REAAA Technical Report

Compendium on Pavement Maintenance and Rehabilitation Practices

Working Group/Review Panel on QA of Pavement Structures & REAAA Pavement Technology Committee
on behalf of REAAA Pavement Technology Committee

Dr Keizo Kamiya & Kieran Sharp

REAAA Technical Report TC-13

REAAA Project: QA of Pavement Structures

REAAA Technical Report TC-13 – December 2025

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REAAA Technical Report TC-13

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COMPENDIUM ON PAVEMENT MAINTENANCE AND REHABILITATION PRACTICES

REAAA 2025
Kuala Lumpur, Malaysia

REAAA Profile

The Road Engineering Association of Asia and Australasia (REAAA) promotes the science and practice of road engineering and related professions in the Asia-Pacific region through the development of professional and commercial links within, and between, countries in the region. REAAA Chapters have been set up in Australia, Brunei, Korea, Malaysia, New Zealand and the Philippines. REAAA is also active in Indonesia, Japan, Singapore, Taiwan and Thailand.

REAAA was established in June 1973 with a permanent secretariat in Malaysia. Currently there are more than 1,200 members in 23 countries. It holds regular events including two Governing Council meetings each year, business forums, a quadrennial international conference, technical visits and study tours, trade exhibitions, seminars, forums and workshops. It also published technical reports addressing issues of concern in the region and a Newsletters twice each year.

REAAA Technical Reports

This is the thirteenth in the series of Technical Reports since the first report was published in 2008. The following Technical Reports have been published to date:

TC-1 Guide to privatisation of expressways and highways

TC-2 Disaster risk management

TC-3 Efficient operation of the road network

TC-4 Road safety – make it happen

TC-5 Pavement durability

TC-6 Guide to the public-private partnership of road and highway projects

TC-7 Incorporating Japanese pavement design practice for a community road in Mongolia

TC-8 Pavement maintenance and rehabilitation practices

TC-9 Compendium on pavement recycling

TC-10 Report on FEHRL scanning tour to South Korea and Japan: infrastructure resilience

TC-11 Compendium on pavement structural design and rehabilitation methods

TC-12 Incorporating Japanese pavement design practice for a community/local road in Myanmar

TC-13 Compendium on pavement maintenance and rehabilitation practices

TC-14 Vulnerable road users: safety status among REAAA countries

TC-15 Technical report on resilience and disaster management: iCHE2024, Thailand

REAAA Technical Sub-Committee: Pavement Technology

The REAAA Pavement Technology Committee (PTC) is one of three sub-committees reporting to the Technical Committee. It was established at the 108th Governing Council meeting in Brisbane, Australia, in May 2018. The first meeting focussed on the topics to be dealt with by the sub-committee. The committee has managed the publication of several technical reports since its foundation. Cooperation with, and reference to, the relevant PIARC committees has also been maintained so that collaborative activities of mutual interest to both REAAA and PIARC can be addressed.

Membership of REAAA Working Group: QA of Pavement Structures

Member	Organisation
Dr Keizo Kamiya	NEXCO Central (Chair)
Mr Kieran Sharp Dr James Grenfell	Ex-officio Chair REAAA Technical Committee Chair REAAA Technical Committee
Mr Kazunari Hirakawa	Japan Road Association
Mr Masahiko Iwama	NIPPO Corporation
Mr Atsushi Kawakami	Public Works Research Institute
Mr Yasumasa Torii	Japan Road Association
Mr Toshiyuki Nakamura	Japan Road Association

Membership of REAAA Pavement Technology Committee (2022-2025)
Including Cooperation with PIARC Committee: TC.4.1 – Pavements

Chapter/Country	Member	Organisation
Chair (Japan)	Dr Keizo Kamiya	NEXCO Central
Australia	Dr Didier Bodin[1]	National Transport Research Organisation
	Dr James Grenfell	National Transport Research Organisation Chair, REAAA Technical Committee
	Dr Michael Moffatt	National Transport Research Organisation
	Mr Andrew Beecroft	HDR
Brunei	Mr Rafitra Razak	Public Works Department
Indonesia	Mr Hedy Rahadian	Ministry of Public Works
	Dr Herry Vaza	Indonesian Road Development Association
Japan	Mr Kazunari Hirakawa	Japan Road Association
	Mr Masahiko Iwama	NIPPO Corporation
	Mr Shunsuke Tanaka	Public Works Research Institute
	Mr Yasumasa Torii[2]	Japan Road Association
Korea	Dr Sueng-Hwan Han	Korea Expressway Corporation
	Dr Junyoung Park	Korea Expressway Corporation
	Mr Insoo Yeo	Korea Road Association
Malaysia	Mr Hamzah bin Hashim	Public Works Department
New Zealand	Mr Thorsten Frobel	Downer
Philippines	Mr Abdulfatak A Pandapatan	Department of Public Works and Highways
Singapore	Ms Leong Yin Fong	Land Transport Authority
	Dr Nyunt Than Than	Land Transport Authority
Taiwan	Professor Yu-Min Su	National Kaohsiung Univ. of Science & Technology (NKUST)
	Mr Jiun-Iue Gau	Freeway Bureau, MOTC
	Prof. Jia-Ruey Chang	National Ilan University
Thailand	Dr Montri Dechasakulsom	Department of Highways
	Dr Auckpath Sawangsuriya[2]	Department of Highways
REAAA Secretariat	Ms Zalilahwati bt Latif (Ila)	REAAA
PIARC	Mr Shigeki Takahashi[1]	Kanazawa Institute of Technology
Observer	Mr Kieran Sharp	Ex-officio Chair of Technical Committee

1 Member of PIARC Committee TC.4.1 (Pavements). 2 Advisor.

SUMMARY

The rehabilitation of damaged pavements in urban or rural areas is an important issue for each member country. The purpose of an initiative managed by the REAAA Pavement Technology Committee (PTC) was to investigate the challenges faced, and practices used, in member countries to improve the life of damaged pavements, by focusing on factors such as structure, mix design, materials, repair techniques, etc. It was proposed that case studies of practices that have been used, or trialled, to rehabilitate damaged pavements in urban or rural areas be collated so that experiences and knowledge on pavement maintenance and repair practices in REAAA member countries could be shared.

The following three topics were suggested as the focus of the compendium:

1. pothole technology
2. recycling technology
3. pavement resilience.

This report presents the 11 papers submitted by authors from six REAAA member countries in support of this initiative.

ACKNOWLEDGEMENTS

The input from the member countries who provided papers addressing the key issues is gratefully acknowledged.

Contents

1 INTRODUCTION

The REAAA *Pavement Technology Committee* (PTC) was formed during the 108th REAAA Governing Council meeting, held in Brisbane, Australia, in May 2018. It arose out of REAAA Technical Sub-Committee TC-2 (Pavements), which was one of eight Technical sub-committees established at the 90th meeting of the REAAA Governing Council in April 2010 when it authorised its *Strategy Map & Initiatives (2010-2012)*.

During its first cycle from 2010 to 2013, Committee TC-2 addressed the issue of ‘pavement durability’. The Committee organized a workshop on that theme during the 14th REAAA Conference in Kuala Lumpur in March 2013. A *Compendium on pavement durability* (TC-5) was published in July 2015 and an REAAA technical report (TC-7) titled *Incorporating Japanese pavement design practice for a community road in Mongolia*, was lodged on the REAAA website in November 2015.

During its second cycle from 2013-2017 the sub-committee addressed ‘Pavement maintenance and rehabilitation practices’ as its main theme, with ‘recycling of pavement materials’ included as a sub-theme. An REAAA technical report *Pavement maintenance and rehabilitation practice* (TC-8), and a *Compendium on recycling of pavement materials* (TC-9) was published in 2017.

Dr Keizo Kamiya was appointed Chair of the PTC in 2018 as he had been a member of the previous Technical Sub-Committee TC-2 (Pavements), which was led by Japan, and also because he was the Japanese member of PIARC Committee TC D.2 (Pavements).

The goals of the PTC reflect issues of major concern in REAAA member countries and also the need to be in line with PIARC Strategic Theme D (Infrastructure) which was operating at that time (2018):

1. Investigate the challenges and incentives used in different countries to encourage the use of methods and materials that minimize the use of natural resources, reduce energy consumption and emissions, and improve health impacts during the lifetime of pavements (recycling, low temperature mixes/warm mix asphalt, new binders/aggregates).
2. Evaluate available technologies and practices for better sustainability and management of low-cost pavement systems.
3. Review the use of technology such as laser, image processing, etc. in pavement monitoring and evaluation techniques; and, ideally, contribute to the state-of-the-art report on road condition monitoring and road/vehicle interaction to be presented at the SURF Symposium in Brisbane in May 2018.

In line with these goals, the PTC sought approval from the REAAA Technical Committee and the REAAA Governing Council to develop a compendium on the current practices adopted by each member country for the maintenance and rehabilitation of their highway and urban pavements.

The rehabilitation of damaged pavements in urban or rural areas is an important issue for each member country. The purpose of the study was, therefore, to investigate the challenges faced, and practices used, in member countries to improve the life of damaged pavements, with the focus to be placed on factors such as structure, mix design, materials, repair techniques, etc. It was proposed that case studies of practices that have been used, or trialled, to rehabilitate damaged pavements in urban and rural areas be collated so that experiences and knowledge on pavement maintenance and repair practices in REAAA member countries could be shared.

The following three topics were suggested as the focus of the compendium:

1. pothole technology
2. recycling technology
3. pavement resilience.

This report presents the 11 papers submitted by authors from six REAAA member countries in support of this initiative.

2 CONTENT OF COMPENDIUM

The titles of the 11 papers submitted by authors from six REAAA member countries are as follows.

