



WARRIP

WESTERN AUSTRALIAN ROAD RESEARCH
AND INNOVATION PROGRAM



Review of Future Pavement Technologies

2016-006

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Review of Future Pavement Technologies 2016-006

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REVIEW OF FUTURE PAVEMENT TECHNOLOGIES

SUMMARY

In late 2015, Main Roads Western Australia (MRWA) and ARRB Group Ltd (ARRB) signed an agreement which strategically targeted a commitment to research and development, technology transfer and capability development. Specifically, the agreement reflects a stronger commitment to building professional capability and implementing innovative practices that will achieve significant savings for MRWA in total road expenditure, and a higher rate of return through targeted research. A key component of the agreement is the establishment of the Western Australia Road Research and Innovation Program (WARRIP), a program of research that specifically targets the areas of road pavements and surfacings, asset management and structures.

In developing the WARRIP program, MRWA identified innovative practices that, if applied correctly, could potentially result in improved value-for-money outcomes for Western Australia (WA). However, in some cases, very little was known about these technologies. As a result, and before any in-depth research projects could be developed, feasibility studies were required to assess whether or not these technologies had potential application to WA, what benefits could be expected and what work would be required to demonstrate the practical viability of these technologies.

The purpose of this *Review of Future Pavement Technologies* project was to conduct preliminary evaluations of the potential applicability of solar power generating pavements, recycled plastic roads and the modification of pavement materials with nanotechnology. The focus of the review was assessment of the potential impact on the management of MRWA's infrastructure assets, and to make recommendations regarding future work that should be conducted that would allow MRWA to make more informed decisions regarding the widespread implementation of these technologies.

An overview of WARRIP and the background to the project is provided in Section 1. The initial technologies reviewed are reported independently as three discrete sections:

- the potential use of solar pavements to produce energy that could be used to power roadside facilities such as overhead lighting (Section 2)
- the potential use of recycled plastic in bituminous binders and modular pavement sections (Section 3)
- the potential use of nanotechnology to improve the properties of pavement materials, including asphalt and concrete (Section 4).

The collective findings and recommendations are presented at the end of the report (Section 5).

CONTENTS

REVIEW OF FUTURE PAVEMENT TECHNOLOGIES.....	I
1 BACKGROUND	1
1.1 Approach	2
1.2 Report Outline.....	2
2 SOLAR PAVEMENTS	3
2.1 Introduction.....	3
2.2 Literature Search	4
2.2.1 Household Solar Photovoltaic (PV) and Battery Capability.....	4
2.2.2 Solar Roadways.....	4
2.2.3 SolaRoad.....	5
2.2.4 Wattway Technology.....	5
2.2.5 Electric Vehicle Charging Stations.....	6
2.2.6 Solar Roadside Infrastructure.....	7
2.2.7 Road Pavement Solar Collector Systems.....	8
2.2.8 ‘Smart Highway’ Developments and Artistic Solar Initiatives	9
2.2.9 Conductive Electrical Vehicle Charging.....	9
2.3 Summary and Recommendations	10
2.4 References	11
3 RECYCLED PLASTIC ROADS	14
3.1 Introduction.....	14
3.2 Modified Bitumen	14
3.3 Processes.....	17
3.3.1 Dry Process	17
3.3.2 Wet Process.....	18
3.4 Types of Plastic	18
3.5 Current Recycling Practice in Australia	18
3.6 Current Recycling Practice in Western Australia	20
3.6.1 Market Survey of WA Plastic Recyclers.....	22
3.6.2 Recycling Processes.....	23
3.7 Cost of Virgin Plastic versus Recycled Plastic.....	23
3.8 Review of the Use of Recycled Plastics in Asphalt.....	24
3.9 Case Studies	26
3.9.1 India.....	26
3.9.2 Toner-modified Asphalt.....	27
3.9.3 Modular Pavements	28
3.9.4 Vancouver Roads.....	29
3.9.5 Western Australia.....	30
3.10 Summary and Recommendations	30
3.11 References	32
4 NANOTECHNOLOGY-MODIFIED MATERIALS	35
4.1 Introduction to Nanotechnology	35
4.2 Application of Nanotechnology in Pavement Engineering	35
4.2.1 Application of Nanotechnology in Asphalt Pavements.....	35

4.2.2	<i>Application of Nanotechnology in Concrete Pavements</i>	4
4.3	Summary and Recommendations	8
4.4	References	8
5	CONCLUSIONS AND RECOMMENDATIONS	11
5.1	Solar Pavements	11
5.2	Recycled Plastic Roads	11
5.3	Nanotechnology-Modified Materials	12
APPENDIX A	WESTERN AUSTRALIA ROAD RESEARCH AND INNOVATION PROGRAM (WARRIP)	14

TABLES

Table 3.1:	Examples of additives used in bitumen modification	16
Table 3.2:	Advantages and disadvantages of polymers used to modify bitumen.....	17
Table 3.3:	Plastic identification code summary (Plastics and Chemicals Industries Association 2011)	19
Table 3.4:	Price comparison: recycled plastic and commodity plastic	24
Table 4.1:	Definition of nanotechnology by different jurisdictions	36

FIGURES

Figure 2.1:	Artist's impression of how Solar Roadways may look.....	4
Figure 2.2:	SolaRoad bicycle path in Krommenie, North Holland	5
Figure 2.3:	Wattway Technology – applied directly on the existing road surface	6
Figure 2.4:	van Gogh bicycle path in Eindhoven	9
Figure 3.1:	Materials recycled in WA in 2014/15	20
Figure 3.2:	Recycled plastic by weight in WA in: a) 2013/14 and b) 2014/15	21
Figure 3.3:	Number of plastic reprocessing facilities in each state	21
Figure 3.4:	Conceptual model of Dutch modular pavement system	28
Figure 4.1:	Schematic focusing on areas of nanotechnology related to an asphalt pavement structure	1
Figure 4.2:	Nanoclay surface treatment	2
Figure 4.3:	Formation of intercalated and exfoliated nanocomposites from layered silicates (nanoclay) and polymers	2
Figure 4.4:	Examples of single-wall carbon nanotubes, armchair type, zig-zag type and helical type	3
Figure 4.5:	Soil and aggregates surface structure: (a) without (b) with ZycoSoil	4
Figure 4.6:	Sample data output from CNT pavement sensors.....	5
Figure 4.7:	Applications of self-cleaning concrete: (a) Dives in Misericordia Church (Rome, Italy), (b) Air France Headquarters Roissy – Charles de Gaulle International Airport (Paris, France)	6
Figure 4.8:	Schematic self-healing process using microencapsulation technique.....	6
Figure 4.9:	Nano-scale pictures of material a) without and b) with encapsulated healing agent	7
Figure 4.10:	Schematic process of self-healing in bio-concrete: a) water ingress through the cracks in the concrete; and b) active bacteria seals the cracks by producing limestone and protects the steel reinforcement from corrosion.....	7

1 BACKGROUND

Main Roads Western Australia (MRWA) identified future technologies during the development of the Western Australia Road Research and Innovation Program (WARRIP) that could result in cost-effective, value-for-money outcomes for WA. However, in some cases, very little was known about these technologies. Therefore, before any detailed research projects could be developed, feasibility studies were required to assess the applicability of these technologies for WA, what benefits could be expected and what work would be required to demonstrate the practical viability of these technologies.

The future technologies identified were:

1. the use of solar power generating pavements to produce energy that could be used to power roadside facilities such as overhead lighting or electric vehicle charging stations
2. the use of recycled plastic in bituminous binders and modular pavement sections, the types of plastics that may be relevant and their potential usage
3. the use of nanotechnology to improve the properties of pavement materials including asphalt and concrete, considering:
 - (a) the role it could play in increasing fatigue life through the self-healing of cracks
 - (b) the self-cleaning of pavement surfaces
 - (c) improvements in engineering characteristics, e.g. durability
 - (d) the identification of the structural composition of pavements.

The purpose of this project was to conduct preliminary evaluations of these three technologies and to make recommendations regarding future work that should be conducted that would allow MRWA to make more informed decisions regarding the implementation of these technologies in general practice.

Anticipated short-term benefits include:

- improved knowledge of the current state-of-the-art of these technologies including details of any current applications
- the development of more detailed research proposals to further investigate these technologies, or recommendations that no further action be taken, thus saving MRWA time and money on work that would not have any near-term benefits.

It is envisaged that following the review, and where potential benefits of the technologies were identified, MRWA would be in a position, following more detailed evaluation, to consider implementing one, or all, of these technologies. Technical outcomes, and associated benefits, could not be determined until more detailed follow-up work was conducted.

The outcomes of any follow-up projects would be incorporated into current MRWA specifications. Field trials may be required to assist in the evaluation of these technologies. Relevant applications of technology that would assist MRWA in the management of their road pavements would be incorporated into routine practice.

Brief details of WARRIP are presented in Appendix A.

1.1 Approach

The objectives of the project were pursued through:

1. literature reviews of current practice, both in Australia and overseas, including the identification of products that have been developed and/or are in use
2. evaluation of recent research that addressed these technologies, particularly their likely application into practice
3. assessment of the relevance of current practice, products and recent research to MRWA
4. recommendations regarding whether or not MRWA should investigate these technologies further and, if so, what research should be conducted to allow MRWA to make more informed decisions regarding implementation into practice.

1.2 Report Outline

This report presents the findings of the three preliminary investigations. They are reported independently as three discrete sections including:

- the potential use of solar pavements to produce energy that could be used to power roadside facilities such as overhead lighting – Section 2
- the potential use of recycled plastic in bituminous binders and modular pavement sections – Section 3
- the potential use of nanotechnology to improve the properties of pavement materials – Section 4.

The collective findings and recommendations are presented in Section 5 of this report.

2 SOLAR PAVEMENTS

2.1 Introduction

Australia has the highest average solar radiation per square kilometre of any continent (Infrastructure Australia 2016). Western Australia's climate is well-suited to embrace solar power to generate electricity that could be used to power roadside infrastructure, including adjacent buildings, or sold to the electrical grid – a potential revenue source.

This review of solar pavements supports MRWA's strategic direction *Keep WA Moving* released in 2016. One of its guiding principles is to 'recognise and cultivate innovations to take up challenges and stay ahead' (MRWA 2016).

Research and development into the ability of roads and roadside infrastructure to harness solar energy to power roadside lighting and adjacent buildings is currently being undertaken by businesses, academic institutions and research agencies around the world. Projects related to pavements include solar collector systems embedded into the pavement layers or solar collector panels placed over, or next to, the road. Novel projects include those that aim to charge electric cars while they are moving, solar-powered electric vehicle charging stations and 'smart roads' incorporating solar line-marking technology. Other solar advances include the incorporation of solar panels into roadside infrastructure such as lighting, pedestrian paths, highway noise walls and car park canopies.

A critical element in the generation of electricity from solar sources is the commercialisation of large-scale solar energy technologies that reduce investment costs and risks compared to smaller systems. As the global deployment of solar energy technology increases, the cost of this technology is likely to decrease. Other factors such as safety, durability, efficiency and the maintenance of these technologies must also be considered before large-scale government investment can be committed. Research, development and demonstration projects by both the public and private sectors will be crucial in accelerating the development and commercialisation of solar energy in Australia (Carson 2014).

Currently, the USA and the Netherlands are leading the way in terms of innovation and the adoption of solar road technology. This is being achieved through a combination of sales, policies and incentive programs, research and development, and education and public awareness programs (e.g. California Department of Transportation 2016).

The growth of the solar technology market can work in MRWA's favour as it strives to reduce costs and expand product options that can be incorporated into road infrastructure. Emerging technologies such as battery storage systems have the potential to alter patterns of energy demand over coming decades. When combined with other forms of solar energy generation, battery storage is likely to greatly improve the economic viability of renewable power generation.

This section of the report presents details of what solar road technologies are currently being trialled and/or implemented, what benefits they could provide to WA, the feasibility of implementing these technologies, and recommendations regarding what actions would be required to demonstrate the practical viability of these technologies.

2.2 Literature Search

2.2.1 Household Solar Photovoltaic (PV) and Battery Capability

The advent of greater energy storage capacity will enable households to sustain themselves over longer periods of low sunshine without requiring electricity from the grid. This will facilitate a smoothing of demand throughout the day – thus reducing the costs of providing electricity through the grid – and an extension of the life of existing network components. The ability of household systems to store more energy for transfer to the grid during peak periods would result in many localised networks becoming net contributors to the grid (Infrastructure Australia 2016).

2.2.2 Solar Roadways

The *Solar Roadways* project is being developed by Solar Roadways in Idaho, USA. The solar road can potentially integrate light emitting diodes (LEDs) which could provide lane-marking and thermal control elements. Theoretically, the generation of electricity would, over time, cover the cost of construction. Lamb et al. (2011) suggested that, if deployed widely, this could enable the development of a decentralised electricity grid.

Solar Roadways was awarded funding from the US Department of Transportation (US DoT) to develop and construct a prototype panel, which was completed in 2010. The concept involves a multi-layered, prefabricated panel with a transparent surface layer of glass, underlain by solar panels with embedded LED lighting. Beneath this is an electronics layer containing a microprocessor that controls the lighting, heating and communications and, finally, a base-plate layer that distributes power and data signals. The project was boosted by an 'Indiegogo' crowd-funding campaign that generated just over US\$2 million (Indiegogo 2014).

In November 2015, the US DoT provided further funding to conduct a series of tests on the products, including freeze/thaw cycling, moisture conditioning, shear and advanced loading. An artist's impression of how a solar road may look is shown in Figure 2.1.

An ongoing phase of the development of *Solar Roadways* is material research and development for the high-strength glass panels. According to Wired (2010), the estimated cost estimates of developing the glass was approximately US\$50 million just for the research alone; this did not include the solar technology and production cost.

The *Solar Roadways* technology has not been tested on public roadways and therefore its safety and durability in road applications is largely unknown. Another shortcoming of *Solar Roadways* is its very costly manufacturing process.

Figure 2.1: Artist's impression of how Solar Roadways may look



Source: Solar Roadways (2016).

2.2.3 *SolaRoad*

SolaRoad is another company that has developed novel solar pavement technology. It consists of prefabricated concrete slabs with a translucent top layer of tempered glass, under which are crystalline silicon solar cells. One of the technical challenges is that the top layer must not only be skid resistant but also strong enough if it is to deliver a safe road surface for vehicles. The slabs must be translucent if they are going to absorb sunlight but also must repel as much dirt as possible (*SolaRoad* n.d.).

The first *SolaRoad* project is a solar cycle path in Krommenie in North Holland, which was opened in November 2014 (Figure 2.2). During the first year, the 70-metre long *SolaRoad* section generated 9,800 kWh of energy – enough to provide a number of households with electricity for an entire year. Testing will continue over a three-year period (*SolaRoad* 2016).

