1. INTRODUCTION

Many road, airport and port pavements are surfaced with asphalt. Asphalt surfaces typically require replacement every 10-20 years, depending on the environmental conditions, mixture design, traffic loading and performance requirements. The distresses that trigger asphalt resurfacing generally include rutting, cracking, moisture damage and ravelling [1]. However, when well designed and constructed asphalt surfaces perform as intended, rutting and moisture damage will not occur. In such cases, resurfacing is triggered by age cracking and ravelling as a result of binder oxidation and embrittlement over time, primarily due to exposure to oxygen, ultra-violet radiation and elevated temperatures [2].

To extend the period between resurfacing, many pavement owners preserve asphalt surfaces. Asphalt preservation encompasses a range of approaches including rejuvenation, enrichment and seal coating, also known as surface filling [3]. Different asphalt preservation approaches are more or less suited to different asphalt conditions, which generally reflect the stage in the bituminous binder ageing process of the surface.

The paper consolidates and reviews early life rejuvenation as an alternate approach to asphalt pavement surface preservation. Asphalt surfacing and resurfacing requirements are outlined and established approaches to asphalt preservation are described. Early life preservation products and the associated cost-effectiveness are considered. In addition, the practical limitations of this approach are explored before further research is recommended.

2. ASPHALT SURFACING AND RESURFACING

Asphalt has been a common road, airport and port pavement surfacing material for many decades. Although different asphalt mixtures are used by different jurisdictions and applications, asphalt for pavement surfacing is generally [4]:

1. A dense, open or gap graded aggregate skeleton with 15-20% voids in the aggregate.
2. With 7 mm to 14 mm maximum aggregate particle size.
3. Bound with an unmodified or modified bituminous binder.
4. With approximately 2-6% air voids after compaction in the field.

Asphalt is expensive compared to granular base course material and other bituminous surfacing options. It is also disruptive to construct, requiring lane or pavement closures, specialised production equipment and specialised paving and compaction equipment. Consequently, there is significant interest in extending the period between asphalt resurfacing and asphalt preservation provides an attractive option due to its low cost and minimal disruption, as well as the potential to increase the time between resurfacing, typically by two to five years, depending on the treatment type, the asphalt mixture characteristics and the properties of the bitumen in the asphalt.

Bitumen rheology and its oxidative ageing are complex and variable, reflecting the different sources of crude oil and the different refineries and refining processes used for its distillation [5]. One of the most accepted and digestible models for bitumen composition is the proportion of molecules classified as saturated, aromatics, resins and asphaltenes, also known as the saturate, asphaltene, resin and aromatic (SARA) fractions. Asphaltenes are large and hard molecules and bitumen ageing is often characterised as the conversion of aromatic molecules to asphaltene molecules, resulting in a harder and more brittle binder [6]. Slowing, ceasing or reversing the conversion of aromatic molecules to asphaltene molecules is key to reducing surfacing ageing effects and preserving asphalt surfaces.

3. ASPHALT PRESERVATION

Asphalt preservation is well established as a post-construction treatment applied to the surface of an asphalt wearing course to slow, reverse or remedy the effects of binder oxidation, in order to extend the period between resurfacing [6]. Most engineers understand the principle of early and repeated maintenance to avoid pavement rehabilitation being necessary (**Figure 1**). If the ‘surface’ is considered in place of the ‘pavement’, then ‘time’ dominates the horizontal axis and we consider the preventive treatment to be ‘preservation’ and for rehabilitation to represent ‘resurfacing’, then **Figure 1** applies to asphalt surface preservation.

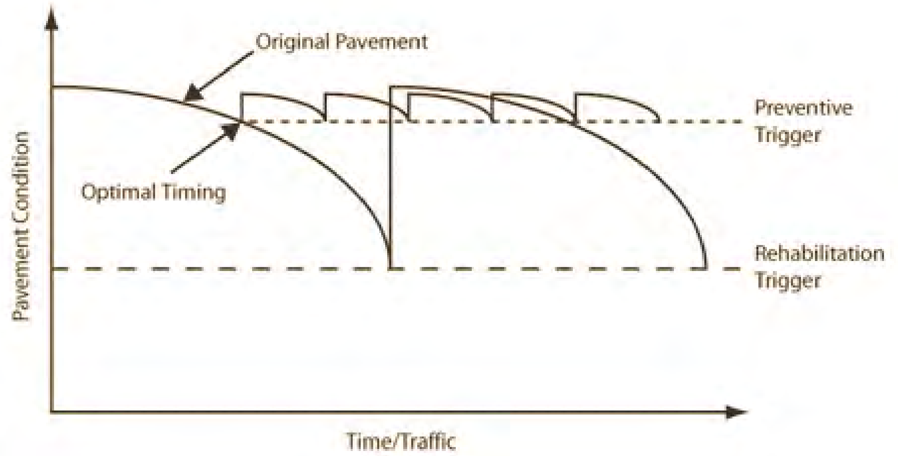


Figure 1: Example pavement maintenance optional timing

Once the benefit of asphalt preservation is established, it is necessary to select a type of preservation treatment. Importantly, the most appropriate treatment is dependent on the condition of the surface, with three treatment types generally available [3]:

1. **Rejuvenation**. Usually a maltene (or maltene-like) rich product without any significant bitumen content, intended to rejuvenate the binder by rebalancing the relative asphaltene-maltene content.
2. **Enrichment**. Usually a modified or unmodified bituminous product intended to replace the oxidised binder lost from the surface over time, as well as protecting the remaining binder from further oxidation by forming a sacrificial film over the asphalt surface.
3. **Surface filler**. Usually a modified bituminous product filled with sand or other mineral material intended to replace lost binder and fine aggregate from the asphalt surface, similar to an enrichment, but for more significantly eroded surfaces.

Rejuvenation treatments are unlikely to provide significant benefit if applied to significantly eroded surfaces. Similarly, a surface filler is likely to sit on top of a new and uneroded asphalt surface, adversely affecting the surface texture and potentially compromising the skid resistance available to vehicle tyres. Examples of surfaces suited to rejuvenation (**Figure 2**), enrichment (**Figure 3**) and surface filling (**Figure 4**) demonstrate the difference in surface condition expected at different points in the asphalt surface life cycle and the importance to applying a treatment that is appropriate for the surface condition.

Figure 2: Typical asphalt surface suited to rejuvenation.

Figure 3: Typical asphalt surface suited to enrichment.

Figure 4: Typical asphalt surface suited to surface filler.

It is well established that asphalt preservation must be planned and executed to not adversely impact the operational availability, nor the safety of the pavement. Operational availability is impacted if the preservation treatment sticks to vehicle tyres and tracks-off onto other pavement areas. Furthermore, pavement safety is impacted if the skid resistance is compromised by an inappropriate reduction in surface texture and/or surface friction.

4. EARLY LIFE PRESERVATION

Asphalt preservation by enrichment and surfacing filling are well established. However, early life preservation by true binder rejuvenation is a relatively new concept, although there are examples of enrichment products being claimed to also provide rejuvenating effects. However, these claims are questioned, are difficult to validate and these products generally have a high bituminous content, reducing their suitability to early life preservation. In contrast, maltene (or maltene-like) rich materials without significant bitumen content (**Table 1**) are available and are more suited to early life asphalt preservation. Due to its non-carcinogenic categorisation and high bio oil content, Biorestor is a favoured product and was the focus of this research.

Table 1. Common maltene (or maltene-like) rich, non-bituminous, rejuvenators

Product	Base	Nature	Health rating
Reclamite	Petroleum	Aqueous emulsion	1B (carcinogenic)
Biorestor	95% bio oils	Bio oil solvent	Not categorised
Replay	88% bio oils	Bio oil solvent	Not categorised

Early life rejuvenators are intended to be applied to unaged asphalt surfaces, typically within the first six months after surfacing and then repeated approximately every four years. To allow repeated applications of a generally unaged surface, the products must be applied at low residual application rates and must not fill the limited available surface texture. In theory, if effective products are repeatedly applied at the appropriate times, the asphalt surface is rejuvenated at a rate that matches the rate of oxidation and the surface does not age and erode over time. The theoretical result is an infinitely long surface life, at least from the perspective of age related erosion, ravelling and cracking. However, in practice, the effect of treatments on vehicle skid resistance impact the ability to treat surfaces indefinitely, which affects the efficacy of the products.

5. EFFECT ON SKID RESISTANCE

Vehicle skid resistance is provided by the friction between the tyre and the pavement surface and is created by the surface micro- and macro-textures. However, during wet weather the film of water between the vehicle tyre and the pavement surface prevents the tyre from interacting with the surface micro- and macro-textures, a phenomenon known as aquaplaning. The surface macro-texture allows the water film to escape from between the vehicle tyre and the pavement surface. Consequently, surface friction and surface texture are both important for wet weather skid resistance.