Pothole Technology

1. Hot-in-place Recycling Patching Technology in Taipei City
   Jia-Ruey Chang, National Ilan University, Taiwan
   Kun-Hu Lin, Public Works Department, Taiwan
   Po-Sen Yang, Saint-Dong Building Production and Service Inc., Taiwan
   Su-Wun Chou, Saint-Dong Building Production and Service Inc., Taiwan
2. Malaysia National Case Study: Cold Mix Standard For Pothole Patching
   Hamzah Bin Hashim, Public Works Department, Malaysia
3. All-weather, Highly-Durable Cold Asphalt Mix for Pavement Repair
   Akihito Hirota, formerly Central Research Institute, Seikitokyu-Kogyo Co. Ltd, Japan
   Hiromi Murai, Central Research Institute, Seikitokyu-Kogyo Co., Ltd, Japan
   Tsutomu Gento, Central Research Institute, Seikitokyu-Kogyo Co., Ltd, Japan

Recycling Technology

4. Use of Steel Slag Aggregates and Crumb Rubber in Asphalt Mixes
   Than Than Nyunt, Land Transport Authority, Singapore
5. Study of the Effects of Repeated Recycling for Asphalt Pavements in Japan
   A Kawakami, Public Works Research Institute, Japan
   H Nitta, Public Works Research Institute, Japan
   Y Kawashima, Public Works Research Institute, Japan
   M Yabu, Public Works Research Institute, Japan
6. Excellence in Pavement Recycling and Stabilization In Local Government In Australia
   Nick Ryan, Stabilised Pavements of Australia

Pavement Resilience

7. Pavement Resilience of National Highway No. 117: Nakornsawan – Nongtao, Thailand
   Auckpath Sawangsuriya, Department of Highways, Thailand
   Manoth Chaosuan, Department of Highways, Thailand
   Lee Ching Hua, Mattech Co. Ltd, Thailand
   Sathapat Daolert, TenCate Geosynthetics (Thailand) Ltd, Thailand
   Apiniti Jotisankasa, Kasetsart University, Thailand
8. Development of a New Test Method Applying Pore Water Pressure for Evaluating Interlayer Bonding Properties of Asphalt Pavements
   Hiroki Takebayashi, Nippon Expressway Research Institute Co. Ltd, Japan
   Shigeki Takahashi, Nippon Expressway Research Institute Co. Ltd, Japan
   Koki Bamba, Nichireki Co. Ltd, Japan
   Toshiyuki Chikamatsu, Nichireki Co. Ltd, Japan
9. Reformation of Bridge Slab Maintenance: Development of Specialized Waterproofing Materials for Manual Pavement Work
   Gaku Suzuki, Central Nippon Highway Maintenance Nagoya Co. Ltd, Japan
   Yuki Hiramatsu, Central Nippon Highway Maintenance Nagoya Co. Ltd, Japan
10. Foamed Asphalt Pavement Recycling in Canberra, Australia
   Alvaro Amorim, Transport Canberra and City Services (TCCS), Australia
   Davina Smith, Stabilised Pavements of Australia Pty Ltd (SPA), Australia

11. Improved Design and Construction Methodology for Urban Local Roads in Flood-prone Areas
    Scott Young, Stabilised Pavements of Australia Pty Ltd (SPA), Australia
    Zach Fryer, Byron Shire Council, Australia
    Andrew Middleton, Stabilised Pavements of Australia, Pty Ltd (SPA), Australia

The papers are now presented in order.

3 POTHOLE TECHNOLOGY

Hot-In-Place Recycling Patching Technology in Taipei City

Jia-Ruey Chang, Professor, Graduate Institute of Architecture and Sustainable Planning, National Ilan University, Taiwan[1]

Kun-Hu Lin, Director, New Construction Office, Public Works Department, Taipei City Government, Taiwan[2]

Po-Sen Yang, Chairman, Saint-Dong Building Production and Service Inc., Taiwan[3]

Su-Wun Chou, Deputy General Manager, Saint-Dong Building Production and Service Inc., Taiwan[4]

Background

Traditionally, a damaged road profile is often improved milling the road surface and then overlaying with asphalt. In addition to creating multiple patches and causing unevenness, this construction process often requires large-scale machinery that occupies a large area of the road and blocks traffic. Moreover, noise, air pollution, and construction waste are produced due to repeated milling and overlay, which affect the quality of the environment and does not conform to the concept of environmental protection.

Taipei City pioneered the introduction of hot-in-place recycling patching technology in 2016. The New Construction Office, Public Works Department, purchased a hand-push hot-in-place recycling patching machine in 2017, as shown in Figure 1(a). It was the first maintenance unit in the country to use hot-in-place recycling patching technology. However, the hand-push hot-in-place recycling patching machine can operate in a small construction area. In addition, due to continuous heating, the surface of the road can become scorched without an adequate heating depth being achieved, and smoke can also be generated due to overheating. In 2019, a large-scale hot-in-place recycling repair unit (PM220) was purchased, as shown in Figure 1(b). Hot-in-place recycling repair equipment is suitable for roads where it is difficult for heavy equipment to enter or where there is concern about environmental noise. It is appropriate in applications such as potholes, depressions, rutting, alligator cracking, cracking, ravelling, grooving, and thin overlay separation in urban roads and alley roads.

Hot-in-Place Recycling Patching Technology

Technical Features

Hot-in-place recycling repair is a high-efficiency, energy-saving, and environmentally friendly asphalt concrete repair technology. Using the intermittent radiant heating technology, the road surface is not burnt with an open flame. As a result, the original characteristics of the asphalt can be retained and the service life of the road can be extended.

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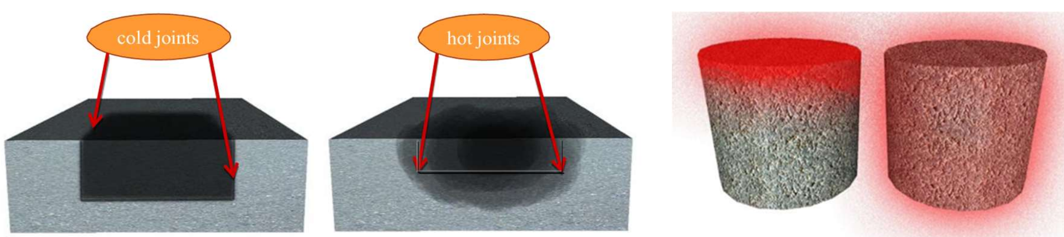
(a)

(b)

Figure 1: Hot-in-place recycling patching technology:
(a) Hand-push hot-in-place recycling patching machine; (b) Hot-in-place recycling repair unit

If directly heated by the flame from above, the surface will become overheated and the asphalt surface layer will be damaged due to aging (Figure 2, left). However, if intermittent radiant heating is used, the surface of the pavement can be evenly heated (Figure 2, right).



Traditional repair **Heating repair**

Figure 2: Advantages of hot-in-place recycling patching technology:
(a) evenly heated by intermittent radiant heating; (b) cold joints can be avoided

The operation is simple and efficient, and the heating time can be set. The road surface can be heated to a working temperature of 170-200°C after 8-10 minutes. Intelligent control, with solar charging and an automatic electronic ignition device, addresses safety concerns such as gas leakage caused by flameout. It is safe and reliable to use and it is lined with heat-insulating material to prevent the operator from being scalded by the high temperature of the shell during the combustion process.

Technical Advantages

The main advantages of the system are as follows.

- Good repair effects and strong water resistance: the repaired area and the surrounding area are heated at the same temperature to avoid cold joints and repair gaps, as shown in Figure 2.

- Recyclable, dust-free, and disposal-free: the original asphalt is heated and reused, leading to a saving in new asphalt because only a small amount of new asphalt is added to reduce waste of raw materials and waste disposal costs.
- Short repair time and reduced traffic impact: it only takes 15-20 minutes for one person to complete a repair, and generally traffic can be restored within 30 minutes of a single repair.
- Few construction tools, environmental protection, and minimum noise: construction does not require cutting tools, milling, transportation, and waste removal, and exhaust gas emissions and noise pollution are not generated.
- Low repair cost and high economic benefit: by saving raw materials, manpower, time, and equipment, the cost of the repair is reduced, the quality is more stable and durable, and the overall economic benefit of road repair can be effectively improved.

Differences Between Hot-In-Place Recycling Patching Technology and Traditional Saw-Break-fill

In traditional saw-break-fill methods such as pothole repair, the technique of breaking the original pavement around the pothole after square cutting is often used, as shown in Figure 3. The process involves:

- drawing a cutting line on the pavement around the pothole
- using a hydraulic pick hammer to break the surface materials
- removing the scrap materials and cleaning the repaired area
- spraying a tack coat
- filling the hole with new asphalt
- manual levelling and compaction.

The sides and lower layer of the broken pavement and the new asphalt will be bonded together using a tack coat. However, the sides and lower surface of the pavement are at room temperature, and the new hot asphalt will cool and shrink after contact. Therefore, it is easy for weak interfaces and gaps to form. Rainwater can then infiltrate into the asphalt, causing fall-off, with the potential for the pothole to reappear.

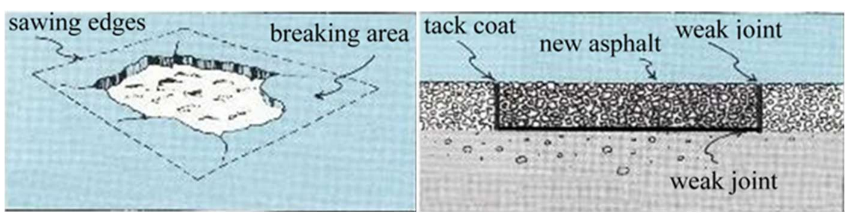


Figure 3: Traditional pothole repair method

While hot-in-place recycling patching technology for pothole repair involves sawing and breaking-free, heat is used to soften the asphalt on the road surface while retaining and using the original asphalt. As a result, the asphalt on the original side and lower surface is also hot. When laying new hot asphalt, both the new and original asphalt are at a high temperature that is close to each other, resulting in a good thermal bonding effect being achieved, and the asphalt is fused together in a manner similar to welding. This reduces the generation of weak interfaces and gaps, and the strength can be improved. Like a newly-paved road, it is difficult for the pothole to reform, as shown in Figure 4.

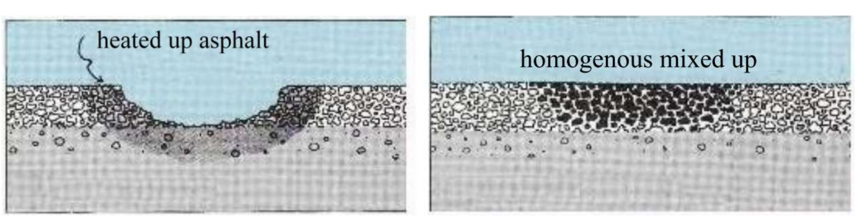


Figure 4: Hot-in-place recycling patching technology for pothole repair

Construction

The hot-in-place recycling repair construction process using the PM220 is shown in Figure 5(a) to (f), whilst the self-check form for hot-in-place recycling patching projects is provided in the Appendix. The process is as follows:

a) Drive the repair vehicle to the damaged location, start the power supply and hydraulic system, and lower the transformable heating panel onto heat the road surface.
b) After softening the asphalt on the surface, close the transformable heating panel, lay down the iron rake, and start the self-propelled iron rake to scarify the road surface
c) Spray emulsified asphalt.
d) Open the dual hoppers with the heating and keeping functions and fetch new asphalt mix.
e) Add new asphalt mix to the road surface.
f) After manual levelling, use a VR50 single-drum vibratory roller to compact the repaired road surface.