Figure 2.2: *SolaRoad* bicycle path in Krommenie, North Holland



Source: *SolaRoad* (2014).

In April 2016, it was announced that the Director of the California Department of Transportation (Caltrans) had signed a letter of intent with the Vice-Governor of the Province of North Holland (Netherlands) to look at sustainable options for capturing solar energy in transportation infrastructure. In 2016, Caltrans and the province of North Holland signed a declaration of intent to explore sustainable options for solar energy in transportation infrastructure, including *SolaRoad* (*SolaRoad* 2016).

2.2.4 *Wattway Technology*

Wattway Technology, a subsidiary of the French civil engineering company Colas Group, has developed a photovoltaic (PV) cell-based solar collector that can be installed directly onto existing pavements, as shown in Figure 2.3. The product was developed in partnership with the French National Solar Energy Institute. The company claims that ‘a one-kilometre stretch of road paved with *Wattway* can provide the electricity to power public lighting in a city of 5000 inhabitants’ (*Wattway* 2016). The technology was piloted in 2015. *Wattway* claimed that testing confirmed adequate skid resistance and that it could bear all types of traffic including trucks; however, no test results are publicly available (*Wattway* 2016). The French Government recently announced a commitment to install 1000 km of *Wattway* solar roads over the next five years; if successful, this would provide enough solar energy to supply power to a town of 5 million people (*Guerrini* 2016).

Figure 2.3: Wattway Technology – applied directly on the existing road surface



Source: Wattway (2016).

In terms of predicted cost, the manufacturer quotes a figure of €6/Watt-peak (A\$8.85), which is likely to decrease over time as efficiencies in manufacturing and materials are realised (Wattway 2016). Yield is estimated at 15%, which is somewhat lower than conventional photovoltaic panels that typically deliver approximately 18-19%.

Wattway plans to install 100 implementation sites around the world by the end of 2017 and there are plans to enter the commercial manufacturing phase in 2018 (e-mail conversation with Wattway/Colas representative, 20 July 2016). It was noted that, whilst those investing in an implementation site should not expect a return on investment in terms of solar energy capture, the primary motivation would be corporate image and the promotion of green initiatives. Commercial-sized installations from 2018 onwards would be better positioned to generate a positive return on investment. The installation cost for each implementation site is estimated at €110 000 (A\$161 000).

MRWA could consider being an early adopter and applying for a Wattway implementation site. The site would be ideally placed at a high-visibility location subjected primarily to light vehicle traffic.

2.2.5 Electric Vehicle Charging Stations

The Queensland government has recently put forward a vision to deliver solar-powered electric vehicle fast-charging stations for 'drivers travelling up and down the length of Queensland'. Businesses located along the proposed solar road network, including fast food chains and petrol stations, could offer this service. Solar-powered electric vehicle chargers have already been installed at the University of Queensland's St Lucia and Gatton campuses (University of Queensland 2016).

It was announced in July 2015 that Queensland's first solar-powered fast-charging station would be built in Townsville, with the government offering small businesses a plan to help reduce costs (Queensland Government 2015). The charging stations would have the capacity for two cars to plug in at the same time, with the process taking 15 to 30 minutes. The RAC have initiated an electric vehicle charging station initiative, titled 'Electric Highways', where a number of charging

stations in WA's South West have been constructed to encourage consumer uptake of electric vehicles (RAC 2017).

MRWA has already trialled and implemented electric vehicle charging stations connected to the traditional electricity grid. However, there is potential for MRWA to trial solar-powered electric vehicle charging stations in the future.

2.2.6 Solar Roadside Infrastructure

In 2013, VicRoads released a *Renewable Energy Roadmap* that presented options for the take-up of renewable energy initiatives across the Victorian road network (VicRoads 2013). The Roadmap sets out the Government's plan to attract Victoria's share of renewable energy investment, including an outline of a set of initiatives aimed at accelerating the development of renewable energy projects in Victoria.

A potential revenue generator includes making land available to a utility for solar electricity generation and committing to purchase electricity from the utility. The *Renewable Energy Roadmap* claims that 'the use of renewable energy generating systems on the roadsides provides the opportunity for VicRoads to demonstrate its commitment to sustainability and to leverage its brand' (VicRoads 2013).

According to VicRoads (2013), the use of PV electricity generation for small roadside devices such as variable message signs and radio-operated help phones represents a mature and low-cost technology. PV is a cost-effective solution for such devices as it avoids the cost of providing power connections. An example of effective roadside solar infrastructure is the solar-powered flag lighting that has been installed at intersections along the Hume Freeway in New South Wales. According to VicRoads (2013), 'these installations have sufficient battery capacity to run for five nights without solar power'.

VicRoads (2013) also suggested that the use of PV panels to power street lighting represents a potential area for expansion of small-scale photovoltaics with pedestrian standard installations incorporating PV and LED lights at a cost of approximately \$8 000 each. These products are entirely self-contained, with the pole, PV panels, battery and controller in one unit. PV-powered lighting is likely to be cost-effective at locations away from the electricity network, where the cost of connecting to the grid is high.

Another option is to dedicate roadside land to the harvesting of energy from a series of roadside solar collector panels. An example of this is the *Oregon Solar Highway* roadside solar harvesting project which feeds electricity to the grid. The project was developed in 2008 through a public-private partnership between the Oregon Department of Transportation, Portland General Electric and US Bank (Oregon Department of Transportation 2016).

MRWA have successfully implemented solar powered lights on the state-controlled road network along the Brand Highway, Dongara and in the Derby road-train assembly area.

Barriers to the wider introduction of solar roadside technology include site-specific factors such as shadowing from trees or buildings, the need to provide safety clear zones, access for maintenance, and security issues.

Any decision by MRWA to further integrate solar technology into their roadside infrastructure would require a benefit-cost analysis that compares the marginal cost of constructing the infrastructure and the energy generating capacity compared to maintaining current practice.

2.2.7 Road Pavement Solar Collector Systems

Asphalt pavement surface temperatures can reach up to 70 °C. This not only causes environmental problems such as the heat island effect in cities, but also structural damage due to rutting or cracking as a result of thermal and loading cycles (Bobes-Jesus et al. 2013).

The solar thermal energy collected by an asphalt pavement can be harvested and controlled by circulating fluid via a pipe system (Rohini & Sheebah 2014) or by integrating air conduits into a pavement system to effectively create a pavement solar turbine (García & Partl 2014).

Pascual-Muñoz et al. (2013) described a new technology in which a multi-layered pavement with a highly-porous middle layer is used rather than a solar collector with an embedded pipe network. Excellent thermal efficiencies from 75% up to 95% were obtained in laboratory tests, with the level depending on the irradiance from the solar lamp, the porosity of the intermediate layer and the slope applied to the collector.

A laboratory study conducted by Chen, Wu and Jizhe (2011) showed that asphalt pavements could be cooled down by solar collection, thus effectively reducing the heat island effect in cities. However, the temperature gradients between the mat surface and the pipes could potentially compromise pavement durability.

According to Rohini and Sheebah (2014), the three major advantages of an asphalt solar collector are:

- if heat can be collected with reasonable efficiency and cost, then it can be considered as an energy source
- part of the stored heat can be utilised for heating the road during the winter to avoid ice formation
- the extraction of heat in the summer helps to reduce the development of thermal stresses and therefore rutting (Rohini & Sheebah 2014).

Many working parameters such as pipe diameter, pipe spacing, pipe depth, pipe arrangement, the type of conducting material, heat exchange fluid and flow rate can influence the performance of solar collectors. Whilst studies have attempted to analyse the effect of each of these parameters on small-scale asphalt mats, most of the studies considered the influence of the design variables individually. Bobes-Jesus et al. (2013) suggested that a comprehensive study of the combined influence of several design variables would be required if the uncertainty surrounding these factors was to be reduced.

A limitation of pavement solar collectors is that testing is yet to be conducted on larger samples subject to actual weather conditions, with testing to date only conducted in the laboratory on a small scale. Few investigations have considered how moisture, dust and silt build-up affects the performance of a solar collector. The impact of compaction and construction methods on the performance of a solar collector is also unknown.

It is recommended that further structural investigations of asphalt solar collectors be conducted, as the strength of a system is determined by the weakest component. Despite a reduction in thermal stresses through the inclusion of a pipe system, the addition of weak elements will affect the strength of the pavement and create an uneven stress distribution.

A comparison of efficiency, initial investment, maintenance costs, operational costs and life span of asphalt solar collectors versus conventional solar thermal collectors is considered necessary in

order to establish the advantages and disadvantages of these technologies, and hence the feasibility of introducing these technologies into WA.

2.2.8 'Smart Highway' Developments and Artistic Solar Initiatives

Smart Highway is an innovative concept developed by Heijmans NV, a European construction services company based in the Netherlands. It includes designs such as 'glow-in-the-dark lining', 'dynamic paint', 'interactive light' and 'electric priority lane'. According to Heijmans NV (n.d.a.), 'these initiatives work towards making roads more sustainable and interactive through the harvesting of solar energy and the incorporation of smart lighting and traffic signs that adapt to road conditions'.

The 600 metre long *van Gogh-Roosegaarde* bicycle path in Eindhoven is an illuminated pathway developed by artist Daan Roosegaarde (Figure 2.4). It consists of thousands of light-emitting solar stones – a design that is inspired by Vincent van Gogh's work 'Starry night'. The aesthetic bicycle path serves as a tourist attraction, as well as providing lighting for the pathway in a sustainable manner without disturbing the existing ecology (Heijmans NV n.d.a).

Figure 2.4: van Gogh bicycle path in Eindhoven



Source: Inhabitat (2016).

2.2.9 Conductive Electrical Vehicle Charging

Roads incorporating solar panels could help make electric vehicles more practical by providing electric charging by induction.

In 2013, the local government authority responsible for the Greater London transport system, Transport for London (TfL) partnered with the International Association of Public Transport to begin trialling conductive vehicle charging for a bus route in London as part of an effort to reduce urban bus emissions (TfL n.d. & UITP n.d.). As part of their long-term vision, the creators of *Solar Roadways* aim to allow for electric vehicle inductive charging as vehicles move along the road at highway speeds (Solar Roadways 2016).

In 2015, the British government agency, Highways England announced that it had committed to fund testing of magnetic induction technology that allows for electric vehicle charging while driving (Highways England & Andrew Jones 2015). The trial is currently restricted to non-public roads and follows the completion of the feasibility study commissioned by Highways England into 'dynamic

wireless power transfer' technologies (Highways England & Andrew Jones 2015). The idea is that cables beneath the road pavement surface generate electromagnetic fields that can be picked up by a receiver car and transformed into electricity. There is potential for solar technology to be incorporated into this concept.

2.3 Summary and Recommendations

This section of the report has examined the potential for introduction of solar pavements along the WA state-controlled road network. As a result of this study, the following comments are offered:

1. WA's climate is well-suited to embrace solar power to generate electricity which could be used to power roadside infrastructure, including adjacent buildings, or sold to the electrical grid – a potential revenue source. However, whilst the WA road network is vast, the majority of the sealed road network, particularly in rural areas, is composed of a sprayed sealed surfacing rather than an asphalt surfacing. No studies have been reported in the literature which examined the potential use of solar energy in pavements consisting of a sprayed seal surfacing.
2. In terms of solar road collector technology installed in the pavement:
 - (a) It is not recommended that MRWA deploy large-scale pavement solar road collector technology at this stage. The technology is very immature and potentially very expensive. The current status of the technology poses significant risks to MRWA, such as compromising road safety or pavement durability, or simply failing to generate as much energy as expected.
 - (b) Before solar road technology could be introduced into asphalt pavements in urban areas, it would have to be demonstrated that the technology provided at least equal levels of skid resistance, strength and durability compared to a traditional asphalt pavement when subject to high levels of dynamic loading, including turning and braking forces. Whilst bitumen is soft and flexible, solar road technology often involves the use of a tempered glass top layer which may fatigue crack under loading. The safety consequences of this type of material failure in a road setting are not well understood.
 - (c) In addition, roads will typically be covered in a layer of dirt and/or silt. The efficiency and effectiveness of the solar collector will likely be compromised unless innovative maintenance or self-cleaning solutions are developed. A solar panel placed in the surface of a road is also likely to yield less power than infrastructure placed at the roadside, as the solar panels must lay flat rather than being angled to take optimal advantage of the movement of the sun throughout the day.
 - (d) Testing of solar road panels and pavement collectors would need to be conducted on a range of pavements subject to actual weather and loading conditions since most of the studies reviewed were conducted in the laboratory and the sample size was small. Safety and operational concerns, including repair and maintenance work, would also need to be explored further.
 - (e) Another disadvantage of this technology is that it is more expensive to build road pavements with solar technology compared to standard methods. Similarly, the cost of repairing the solar panels is likely to be higher than the cost of repairing an asphalt pavement. The literature review suggests that the scale of infrastructure required for trials of solar road collectors, let alone widespread implementation, would require extensive investment with no guarantee of financial return for many years.
 - (f) However, MRWA could consider being an early adopter and applying for a Wattway implementation site. The site would be ideally placed at a high-visibility location

subjected primarily to light vehicle traffic. This would allow issues such as power generation and skid resistance to be evaluated.

3. The integration of solar technology into roadside infrastructure such as lighting and noise barriers is already widely adopted within Australia and across the world. It has been shown to be an effective means of generating energy and often presents a mature and low-cost option. The wider use of this technology could be considered for WA including, for example, the powering of advance warning signs in remote areas.
4. One feature of solar panel collector technology currently in the prototype phase is the potential to charge electric vehicles. To be effective, this would require enough solar highways and electric cars fitted with equipment to enable them to be charged from electric induction plates on the road. Whilst electric vehicle induction charging technology already exists for stationary vehicles and buses, and research is looking into ways to charge vehicles with electric induction while they are moving, no solution has yet been documented in the literature.
5. At the policy level, MRWA could consider expanding its use of solar roadside infrastructure to demonstrate its commitment to sustainability and green energy, as well as potentially cutting operating costs.
 - (a) To this end, it is recommended that a 'solar road development alliance' be formed and a proposal for additional funding to pursue solar pavement technology in WA be drafted. Such an alliance should ideally include tertiary and industry partners.
 - (b) MRWA could look to develop a document similar to the VicRoads *Renewable Energy Roadmap* that would provide guidance to MRWA's planners and engineers regarding the options for greater uptake of renewable energy generation.
6. In terms of solar-powered electric vehicle charging stations, there is a potential opportunity for industry collaboration to develop this service. MRWA could work with the RAC and industry partners to further this technology and engage business partners. This could benefit MRWA as a sustainable initiative supporting the practical use of electrical vehicles for road users.
7. Opportunities for solar road technology initiatives that may feature as a tourist attraction and boost the economy, such as the Van Gogh Roosegaarde bicycle path, could be explored in association with local governments.