A self-wetting continuous surface friction measuring device was operated at 95 km/hr (method ASTM E-274) to evaluate two sections treated with Biorestor (0.1 L/m^2) compared to an untreated control section. Based on ten repetitions, the resulting skid numbers were approximately 20% lower for the treated sections compared to the untreated control section (**Table 2**). However, all results were consistent with levels of friction considered to be adequate.

Table 2. Statistics for ten runs of continuous friction measuring device (Skid Number)

Statistic	Untreated	Biorestor
Average	59.5	48.6
Std. Dev.	3.8	2.4
CoV	6.5%	5.0%
Number	10	10

Std. Dev. = Standard deviation and CoV = coefficient of variation.

In another study, three areas of a one week old asphalt surface were treated with Biorestor, one in the shade and one two in the sun, each at a different application rate. Sand patch testing was used to measure the surface texture (method ASTM E-965) of the various areas, as well as control areas, one year after treatment (**Table 3**). In all cases, the surface texture was 10-20% less for the treated areas, indicating either the filling of the surface interstices by the product or the reduction in surface erosion over a period of one year, as a result of the rejuvenating effect of the treatment. Because the surface texture was not measured immediately after the application, the two affects could not be separated.

Table 3. Sand patch surface texture (mm) measurement in different areas of the same surface

Area	Untreated	Biorestor
Shaded at 0.07 L/m^2	0.84	0.75
Sunny at 0.07 L/m^2	0.75	0.65
Sunny at 0.09 L/m^2	0.74	0.60

Furthermore, the immediate surface texture reduction due to the application was reported by ODOT [7] across six new surfaces on highways treated with Reclamite, Biorestor and Replay (**Table 4**). The reduction in surface texture associated with the treatment was comparable for all three products, with an average surface texture reduction of 0.05 mm (**Figure 5**). If the same reduction in surface texture occurred to the surfaces reported in **Table 3**, then approximately 50% of the measured surface texture reduction was associated with the initial application of the treatment and the other 50% was associated with a reduced rate of surface erosion.

Table 4. Sand patch surface texture (mm) measurements for six different highways

Treatment	Before treatment		After treatment	
	Average	Std. Dev.	Average	Std. Dev.
Untreated	0.26	0.10	Not applicable	
Biorestor	0.26	0.10	0.22	0.07
Replay	0.26	0.08	0.21	0.06
Reclamite	0.29	0.11	0.23	0.06

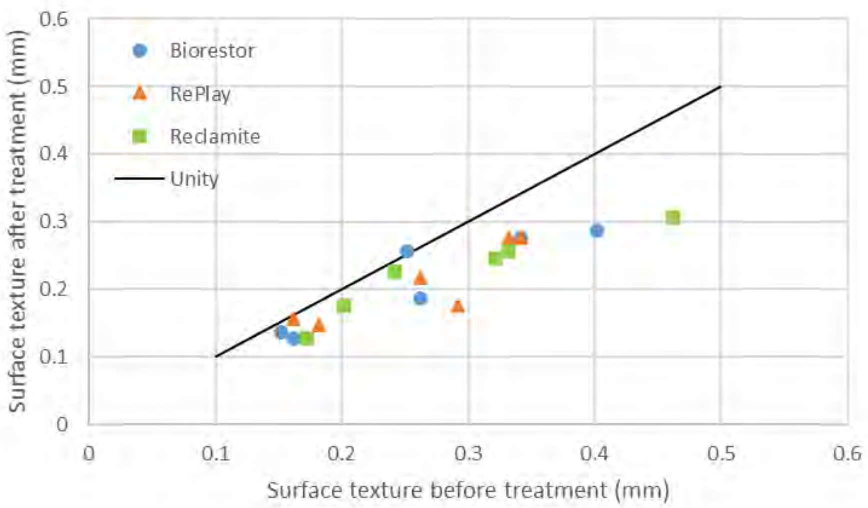


Figure 5: Effect of treatment on sand patch surface texture

The same investigation [7] measured friction by continuous friction measuring device (method ASTM E-274) before treatment, immediately after treatment drying, one day later, seven days after treatment and 30 days after treatment (**Figure 6**). The immediate effect was significant, with a 33-41% reduction in the skid number. However, the lost friction was substantially recovered by 30 days after application. Reclamite was associated with the greatest surface friction reduction, likely reflecting the emulsified nature of the product that tends to sit on the surface rather than penetrating like the non-emulsion based products.

