for Resealing in 2002/03 (adapted from Ball and Patrick, 2005) pro-rated to account for ‘undisclosed reasons’ and ‘multiple reasons’ that would include at least one of the 4 primary reasons listed herein.

Reason	Failure within 2 years		All Failures	
	Actual (%)	Pro-rated (%)	Actual (%)	Pro-rated (%)
Cracking	8	18.6	14	32.6
Low Texture	12	27.9	18	41.9
Low Friction	17	39.5	9	20.9
Scabbing	7	16.3	2	4.7
All Other Reasons	56	-	57	-

1. Use of emulsion is not expected to affect the frequency of the following failures modes:
 - Cracking
 - Low texture as a result of embedment
 - Low texture as a result of aggregate degradation and abrasion
 - Low friction as a result of aggregate polishing

2. Improvement in low texture caused by higher spray rates was estimated from data given by Bagshaw (2014) who observed that emulsions tend to be applied at a lower spray rates (4%) and it is assumed that the resulting texture improvement of 0.05 – 0.10 mm gives an increase in life of 5%. Table A.1 indicates that 41.9% of all failures are a result of flushing. Estimated overall life improvement is $41.9\% \times 5\% = 2.1\%$.

3. Low texture caused by embedment is usually a result of sealing over an already flushed surface and occurs early in life. Table A.1 estimates that 27.9% of seals fail early through low texture. From data in Towler et al (2010), it is estimated that 12% of seals achieve a life of only 2 years in 2002/03. Therefore, it is estimated that $27.9\% \times 12\% = 3.3\%$ of seals failure through embedment.

4. The overall failure rate for low texture as a result of end of life conditions is estimated by subtracting the failures attributed to embedment and high spray rates from the 41.9% pro-rated value in Table A.1. Estimated failure rate for low texture as a result of end of life is $41.9\% - (3.3\% + 2.1\%) = 36.5\%$. Gransberg and Carlisle (2005) observed that emulsion chipseals displayed superior performance and approximately 0.5mm better texture compared to hot bitumen seals. This is expected to increase chipseal life by 2 – 3 years. Bagshaw (2014) also observed that emulsified binders had cohesive strengths 20% higher than cutbacks, which will slow the rate of binder migration in the chipseal. Recognising that emulsion use will not affect low texture as a result of aggregate abrasion and degradation, and detritus build up, it is conservatively estimated that emulsions will give a 10% improvement in failure rates for low texture as a result of end of life. Estimated overall life improvement is $36.5\% \times 10\% = 3.7\%$.

5. Because Bagshaw (2014) observed that emulsified bitumen was 20% stronger than cutback and was applied at lower application rates, it is less likely to result in chip rollover or low friction caused by bleeding and binder tracking, which usually occurs in early life. Pro-rated early life low friction failures from Table A.1 is 39.5% of early life failures. Early life failures are estimated from Towler et al (2010) as being 12%. Assuming 20% of these failures are a result of binder tracking this gives an overall failure rate of $39.5\% \times 12\% \times 20\% = 0.95\%$. Assuming emulsion use reduces this by 50%, estimated overall life improvement is $0.95\% \times 50\% = 0.5\%$.

6. Low Friction caused by polishing is the difference between the pro-rated low friction failure rate from Table A.1 and the low friction caused by bledign and binder tracking: $20.9\% - 1.0\% = 19.9\%$.
7. Pro-rated scabbing failures from Table A.1 are 16.3% of early life failures. These early life, scabbing or stripping failures are usually caused by poor adhesion. Early life failures account for 12% of all failures (from Towler et al, 2010). Therefore $16.3\% \times 12\% = 2.0\%$ of all failures are estimated to be as a result of poor adhesion. Experience has indicated that emulsions can reduce stripping failures by 80%. The estimated overall life improvement for scabbing caused by early life poor adhesion is $16.3\% \times 12\% \times 80\% = 1.6\%$.
8. Scabbing caused by aged bitumen is estimated to be the difference between all pro-rated scabbing failures (4.7% from Table A.1) and those attributed to early life stripping: $4.7\% - 2.0\% = 2.7\%$. Zhao et al (2012) observed that emulsification improves bitumen durability. Assuming a 10% improvement in scabbing resistance as a result of improved durability, it is estimated that emulsification will result in an overall life improvement of $2.7\% \times 10\% = 0.3\%$.