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3 RECYCLED PLASTIC ROADS

3.1 Introduction

Polymers have been used as modifiers to improve the performance of bituminous binders (e.g. stiffness, durability) for decades. The use of recycled polymers, on the other hand, is not well-established. However, they may have the potential to provide equivalent performance improvement, while at the same time delivering environmental benefits.

With so much plastic waste entering landfill each year, and the increasing costs of petroleum, the recycling of plastics has become a major sustainability issue. The energy required to recover and recycle plastic is considerably less than the energy required for production from raw materials (EPA 1990). However, recycled plastics are still vastly underutilised in WA. MRWA was therefore keen to investigate whether this manufactured resource could effectively be employed in civil engineering projects, in particular as a bitumen modifier in road applications.

The purpose of this review was to investigate the current usage of recycled plastic in roads around the world, the benefits of utilising these technologies and the feasibility of implementing these technologies in WA. The review supports MRWA's guiding principle of adopting 'sustainable business practices that achieve social and environmental benefits' (MRWA 2016).

3.2 Modified Bitumen

Polymer modified binders (PMBs) are bituminous binders, the properties of which have been improved by the addition of polymers or other chemicals. Small percentages of polymers are added to the binder to improve the resistance to deformation and cracking, the properties at service temperatures, and the response to repetitive loading (Austroads 2013).

As there are different types of failure that may occur, there is a wide variety of PMBs, each designed for a particular application. A particular polymer may increase the strength of a binder but the same polymer may make the binder less flexible. As such, PMBs must be selected carefully to provide optimal performance for specific applications.

According to Hunter, Self and Read (2015), a bitumen modifier must:

- be readily available
- be cost effective
- blend with bitumen
- resist degradation at mixing temperatures
- improve the softening point of bitumen
- improve binder cohesion properties
- maintain satisfactory storage properties
- not require the use of uncommon equipment.

According to Austroads (2014) an asphalt binder should have:

- low stiffness at construction temperatures
- high stiffness at in-service temperatures
- low stiffness at low in-service temperatures
- excellent long-term durability.

The polymers most commonly used for bitumen modification are classed as thermoplastic elastomers, plastomers and rubbers:

- *Thermoplastic elastomers* provide flexibility to the bitumen, resulting in improved resistance to cracking and permanent deformation. Elastomers influence the softening point properties of the PMB. The most commonly used elastomer in Australia is styrene-butadiene-styrene (SBS).
- *Plastomers* provide a more rigid binder which provides good deformation resistance under heavy loads; however, they may be prone to cracking due to a lack of flexibility. The most common plastomer used in Australia is ethylene vinyl acetate (EVA).
- *Rubbers* behave in a similar manner to elastomers in that they enhance the elastic properties of the bitumen. Particle size and shape are very important factors when adding rubber polymers to bitumen, as is the volumetric concentration of the rubber.

Some common examples of each type of modifier are listed in Table 3.1.

Table 3.1: Examples of additives used in bitumen modification

Type of modifier	Example	Abbreviation
Thermoplastic elastomers	Styrene-butadiene elastomer	SBE
	Styrene-butadiene-styrene elastomer (linear or radial)	SBS
	Styrene-butadiene rubber	SBR
	Styrene-isoprene-styrene elastomer	SIS
	Styrene-ethylene-butadiene-styrene elastomer	SEBS
	Ethylene-propylene-diene terpolymer	EPDM
	Isobutene-isoprene random copolymer	IIR
	Polysobutene	PIB
	Polybutadiene	PBD
	Polyisoprene	PI
Thermoplastic polymers (plastomers)	Ethylene-vinyl acetate	EVA
	Ethylene-methyl acrylate	EMA
	Ethylene-butyl acrylate	EBA
	Atactic polypropylene	APP
	Polyethylene	PE
	Polypropylene	PP
	Polyvinyl chloride	PVC
	Polystyrene	PS
Thermosetting polymers	Epoxy resin	–
	Polyurethane resin	PU
	Acrylic resin	–
	Phenolic resin	–
Rubbers	Natural rubber	NR
	Crumb rubber (manufactured using used tyres)	CR

Source: Based on Table 8.1 of the Shell Bitumen Handbook 6th edition (Hunter et al. 2015).

Each type of polymer has its own advantages and disadvantages. There are normally certain types of polymers more appropriate for different applications such as one for high traffic volumes, or another for high strength due to large truck loading. A summary of the advantages and disadvantages of some well-known polymer modifiers is presented in Table 3.2.

Table 3.2: Advantages and disadvantages of polymers used to modify bitumen

Modifier type	Polymer	Advantages	Disadvantages
Elastomer	Styrene–butadiene block copolymer (SBS)	Higher flexibility at low temperatures Strength and very good elasticity Increase in rutting resistance Better flow and deformation resistance at high temperatures	High cost Reduced penetration resistance Higher viscosity at layout temperatures Resistance to heat and to oxidation is lower than that of polyethylene (due to the presence of double bonds in the main chain)
	Styrene–isoprene block copolymer (SIS)	Higher aging resistance Improved adhesion to aggregate Good blend stability, when used in low proportion	To be suitable for SBS blends, a bitumen with a high aromatic and a low asphaltene content is required
Plastomer	Polyethylene (PE)	High temperature resistance Aging resistance High modulus Low cost	Hard to disperse in the bitumen Instability problems High polymer contents are required to achieve better properties No elastic recovery
	Polypropylene (PP)	No marked increase in viscosity even though high amounts of polymer are necessary (for ease of handling and layout) Low penetration Widens the plasticity range and improves the binder's load resistance	Separation problems No improvement in elasticity or mechanical properties Low thermal fatigue cracking resistance
	PVC	Lower cracking PVC disposal	Acts mostly as filler

Source: Based on Becker, Mendez and Rodriguez (2001).

3.3 Processes

There are two methods used to add polymer modifiers to the asphalt mix: addition of solid additives directly to the mix (dry process), and modification of the binder (wet process).

3.3.1 Dry Process

In the dry process, solid modifiers are added directly to hot aggregate prior to the addition of the binder. An extended period of mixing follows to ensure sufficient mixing has occurred. This method allows high concentrations of modifier to be added to the mix for increased elasticity in the asphalt and improved adhesion to the aggregate. The use of the dry process is mainly limited to the use of crumb rubber modifiers.

3.3.2 *Wet Process*

During the wet process, the modifier is mixed with the binder prior to addition to the aggregate. This may take place on- or off-site, the latter requiring good storage and transportation facilities. The wet process is usually used due to its better overall performance. However, the process has an upper limit in terms of how much modifier can be added. The wet process is the more common of the two methods.

3.4 Types of Plastic

Plastics are categorised using a Plastics Identification Code (PIC), represented by a number in a triangle (Clean Up The World (CUTW) 2016). The PIC identifies seven types of materials typically used in the plastic industry. A summary of the plastic types, their general properties and their virgin and recycled applications is presented in Table 3.3.

The plastics in categories 1, 2 and 3 are generally recycled whereas the plastics in categories 4-7 are not; this is often due to the difficulty and expense associated with the recycling process.

3.5 Current Recycling Practice in Australia

According to the Plastic and Chemical Industry Association (PACIA) annual national plastics recycling survey (Thompson 2011), Australia is now sending more than 1 million tonnes of plastic waste to landfill each year. This figure is projected to rise to at least 1.5 million tonnes by 2030, due to increasing plastics consumption and an increasing proportion of durable plastic goods entering the waste stream. It is important to note that data regarding the quantity of the various plastic types entering landfill in Australia is currently not available; as a result, it is difficult to assess the proportion of recyclable plastic that is sent to landfill.

This domestic consumption figure does not include imported plastics in the form of finished goods or packaging, as there is no data on this volume. However, if Australian per capita plastics consumption is similar to that of Western Europe (i.e. 99 kg per person in 2005 according to the European Plastics Industry Association (Plastics Europe)), then it is estimated that an additional 500 000 tonnes of plastics per year are imported in this form. This would bring total consumption, including imported plastic goods, to about 2.5 million tonnes by 2030.

It is estimated that about 15% of the consumption goes into long-term applications such as pipes, window frames and electrical cable insulation; these applications will have a life of at least 30 years and possibly more than 100 years. Hence, only a small amount of this material currently enters the waste stream, mainly through demolition activity. The remaining 45% goes into applications classed as 'durables'. This includes plastics used in cars, appliances, furniture, TVs, computers, mobile phones, carpets, textiles, crates and pallets. Durables have an estimated life of between two and 30 years. Durables have not been a major part of the waste stream because their entry lags behind the consumption curve. However, assuming that they enter the waste stream at an even rate from the second year to the thirtieth year after manufacture, then they will reach the same volume in the waste stream by 2030 as packaging.

If the estimate of 500 000 tonnes per year of imported plastic goods is included (and scaled to local consumption before and in 2008), then the total amount of plastic waste entering the waste stream in 2008 was estimated to be 1.3 million tonnes. However, not all of this goes to landfill; the PACIA survey found that 282 000 tonnes of plastic were recycled in that year. Subtracting this figure still leaves over 1 million tonnes going to landfill and the trend is clearly upward.

Table 3.3: Plastic identification code summary (Plastics and Chemicals Industries Association 2011)

Type of plastic			Properties including specific gravity	Virgin applications	Recycled applications: MAJOR USE Minor use
1	PET	Polyethylene terephthalate (PET)	Clear, tough, solvent resistant Used for rigid sheets and fibres Softens: 85 °C; SG = 1.38	Carbonated soft drink bottles, fruit juice bottles, pillow and sleeping bag filling, textile fibres	BEVERAGE BOTTLES Clothing, geotextiles, bottles for detergents, etc. Laminated sheets, clear packaging film, carpet fibres
2	HDPE	High density polyethylene (HDPE)	Hard to semi-flexible, waxy surface, opaque Softens: 135 °C; SG = 0.96	Crinkly shopping bags, freezer bags, milk bottles, bleach bottles, buckets, rigid agricultural pipe, milk crates	FILM, BLOW-MOULDED CONTAINERS Agricultural pipes, pallets, bins for compost and kerbside collections, extruded sheet, crates, garden edging, household bags, oil containers, pallets
3	PVC	Unplasticised polyvinyl chloride (UPVC)	Hard, rigid, can be clear, can be solvent welded Softens: 70-100 °C; SG = 1.40	Electrical conduit, plumbing pipes and fittings, blister packs, clear cordial and fruit juice bottles	PIPE, FLOORING Pipe and hose fittings, garden hoses, electrical conduits, shoes, road cone bases, drainage pipes, electrical conduits & ducting, detergent bottles
		Plasticised polyvinyl chloride (PPVC)	Flexible, clear, elastic, can be solvent welded Softens: 70–100 °C; SG = 1.35	Garden hoses, shoe soles, cable sheathing, blood bags and tubing, watch straps, rain wear	
4	LDPE	Low density polyethylene (LDPE) Linear: LLDPE	Soft, flexible, waxy surface; translucent, withstands solvents Softens: 115 °C; SG = 0.92	Garbage bags, squeeze bottles, black irrigation tubes, silage and mulch films, garbage bins	FILMS: BUILDERS, CONCRETE LINING and BAGS Agricultural pipes, nursery & other films
5	PP	Polypropylene (PP)	Hard, flexible, translucent (can be transparent); wide property range for many applications, good chemical resistance Softens: 165 °C; SG = 0.90	Film, carpet fibre, appliances, automotive, toys, housewares, crates, palls, bottles, caps and closures, furniture, rigid packaging	CRATES, BOXES, PLANT POTS Compost bins, garden edging, irrigation fittings, building panels
6	PS	Polystyrene (PS)	Clear, glassy, rigid, brittle, opaque semi tough, melts at 95 °C; affected by fats and solvents Softens: 90 °C; SG = 1.06	Refrigerator bins & crispers, stationery accessories, coat hangers, medical disposables Meat & poultry trays, yoghurt & dairy containers, vending cups	INDUSTRIAL PACKAGING, COAT HANGERS, CONCRETE REINFORCING CHAIRS Moulded products, coat hangers, office accessories, spools, rulers, video cases and printer cartridges
		Expanded polystyrene (EPS)	Foamed, light weight, energy absorbing, heat insulating Softens: 90 °C; SG = 0.90–0.93	Drinking cups, meat trays, clamshells, panel insulation, produce boxes, protective packaging for fragile items	SYNTHETIC TIMBER Picture frame mouldings, under slab void pods for buildings
7	Other	OTHER : Includes all other resins and multi materials (laminates) acrylonitrile butadiene styrene (ABS), acrylic, nylon, polyurethane (PU), polycarbonates (PC) and phenolics		Automotive, aircraft and boating, furniture, electrical and medical parts	AGRICULTURAL PIPING Furniture fittings, wheels and castors, fence posts, pallets, outdoor furniture and marine structures

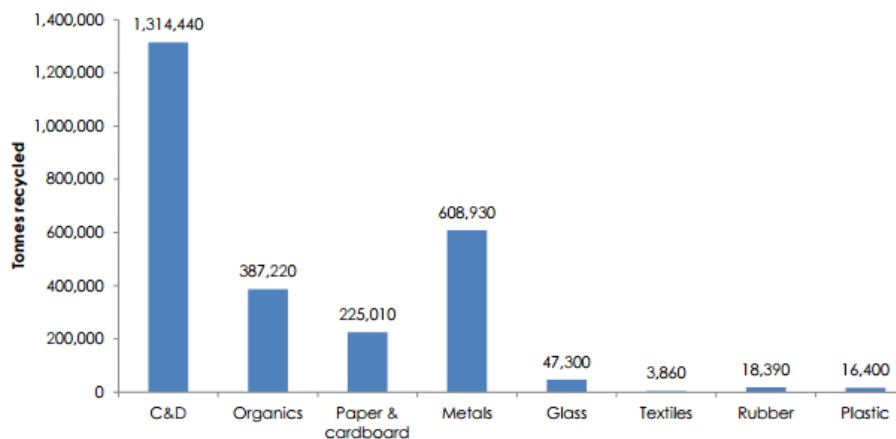
Of the material that was reprocessed in Australia, 89% was sold to local manufacturers, with the remaining 11% sold directly to overseas markets (A'Vard & Allan 2014). In Australia, recycled plastics are mostly used for the production of pipes, flooring, synthetic timber, industrial packaging and crates.

Further information is available at: <http://sustainabilitymatters.net.au/content/sustainability/article/the-rising-tide-of-plastics-in-landfill-211515950#ixzz4BboCTUNq>.

3.6 Current Recycling Practice in Western Australia

According to Perryman and Green (2015), 2 605 460 tonnes of material were recycled in WA in 2013/14 whilst 2 622 090 tonnes were recycled in WA in 2014/15 (Waste Authority WA 2016a). Of this, plastics accounted for only 13 200 tonnes (or approximately 0.5%) and 16 400 tonnes (approximately 0.6%) in 2013/14 and 2014/15 respectively. The breakdown for the materials recycled in WA in 2014/15 is presented in Figure 3.1.