The road is opened to traffic after the road surface cools down.

(a) (b) (c) (d) (e) (f)

Figure 5: Hot-in-place recycling repair unit PM220 in operation

Cost-benefit Analysis of Hot-in-place Recycling Patching Technology

The construction cost and production capacity of the PM220 is analysed as follows:

- Materials: 1.7 kg of liquefied petroleum gas (LPG) (fuel consumption of approximately 1 kg/m^2). The average rate of spraying of the emulsified asphalt is approximately 0.5-1.0 L/m^2, and the new asphalt mix is approximately 30-40 kg/m^2 (500 mm surface course).
- Three to four workers: drivers, equipment operators, construction workers.
- A single repair area ranges from 2-10 m^2, and each repair takes about 20-50 minutes. If the repaired area is less than 4 m^2 in area, then it takes only 20-30 minutes to complete the entire repair work.
- One PM220 loaded with new asphalt can repair: an insulation silo having a volume of 2 m^3 can hold 3 t of hot asphalt mix. This can be used to repair an area of about 70 m^2.
- The number of repairs per day depends on the concentration, or dispersion, of the damaged locations. If the damaged locations are relatively concentrated and there is no need to continuously move the equipment, then large-area repairs can be conducted. An area of 10 m^2 can be repaired at one time, which takes about 20-50 minutes. It is estimated that the daily production capacity is about 40-60 m^2 (not including workers' rest time). If the damaged areas are small but scattered, it is difficult to quantify the number of repairs in a day.
- The unit price of the PM220 hot-in-place recycling patching technology is approximately TWD 860/m^2 (USD 28/m^2).

Case Studies

Hot-in-place recycling patching technology has been widely used on urban roads in Taipei City since it was introduced by the Taipei City Government in 2016. Examples of the use of the technology in Taipei City in recent years, which demonstrate the practical achievements of the method, are shown in Figure 6.

(a) construction area
2.1 m * 3.5 m = 7.35 m^2

(b) construction area
1.7 m * 1.9 m = 3.23 m^2

(c) construction area
(1.7 m * 1.9 m) * 2 = 6.46 m^2

(d) heating depth = 40 mm
construction area
1.9 m * 1.7 m = 3.23 m^2

(e) construction area
1.7 m * 1.9 m = 3.23 m^2

(f) construction area
1.7 m * 1.9 m = 3.23 m^2

Figure 6: Case studies of hot-in-place recycling patching technology application in Taipei City

Conclusions

Hot-in-place recycling patching technology is one of many road patching technologies. It has the advantages of low cost, low pollution, high efficiency, and high quality. The Taipei City Government continues to encourage road contractors to introduce new construction methods and new equipment into road repair works; trial various new materials and new technologies; identify the best repair method in order to extend the service life of roads; and provide travellers with a more comfortable, smooth, convenient, and safe road environment.

References

Freetech Road Recycling Technology (Holdings) Co. Ltd 2022, Retrieved from http://www.freetech.com.hk/en; Saint-Dong Building Production and Service Inc., Retrieved from https://www.bim- group.com/en.

New Construction Office, Public Works Department, Taipei City Government 2022, Retrieved from https://english.nco.gov.taipei/

Appendix: Self-check Form for Hot-in-place Recycling Patching

Project			
Sub-project	Hot-in-Place Recycling Patching	File No.	
Third party		Date of examination	YYYYMMDD Time:
Location			
Construction procedure	□ before construction □ during construction □ after construction		
Results	【○】approved 【×】deficiencies/to be corrected 【/】not applicable		

Check item	Check standard of design drawings and specifications (quantitative/qualitative)	Actual status (describe in value)	Result
Supplier checked?	Reference (File No.)		
Mix design checked?	Reference (File No.)		
Testing data for asphalt concrete	Reference (File No.)		
Environmental survey data (marking lines, induction coils)	Current situation photos, records		
No of construction on rainy days at the construction site	The temperature is above 10°C, the background photo		
Traffic safety facilities and traffic conductors around the construction site	Set up according to regulations? Security personnel are present?		
Ditch cleaning hole (galvanized grille) covered?	Already covered		
Heating and milling for heating machine	Heating 4 cm below the pavement surface up to 170°C, on-site photos		
Old materials and puffy, bad materials, sundries, etc. of the subgrade are removed, dry and free of water accumulation	On-site photo of site showing clean and dry		
Spray emulsified asphalt	Evenly apply the tack coat on the repaired area and the vertical section of the original surface course		
Asphalt mixes	No segregation		
Temperature of asphalt mixes	120°C≦ temperature ≦163°C		
Use compaction equipment to roll to the specified evenness	The height difference shall not be greater than 0.6 cm		
Pavement cooling	Open to traffic when the temperature is below 50°C		
Road cleaning	Asphalt residue removed		

Results of Defect Re-examination:

☐ Complete improvement

☐ Incomplete improvement, fill in Item ________________ in "Non-conforming Product Control Summary Form" to track and improve

Date of Re-examination:

Title of Re-examiner: Signature:

Remarks:

The checking standards and actual checking situation should be specific and clear (for example: the brickwork must be opaque after completion) or quantified size (for example: brick joints 7 mm ~ 10 mm).

Mark "○" for those who pass check, "×" for those who fail, and "/" for items that do not need to be checked.

Serious deficiencies, deficiencies in which, on re-examination, failed to complete the improvement in time, should fill in the "Non-conforming Product Control Summary Form" for tracking and improvement. This form can be archived first.

This form shall be verified and recorded by the on-site engineer or foreman after on-site checks.

Field Engineer (Examiner) Signature	Worksite Directors (Person in Charge of Worksite) Signature

Malaysia National Case Study: Cold Mix Standard For Pothole Patching

Hamzah Bin Hashim, Public Works Department of Malaysia[5]

Introduction

The Road Engineering Association of Malaysia (REAM) (previously known as the REAAA Malaysian Chapter) has been an active member of REAAA since its establishment in 1973. It is also a member of the PIARC National Committee. It has played a pivotal role in the fostering of road engineering practices in Malaysia through its initiatives and documentation produced by its members who represent both the government and private sectors. Through its Technical Committee Group, REAM had produced a number of technical documents for the benefit of the road industry in Malaysia.

The idea of producing a standard for the use of cold mix asphalt was based on the need for the industry to capitalize on the potential of cold mix asphalt and to change how pothole repair and management could be conducted more efficiently in Malaysia. The REAM Technical Committee initiated a project to establish a standard for cold mix asphalt during its term in 2017-2019. Despite delays owing to the Covid-19 virus, the standard was finally launched during the International Pavement Seminar in Kuala Lumpur on 7th March 2023.

Objectives of the Initiative

The objective of this initiative was to develop a standard for the use of cold mix asphalt that could be used by the road industry in Malaysia. Prior to this, there was no agreed standard in use apart from various specifications developed by manufacturers. The main objectives of the initiative were to: develop the crucial parameters for cold mix asphalt; develop a set of testing methods that were suitable and practical for industry; and escalate the status of the standard so it could become comparable to hotmix asphalt to perform permanent patching works.

Team Members

Two tiers of team members were appointed to in produce the document. The first-tier team members were the users of cold mix in their daily operations, including concessionaries of road and contractors involved in road maintenance activities. There were also representatives of Public Works Department (PWD) District Offices that use cold mix to repair potholes. The first-tier group contributed on the issues that they are facing in applying cold mix to address the pothole issue. The team managed to establish a clear direction towards the application of cold mix to produce the intended document.

The second-tier group was the manufacturers of the cold mix. Based on the input from the first-tier group, there were more than 20 local and international manufacturers in Malaysia that actively produce cold mix for local usage. During a series of discussions and engagement, six major cold mix manufacturers actively participated and contributed their personnel, time, resources and reference towards the initiative. Their names and companies were recorded on the document as a gesture of appreciation.

Methodology

Upon forming the committee, mutual agreement on the methodology had to be established. The members shared their resources to achieve an acceptable and agreeable cold mix standard. They were willing to discuss and accept any shortcomings in their manufactured cold mix and raise performance to the agreed standard. However, in order to maintain proprietorship, the committee agreed not to review their mixes but only the performance of their products.

As a kickstart to standardization, manufacturers listed the properties of their products so that the committee could identify the similarities and differences between them – thus establishing a basis for the standard. Since the proprietorship was not the focus but the performance itself, the committee was seeking benchmark parameters that could be used to set the performance standard. The main parameters set were workability, stability, adhesive properties, and stiffness. Nevertheless, the basic properties such as aggregate and bitumen

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were also discussed and standardized. All the cold mix products were then tested for these parameters and the results used to establish the acceptable standard.

Challenges and Solutions

One of the major challenges involved the setting of the reference that could be used to guide the committee to establish the standard. Since this was a new document for the Malaysian road industry, there were no local references, except some literature, that could be used as a guide. The committee agreed to modify the Marshall Method to derive the intended properties of the cold mix. This turned out to be acceptable in terms of both the method and results. Another major challenge faced by the committee was to set the acceptable values of the proposed performance parameters. Following further discussion, the committee achieved mutual understanding on the acceptable values to be used to establish the standard.

Visits to laboratories and committee meetings

Engagement Session

An engagement session involving cold mix manufacturers, road authorities, road consultants, road contractors, researchers and government agencies was carried out on 25th November 2021. Eighty delegates registered to share their input on the draft standard before it was finalized. Opinions and concerns were recorded to be further discuss between committees. In a nutshell, participants were excited to have the standard because it would be a 'game changer' in terms of addressing the pothole issue. Furthermore, it would boost the marketability of cold mix, thus growing the industry for the key players.

Engagement session, 25th November 2021

Final Document

The final draft of the document, *REAM Guidelines on Cold Mix Standard for Permanent Pothole Patching*, was completed in April 2022. The printed document was ready for industry use by December 2022 after going through proof reading and other related printing procedures. It is available in hard copy at REAM office in Shah Alam, Malaysia for RM20 (≈USD4.2). REAM can be reach at ream@ream.org.my.

Launching of the Document

Members of PIARC Committee TC.4.1 ‘Pavements’ organized a meeting of the committee during the International Pavement Seminar (KLIPS2023), held in Kuala Lumpur from 7-9 March 2023. The committee believed that it was a good opportunity for the new document to be launched during the event. The REAM President handed over the document to the Director General of the Public Works Department of Malaysia as a symbol of launching the document and to promote the document to national and international participants. The Deputy Minister of Works Malaysia witnessed the launching, together with representatives from the PIARC Technical Committee and the REAAA Technical Committee. In the same event, a paper entitled ‘Formulating cold mix standard for pothole patching works in Malaysia’ was presented. It described the standard and the journey taken in establishing it. One of the cold mix manufacturers also presented their product that complied with the standard in a paper entitled ‘Performance of all-weather cold mix asphalt reinforced with aramid and polyolefin fibres’.