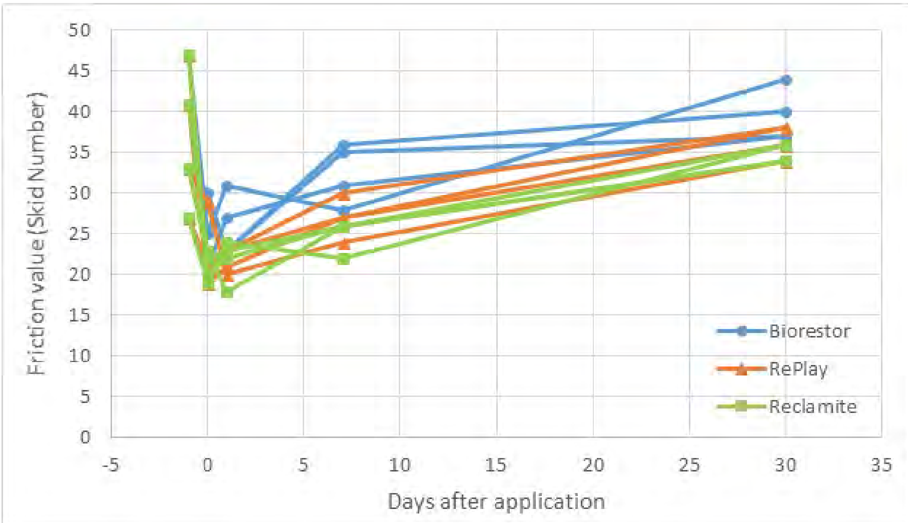


Figure 6: Effect of treatment on surface friction

In another study, an Australian airport applied Reclamite and Biorestor to a small area of six month old taxiway asphalt. The surface texture was measured by a laser texture meter before and after the treatment, at eight locations (**Table 5**). The effect of the treatments on surface texture was not statistically significant, with t-test p-value for the means of paired surface texture results of 0.10 and 0.34 for Biorestor and Reclamite, respectively. The average reduction in surface texture was 6% for Biorestor and 9% for Reclamite (**Figure 7**). Furthermore, the day after the application, it was observed that the Reclamite treatment had been tracked by aircraft tires, while the Biorestor had not (**Figure 8**). This again reflects the emulsified nature of Reclamite, which leaves it sitting on top of the surface, compared to Biorestor, which penetrated rapidly into the asphalt surface.

Table 5. Surface texture depth (mm) before and after treatment for the same surface

Statistic	Biorestor		Reclamite	
	Before	After	Before	After
Average	0.68	0.64	0.63	0.54
Std. Dev.	0.13	0.12	0.12	0.09
CoV	19.0%	18.2%	18.5%	16.6%
Number	8	8	8	8