Figure 3.1: Materials recycled in WA in 2014/15

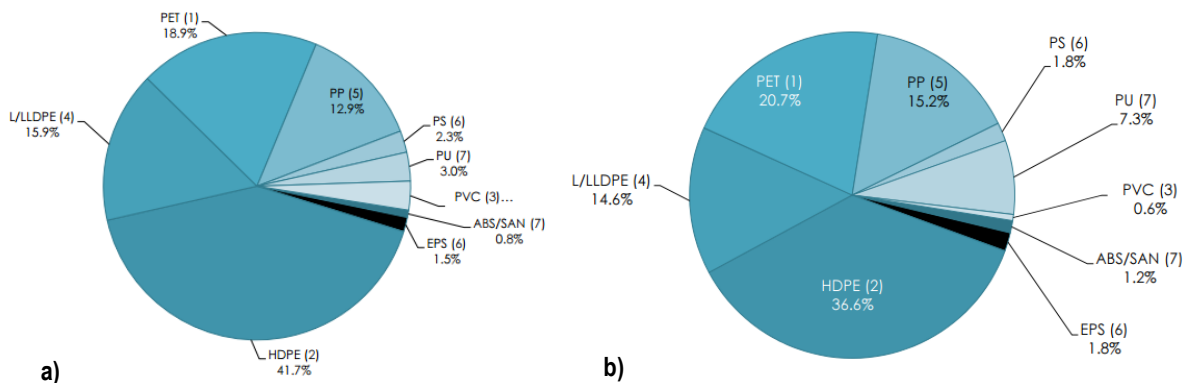


Source: Perryman and Green (2016), p.v.

According to A'Vard and Allan (2014), approximately 168 200 tonnes of plastic was consumed in WA in 2013/14. However, the amount of plastic recycled was only 8% of the amount of plastic consumed. This is very low compared to 18.1% in NSW and 20.9% in South Australia. This suggests that there is potential for increasing the amount of plastic recycling in WA.

The proportion of plastic recycled in WA during 2013/14 and 2014/15 according to type is shown in Figure 3.2. It can be seen from the Figure that the most common type of plastic recycled was HDPE, comprising 36.6% of the total. This indicates that, although HDPE as a proportion of the total recycled plastics decreased from 2013/14 (41.7%), there was a slight increase in the total plastic recycled. The three other major plastic types recycled were L/LLDPE, PET and PP. The remaining plastics contributed only 10.6% of the total plastics recycled in WA during 2013/14 and 12.7% in 2014/15 respectively (Waste Authority WA 2016a).

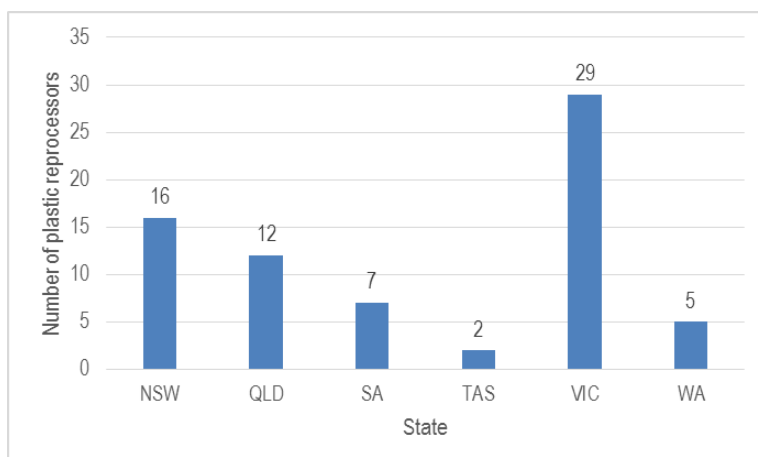
Figure 3.2: Recycled plastic by weight in WA in: a) 2013/14 and b) 2014/15



Source: Perryman and Green (2015), p. 35 & Perryman and Green (2016), p. 26.

According to the 2013/14 National Plastics Recycling Survey (A'Vard & Allan 2014) 400 tonnes of the recyclable plastic produced in WA was shipped to Victoria for reprocessing, 1 700 tonnes to South Australia and 7 500 tonnes to overseas facilities. This suggests that only 3 600 tonnes (27%) of recyclable plastic was processed in WA. It is noted that WA has five plastic reprocessing facilities; only Tasmania (two facilities), Northern Territory (no facilities) and the Australian Capital Territory (no facilities) have less, as presented in Figure 3.3.

Figure 3.3: Number of plastic reprocessing facilities in each state



Source: A'Vard & Allan 2014.

Many manufacturers will not use recycled plastics for general industrial applications (e.g. pipes, flooring, etc.) due to concerns about the presence of impurities in the plastic. This appears to be the same main barrier to using recycled plastic in road construction applications. It would appear, therefore, that there is a need to investigate whether the use of 'impure' recycled plastic is safe for binder modification and if its use can lead to benefits in terms of enhanced performance. If this can be demonstrated, then the use of recycled plastic could be expected to increase.

In a report prepared for the Department of Environment and Conservation in 2006, Cardno BSD (2006) suggested that there was a lack of financial incentive for using recycled materials, and a lack of domestic demand in WA. This at least partially explains why a large proportion of the recycled plastic material is exported interstate or overseas. More recent reports suggest that WA was still exporting the majority of its raw plastic waste, with approximately 71-73% being sent interstate or overseas (A'Vard & Allan 2014; Perryman & Green 2015).

Despite a larger supply of recyclable material in WA than in previous years, Perryman and Green (2015) reported that plastic re-processors in WA still had to seek out quality pre-consumer waste plastics from manufacturers of durable or packing plastics.

3.6.1 Market Survey of WA Plastic Recyclers

In order to identify any gaps in the plastic waste stream from landfill, between October and December 2016 ARRB conducted a market survey of the main types of plastics recycled in WA. Documentation of current practices was accomplished through a review of literature, consulting Western Australian government databases on recycling and querying the major industry recyclers based in WA. The three primary types of plastic recycled in Western Australian, in descending order of value were determined to be high density polyethylene (HDPE), polyethylene terephthalate (PET) and mixed plastics.

High Density Polyethylene (HDPE)

The total HDPE recycled in WA was 6 000 tonnes in 2014/15. This was primarily processed and sorted by Cleanaway (2 400 tonnes), SUEZ (720 tonnes), Visy (could not provide data) and the Southern Metropolitan Regional Council (420 tonnes). CLAW Environmental is an independent recycler that reprocesses HDPE into granules and pellets. However, HDPE from CLAW is supplied by industrial and commercial companies where the materials are pre-sorted.

Cleanaway ships their sorted HDPE to the highest bidder, typically China, for further processing. Visy ships all HDPE to be sorted at their facilities to Smithfield, NSW where 'rHDPE' is produced using Visy's state-of-the-art rPlastics facility. The rHDPE is typically found in milk and juice bottles, containing up to 50% recycled HDPE (Sai Platform Australia 2016). SUEZ and the SMRC have stated that the majority of HDPE sorted in their facilities is shipped overseas for reprocessing, while some is shipped interstate. CLAW Environmental typically reprocesses approximately 600 tonnes/year of HDPE into granules and pellets. They are then sold to companies based in Hong Kong and mainland China for processing into new products such as bottles, clothes and bins.

HDPE is the most expensive recycled plastic for sale on the WA market. At the time of the survey (December 2016), CLAW stated that HDPE sold for approximately \$1 200/tonne (based on personal conversation with Richard Olsen of CLAW Environmental on 1 December 2017). However, it is important to note that the price of recycled materials is subject to price fluctuations and market demand, similar to other commodities sold on the open market.

Polyethylene Terephthalate (PET)

PET comprised approximately 20% by mass (3 400 tonnes) of the total plastic recycled in WA in 2014/15 (Waste Authority WA 2016a). There is currently no local use for PET as all processed material is sent interstate or internationally. The SMRC recycles approximately 430 tonnes/year while Cleanaway recycles approximately 2 400 tonnes/year of PET. The other major recycler in WA, Visy, could not provide figures due to commercial confidentiality.

Cleanaway ships their sorted PET to the highest bidder, typically China for further processing. PET recycled by Visy is processed at their rPlastics facility in Smithfield, NSW, which is Australia's first large-scale food-grade plastic recycling facility. The 'rPET' produced by the facility can consist of 100% recycled PET; it is used in drink bottles displaying the Re+ logo. PET recycled by the SMRC is baled and sent to Asia for further processing.

Mixed Plastics

Mixed plastics are collected in two categories by the local government agency, Southern Metropolitan Regional Council (SMRC): 'mixed rigid plastic' and 'mixed plastic'. The SMRC recycles the verge side collection from Cockburn, East Fremantle, Fremantle, Kwinana, and Melville. The SMRC recycles approximately 1 000 tonnes/year of mixed plastic and 350 tonnes/year of mixed rigid plastic whereas Cleanaway recycles approximately 1 200 tonnes/year of mixed plastic.

Cleanaway ships their mixed plastic to the highest bidder, typically China, for further processing. All plastic recycled by the SMRC is baled and shipped to Asia for further processing. The SMRC sell their recovered recyclables by public tender and, as such, were not able to provide the typical values of their plastics. However, the SMRC did state that there is a big difference between the value of mixed types of plastic and single types of plastic.

3.6.2 Recycling Processes

The general recycling process for plastic products consists of: collecting the used materials from the consumer, sorting recyclables into their material streams, baling the products, shredding and washing, melting and pelletisation of the plastic for the material to be further processed into new products such as bottles, clothes or furniture. The sorting of the recyclables into their material streams is often done using high-tech plants known as material recovery facilities.

Material Recovery Facility

A material recovery facility (MRF) is plant and equipment used for sorting and pre-processing materials from the waste stream for resource recovery. The MRF receives recyclable material from the households and businesses where they are unloaded into an area called the 'tipping floor'. From the tipping floor, recyclables are placed on a conveyor belt and, using the MRF, sorted in material streams of glass, steel, paper, aluminium cans and plastic.

Plastic is sorted into three categories using a National Recovery Technologies (NRT) inflight sorting machine. This machine uses an optical eye and lasers to identify three main types of plastics: polyethylene terephthalate (PET), high density polyethylene (HDPE) and mixed plastic containers. A jet of compressed air sends the bottles to the correct bins to be baled. The bales are then typically sent to China to be reprocessed. Cleanaway stated that less than 2% of the material sent to their MRFs are sent to landfill, the rest is on-sold to international markets.

Reprocessing

The process of further breaking down the baled plastic into usable pellets is often conducted in facilities independent of the MRF. This may involve selling the baled material to another company or agency to reprocess the recycled materials should the original separator not have the necessary plant or equipment. Reprocessing typically occurs internationally in China and Malaysia, although there has been a recent preference for Malaysia who have lower quality standards for received recyclables (Perryman & Green 2016).

3.7 Cost of Virgin Plastic versus Recycled Plastic

The relative costs of recycled plastics compared to their virgin counterparts are not definitive and appear to be influenced by many factors. The prices are also known to be highly subject to market fluctuation. Cardno BSD (2006) reported that the cost of recycled plastics was comparable with virgin materials in WA. If the recycling technology and skills has improved over time, the current cost of recycled plastics in WA could be lower.

A recent price survey conducted in the US (Plastics News 2016) is presented in Table 3.4. It can be seen that the recycled plastics were markedly cheaper than their virgin counterparts in all cases. It should be noted, however, that several days after this data was accessed the trend reversed (i.e. virgin plastics became cheaper). This may be attributed to the decrease in oil prices around that time. It clearly demonstrates the effect of market fluctuations.

Table 3.4: Price comparison: recycled plastic and commodity plastic

Plastic type	Recycled plastic (AUD/kg)	Commodity plastic (AUD/kg)	Difference (AUD/kg)	Difference (% of commodity price)
ABS	1.96	3.79	-1.83	-48%
PC	2.55	-	-	-
HDPE	1.36	2.17	-0.81	-37%
LLDPE	0.34	2.13	-1.79	-84%
LDPE	0.51	2.21	-1.70	-77%
PET	1.22	2.52	-1.30	-52%
PP	1.32	2.65	-1.33	-50%
PS	2.07	3.38	-1.30	-39%
PVC	0.99	2.10	-1.11	-53%

Note: Prices are based on the current price and conversion rate from USD to AUD as at 19 April 2016.

Source: Esposito (2016).

3.8 Review of the Use of Recycled Plastics in Asphalt

Numerous studies have investigated the effect of adding waste plastics into bituminous materials, including:

- polyethylene (PE) – Awwad and Shbeeb (2007)
- low density polyethylene (LDPE) – Garcia-Morales et al. (2006)
- polyethylene terephthalate (PET) – Sulyman, Haponiuk and Formela (2016) and Ahmadinia et al. (2012)
- high density polyethylene (HDPE) – Hinislioglu and Agar (2004)
- polypropylene (PP) and acrylonitrile-butadiene-styrene (ABS) – Casey et al. (2008)
- polyvinyl chloride (PVC) – Behl, Jain and Sharma (2012).

Kalantar, Karim and Mahrez (2012) conducted a general review of the typical waste polymers.

The general consensus from the various studies was that recycled waste polymers could be utilised as bitumen modifiers and produce noticeable changes in binder/mix properties. However, in many cases the noted changes were relative to a non-modified binder/asphalt. When a comparison between common virgin polymers and recycled plastics was undertaken, in most cases the types of polymers were not the same. This may not be a meaningful comparison as any property/performance differences observed between virgin and recycled polymers may have been due to their different inherent properties, e.g. an elastomer-based commercial modifier being compared to a plastomer. A more rational approach to investigating whether the recycled modifier could provide equivalent/similar performance despite some impurities being present in the material would be to compare a recycled plastic modifier with its virgin counterpart.

A Portuguese study (Costa et al. 2013) sought to evaluate the advantages of bitumen modification with different types of plastic waste including HDPE, LDPE, EVA (virgin and recycled), SBS

(virgin), ABS and crumb rubber. In order to assess performance, a commercial PMB, Styrelf, was used as the control. Styrelf is a proprietary high-performance PMB product reported to provide excellent durability, enhanced fatigue and rutting resistance and cohesion under heavy intense traffic in harsh conditions (Total n.d.). A series of binders were produced using these modifiers (5% by weight added to base bitumen using a wet process) and their typical test properties were compared with those of Styrelf.