Launching of the Malaysia Cold Mix Standard

Acknowledgements

The committee would like to thank all the individuals and organizations that directly and indirectly contributed to the development of this document. It highlighted the advantages of cooperation when establishing new technical standards for national adoption. It is hoped that the document will promote further opportunities to enhance the use of cold mix asphalt in road maintenance activities.

All-weather, Highly-Durable Cold Asphalt Mix for Pavement Repair[6]

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Introduction

Generally, in Japan, bagged cold-mix asphalt mixes are used to repair distress in bituminous pavements (e.g. potholes) during warm periods and to generally help to maintain and manage pavements (Hatakeyama, Koshi & Okamura 2019; Hirota & Gento 2021). One reason for this is that the mix can be stored on site and it is readily available when required. The range of treatment methods used are shown in Table 1. In recent years, studies have been conducted to develop a highly-durable, all-weather cold-mix asphalt that develops high strength after construction and can be applied even on wet roads or during rainfall (Koshiba, Kitajima & Gento 2019). However, the mix tends to stiffen at low temperatures, and this causes low workability and brittle fracture, leading to cracking and the scattering of aggregates, especially on roads with heavy traffic.

Table 1: Methods for treating asphalt pavements

Maintenance	Prevention	Repairing
Patching (hot/cold-mix) Sealant grouting	Sealant grouting Surface treatment Thin layer overlay	Reconstruction Mill and overlay Resurfacing

Moisture-hardened mixes can be applied even to submerged potholes. As a result, they are considered suitable for pavement maintenance immediately after snowfall, and thawing, in cold snowy regions. However, carrying out repair work at low temperatures when the viscosity of the asphalt and fatty acid increases, results in decreased workability and durability in mid-winter. Moreover, brittle fracture occurs frequently at low temperatures, leading to cracking and aggregate scattering.

This paper describes a study to develop a cold-mix asphalt that develops a high strength in a short time period, has high durability, and can be used during rainfall. The results of field trials of the mix that was developed are also reported. Testing was conducted on a moisture-hardening mix developed earlier (Koshiba et al 2019).

[6] This paper was awarded a Katahira Award at the 16th REAAA Conference, Manila, Philippines, in March 2021.

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Types of Cold-mix Asphalt Mixes

Conventional cold-mix asphalts are softened by petroleum products such as kerosene oil. Because they need time to harden and are easy to transport, they are often used for temporary repairs. While the mixes harden at temperatures of about 20°C, their strength and durability is inferior to hotmix asphalt so their applications are limited. Studies have recently been conducted to develop all-weather cold mixes that have improved strength and durability and can be constructed even under severe conditions including rainy weather (Gento, Murai & Nakamura 2019). They not only enable construction in poor weather but also have rapid hardenability and high durability properties. The work described in this paper focused on the cold-mix asphalt mixes shown in Table 2.

Table 2: Types of cold-mix asphalt mixes

Types	Features	Application	Softening agent
Conventional	Low cost Slow hardening	General roads Sidewalks	Petroleum product
All-weather	Applicable in rainy weather Relatively rapid hardening	Heavy traffic roads	Drying oil
Moisture-hardening	Applicable in rainy weather Very rapid hardening	Heavy traffic roads	Fatty acid

Results of Laboratory Studies

Hardening Mechanism

The authors chose to use a neutralization reaction for the hardening mechanism. In this process, cement, fatty acid and asphalt was mixed with aggregates in advance, with water added during construction. Cement is hydrated to form alkali, which neutralizes the fatty acid, leading to hardened of the mix during construction. The hardening mechanism is shown in Figure 1.

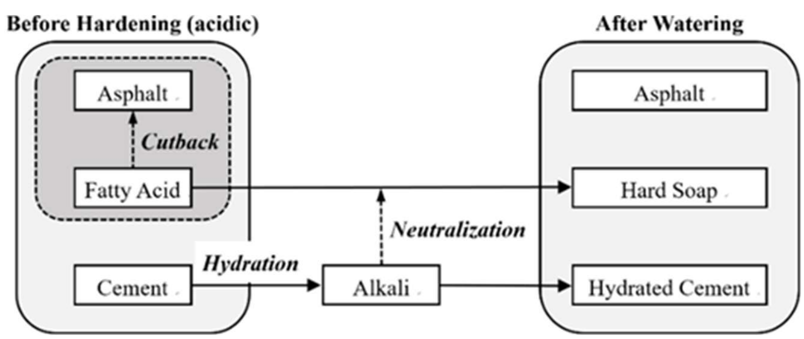

Figure 1: Hardening mechanism adopted in the study

Binder

In order to improve the workability and durability of the moisture-hardened mix, the physical properties of more than ten types of fatty acid were investigated. It was found that the fatty acid used by the authors in an earlier study had a high viscosity at low temperatures and was likely to harden (Figure 2).

Figure 2: High-viscosity fatty acid (–10°C)

It was also found that there were other types of low-viscosity fatty acids that could be used in a low-temperature environment. As a result, a binding material which had a low melting point and low viscosity at –10°C was selected for study. Mixes composed of old and new binders were tested. The results of viscosity testing confirmed that the mix with the new binder had a lower viscosity at low temperatures compared to the old binder (Figure 3).

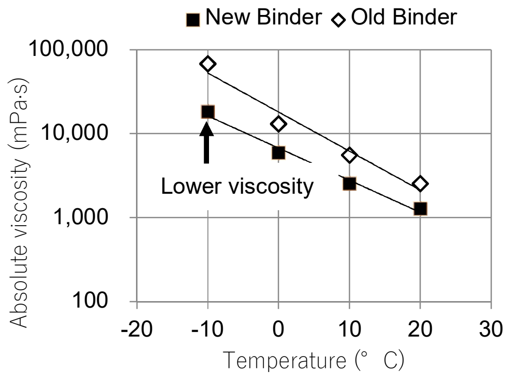

Figure 3: Relationship between absolute binder viscosity and temperature

Additives

The prototype moisture-hardened mix, when mixed with the old binder, became stiff and fragile at low temperatures even if construction was carried out in optimal conditions. As a result, cellulose fibre was chosen as the additive to improve its strength. A range of fibres were selected for study. Each of them was added to the mix and then subject to Cantabro loss rate testing at –10°C. The Cantabro test machine, and the test samples after testing, are shown in Figure 4 and Figure 5 respectively.

The results, shown in Figure 6, showed that the best results were achieved with Fibre 1 and so this was selected as the additive to use in the study.

Figure 4: Los Angeles (Cantabro) machine

Figure 5: Test specimen (fibre 1, –10°C)

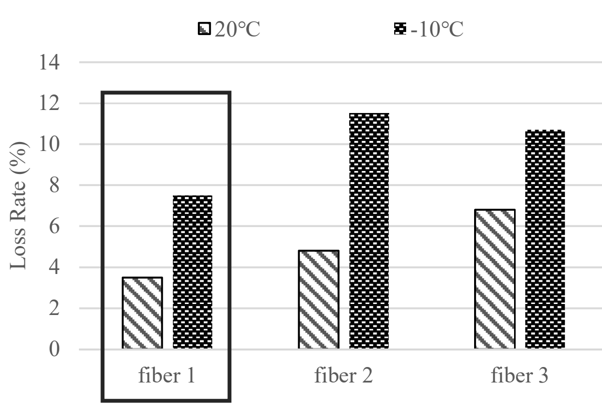

Figure 6: Results of Cantabro loss testing: cold mix including cellulose fibres

Results of Mix Evaluation

Marshall Stability

The stability of the cold mix, including cellulose fibre, was examined using the Marshall Stability test, with the stability measured for different times of adding water. The resulting neutralization reaction leads to the development of the strength of the cold mix. The results of the testing conducted with non-immersed test specimens at 20°C. The results (Figure 7) showed that the fibre-added mix had much better stability than the conventional all-weather mix. This result confirmed that the use of a fibre-added mix enables traffic restrictions to be lifted shortly after construction, much earlier than would be the case with standard mixes.

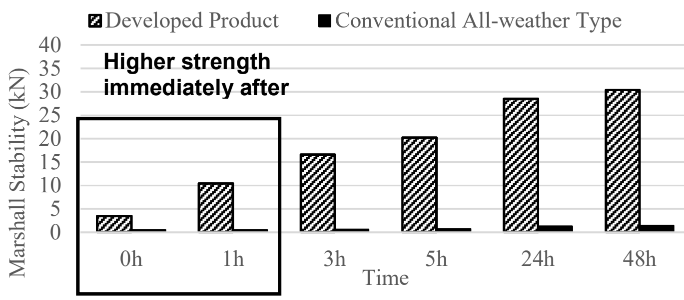

Figure 7: Results of Marshall stability testing at 20°C

Workability at Low Temperatures

The moisture-hardened cold-mix asphalt, which had a high durability at 20°C, was examined using the Raking Workability Test (Gento, Murai & Kakinuma 2017). The procedure, using a modelled rake, is shown in Figure 8 and Figure 9.

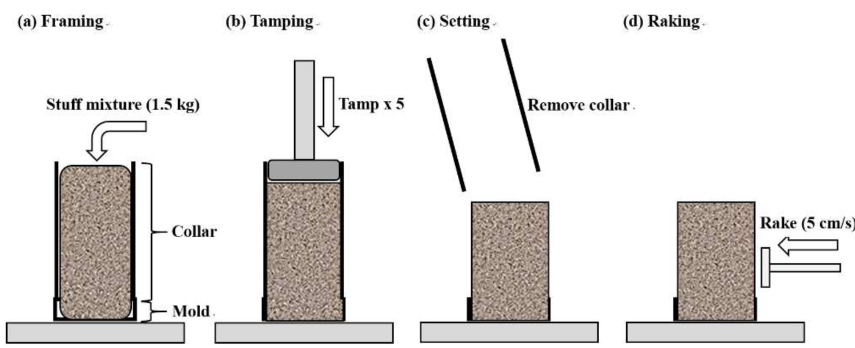

Figure 8: Raking Workability test procedure

Figure 9: Raking Workability test machine

Testing was conducted at four different temperatures. For all temperature ranges, the moisture-hardened mix had a lower maximum load than the prototype mix, meaning that the newly-developed mix had excellent workability (Figure 10).