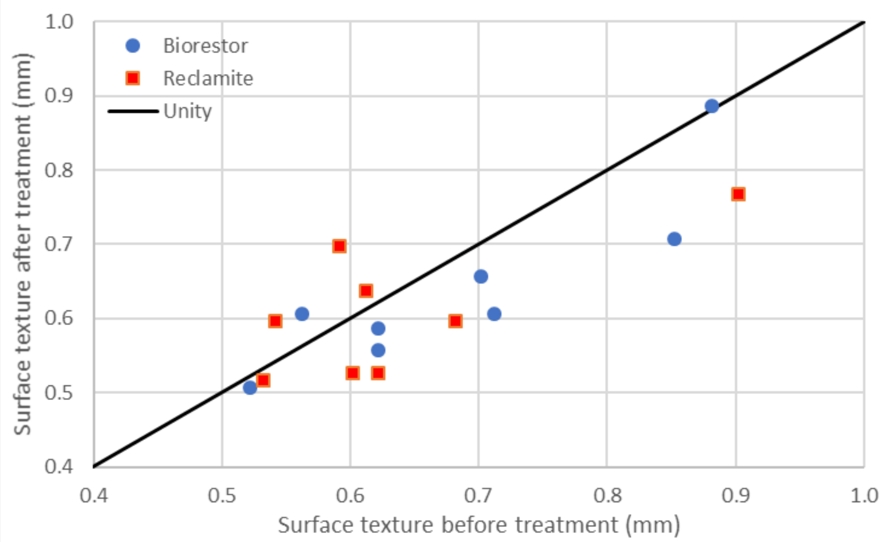


Figure 7: Effect of treatment on taxiway surface texture

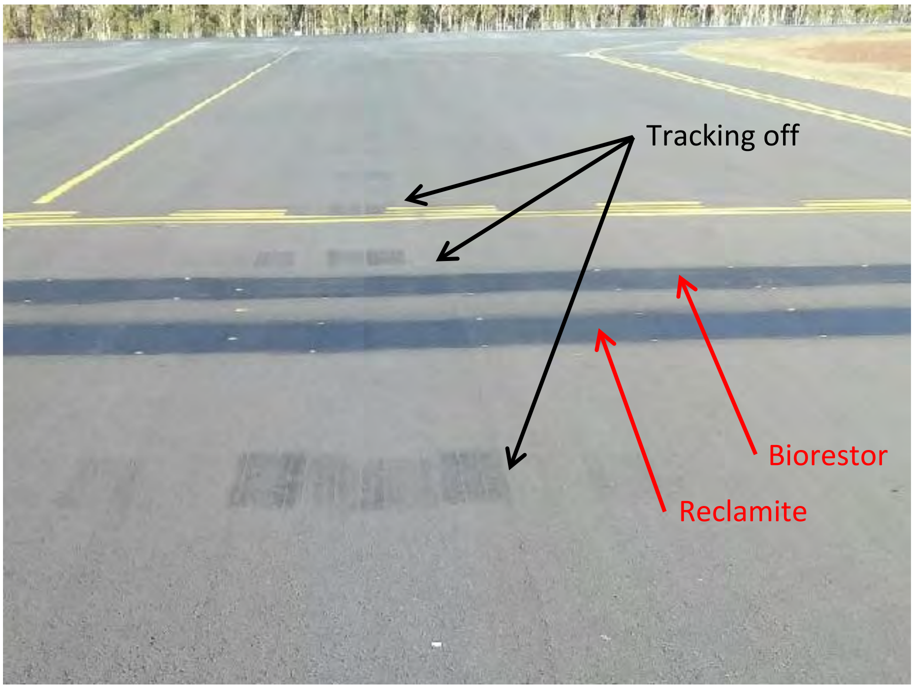


Figure 8: Tracking off of Reclamite 24 hours after application

6. EFFICACY AND EFFICIENCY

Even the minor operational impact of early life preservation treatment is only justified if the treatment is effective for the efficient extension of surface life. The efficacy of the treatment was assessed in the laboratory as well as in the field, while the efficiency was determined by the cost-effectiveness and is more challenging to quantify.

Asphalt samples were prepared in the laboratory by 50 blows of a Marshall hammer, producing approximately 8% air voids. Half the samples were treated with Biorestor (0.1 L/m^2) and the other half were used as controls. All samples were aged in an oven at 60°C for four months, intended to simulate five years of field ageing. The asphalt samples were tested for Marshall stability at seven, 30, 90 and 120 days of accelerated ageing. In the same investigation, samples of a 7 µm film of binder were prepared in pans and half exposed to an equivalent rate of Biorestor. The samples were tested for viscosity at 60°C and penetration at 25°C.

The asphalt sample results show continual hardening of both treated and untreated samples with accelerated ageing (**Figure 9**). The immediate reduction in Marshall stability immediately after treatment was largely recovered within 30 days and the subsequent rate of ageing was less than for the untreated samples. The binder testing returned similar results with penetration (**Figure 10**) increasing after treatment and then returning to a level slightly higher than for the untreated sample, while the viscosity (**Figure 11**) initially reduced but then increased at a rate approximately 50% of that of the untreated samples.