The results showed that:

- the softening point of the HDPE-modified binder was higher than both Styrelf and the unmodified bitumen
- the softening point of both the virgin and recycled EVA was similar to Styrelf
- virgin and recycled EVA, HDPE and LDPE had a lower penetration than Styrelf
- recycled EVA was more resilient than Styrelf
- HDPE, LDPE and EVA had good digestion in bitumen
- Only ABS and crumb rubber had good storage ability.

It was concluded that it was possible to obtain similar properties, or even better, than those of a commercial modified bitumen.

A similar study conducted by Casey et al. (2008) involved standard wheel-tracking and fatigue testing of asphalt mixes manufactured using a binder modified with recycled HDPE (4% by weight of binder). The results suggested that the HDPE mix did not perform as well as proprietary commercial binders. However, enhanced performance was seen relative to an unmodified binder and the 'recycled polymer modified binder had great promise'.

Dalhat and Al-Abdul Wahhab (2015) examined the use of recycled HDPE, LDPE and PP modifiers and found that all three modified asphalt mixes had a higher resilient modulus relative to an unmodified asphalt mix. The long-term (over 20 years) in situ performance of these mixes was predicted using a pavement simulation model. The modelling suggested that all of the modified asphalt mixes would stay within the allowable rutting limit for 17 years without the need for maintenance. The modelling also suggested that surface cracking in the modified mixes would be much lower, as low as 10% of the unmodified mix. However, the credibility of this finding depends on the robustness of the simulation model adopted. It appears that the model was solely based on the viscoelastic properties of the binders whereas actual performance would be affected by various factors.

In terms of the two methods of adding polymer modifiers into an asphalt mix (Section 3.3), most of the Indian studies involved the use of only one of the methods. However, studies conducted by Gawande (2013) and Gawande et al. (2012) directly compared the two methods in order to identify their advantages and disadvantages. It was reported that, whilst the dry process provided the best results, this needed to be confirmed on a case-by-case basis. This is discussed further in Section 3.9.1.

It is also noted that the performance of recycled plastic modifiers is dependent upon many factors, especially the polymer content and asphalt mix properties. Garcia-Morales et al. (2006) reported that there were varying degrees of compatibility between different binders and the polymers used. Studies generally found that adding recycled polymer modifiers increased the softening point of binders (Punith & Veeraragavan 2003; Costa et al. 2013) and the stiffness of the binder at in-service temperatures (Behl et al 2012). This understandably improved the rut resistance of the asphalt mixes in many cases (Behl et al 2012; Austroads 1999).

Garcia-Morales et al. (2006) investigated the use of four different waste polymers: crumb rubber, a blend of EVA and LDPE, EVA and ABS. The properties were superior to those of unmodified bitumen over a wider range of in-service temperatures. The binder modified with a blend of EVA and LDPE had improved properties at high road temperatures at which unmodified mixes would deform significantly. The binder modified with crumb rubber, on the other hand, had a higher resistance to thermal cracking at low in-service temperatures.

One area that was not investigated in the studies reviewed was a comprehensive study of the long-term performance (e.g. durability) of recycled plastic-modified material, and the economic benefits associated with its long-term use. This is primarily due to the relatively recent applications of recycled polymers in roads. Similarly, there is a lack of comparison between a recycled polymer and its virgin counterpart. The only direct-comparison study found during this review was that of Costa et al. (2013), who investigated the performance of recycled and virgin EVA. It was found that, in most cases, there was little to no difference between the recycled and virgin materials. Minor differences were noted for the penetration and resilience tests, where the recycled polymer modified binder produced higher values.

Another area that is very important in the Australian context, but was not addressed in any of the studies, is the health and safety issues associated with the production and laying of these asphalt mixes. It is possible that, when heated to a high temperature, recycled plastics may emit harmful fumes, raising health and safety concerns both at the plant and at the work site. The type of plastic on its own could be the source of this problem but impurities contained in any recycled plastics could also be a concern. Studies will need to be conducted which specifically focus on this issue in addition to the generic 'performance assessment studies' reviewed in this report.

3.9 Case Studies

3.9.1 India

The use of recycled plastic has been investigated in India from a predominantly environmental perspective, i.e. in terms of it being an effective method of minimising plastic waste. The use of recycled plastic in India has proven to be so beneficial that the Indian Ministry of Environment, Forest and Climate Change has declared it mandatory that newly-constructed roads are to use waste plastic with bituminous mixes (Sinha 2016).

Gawande (2013) reviewed the processes used in India, including their economics and viability. The study examined both the wet and dry processes using HDPE, LDPE, PP and crumb rubber. The results showed that the coated aggregate using the dry process had a higher strength, whilst the binder modified using the wet process had a lower penetration and higher softening point. Gawande concluded that laboratory and in situ testing conducted in India had shown that the life of a recycled plastic-modified mix can be at least double that of a non-modified mix. Although the short-term costs were slightly higher due to the need to collect and sort the plastic, the long-term savings due to roads lasting much longer would be significant.

Gawande et al. (2012) concluded that the addition of recycled plastic to the mix could increase its resistance to water damage and hence life. This was particularly important in the high rainfall and tropical regions along the western coast and north-eastern India. In addition, Chavan (2013) reported that rutting was reduced as was the probability of ravelling and pothole formation.

The Indian Roads Congress (2013) produced a specific standard for the use of waste plastic as a modifier for asphalts. The guidelines specify that only LDPE, HDPE, PET and PU are to be used in pavement construction and the plastics must pass the 2.36 mm sieve but be retained on a

600 µm sieve. For both dense-graded and open-graded mixes, the waste plastic content is designated as 6-8 % of the mass of the bitumen.

Further investigation of the quality of the Indian pavement design standards relative to Australian standards would need to be undertaken. Although the use of recycled plastic in Western Australian asphalt may exhibit strength benefits, the largest constraint to implementation is the economic feasibility due to the high cost of recycled plastic.

3.9.2 Toner-modified Asphalt

Solaimanian et al. (1997) reported work undertaken in Texas in 1997 to investigate the feasibility of utilising waste toner in hot mix asphalt. It was found that there were several positive benefits, with a 98% reliability, including increased strength and stability compared to non-modified asphalt. Generally, it was observed that, as the percentage of toner increased, the stiffness and viscosity increased. The binder stiffness relative to a non-modified asphalt also increased at all temperature ranges. However, owing to the variety of toner used, and the very fine powder form being messy and potentially unsafe to handle, this approach did not progress into practice in Texas.

Four modified toner asphalt test sections from the Texas study were described as having performed well for a period of ten or more years. It was reported that these sections have shown minimal rutting and no deterioration or material defects.

In Australia, a resource recovery and recycling company named Close the Loop (CtL) have processed approximately 12 320 tonnes of waste toner and cartridges, 1 600 tonnes of which is residual toner powder. Close the Loop (CtL), in collaboration with Downer EDI have been using a toner-modified asphalt product in numerous developments throughout Australia, including a housing development in Hume City Council, north of Melbourne (Morriss 2014). The product, TonerPave™, is an asphalt mix predominantly modified using modified toner polymer (MTP) sourced from recycled toner powder (Close the Loop & Downer 2016). Toner powder is predominantly plastic including styrene acrylate, styrene butadiene and polyester with minor amounts of minerals, pigments, wax, iron oxide and silica.

The MTP is unique in that it has a low melting temperature, which allows it to readily homogenise with the binder in asphalt plants utilising the same equipment and manufacturing plants as conventional asphalt types. Other polymers are known to require additional processing to achieve homogeneity. Although toner is the predominant ingredient in TonerPave™, other ingredients include toner cartridges, waste acrylic paint, recycled engine oil and/or rubber crumb from recycled tyres. Test results have indicated that mixes containing MTP showed approximately an 11% decrease in the modulus, a 30% increase in fatigue life and a 50% reduction in cracking relative to a control mix (Morriss 2014).

Salisbury Council in South Australia has also used TonerPave™ with the Mayor stating that 'cost, performance and final appearance of the product are like-for-like with conventional asphalt' (Local Government FOCUS 2015). Although the use of TonerPave™ has the added benefit of reducing the amount of waste entering landfill compared to conventional asphalt.

Personal correspondence with the Technical Manager of CtL on 29 April 2016 stated that testing conducted by Downer EDI had indicated that TonerPave™ met all specification requirements for local council roads.

As it is a proprietary product, the properties of TonerPave™ are not disclosed. Therefore it is unclear whether the properties would meet the requirements of MRWA. It is also unclear what

particular local council road specifications were referred to in the correspondence. Thus we cannot undertake a comparison to MRWA Guidelines.

TonerPave™ is currently available exclusively through Downer in all states excluding Tasmania, Northern Territory and WA. Details are available at: <http://tonerpave.com.au/>.

3.9.3 Modular Pavements

A Dutch construction company, VolkerWessels, has developed a design for prefabricated pavement modules made from 100% recycled plastics. A conceptual model of the system is shown in Figure 3.4 (Koudstaal & Jorritsma n.d.).

Figure 3.4: Conceptual model of Dutch modular pavement system



Source: Koudstaal and Jorritsma (n.d.).

Plastic waste is recycled into lightweight prefabricated elements with a hollow core. It is believed that the prefabricated segments will allow for easier transportation and require less specialist machinery to install, reducing the overall environmental impact. Similarly, replacement of damaged sections will be relatively easy, with the damaged section being removed and immediately replaced by a new prefabricated component.

VolkerWessels claims that the modular pavement will 'last three times longer than conventional pavement', providing a 'lifespan of at least 50 years'. It is important to note that the design life of a Dutch open-grade asphalt pavement is typically 10-15 years (AAPA 2012). This is based on 'the lifespan of other plastic products such as sewage pipes and plastic platforms' (Koudstaal & Jorritsma n.d.). Similarly, it is reported that the road can support extreme temperatures from -40 to 80 °C. However, as the system may not be able to support large, heavy vehicles, the primary applications of plastic road modules are expected to be on minor urban roads and bicycle paths (Koudstaal & Jorritsma n.d.).

In correspondence dated 28 April 2016, VolkerWessels confirmed that the plastic road module was still only in the development stage and that no testing has been conducted. It is expected that a pilot will be ready for trialling towards the end of 2017.

3.9.4 Vancouver Roads

The City of Vancouver, Canada, has been experimenting with waste plastic in pavements since 2012 and several roads in the metropolitan area are paved with a recycled waste plastic product. The City has worked with an Ontario based company, GreenMantra, to develop an additive that can be mixed into warm mix asphalt. The result was a wax, an additive that melts in a temperature range between the high pavement temperature and the desired compaction temperature, made from 100% recycled plastic.

In an email dated 20 April 2016 from City of Vancouver Manager of Engineering Services, Jeff Markovic, it was stated that the wax is produced from HDPE and LDPE recycled plastics typically found in squeeze bottles and plastic bags. Trials are also being conducted using soy mixed with the recycled wax to produce a warm mix asphalt (WMA) workable at lower temperatures.

The City's primary requirements when considering new technology of this type include:

- no additional infrastructure required to produce the WMA
- no major change to operations when commencing the trials
- current asphalt mix designs still to be used
- the use of reclaimed asphalt pavement (RAP) in current designs could continue (the City of Vancouver currently uses up to 25% RAP)
- the repetitive reuse of asphalt without major impacts to current emissions standards, health and safety, and quality control
- the system to be cost-effective.

The City of Vancouver reported that the product produced by GreenMantra met all of these requirements.

The application of the product requires no changes to traditional methods of manufacturing asphalt. Flaked wax is blended with the RAP mix which is then fed through a bin. If a plant has two bins then one is used as a wax feed while the other is used to feed the RAP. Typically, the City uses a final modified binder mix temperature of 160 °C. However, with the introduction of recycled wax, it was found that the final temperature could be lowered to approximately 120 °C.

All components undergo quality checks to ensure they meet the conventional design criteria. However, the property that is most desired by the City is the tensile stress ratio (TSR), used for evaluating stripping potential. If the ratio is above 80% then the wax is accepted for use in the WMA. The typical TSR is in the region of 95% whilst the typical range for the WMA is 80–90% or, in some cases, higher. Unconditioned samples of the recycled asphalt are reported to have a shear strength of up to 21 kN. The voids filled with asphalt of the WMA is in the range of 60-75% (Hein 2014).

Currently, the City uses a weight ratio of wax to mix of 0.25-0.5% depending on the different variables in a mix. Generally, this indicates that 1 000 kg of wax will produce approximately 400 tonnes of WMA. Initial trials involved the use a 20% RAP WMA. It was reported that the introduction of the wax to the mix has resulted in significantly better working conditions for the workers, both at the plant and at the site. Initial measurements indicated an approximately 25% reduction in the volatile organic compounds (VOC's). Further testing is being conducted to verify this figure while visible reductions in fumes were reported by the workers. No noticeable added fumes were detected.

Overall, the results were positive. Field results indicated that good compaction was achieved. However, this required more rubber-tyre rolling than for conventional asphalt. TSR testing is currently being conducted for comparisons with the City's standard 12.5 mm nominal and 19 mm nominal Superpave mixes.

To date, the City has experienced no performance issues with the warm-mix Superpave asphalt with 20% RAP. Current research aims to reduce the melting point of the wax to a temperature between 60 °C and 80 °C. This will influence the workability of the asphalt at lower temperatures, and assist in the laying process. It was also reported that the mix became slightly softer, however this was considered negligible in terms of the City's performance standards.

One of the City's engineering managers stated in an interview (Ball 2012) that there was a small (1–3%) increase in cost due to the purchase of the wax, however this was 'balanced by very large savings on the greenhouse gas side'.

A representative of the Canadian Technical Asphalt Association stated that 'these types of waxes compared to other waxes from coal tar, for example, may make asphalt more sensitive to cold temperatures and fatigue. They may become crystalline and brittle. It will be interesting to see how the [recycled plastic] wax asphalt stands up in the long term, remembering that Vancouver doesn't get as cold as many other areas of Canada' (Hein 2014). However, it is important to note that the average temperature of Vancouver ranges from 1-22°C (WWO 2017), which is considerably colder than the average range of 8-32 °C in Perth (BOM 2017).

3.9.5 Western Australia

Research is currently being undertaken at Curtin University into the performance of recycled plastic modified asphalt (Waste Authority 2016b). Whilst the results of the work are unpublished, it has been reported that general indications are promising in terms of rutting and fatigue performance.

The tests conducted to date have examined the effects of common recycled plastics, including HDPE, PP, PET and PVC, on fatigue life, rutting and resilient modulus for a range of binder contents.

3.10 Summary and Recommendations

The majority of the studies reviewed in this report were conducted overseas and generally involved an examination of the performance of recycled polymer modifiers relative to a generic commercial polymer modifier or unmodified binder. In addition, when the performance of recycled polymer modifiers was compared with virgin polymer modifiers, the polymer types were often different, thus making any direct comparisons difficult. As the recycled plastics were mainly 'plastomers', it is unlikely that the elastic properties would be enhanced, which is a primary reason for bitumen modification.