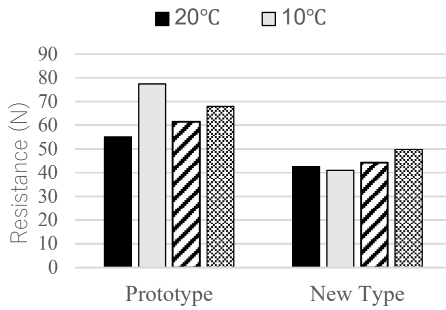

Figure 10: Comparison of maximum load: Ranking test

Durability against Scattering of Aggregates at Low Temperatures

In order to evaluate the durability of the cold asphalt mixes, Cantabro testing was carried out at 20°C and –10°C and the results are shown in Figure . It can be seen that the loss rate/durability of the new mix was much lower than the prototype mix, with the loss rate of the new mix half that of the prototype mix, even at –10°C (Figure 11).

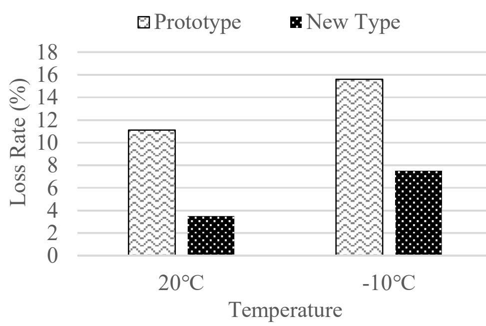

Figure 11: Comparison of loss rate/durability

Application to Existing Roads

Construction Process

The construction procedure for the newly-developed mix is generally the same as for conventional cold mixes. However, the new mix needs 1 Litre of water to be added for every 20 kg of the mix because of its hardening mechanism (Figure 12). It is usually compacted by a tamper but foot stamping is possible.

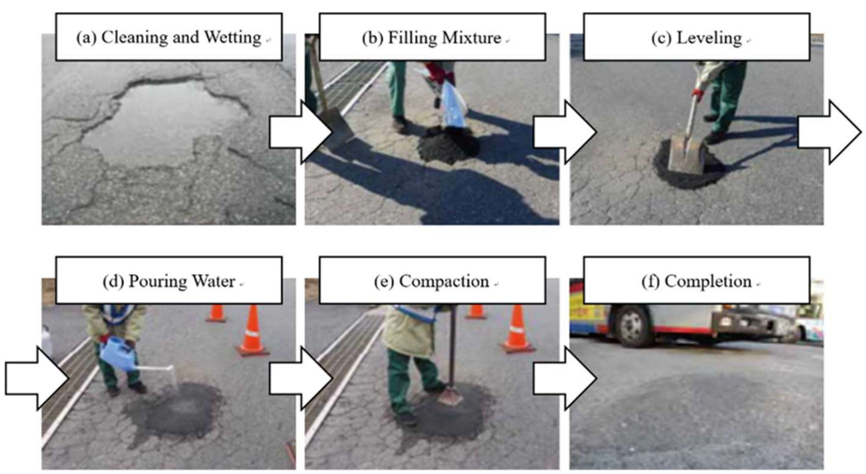

Figure 12: Construction of pavement with new mix

Trial Construction on Road in Japan

In February 2019, a trial construction with the moisture-hardened cold mix was carried out on a heavily-trafficked intersection in Sapporo, Hokkaido. The area requiring repair was almost submerged in melting snow water (~0°C). Nevertheless, It was filled with the moisture-hardened cold mix in that condition. Photos of the intersection before repair are shown in Figure 13 and Figure 14.

Although the temperature was near 0°C on that day, the cold mix did not have any lumps and the workability was good. There was no further pavement distress after two months and the mix continued to perform well until full-scale repair work was conducted one year later.

Figure 13: Intersection 2 months after construction

Figure 14: Close-up view of surface

Trial Construction at Airport in Mongolia

In February 2020, a trial construction with the moisture-hardening cold mix was carried out on a service road in Ulaanbaatar airport in Mongolia. Since the temperature was –20 C, hot water (with and without rock salt) was used for hardening (Figure 15 and Figure 16). The cold mix did not have any lumps and had good workability (Figure 17). Trafficking of the road by a vehicle confirmed that it had hardened enough (Figure 18). The density was measured using two methods: electromagnetic wave (Figure 19), and core sampling. The measured density was 2.26 g/cm^3 (2.26 t/m^3) indicating that a satisfactory degree of compaction had been achieved.

Figure 15: Levelling

Figure 16: Water pouring

Figure 17: Rolling compaction

Figure 18: Driving on repaired location

Figure 19: Density measurement using electromagnetic wave

Summary and Conclusions

This paper has described the development of a highly-workable, moisture-hardened cold-mix asphalt for use in repair work in low temperature environments. The product developed a high level of strength immediately after construction which enabled traffic restrictions to be lifted quickly. The durability at low temperatures was confirmed using the Cantabro Loss Rate Test and performance observed in field trials.

The manufacture of this product has commenced at multiple mixing plants in Japan, and it has been favourably received by users. Work will continue to develop a mix with better workability and durability.

While the work reported in this paper focused on the development of cold-mix asphalt for use in low-temperature environments, it has also been used as well as conventional mixes in warmer environments.

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4 RECYCLING TECHNOLOGY

Use of Steel Slag Aggregates and Crumb Rubber in Asphalt Mixes

Than Than Nyunt, Land Transport Authority, Singapore[10]

Background

The Land Transport Authority (LTA) has been actively exploring the utilization of recycled materials to promote sustainability in road construction and resurfacing projects since the 1990s. These materials include recycled concrete aggregates, which are processed aggregates derived from demolition wastes, steel slag aggregates obtained from steel mills as a by-product, and reclaimed asphalt pavements, which are processed mill waste from road resurfacing projects.

Figure 1 showcases LTA's commitment to green initiatives in the road industry. These initiatives contribute significantly to LTA's goal of creating a more environmentally friendly and sustainable road infrastructure. In addition, the LTA, in collaboration with the National University of Singapore, is currently researching the use of plastic waste in asphalt to promote circular economy principles and sustainability within the road construction industry.

This paper presents details of the successful implementation of an environmentally-sustainable mix – steel slag porous asphalt – in expressway pavements in Singapore. Expressways are high-speed road network in Singapore, with a typical speed limit of 90 km/h, facilitating the smooth flow of traffic and the movement of people and goods within Singapore.

Figure 1: LTA's green journey for road construction

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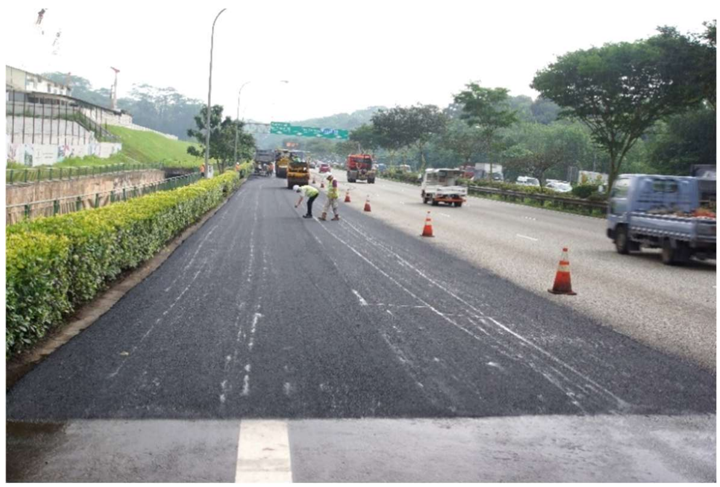
Design and Testing of Steel Slag Porous Asphalt

Porous asphalt contains a high percentage of interconnected air voids (20-25%) to facilitate efficient drainage of surface water during rainfall, thus reducing the risk of hydroplaning. It is commonly employed on high-speed roads, such as expressways, to enhance safety during wet weather conditions. However, the previous version of porous asphalt utilized in Singapore had durability issues due to its high air void content. In order to improve the wet weather performance of porous asphalt (including enhanced skid resistance and reduced splashing for better visibility of road markings during rainy days), a research study was undertaken in partnership with the National University of Singapore and NSL Ltd.

The aim of the research was to enhance the durability of the porous asphalt then being used, and also to improve its wet weather performance. Key design modifications were implemented, including a reduction in air voids to approximately 15% to enhance durability, as well as the incorporation of steel slag aggregates to enhance skid resistance. In addition, the acoustic performance of a new porous asphalt (steel slag porous asphalt) using the on-board sound intensity (OBSI) method was evaluated.

Laboratory testing and field performance monitoring was conducted to assess the effectiveness of the steel slag porous asphalt compared to the older version, as well as another type of asphalt mix commonly used for expressways. The steel slag porous asphalt mix, along with the control asphalt mixes, were paved along the Kranji Expressway (KJE) for performance monitoring in 2012. The field trial and the testing methods employed for performance monitoring purposes is shown in Figure 2.



(a)

(b) **(c)** **(d)**

Figure 2: Trial of steel slag porous asphalt along KJE:
(a) laying of steel slag porous asphalt, (b) sideway-force coefficient machine for measuring skid resistance, (c) laser profiler for measuring riding comfort and wheelpath deformation/rutting, and (d) OBSI test for measuring tyre-pavement noise

After one year of field monitoring, it was observed that the performance of the steel slag porous asphalt (in terms of skid resistance, ride comfort, and rutting) was comparable to that of the old porous asphalt and the traditional asphalt mix used for expressways. Additionally, the steel slag porous asphalt generated a lower level of tyre/road noise compared to the control mixes. Based on these findings, a subsequent research study was conducted in 2017 to further enhance the acoustic performance of the steel slag porous asphalt. This study involved the utilization of crumb rubber/recycled tyres and latex rubber as additives to improve the acoustic characteristics of different types of asphalt mixes.

The research study focused on three asphalt mixes:

- M1 – the traditional asphalt mix used for expressways
- M2 – the steel slag porous asphalt
- M3 – the traditional asphalt mix used for non-expressways.

In total, nine different combinations of asphalt mixes were investigated for performance assessment. Details are provided in Table 1.

Table 1: Summary of asphalt mixes tested

Asphalt mix	Modifier	Symbol
Traditional asphalt mix for expressways	Control: PMB	M1
	Crumb rubber	M1-CR
	Latex	M-L
Steel slag porous mix	Control: PMB	M2
	Crumb rubber	M2-CR
	Latex	M2-L
Traditional asphalt mix for non-expressways	Control: Pen 60/70	M3
	Crumb rubber	M3-CR
	Latex	M3-L

However, as demonstrated in Figure 3, the addition of the rubbers had limited influence in terms of improving acoustic performance. Instead, the main parameters contributing to the lower tyre-pavement noise were the inherent design features of the M2 mix, including the interconnecting air voids and a smaller surface texture. Notably, the M2 mix generated approximately 5 dBA lower tyre-pavement noise compared to the M1 mix at each measured speed.