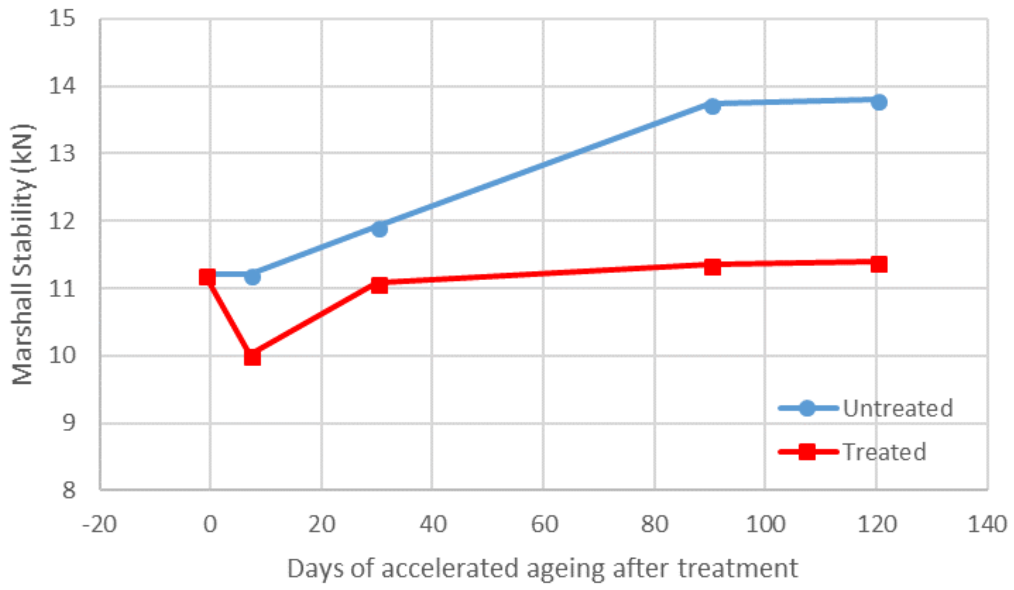


Figure 9: Asphalt Marshall stability evolution with accelerated ageing

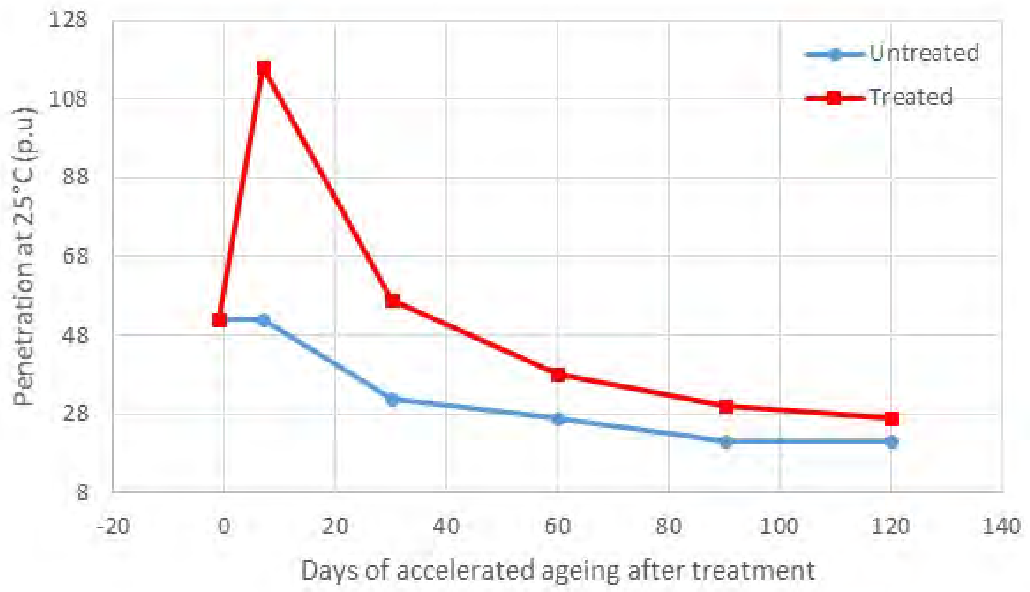


Figure 10: Binder penetration evolution with accelerated ageing

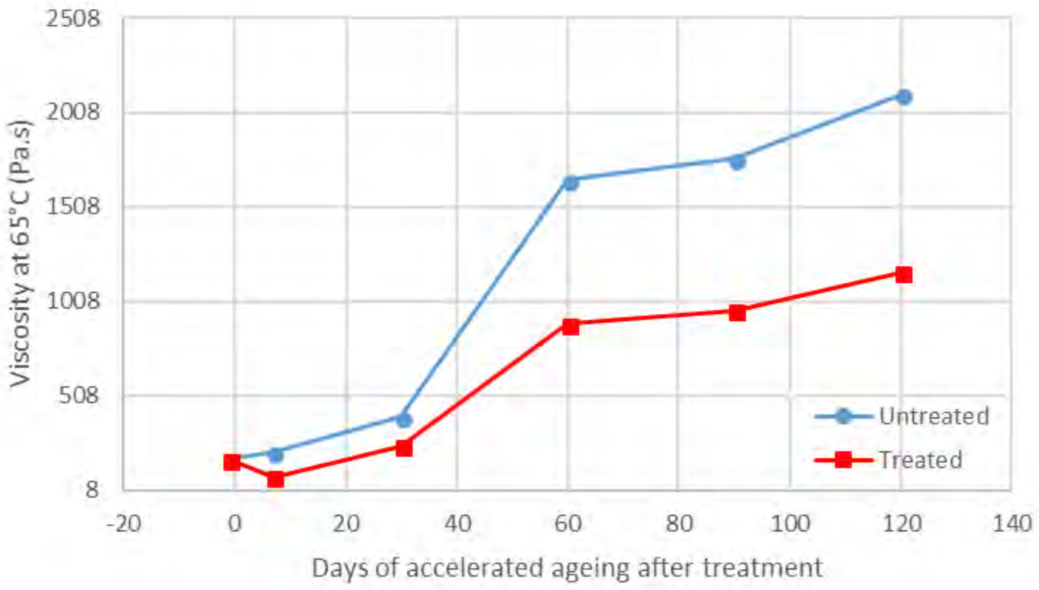


Figure 11: Binder viscosity evolution with accelerated ageing

In a controlled field study, the National Centre for Asphalt Technology (NCAT) applied seven different commercially available products for asphalt preservation to their test track surface in 2012 [8]. The products included early life rejuvenators as well as bitumen-based enrichments. Although the reported details are limited, based on the measured surface friction reduction and extracted binder rheological test results, the bio-based rejuvenators (eg. Biorestor and Replay) were assigned the highest performance classification [8].

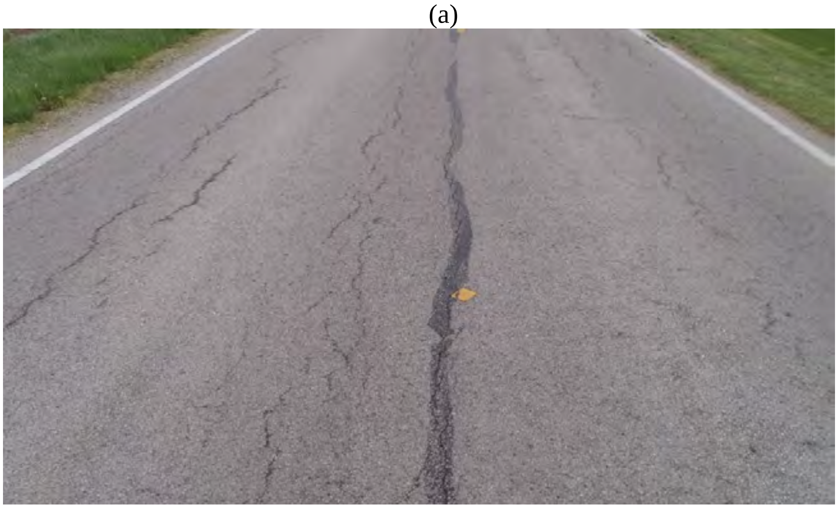
During field trials, treatment efficacy can be measured by the overall pavement condition or by specific indicators of binder oxidation and ageing. An homogenous and consistent section of road constructed in 2004 was partly treated with Biorestor shortly after construction. It was evaluated for Pavement Condition Index (PCI) in 2011 and again in 2014. The results (**Table 6**) show the practical efficacy of early-life preservation on cracking and ravelling, which are consistent with the visual condition of the treated and untreated sections (**Figure 12**).

Table 6. PCI for treated and untreated road surface

Year after construction	Untreated	Biorestor
0	100	100
7	64	75
11	53	61

In the highway investigation mentioned above [7] surface permeability was measured before and after the application of Biorestor, Reclamite and Replay. The emulsion-based Reclamite was less effective at reducing the surface permeability than the non-emulsified products (**Figure 13**). This reflects the reduced ability of products that are emulsified in water to penetrate into asphalt surfaces and is consistent with the tracking of the emulsified Reclamite product observed on an Australian airport taxiway (**Figure 4**). Because the aim of the treatment is to reduce the rate of oxidation and ageing of the bituminous binder, the use of permeability as an indicator of treatment efficacy is inappropriate. If an early life preservation treatment is effective, the bituminous binder near the surface of the asphalt will erode and ravel at a slower rate. Because erosion and ravelling unavoidably increase the surface texture, the differential surface texture increase over time is a more appropriate indicator of product efficacy and should be considered in the future.

(a)



(b)