Studies investigating the use of recycled plastic on roads were usually conducted from an environmental perspective (i.e. to reduce the amount of landfill). Therefore, 'comparable performance' or 'no marked detrimental effects on performance' was often accepted as 'successful outcomes'.

Several companies have developed proprietary modifiers made from recycled plastic. Initial costs are slightly higher because of the need to purchase the proprietary products. However, the long-term costs may be reduced if savings in ongoing maintenance costs can be achieved; a claim suggested by the manufactures.

The production of binders containing recycled plastic would require little additional equipment or expertise to regular bitumen production; the literature suggests that no additional equipment is required. Methods have been developed in India which enable the entire process to be performed on site using raw, recycled, plastic bag chips.

As with virgin polymers, the type and class of plastic used would have to be tailored to WA conditions. Modifiers have been used to achieve optimal binder properties at lower temperatures in England and Vancouver (maximum average temperature in summer: 22 °C), whereas the temperatures in WA in summer can reach 50 °C. Hence, the type of modifier successfully used overseas may not be appropriate for use in WA, especially where applications were intended for winter performance in climates different to Australia.

Overall, the performance of pavements containing binders modified with recycled plastic may result in an enhancement of some desirable properties (e.g. rut resistance of asphalt) compared to an asphalt mix containing an unmodified bitumen. However, a conventional PMB is more likely to provide greater benefit over a broader range of applications.

In general terms the environmental benefits (i.e. the increased rate of recycling and a reduced amount of plastic entering landfill) appears to be the main driver for using recycled plastic as a binder modifier. However, no studies could be sourced in the literature which addressed health and safety concerns associated with the use of recycled plastics (particularly during the asphalt production and paving stages). This issue would need to be investigated thoroughly – in addition to the ‘performance studies’ included in this review – before binders modified with recycled plastic could be introduced into WA. The research currently being undertaken at Curtin University into the performance of recycled plastic modified asphalt (Waste Authority 2016b) should therefore be monitored closely.

Between October 2016 and December 2016, ARRB conducted a market survey of the main types of plastics recycled in WA to identify any gaps in the plastic waste stream to divert waste from landfill. Documentation of current practices was accomplished through a review of literature, consulting Western Australian government databases on recycling and querying the major industry recyclers based in WA. The three primary types of plastic recycled in Western Australian were high density polyethylene (HDPE), polyethylene terephthalate (PET) and mixed plastics.

Based on the results of this market survey conducted for the WARRIP project, *Review of future pavement technology*, the following general conclusions can be made:

- There are no identifiable gaps in the plastic waste stream. All plastic that is currently sent to the recycling plants in WA is on sold to be further processed into new products, mostly internationally.
- Quantification of the plastic types that enter landfill is not currently conducted in Australia. It is therefore difficult to assess how much landfilled plastic could potentially be recycled. Reducing plastic sent to landfill is highly dependent on the consumer placing plastic in the correct bin.
- The price of recycled plastic fluctuates depending on the state of the market. Typical prices for HDPE, PET and mixed plastic in WA are \$700 - \$1 200, \$300 and \$180 per tonne respectively.

Based on this review, it can be concluded that it is not currently economically feasible to use recycled plastic in asphalt. Further research could be conducted to identify any gaps in the Western Australian waste stream for use in pavements to divert waste from landfill.

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4 NANOTECHNOLOGY-MODIFIED MATERIALS

4.1 Introduction to Nanotechnology

The word 'nanotechnology' was first introduced by Professor Norio Taniguchi, from Tokyo Science University, at a conference on production engineering in 1974 (Taniguchi 1974). According to National Nanotechnology Initiative (NNI) the term 'nanotechnology' can be defined as:

The understanding and control of matter at the nanoscale, at dimensions between approximately 1 and 100 nanometres, where unique phenomena enable novel applications. Encompassing nanoscale science, engineering, and technology, nanotechnology involves imaging, measuring, modelling, and manipulating matter at this length scale (NNI n.d.).

A summary of recent definitions of nanomaterials according to various organisations is presented in Table 4.1 (Boverhof et al. 2015).

4.2 Application of Nanotechnology in Pavement Engineering

The field of nanotechnology has developed significantly over the last 20 years mainly due to an improved understanding of the chemistry and physics of the materials at the nanoscale. It is important to understand that the objectives of science and engineering, especially pavement engineering, are different.

Science focusses on composition, structure and the inter-relationships of materials at the nanoscale, while engineering concentrates on the application of chemistry, physics and engineering principals to perform a certain function at the macroscale. For this reason, nanotechnology could be identified as a tool used to fill the gap between macroscale understanding of engineering and the nanoscale understanding of science. It also address the current challenges which cannot be solved by using available macroscale technologies (Steyn 2010). Asphalt modification using nanotechnology typically involves the addition of a nano-material in small quantities (typically 1% to 5% by mass) to the binder, to improve the engineering properties of the mix.

This section of the report summarises the current attempts to apply nanotechnology using nanomaterials in pavement materials, especially asphalt and concrete pavements.

4.2.1 Application of Nanotechnology in Asphalt Pavements

Although bituminous materials are mainly used in a large scale in flexible pavement construction, their performance normally relies on the interconnection of the structural components of the material in the micro and nanoscale (Partl, Gubler & Hugener 2004). As a result, nanotechnology could be used to improve the performance, durability and sustainability of asphalt pavements (Faruqi et al. 2015).

Table 4.1: Definition of nanotechnology by different jurisdictions

Organisation	Definition	Product category	Status
European Commission Cosmetics Directive	An insoluble or biopersistent and intentionally manufactured material with one or more external dimensions, or an internal structure, on the scale from 1 to 100 nm.	Cosmetics	Regulatory definition
Australian Government Department of Health and Ageing	Industrial materials intentionally produced, manufactured or engineered to have unique properties or specific composition at the nanoscale, i.e. a size range typically between 1 nm and 100 nm. It is either a nano-object (i.e. confined in one, two, or three dimensions at the nanoscale) or is nanostructured (i.e. having an internal or surface structure at the nanoscale). Aggregates and agglomerates are included. It applies to materials where 10% or more of the particles by number count meet the above definition.	All non-food	Advisory definition
Health Canada	Any manufactured substance or product and any component material, ingredient, device, or structure is nanomaterial if it is: (1) at, or within, the nanoscale in at least one external dimension, (2) has internal or surface structure at the nanoscale, or (3) if it is smaller or larger than the nanoscale in all dimensions and exhibits one or more nanoscale properties/phenomena. Nanoscale properties/phenomena refer to properties that are attributable to the size of the substance and size effects.	All	Advisory definition
United States Food and Drug Administration	No formal definition. However, 'when considering whether an FDA-regulated product contains nanomaterials, or otherwise, involves the application of nanotechnology, FDA will ask whether an engineered material or end-product has at least one dimension in the nanoscale range (approximately 1 nm to 100 nm) or whether an engineered material or end-product exhibits properties or phenomena, including physical or chemical properties or biological effects, that are attributable to its dimension(s), even if these dimensions fall outside the nanoscale range, up to one micrometre.'	Cosmetics, pharmaceuticals and food	Advisory definition
United States Environmental Protection Agency	No formal definition. However, the agency has outlined key criteria in several documents, including: (1) solid at 25 °C and atmospheric pressure, (2) particle size between 1 and 100 nm in at least one dimension, (3) the material exhibits unique and novel properties because of its size, (4) the material is engineered at the nanoscale; inclusion of primary particles, aggregates and agglomerates, and (5) a distribution of particles with greater than 10% by weight less than 100 nm.	All except cosmetics, pharmaceuticals and food	Advisory definition
European Commission (Recommendation on the definition of nanomaterials)	A natural, incidental or manufactured material containing particles, in an unbound state or as an aggregate or as an agglomerate and where, for 50% or more of the particles in the number size distribution, one or more external dimensions is in the size range 1–100 nm. In specific cases, and where warranted by concern for environment, health, safety or competitiveness, the number size distribution threshold of 50% may be replaced by a threshold between 1 and 50%.. Fullerenes, graphene flakes and single wall carbon nanotubes with one or more external dimensions below 1 nm should be considered as nanomaterials.	All	Advisory definition
European Parliament and the Council of the European Union on the provision of food information to consumers	Any intentionally-produced material that has one or more dimensions of the order of 100 nm or less or is composed of discrete functional parts, either internally or at the surface, many of which have one or more dimensions of the order of 100 nm or less, including structures, agglomerates or aggregates, which may have a size above the order of 100 nm but retain properties that are characteristic of the nanoscale. Properties that are characteristic of the nanoscale include: (i) those related to the large specific surface area of the materials considered; and/or (ii) specific physio chemical properties that are different from those of the non-nanoform of the same material.	Food	Regulatory definition

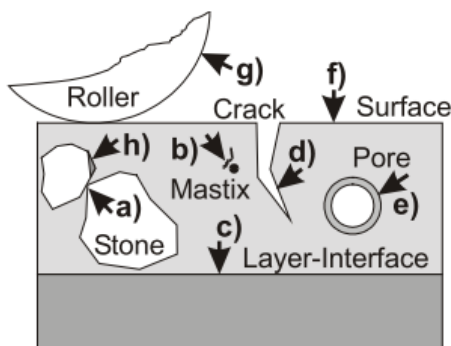
Organisation	Definition	Product category	Status
European Commission, Biocides Directive	A natural or manufactured active or non-active substance containing particles, in an unbound state or as an aggregate or as an agglomerate, and where, for 50% or more of the particles in the number size distribution, one or more external dimensions is in the size range 1-100 nm. Fullerenes, graphene flakes, and single wall carbon nanotubes with one or more external dimension below 1 nm shall be considered as nanomaterials.	Biocides	Regulatory definition
French Ministry of Ecology, Sustainable Development and Energy	A substance intentionally produced at nanometric scale, containing particles, in an unbound state or as an aggregate or as an agglomerate, and where, for a minimum of 50% of particles in the number size distribution, one or more external dimensions is in the size range 1-100 nm. Fullerenes, graphene flakes and single-wall carbon nanotubes with one or more external dimensions below 1 nm are considered as 'substances at nanoscale'.	All	Regulatory definition
Taiwan Council of Labour Affairs (Chemical Substance Nomination & Notification 2012)	A material which is intentionally manufactured or designed and meets any of the following conditions: (a) a material with one or more external dimensions or an internal or surface structure on the scale from 1-100 nm (b) it is smaller or larger than the nanoscale above in all spatial dimensions and exhibits one or more nanoscale phenomena/property (for example, increased intensity and chemical reactivity) (c) 13 engineered nanomaterials by OECD in 2010 which can be used as reference are provided in the definition.	–	Advisory definition
Swiss Federal Office of Public Health and Federal Office for the Environment	Utilises European Commission recommendation regarding the definition of nanomaterials, but also includes particles up to 500 nm and respirable particles of up to 10 microns with nanoscale side chains.	All	Advisory definition
Norwegian Environment Agency	Follows European Commission recommendation regarding the definition of nanomaterials.	All sectors, but only for chemicals classified as hazardous according to stated criteria	Regulatory definition
Belgian Federal Public Service Health, Food Chain Safety and Environment	A substance produced in nanoparticulate state: a substance containing unbound particles, or aggregate or agglomerate of those particles, where 50% or more of the particles in the number size distribution have one or more external dimension is in the size range of 1-100 nm. The definition excludes natural, non-chemically modified substances and those for which the fraction in the 1-100 nm range is 'a by-product of human activity', which is further defined.	Scope is defined by a complex set of exemptions	Regulatory definition
Danish Ministry of the Environment	Follows European Commission recommendation regarding the definition of nanomaterials.	Scope is defined by a complex set of exemptions.	Regulatory definition

Source: Boverhof et al. (2015).

A schematic overview of the following potential areas where the application of nanotechnology could lead to improvements in asphalt pavements is presented in Figure 4.1:

- (a) bond between stones (shear and tension)
- (b) mastic (stiffening, cohesion, durability, workability)
- (c) bond between layers (tack coats)
- (d) self-repair (healing) and rejuvenating agents
- (e) oxidation of binder films and binder segregations
- (f) surface properties (friction, optical properties, water repellent, abrasion resistant, self-cleaning), seal coats for surface protection
- (g) anti-adhesion surface for rollers during compaction
- (h) bond, adhesion between the stone and the mastic.

Figure 4.1: Schematic focusing on areas of nanotechnology related to an asphalt pavement structure



Source: Faruqi et al. (2015).

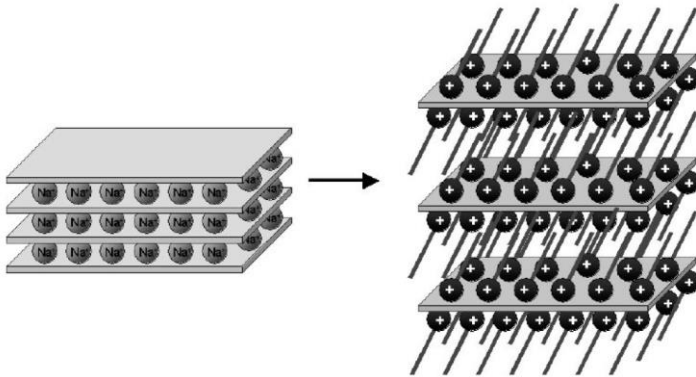
Numerous applications of nanotechnology in asphalt pavements can be found in the literature. The majority of the work reported attempted to modify and enhance the properties of binders by using different nanomaterials. Some of nanomaterials used by researchers include: nanoclay, carbon nanotubes, ZycoSoil and spinifex nanofibres.

Nanoclay

Nanoclays are nanoparticles of layered mineral silicates. Depending on the chemical composition and nanoparticle morphology, nanoclays, in the same way as other clays, are categorised into several classes, including montmorillonite, bentonite, kaolinite, hectorite, and halloysite. Organically-modified nanoclays (organoclays) are hybrid organic-inorganic nanomaterials which have potential uses in polymer nano-composites as rheological modifiers, gas absorbents and drug delivery carriers (Sigma-Aldrich 2016). Montmorillonite is one of the most frequently used nanoclays for asphalt modification as research has indicated it can improve the engineering properties of asphalt.

Nanoclays can be modified to make the clay compatible with organic monomers and polymers. These nano-composites consist of a blend of one or more polymers with layered silicates that have a layer thickness in the order of 1 nm and a very high aspect ratio (Yang & Tighe 2013). By separating the clay discs from each other, nanoclays can be produced with a large active area of up to 700–800 m²/g which intensifies interaction with the binder. A schematic of a nanoclay surface treatment is shown in Figure 4.2 (Ghile 2006).