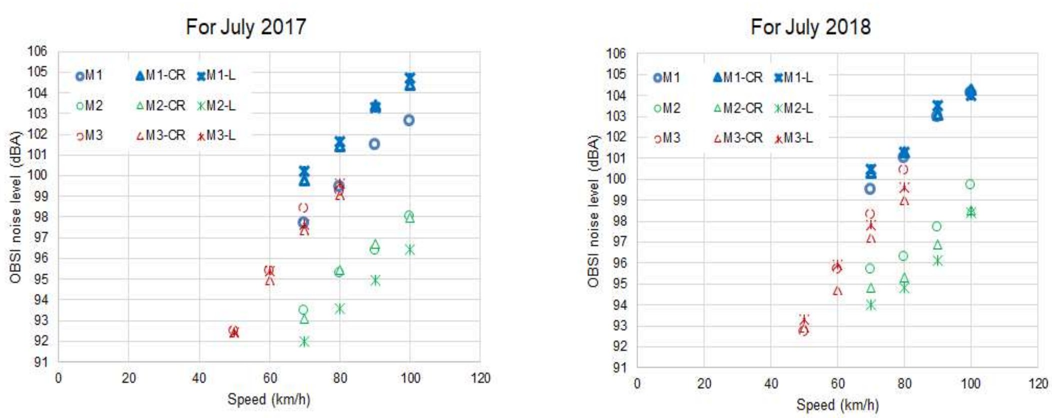


Figure 3: Tyre pavement noise monitoring for three different mixes: (a) data collected in 2017; (b) data collected in 2018

Benefits

The steel slag porous asphalt incorporates three key innovative features that contribute to sustainability:

- enhanced durability compared to standard mixes
- quieter pavement – a noise reduction of ~5 dBA
- utilization of a greener material – steel slag aggregate derived from industrial waste.

Due to its ability to reduce tyre-pavement noise, steel slag porous asphalt has been implemented at selected sections of expressways as a noise mitigation treatment. Currently, 70 lane-km of expressway have been paved using the steel slag porous asphalt, demonstrating its successful adoption and effectiveness in practice.

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Study of the Effects of Repeated Recycling for Asphalt Pavements in Japan

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Y Kawashima, Public Works Research Institute, Japan

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Introduction

Road pavements in Japan, which were constructed rapidly during high economic growth after the Second World War, include a vast quantity of asphalt pavements. Although pavement surfacing material used to be dumped at final disposal sites after the end of their service life, recycling technologies were developed in the early 1970s. Standards were developed in the late 1980s, and asphalt pavement recycling became widely used all over the country. As a result, the rate of recycling of materials from asphalt pavements reached an extremely high level of 98% in 2000, and this recycling rate has been maintained in subsequent years (Figure 1). Asphalt pavement material is now repeatedly recycled, earning it the title, the "honour student" of recycling promotion (Public Works Research Institute 2008).

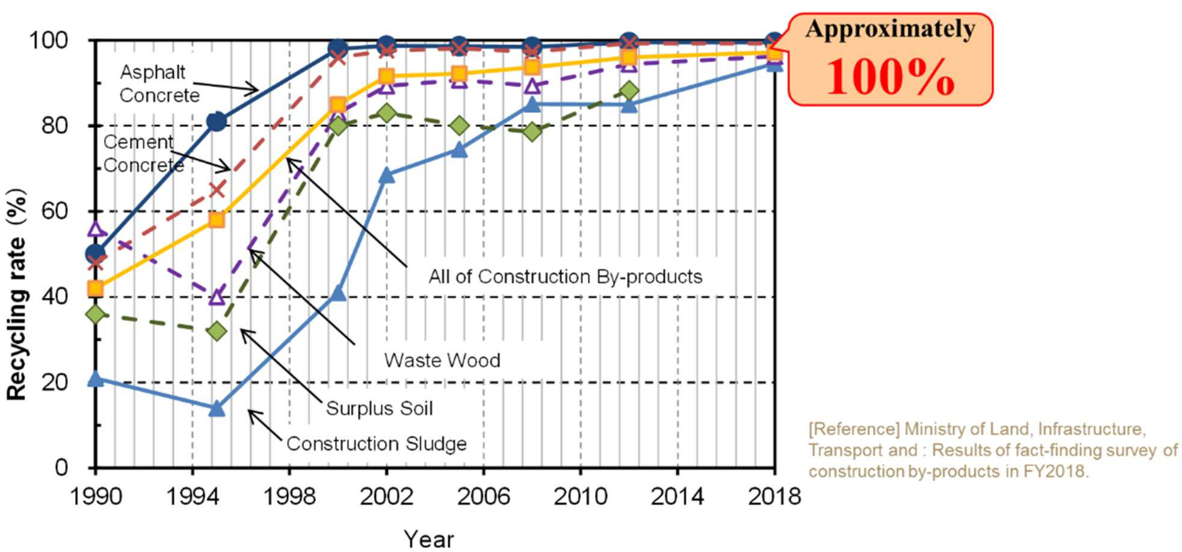

Figure 1: Percentage of recycled resources from construction by-products (Ministry of Land, Infrastructure and Transport 2018)

This high recycling rate has been sustained by a huge number of asphalt mix plants in the country. As of 2021, there were over 1,000 facilities, roughly meaning that one asphalt batch plant is in operation every 20 km across Japan.

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However, and as illustrated in Figure 2, there is a concern about the high usages of reclaimed asphalt pavement materials (RAP), not only in the Kanto region, which includes Tokyo, and also neighbouring areas, which are all using pavements with high RAP contents. This poses a question regarding the effects of rejuvenators in bitumen, which are used in repeated recycling under various compositions that have not yet been clarified.

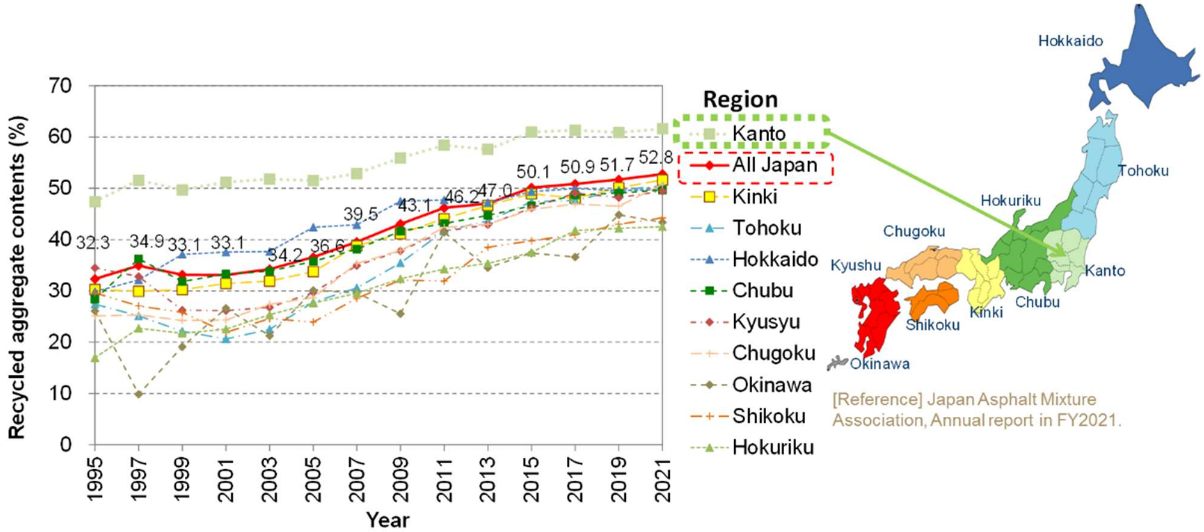

Figure 2: RAP contents in the recycled mix
(Japan Asphalt Mixture Association, Annual report in FY2022)

In this study, three different types of rejuvenators with different compositions, focusing especially on the saturated and aromatic content, were examined in the laboratory. Emphasis was placed on the changes in the properties of the asphalt that had been repeatedly aged and recycled. The full results are available in Kawakami et al. (2023).

Examination Methods

Properties of Bitumen and Rejuvenators

The material properties of the bitumen and the three rejuvenators for recycling used in this research are shown in Table 1. The original bitumen was a straight-run asphalt 60/80 (hereinafter, ORG) which is commonly used in Japan and complies with Japanese industrial standards (JIS). Rej A had a four-component composition with an aromatic content of approximately 90%. Rej B consisted of saturated content and aromatics with contents of approximately 50% respectively. Although not used as a rejuvenating additive, Rej C, which is a mineral oil, was also tested for comparison purposes.

Table 1: Properties of bitumen (ORG) and rejuvenators

Material	Density (g/cm^3)	Penetration (1/10 mm)	Softening point (°C)		Ductility (cm)
Bitumen (ORG)	1.037	70	46.5		Over 100
Rejuvenator A (Rej A)	Density	SARA fractionation (%)			
		Saturates	Aromas	Resins	Asphaltenes
	0.975	5.7	88.1	6.1	0.1
B (Rej B)	0.909	49.9	47.7	2.5	0.0
C (Rej C)	0.863	99.9	0.1	0.0	0.0

Density is often reported in units of t/m^3 in REAAA member countries.

Procedure for Repeat Aging and Recycling

The test procedure for aging and recycling is shown in Figure 3. In order to emphasize the effect of the rejuvenator, and unlike the actual recycling procedure, at the time of recycling, only the rejuvenator was added without any new bitumen. Aging of bitumen was carried out using the Rolling Thin Film Oven (RTFO) test (TFOT) for short-term aging at the asphalt plant using the pressure aging vessel (PAV) test for long-term in-service aging. The aging time for the PAV testing was adjusted to 54 hours so that the penetration value of the ORG reached 20 (Kawakami et al. 2019), as PEN 20 is a criterion for usage in Japan. The aged bitumen was then recycled by adjusting the amount of rejuvenator so that the penetration of the asphalt reached 70. This process was carried out five times for every Rej A, B and C. The recycled bitumen was then mixed with the new aggregate to produce an asphalt mixt specimen.