Figure 12: Example (a) treated and (b) untreated surface in 2014

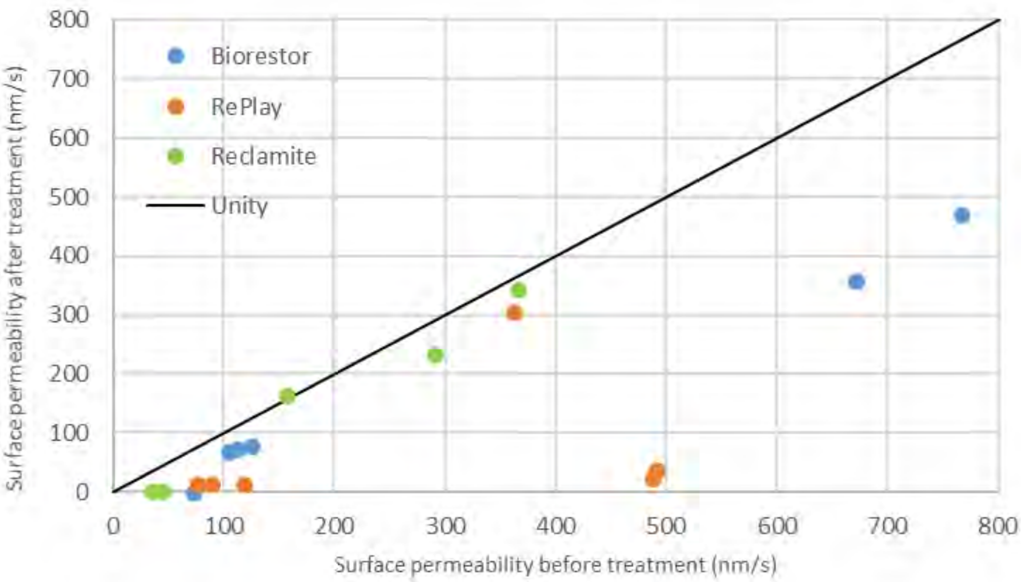


Figure 13: Effect of treatment of surface permeability

7. FURTHER RESEARCH

An initial review of the available information regarding the efficacy and efficiency of early life asphalt preservation treatment is generally positive with indications of softening of the oxidised binder, a reduced rate of surface texture evolution and improved surface condition over time. However, there is little objective information on which to quantify the cost-benefit of this approach to asphalt preservation. If these products are truly effective at reducing binder oxidation and ageing, the rate of surface texture increase with time must be reduced compared to otherwise comparable control sections in similar environments. Consequently, relative surface texture evolution is recommended as the basis for determining treatment efficacy and efficiency. Because the treatment partly fills the pre-treatment texture and because surface texture is inherently variable, multiple test locations within a nominally identical section of surface must be monitored and monitoring must include a pre-treatment measurement as well as measurement immediately after treatment application and curing. It is expected that five years of annual measurements will be required to demonstrate the effectiveness of the products and to estimate the increased life expectancy of the treated surface. The Australian airport taxiway trial is now twelve months old and is recommended to be continually monitored for this purpose.

8. SUMMARY AND CONCLUSION

Early life rejuvenation of asphalt surfaces provides a valuable alternate to the traditional enrichment or surface filling approaches to asphalt preservation. The early life rejuvenators have been demonstrated to reduce aged binder hardness, reduce the rate of surface erosion and slow the rate of pavement condition deterioration over time. At the same time, the light application rate and the absence of bitumen in these products means the effect on surface skid resistance is minimal and only short term. Of the various early life rejuvenators commonly used, the bio oil based products are environmentally friendly, safe to use and are effective rejuvenators. However, further work is required to quantify the long term reduction on surface erosion associated with different products and to understand the whole of life cycle cost effectiveness of early surface life rejuvenation, compared to mid life enrichment or late life surface filling.

REFERENCES

[1] White, G, 'State of the Art: Asphalt for Airport Pavement Surfacing', *International Journal of Pavement Research and Technology*, vol. 11, no. 1, pp. 77-98, 2018.

[2] Airey, GD, 'State of the art report on ageing test methods for bituminous pavement materials', *International Journal of Pavement Engineering*, vol. 4, no.3, pp. 165-176, 2003.

[3] White, G & Thompson, M, 'Australian airport asphalt surface treatments', *6th Eurasphalt & Eurobitume Congress*, Prague, Czech Republic, 1-3 June 2016.

[4] Shell, *The Shell Bitumen Handbook*, 6th edn, ICE Publishing, Italy, 2015.

[5] Lusueur, D, 'The colloidal structure of bitumen: consequences on the rheology and on the mechanisms bitumen rheology', *Advanced in Colloidal and Interface Science*, no. 145, pp. 42-82, 2009.

[6] Lu, X & Isacsson, U, 'Effect of ageing on bitumen chemistry and rheology', *Construction and Building Materials*, vol. 16, pp. 15-22, 2002.

[7] *Effectiveness of Asphalt Penetrating Sealers in Extending New Asphalt Pavement Life*, State Job Number 134702, Final Report, Ohio Department of Transportation, January 2017, <https://ohiomemory.org/digital/collection/p267401ccp2/id/14597/>, accessed 10 May 2019.

[8] *Evaluation of Rejuvenating Fog Seals*, National Center for Asphalt Technology, Auburn, Alabama, USA, <http://eng.auburn.edu/research/centers/ncat/newsroom/2019-spring/fogseals.html>, accessed 10 May 2019.