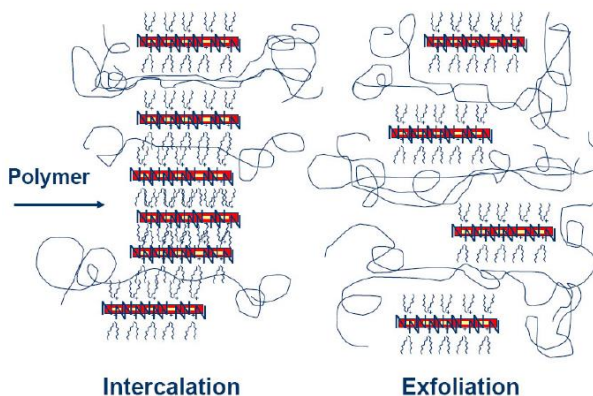
Figure 4.2: Nanoclay surface treatment



Source: Ghile (2006).

Roy et al. (2007) and Hussain et al. (2007) improved the compressive and shear strength of a thermoplastic polymer by reinforcing it with the addition of small percentage of nanoclay (by mass). The nanocomposite (nanoclay and polymer mix) could be synthesised in the form of an intercalated or exfoliated hybrid. As shown in Figure 4.3, when the desired shape of nanocomposite is intercalated, the organic component is inserted between the layers to expand the interlayer spacing, however the layers remain connected. This is in contrast with an exfoliated structure, where the clay layers are totally separated and distributed into the organic matrix (Ghile 2006; You et al. 2010).

Figure 4.3: Formation of intercalated and exfoliated nanocomposites from layered silicates (nanoclay) and polymers



Source: Ghile (2006).

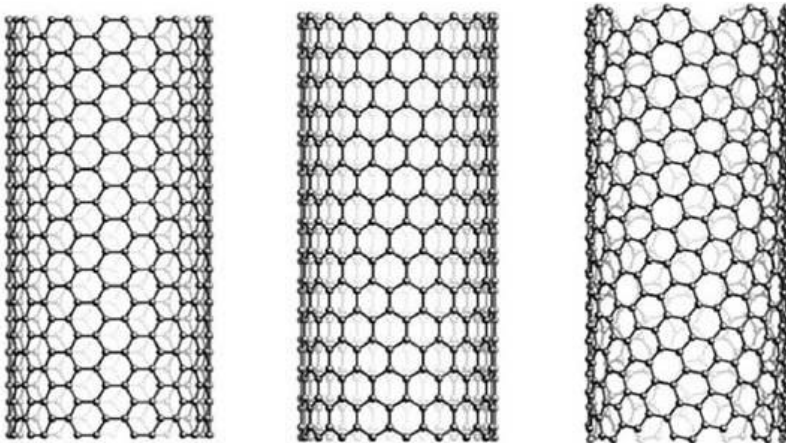
Limited research has been conducted on asphalt samples containing nanoclay. However, whilst there have been very few studies on improving the properties of virgin binders using nanoclay, it has been used in studies to enhance the properties of PMBs. The application of nanoclay showed promising potential in improving rutting resistance (Polacco et al. 2008) and aging resistance (Jahromi & Khodaii 2009). You et al. (2011) showed that the addition of exfoliated montmorillonite nanoclay into asphalt could significantly increase the shear complex modulus, asphalt binder reinforcement and rotational viscosity, while at the same time reducing cumulative tensile strains at the bottom of the asphalt layer.

Carbon Nanotubes

Carbon nanotubes (CNTs) are hollow nano-fibres which have two similar external dimensions on the nanoscale (1–100 nm), and the third dimension which is significantly longer. They consist of

curved graphene layers, graphene being a single layer of carbon atoms in a honeycomb structure. Carbon is the dominant element of CNTs and, depending on manufacturing process, they may contain different percentages of metal impurities. Similar to metals and semiconductors, CNTs can conduct electricity and transfer heat. They can be 100 times stiffer, stronger and at the same time much lighter than steel because they have a very large aspect ratio between their length and diameter, sometimes greater than 100 000:1 (Safe Work Australia 2012). Examples of single-wall carbon nanotubes (SWNT) are shown in Figure 4.4.

Figure 4.4: Examples of single-wall carbon nanotubes, armchair type, zig-zag type and helical type



Source: Iijima (2002).

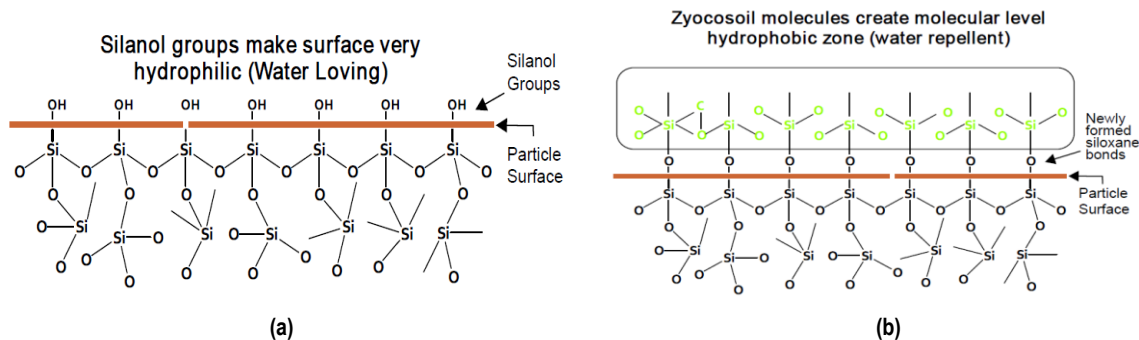
In terms of the application of CNTs in bitumen or asphalt, Xiao, Amirkhani and Amirkhani (2011) reported that the addition of CNTs resulted in higher viscous and elastic modulus values in the binders using CNTs, whilst Motlagh et al. (2012) concluded that the application of less than 0.1% of CNTs to the binder (by mass of binder) improved the Marshall stability and flow of the mix and increased the softening point and ductility of the binder. This would result in higher design modulus values and a reduction in overall pavement thickness. Amirkhani, Xiao and Amirkhani (2011) and Faramarzi et al. (2015) reported that CNTs could be potentially used in asphalt binders to improve the rutting and thermal cracking resistance of asphalt mixes.

ZycoSoil

ZycoSoil is an organo-silane nanomaterial which was developed for soil stabilisation by reacting with soil particles to create hydrophobic layers on the surface of soil, thus decreasing the permeability of the stabilised layer. The different structure of soil and aggregates with and without ZycoSoil is shown in Figure 4.5.

Kim and Moore (2009) evaluated the potential application of ZycoSoil as an anti-stripping agent on Superpave binders and mixes. It was concluded that ZycoSoil could be potentially used as an anti-stripping agent to increase the asphalt mix's resistance to moisture damage, but the conclusion needed to be validated using a wider sample of binders.

Figure 4.5: Soil and aggregates surface structure: (a) without (b) with Zycosoil



Source: Kim and Moore (2009).

Spinifex Nanofibres

The Queensland Government's Advance Queensland Research Fellowships Scheme (AQRFS), in partnership with Queensland TMR, is currently supporting a research program to investigate ways of increasing the strength and durability of bitumen using spinifex nanofibres. Spinifex is a type of grass that thrives in poor, arid soils and are the single most extensive vegetation type in Australia, covering 22% of the continent (NTG 2016). Studies conducted by the partnership to date on polyurethane elastomer and natural rubber have found that the spinifex nanofibrils can improve tensile strength by up to 45% with only 0.5% contents by total mass (Annamalai & Martin 2016). Current research by AQRFS and TMR, with an approximate 2018 finish date, aims to develop processing strategies for improving the compressive strength, rutting resistance and durability of bitumen using spinifex nanofibrils.

4.2.2 Application of Nanotechnology in Concrete Pavements

Based on its nanostructure and multiphase characteristics, concrete is vulnerable to aging over time. The application of nanotechnology in concrete engineering has the potential to generate concretes with the following characteristics:

- self-sensing
- self-cleaning
- self-healing.

Self-sensing

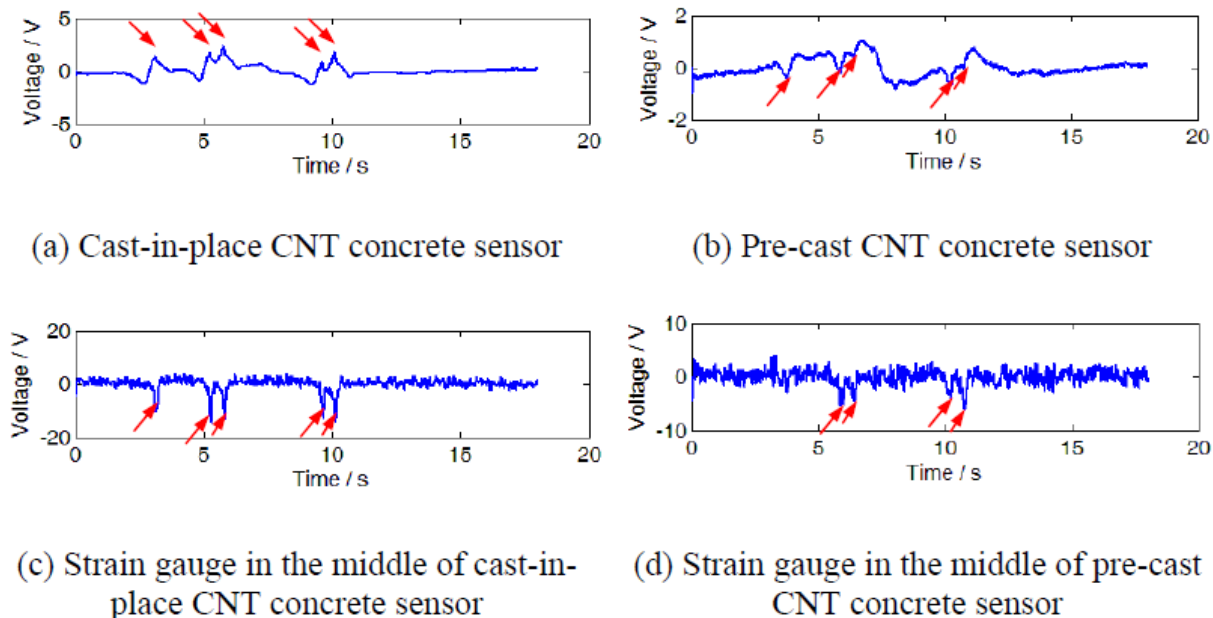
Various methods and procedures have been developed for structural health monitoring over time. The majority of these procedures use embedded sensors, such as electric-resistance strain gauges, optic sensors and piezoelectric ceramic sensors, placed at critical locations in the structure (Auweraer & Peeters 2003; Chong, Carino & Washer 2003). Problems associated with using these sensors include isolated point monitoring, lower durability, high associated costs in terms of analysis and equipment, low sensitivity and undesired compatibility with concrete structures.

Yu and Kwon (2012) investigated the potential use of piezo-resistive CNT/cement composites for concrete structural health monitoring. Two self-sensing CNT concrete sensors, a precast sensor and a cast-in-place sensor were incorporated into a concrete trial section at Minnesota Road Research Facility (MnRoad) of the Minnesota Department of Transportation, USA.

The results obtained from the CNT pavement sensors were compared to the results obtained from buried-in strain gauges. Based on the recorded voltage signals, it was concluded that, due to the

larger effective (sensing) area of the CNT concrete sensors, their detection accuracy was higher than those obtained from the strain gauges. An example of the detection results of a truck passing at low speed is shown in Figure 4.6.

Figure 4.6: Sample data output from CNT pavement sensors



Source: Yu & Kwon (2012).

Self-cleaning

The application of photo-catalytic materials in concrete could help to decrease the amount of organic and inorganic pollutants that gather on the surface and also reduce the air pollution and ultraviolet rays by a photo-catalytic process that absorbs UV photons and degrades pollutants. Titanium dioxide (TiO_2) is a naturally-occurring nano-material which is widely used for preparing self-cleaning concrete. Work by Frazer (2001), Birtwell (2006), Mann (2006) and Hassan (2009) on applications of TiO_2 as a photo-catalyst in concrete showed that there was a significant reduction in the extent of harmful pollutants concentrated on the surface of the concrete.

During the last decade the application of TiO_2 as a photo-catalyst has been commercialised, initially in Japan by Toto Company and then in European countries including TX Active[®] from Italcementi. Applications of self-cleaning concrete in Italy and France are shown in Figure 4.7.

Self-healing

Three methods were identified in the literature for producing self-healing concretes: shape memory effect, microencapsulation, and embedded bacteria.

Shape Memory Effect

Shape memory effect can be defined as the process when materials deform to a temporary shape before recovering to their original shape while exposed to external light, heat, etc. Shape memory polymers (SMP) for use in the self-healing of concrete were first developed in France by CDF Chimie in 1984 under the trade name, *Polynorborene*. An SMP was developed by Li (2012) for use as a sealant in concrete slab joints. It was installed in two expansion joints at the Louisiana State University campus. No macro- and micro-cracks were observed in the joints. The moisture

content in slabs with bitumen and SMP sealants was also compared. The in situ moisture test results indicated that the SMP sealant outperformed the bitumen sealant.

Figure 4.7: Applications of self-cleaning concrete: (a) Dives in Misericordia Church (Rome, Italy), (b) Air France Headquarters Roissy – Charles de Gaulle International Airport (Paris, France)

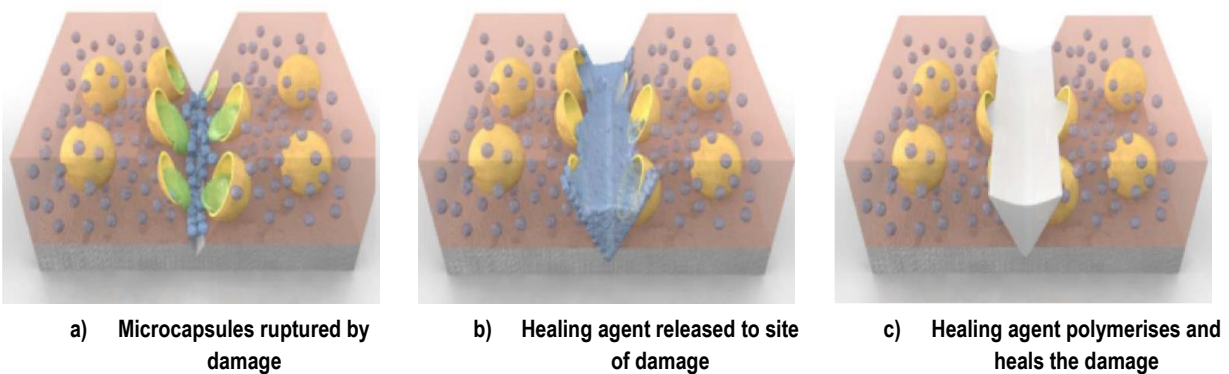


Source: Puzenat (2009).