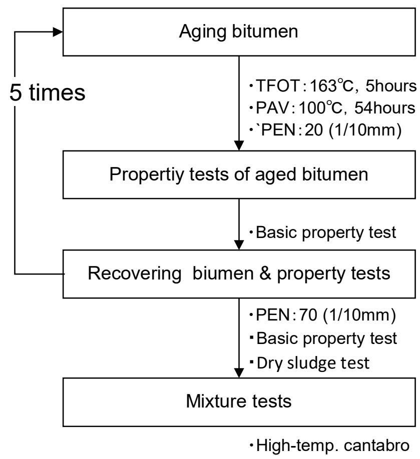

Figure 3: Test procedure for repeatedly aging and recycling bitumen (Kawakami et al. 2019)

Evaluation Methods for Bitumen and Mix

The properties of the bitumen and asphalt mixes that had been repeatedly aged and recycled were evaluated using the material and mixture property tests shown in Table 2. Regardless of the test numbers, all bituminous tests are commonly used globally. In terms of the mix evaluation, since four-point bending testing could not be applied at temperatures above 30°C, the Cantabro test, which is a simplified durability test for porous asphalt mixes, was used instead.

Table 2: Evaluation methods for bitumen and asphalt mixes

Measured property		Test standard
Bitumen property	Needle penetration (1/10 mm)	JARA A041
	Softening point (°C)	JARA A042
	Ductility (mm)	JARA A043
	Saturates, aromas, resins & asphaltenes	JPI-5S-70-10
Mix property	Cantabro loss rate (%) at 60°C	JARA B010

Results

Basic Bituminous Properties

The results of penetration testing of the aged and recycled bitumen are shown in Figure 4. Penetration recovery to 70 was achieved except for Recycling-5 of Rej C. In addition, it was difficult to obtain fluidity of the Age-5 of Rej C, even when heated.

Figure(b) shows the softening point results for the aged and recycled bitumen. Softening point tended to increase as aging and recycling time increased, particularly for those aged with Rej B and C, which had a high degree of saturation. Rej A, which had a higher aromatic content, sustained a constant recyclable level up to 55–65°C, which was relatively close to ORG.

Figure(c) shows the results of the ductility testing of the aged and recycled bitumen. Rej A recovered to about 30 cm in the first and second recycling, while the others hardly recovered. Therefore, it was concluded that the recycled bitumen having a high aromatic content was more advantageous in terms of recovering the ductility, even after repeated recycling. Note, however, that this is a severe test condition, as there is no use of new bitumen, unlike in actual practice.

In conclusion, the softening point increased and the ductility decreased. This indicates that recycled bitumen might become stiff and brittle at high temperatures after repeated aging and recycling. These properties were more pronounced for rejuvenators with higher saturated content than aromatics.

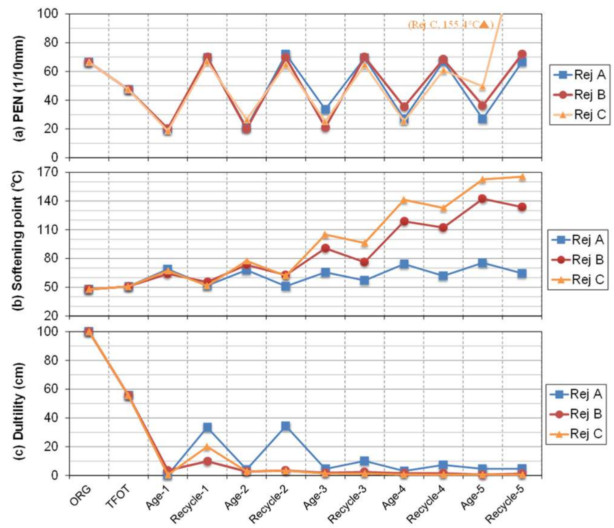

Figure 4: Test results of needle penetration (a), softening point (b), and ductility (c)

SARA Fractionation

The SARA fractionation (four-component composition; saturated, aroma, resin and asphaltene) of the aged and recycled bitumen are shown in Figure 5. As for Rej A having a higher aromatic content, aromatic content was stable at around 40%. In Rej's B and C with lesser aromatic content, aromatics decreased due to repeated aging and recycling, but saturation increased.

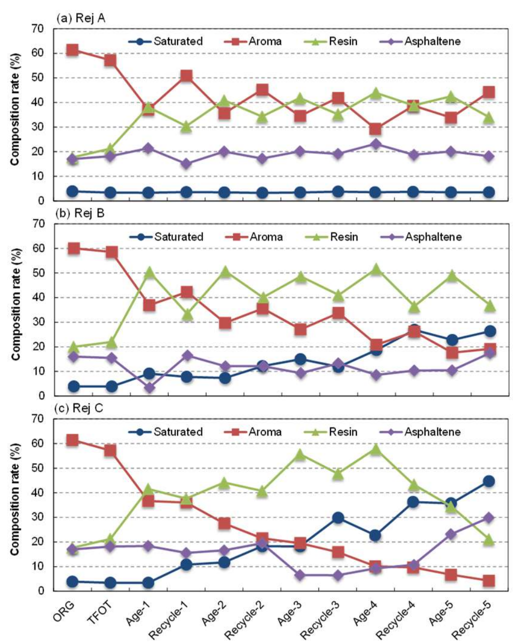

Figure 5: Results of SARA fractionation testing

High-temperature Cantabro Test

The high-temperature Cantabro test loss rate (HCLR) for each recycled mix is shown in Figure. Note that the Recycle-5 mix could not be prepared with only Rej C, so the test results of Recycle-4 are shown in Figure 6. The HCLR of ORG was almost 0%. The Rej A with high aromatic component increased with recycling was comparative to the ORG, in that the HCLR of Recycle-5 was only 6%. On the other hand, the HCLR was about 99% at Recycle-4 for Rej C with high saturation and at Recycled 5 for Rej B, which resulted in almost complete destruction of the specimen.

In conclusion, the adhesive strength of recycled bitumen at high temperatures became weak when the number of times of recycling was too high and when rejuvenators having a high saturated content were used. This is significant, because, if tensile strain near the tyre edge in the low-stiffness condition in midsummer relates to the cause of top-down cracking (Nishizawa et al. 1993), then a mix with a higher HCLR value may be susceptible to top-down cracking.

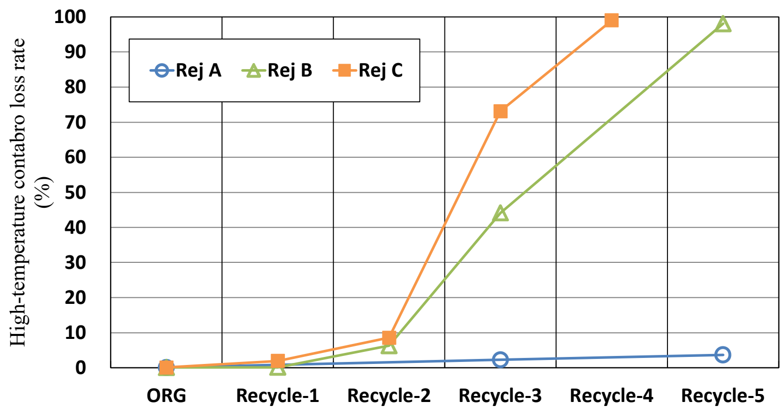

Figure 6: Results of high-temperature Contabro loss rate testing

Conclusions

This paper has described a program of laboratory testing of bitumen and asphalt mixes that had been repeatedly aged and recycled. The main findings of this study were that, after repeated recycling, the bitumen tended to have a higher softening point, lower ductility, and less crack resistance at high temperature. This tendency was greater depending on the type of rejuvenator, especially in the case of a rejuvenator having a high saturates components rather than a high aromatics component.

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Excellence in Pavement Recycling and Stabilization in Local Government in Australia

Nick Ryan, Stabilised Pavements of Australia[12]

Introduction

With limited funds to maintain road assets into the future, Burwood Council in Sydney continues to innovate and push past some previously-held reservations regarding the application of pavement recycling in complex urban environments. Working collaboratively with the contractor to manage and eliminate project risks, the Council has achieved great cost savings and excellent quality pavement rehabilitations to the benefit of the Burwood Council rate payers. One such example is the Everton Road Rehabilitation Works conducted in 2018.

Key Challenges

The key project challenges were as follows.

Weak Subgrade: The contractor was careful to moderate rolling patterns to achieve compaction without destabilizing the entire site.

Multiple buried utilities: Careful utility location and potholing works were performed following strict procedures.

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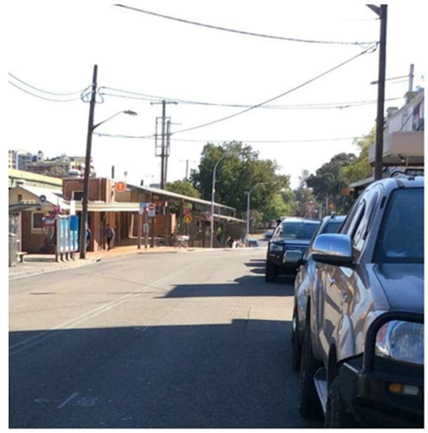
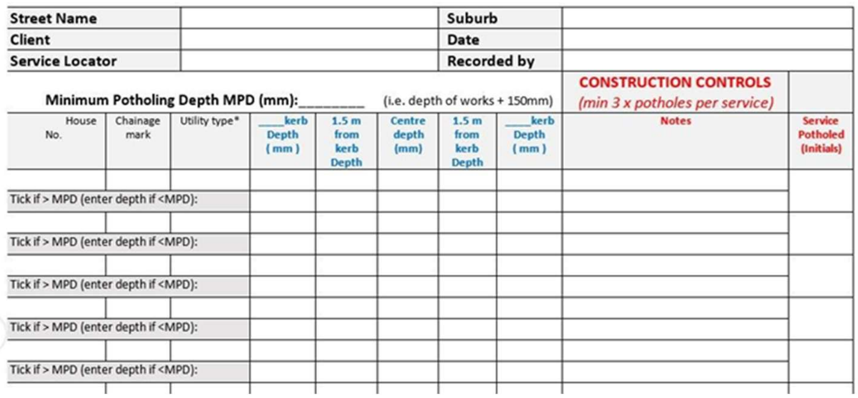