Microencapsulation

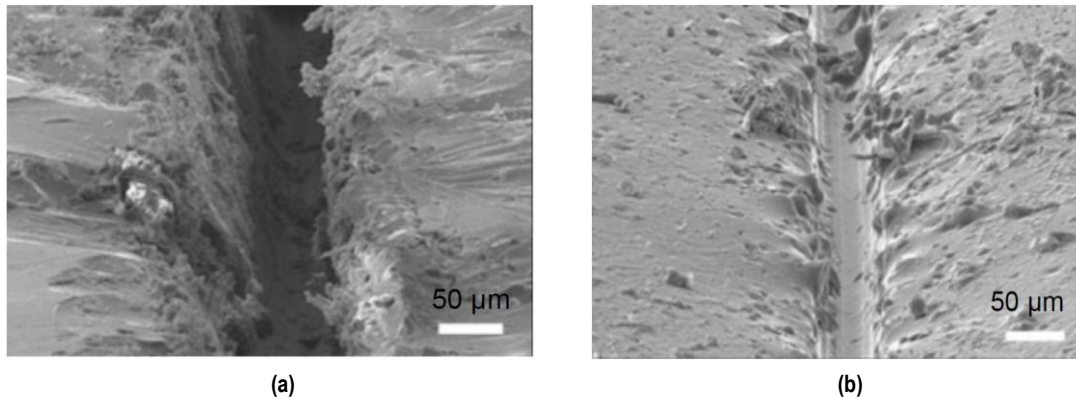
Microencapsulation is a process of enclosing particles at the microscopic scale with a thin coating agent around the particles. In the past decade, research has been carried out using the microencapsulation technique to heal the micro-cracks generated through the concrete. The basic explanation of this method is that micro-capsules rupture after the generation of cracks in the coating layer due to shear stresses releasing the encapsulated healing agent into the cracks. The availability of enough microcapsules is the most important step in embedding them as a self-healing agent in the concrete (Noh & Lee 2013). The self-healing process using the microencapsulation technique is shown in Figure 4.8, whilst a microscopic scale of the comparison between two scenarios of materials with and without embedded microcapsules is shown in Figure 4.9.

Figure 4.8: Schematic self-healing process using microencapsulation technique



Source: Adapted from Pianoforte (2013).

Figure 4.9: Nano-scale pictures of material a) without and b) with encapsulated healing agent



Source: Adapted from Pianoforte (2013).

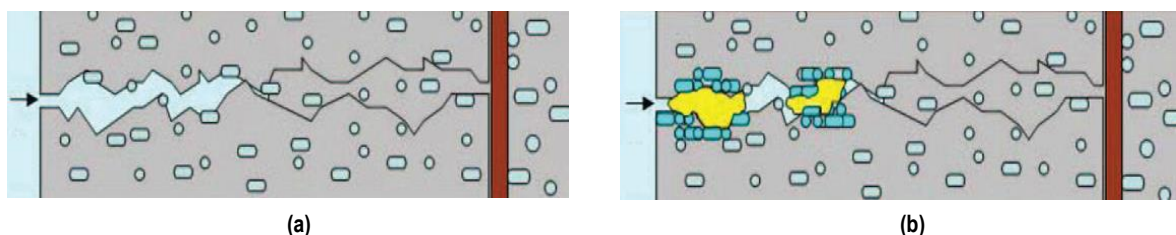
The microencapsulation technique has the potential to address micro-cracking problems in concrete structures such as bridge piers and columns (Birgisson et al. 2012). It was also reported by Yang et al. (2010) that test results on the self-healing performance of cementitious composite with embedded microcapsules containing encapsulated oil with a coating layer of silica were very promising. These microcapsules can be used together with carbon nanofibers.

Embedded Bacteria

Embedded bacteria can be defined as the process when water ingresses into the micro-cracks and activates the embedded bacteria, resulting in the generation of limestone which fills the micro-cracks. Concrete containing embedded bacteria is referred to as 'bio-concrete'.

When cracks propagate through the structure and water ingresses to the generated cracks, the spores of bacteria commence a chemical process and water, oxygen and other nutrients start to convert the soluble calcium lactate into insoluble limestone. The limestone then seals the propagated cracks. The other reported benefit of using this method is a decrease in the rate of corrosion in reinforcement steel as the majority of oxygen is consumed by embedded bacteria. A schematic process of the healing in bio-concrete is shown in Figure 4.10.

Figure 4.10: Schematic process of self-healing in bio-concrete: a) water ingress through the cracks in the concrete; and b) active bacteria seals the cracks by producing limestone and protects the steel reinforcement from corrosion



Source: Adapted from Arnold (2011).

The Engineering and Geosciences Faculty at Delft University has been studying bio-concrete since 2006. A particular type of bacteria called *Bacillus* is mixed with calcium lactate, nitrogen and phosphate. It was claimed by Arnold (2011) that these self-healing agents are able to remain in concrete for up to 200 years.

The major shortcoming of this approach is that the cost was almost double the cost of the conventional concrete prepared in laboratory scale (Arnold 2011).

4.3 Summary and Recommendations

The application of nanotechnology techniques and nanomaterials in asphalt and concrete pavements is currently being researched. However, it has yet to be commercialised for the following reasons:

- Nanotechnology is a new area of research and the cost of the complex equipment required to undertake the work, and the purchase price of the materials, is relatively high.
- The potential environmental risks associated with the use of nanomaterial in pavements needs to be investigated, as nanoparticles could generate harmful particles into the air and ground water.
- The majority of the research carried out to date has been at the nano-scale in modified bitumen; larger-scale asphalt investigations are required.

Whilst the application of nanotechnology in pavement engineering has much potential in terms of improving material characteristics, durability, and performance, further investigations and research would be required to address the challenges before it could be commercialised and introduced into widespread practice.

A potential first step for MRWA is determining the likely practice applications and building a program of research around achieving cost effective applications. Based on this review, potential areas for further investigation include:

- The benefits of using modified binders to enhance the performance of asphalt are well known. Previous research has also pointed to improvements in asphalt performance using nanoclay as binder modifiers. Considering that nanoclays are naturally-occurring materials and cheaper than other nano particles, it could be beneficial to investigate the effects of nanoclay-modified binders on asphalt mix performance.
- The self-healing of cracks in concrete pavements has the potential to reduce maintenance costs as well as associated user costs. It could be worthwhile, therefore, to evaluate the role that self-healing agents play in enhancing the properties and performance of concrete pavements or structures.

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5 CONCLUSIONS AND RECOMMENDATIONS

5.1 Solar Pavements

The Western Australian climate is well-suited to capitalise on solar power generating pavements. However, the vast WA road network is primarily comprised of thin bituminous surfacing rather than asphalt surfacing, particularly in rural WA. The review of literature did not uncover any reported use of solar energy generation in pavements consisting of a sprayed sealed surface.

Therefore, deployment of large-scale solar power generating pavement technology is not recommended for MRWA as the technology is very immature and expensive. However, MRWA could consider being an early adopter of Wattway and conducting a trial at a high visibility location subjected primarily to light vehicle traffic. This would allow issues such as power generation and skid resistance to be evaluated at a safe location.

Solar technology is currently utilised by various Australian state and international road agencies to power roadside infrastructure such as lighting and noise barriers. These uses of solar technology implement mature, low-cost options that have been shown to effectively generate energy. Increased use of mature, low-cost solar technology could be considered for WA, particularly to increase safety on the rural road network by enhancing night-time visibility in areas difficult to access with conventional power.

The implementation of solar panel collector technology to charge electric vehicles is currently in the prototype phase. Effective use of solar technology for electric vehicle charging would require enough solar highways and electric cars to be fitted with equipment to enable them to be charged from electric induction plates on the road. There is a potential opportunity for industry collaboration to develop this service. MRWA could work with the RAC on their Electric Highway initiative and other industry partners to trial this technology and engage business partners. This could benefit MRWA as a sustainable initiative supporting the practical use of electric vehicles for road users.

MRWA could consider developing policy to expand its use of solar roadside infrastructure, especially in rural areas to demonstrate its commitment to sustainability and green energy, as well as potentially cutting operating costs. Therefore, it is recommended that a 'solar road development alliance' be formed and a proposal for additional funding to pursue solar pavement technology in WA be drafted. Such an alliance should ideally include tertiary education and industry partners. MRWA could look to develop a document similar to the VicRoads *Renewable Energy Roadmap* that would provide guidance to MRWA's planners and engineers regarding the options for greater uptake of renewable energy generation.

5.2 Recycled Plastic Roads

The use of recycled plastic in flexible pavements has the potential to reduce the environmental impact whilst improving the performance of asphalt. The majority of the studies reviewed as part of the recycled plastic roads technology review were conducted overseas and typically compared the performance of recycled polymer modifiers relative to a generic commercial modifier or unmodified binder. Furthermore, when the performance of recycled polymer modifiers was compared with virgin polymer modifiers, the polymer types were often different, thus making any direct comparisons difficult. Recycled plastics are typically 'plastomers', therefore, it is unlikely that the

elastic properties would be enhanced, which is the principal reason for bitumen modification. General conclusions resulting from the review of recycled plastic roads include:

- The review of literature found that the use of recycled plastic as a bitumen modifier for asphalt were typically conducted to enhance environmental sustainability (i.e. reduce the amount of landfill). Therefore, 'comparable performance' or 'no marked detrimental effects on performance' were often accepted as 'successful outcomes'.
- Literature suggests that no additional equipment or expertise would be required to produce binders containing recycled plastic.
- Similar to virgin polymers, the type and class of plastic used for modification would have to be tailored to WA conditions. Modifiers have been used to achieve optimal binder properties at lower temperatures in England and Canada (maximum temperature in summer: 22°C), whereas the temperatures in WA in summer can reach 50°C. Hence, the type of modifier successfully used in another region may not be appropriate for use in WA, especially where applications were intended for winter performance in climates different to Australia.
- Overall, the performance of pavements containing binders modified with recycled plastic may result in an enhancement of some desirable properties (e.g. rut resistance of asphalt) compared to an asphalt mix containing an unmodified bitumen. However, a conventional PMB is more likely to provide greater benefit over a broader range of applications.
- In general terms, the environmental benefits (i.e. the increased rate of recycling and a reduced amount of plastic entering landfill) appear to be the main driver for using recycled plastic as a binder modifier. However, no studies could be sourced in the literature that addressed health and safety concerns associated with the use of recycled plastics (particularly during the asphalt production and paving stages).

Between October 2016 and December 2016, ARRB conducted a market survey of the main types of plastics recycled in WA to identify any gaps in the plastic waste stream to divert waste from landfill. Documentation of current practices was accomplished through a review of literature, consulting Western Australian government databases on recycling and querying the major industry recyclers based in WA. The three primary types of plastic recycled in Western Australian were high density polyethylene (HDPE), polyethylene terephthalate (PET) and mixed plastics. Based on this review, it can be concluded that it is not currently economically feasible to use recycled plastic in asphalt in WA. Further research could be conducted to identify any gaps in the Western Australian waste stream for use in pavements to divert waste from landfill.

5.3 Nanotechnology-Modified Materials

The relatively recent development of nanotechnology means there are still a number of challenges and limitations that may affect the implementation and commercialisation of nanomaterials in asphalt and concrete pavements, including:

- complex equipment is required for nanomaterial production and undertaking of work which is relatively expensive, as is the purchase price of the materials
- the potential environmental risks associated with the use of nanomaterial in pavements have not been thoroughly investigated, as nanoparticles could generate harmful particles into the air and ground water
- the majority of the research carried out to date has been to determine changes in materials at the nanoscale; therefore, the scalability of the research must be investigated.

Whilst the application of nanotechnology in pavement engineering has much potential in terms of improving materials characteristics, durability, and performance, further investigations and

research would be required to address the challenges before it could be commercialised and introduced into widespread practice. However based on this review and availability of more robust research findings, it would be beneficial for MRWA to further investigate the following potential areas:

- the effects of nanoclay-modified binders on asphalt mix performance
- an evaluation of the role that self-healing agents play in enhancing the properties and performance of concrete pavements or structures.

It is important to note that Queensland TMR is currently researching the strength and durability benefits of modifying bitumen using spinifex nanofibres. MRWA should monitor this research and consider future applications as applicable.

APPENDIX A WESTERN AUSTRALIA ROAD RESEARCH AND INNOVATION PROGRAM (WARRIP)

In late 2015, Main Roads Western Australia (MRWA) and the Australian Road Research Board (ARRB) signed an agreement that strategically targeted a commitment to research and development, technology transfer and capability development. The agreement provides for a stronger commitment to building professional capability and implementing innovative practices that will achieve significant savings for MRWA in total road expenditure and a higher rate of return through targeted research.

The agreement aligns with the strategic goals of both organisations and recognises MRWA's desire to focus on road infrastructure-related research. It will enable MRWA to significantly increase the capability and effectiveness of its specialist technical areas and deliver excellence and better value for every dollar invested.

The purpose of the agreement is to accelerate the implementation of innovative practices by improving the specialist capability of both MRWA and ARRB through a sustained, collaborative program of projects that deliver superior technology and road infrastructure cost-savings for the people of Western Australia (WA).

The agreement will:

- strengthen the existing strong partnership between MRWA and ARRB through the provision of guaranteed, multi-year committed funding for research and development, targeted at meeting the strategic goals of both organisations
- focus on project activities that deliver savings and/or capability development to MRWA, primarily focused in the areas of road pavements and surfacings, asset management and structures
- deliver:
 - significant savings to the MRWA infrastructure delivery plan
 - improved capacity to manage the existing asset, including the use of relevant testing practices
 - a comprehensive and focussed knowledge transfer program that will enhance staff capability
 - more cost-effective project outputs
- allow for management of the agreement to ensure success by:
 - aligning objectives between the parties to ensure outcomes-focused deliverables
 - selecting the most appropriate personnel to undertake the research tasks and providing young engineers the opportunity to improve their expertise
 - delivering agreed projects efficiently and effectively
- ensure that a national discipline is applied to priority WA projects.

A key component of the agreement is the Western Australia Road Research and Innovation Program (WARRIP), a program of research that specifically targets the areas of road pavements and surfacings, asset management and structures. The goal of WARRIP is to facilitate the provision of better-value infrastructure, through the application of research and by bringing proven

innovations into practice. A key element of the program is the need to invest in the technology and systems necessary to gain a better knowledge of the condition and capacity of MRWA's current and proposed future assets.

WARRIP is a rolling four-year program of work. Agreement Managers propose and prioritise projects and project teams are set up to deliver individual projects, with the Project Leader appointed by ARRB and MRWA providing the Project Manager. A project and program management system, which is jointly managed by MRWA and ARRB, tracks delivery performance and facilitates the preparation of finance and key performance indicator (KPI) reports for consideration by the Agreement Board.