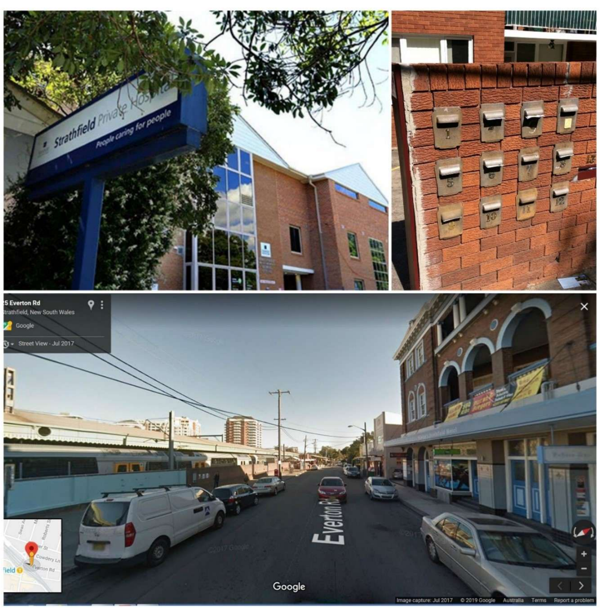
Street Name		Suburb	
Client		Date	
Service Locator		Recorded by	

Minimum Potholing Depth MPD (mm):________ (i.e. depth of works + 150mm)

CONSTRUCTION CONTROLS (min 3 x potholes per service)

House No.	Chainage mark	Utility type*	____kerb Depth (mm)	1.5 m from kerb Depth	Centre depth (mm)	1.5 m from kerb Depth	____kerb Depth (mm)	Notes	Service Potholed (Initials)
Tick if > MPD (enter depth if <MPD):									
Tick if > MPD (enter depth if <MPD):									
Tick if > MPD (enter depth if <MPD):									
Tick if > MPD (enter depth if <MPD):									
Tick if > MPD (enter depth if <MPD):									

Multiple stakeholders: Key stakeholders included Strathfield Station, Strathfield Hotel, a private hospital and local businesses and residents. The contractor delivered notification letters and door-knocked businesses to notify them of the impending works and updated them as relevant.



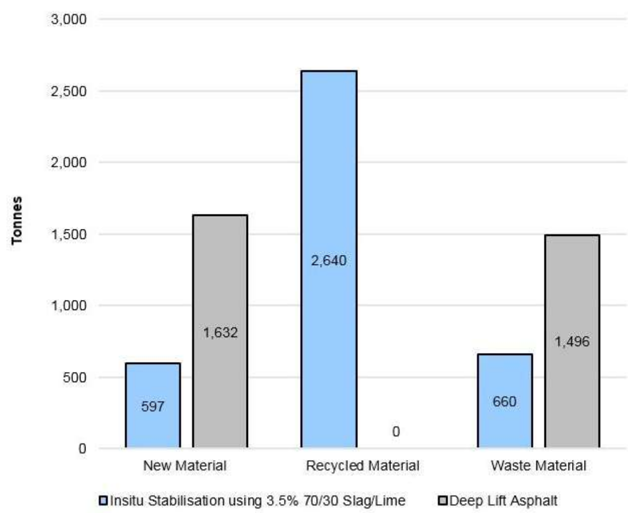
Energy Consumption and Greenhouse Gas Emissions

A summary of the energy consumption and the greenhouse gases generated during the project follows.

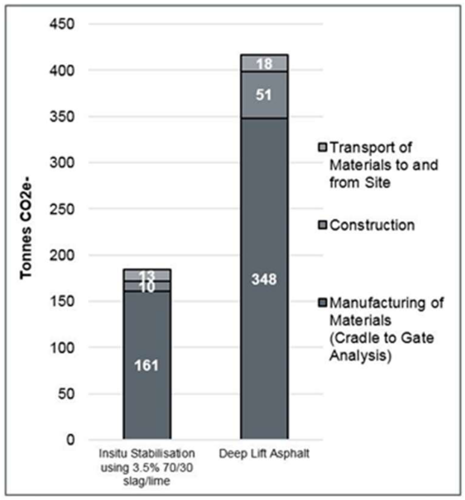
Option	In situ stabilisation using 3.5% 70/30 slag/lime	Deep lift asphalt	In situ stabilisation savings
New material imported	587 tonne Asphalt wearing course Seal GB cement	1,632 tonne Asphalt wearing course asphalt base	Saved importing 1,045 tonne of new material
Existing material recycled and retained on site	2,640 tonne	0	New pavement consists of 100% recycled existing pavement
Existing material removed from site and disposed	660 tonne Allowing for asphalt wearing course product and bulking	1,496 tonne Allowing for asphalt base and asphalt wearing course	Prevents disposal of 70 truckloads of material

Area: 4,000 m^2.

Material dry density	existing material	2.2 t/m^3
	asphalt	2.4 t/m^3.



Process		In situ stabilisation using 3.5% 70/30 slag/lime	Deep lift asphalt
Manufacture of materials (cradle to gate analysis)	3.5% 70/30 slag/lime	65.47 tonne	–
	Hotmix asphalt base	–	284.12 tonne
	Hotmix asphalt wearing course	95.47 tonne	63.65 tonne
Construction	In situ stabilisation with GB cement	5.12	–
	Hotmix asphalt base: place, pave & compact	–	49.73
	One coat sprayed seal (including materials manufacture)	3.68	–
	Hotmix asphalt wearing course: place, pave & compact	1.67	1.11
Evacuation & disposal of existing material	Excavate & load material onto trucks	0.53	1.19
	Fuel consumption: trucks transporting material from site	12.31	16.34
Total tonne of emission (CO_2-e)			
Prevented emission of 231 (CO_2-e) (tonne) of greenhouse gases (56% decrease)			



Sources: Cement Australia, VicRoads, Research Gate, SPA field observations

Conclusions

This bold, innovative, and considered approach adopted by Michael Limnos on behalf of Burwood Council resulted in the following outcomes:

- A saving of AUD132,000 (inclusive of all stabilisation and service lowering and final 45 mm depth of asphalt wearing surface)
- The recycling of 836 tonne of material that would otherwise have gone to waste.
- A 56% reduction in greenhouse gas emissions.
- No utilities disturbed in the project delivery due to thorough location and potholing procedures.
- Lowering utilities clear of the pavement zone establishing a safe pavement working zone for future activities (345 mm depth).
- A long life (20+ years) pavement.
- Stakeholders satisfied with works progress and contractor communications.
- Excellent finished product, strong, deep stable pavement with 45 mm asphalt wearing surface.

Acknowledgements

M Limnos (Burwood City Council) for cost comparison data.

D Smith for energy consumption and greenhouse gas emissions data.

5 PAVEMENT RESILIENCE

Pavement Resilience of National Highway No. 117: Nakornsawan – Nongtao, Thailand

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Introduction

National Highway No. 117 is the major highway connecting three provinces – Nakhonsawan, Phichit, and Phitsanulok – in Thailand. This route also serves as a secondary highway in Phitsanulok and Uttaradit provinces. The average daily traffic and the percentage of heavy vehicles in 2021 were 21,500 and 10%. The existing roadway was a conventional flexible pavement with a four-lane divided carriageway: two lanes northbound (NB) and two lanes southbound (SB). The NB and SB carriageways were originally constructed in 1976 and 1997 respectively. Rehabilitated of the highway commenced in 2015. Following the completion of the rehabilitation work in 2021, the road pavement has been experiencing severe distress, including longitudinal cracking, block cracking, alligator cracking and rutting as shown in Figure 1. This highway was also subjected to flooding during the rainy season. Several routine works and periodic maintenance strategies, e.g. pavement overlay, have been applied but the problem remained unresolved. A site investigation revealed that the possible cause of the problem might be inadequate quality control management during the road construction stage. In addition, this case clearly indicated that the traditional approach was unable to resolve the current situation.

As a result, a hybrid design approach was adopted that had the following benefits:

- enhancing structural integrity by controlling layer stiffness, homogeneity, and uniformity
- incorporating layer reinforcement and/or drainage capacity using innovative or modified materials
- providing a good separator between new stabilized layers and the existing, or problematic, materials.

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It was considered that the adoption of this hybrid approach could reduce the impact of extreme events, minimize moisture damage, prevent pumping of underlying fine-grained material, and increase the load-carrying capacity of this high traffic-volume highway.

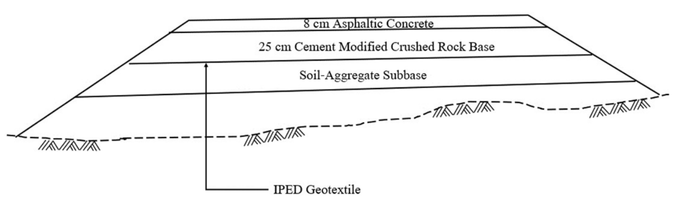
Figure 1: Example of block cracking along National Highway No. 117

Rehabilitation Method

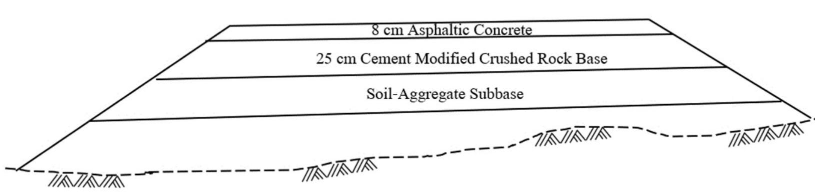
Various rehabilitation methods were considered to address the problems. The purpose of the proposed conceptual approach adopted was to:

- maintain the elevation of the existing road pavement
- ensure layer homogeneity and uniformity as well as structural integrity
- provide additional layer reinforcement and a separator between the new stabilized layers and the existing, problematic, underlying layers.

Based on the available traffic information, the expected number of equivalent standard axle loads (ESALs) for a 15-year design period was 10 million. According to the AASHTO (1993) design procedures, the required minimum structural number (SN) was 6.4. Therefore, a proposed pavement structure consisting of 80 mm an asphalt surface, 250 mm of cement-modified crushed rock base, 300 mm of soil-aggregate subbase, and 200 mm of selected material was acceptable. In addition to this proposed semi-rigid pavement (SN ~ 6.6), a woven geotextile (TenCate Mirafi® H2Rx) was also included to provide additional reinforcement and lateral drainage, and to separate new stabilized layers and the existing underlying layers. The typical cross-section of the proposed road, with and without the woven geotextile, is shown in Figure 2.



(a) Typical cross-section with woven geotextile



(b) Typical cross-section without woven geotextile

Figure 2: Cross-section of proposed four-lane divided road

A field trial, 1 km long, was established for detailed investigation. This trial site was divided into two 500 m long sections, one with geosynthetic reinforcement and one without geosynthetic reinforcement. The project was conducted over 30 days between 22 September and 23 October 2022. Field instrumentation, e.g. horizontal inclinometer, moisture sensors, suction sensors, a rain gauge, data logger, etc. was installed in the sections in order to compare their in-service performance under the prevailing traffic loading and climatic conditions. The layout of field monitoring instrumentation is shown in Figure 3.

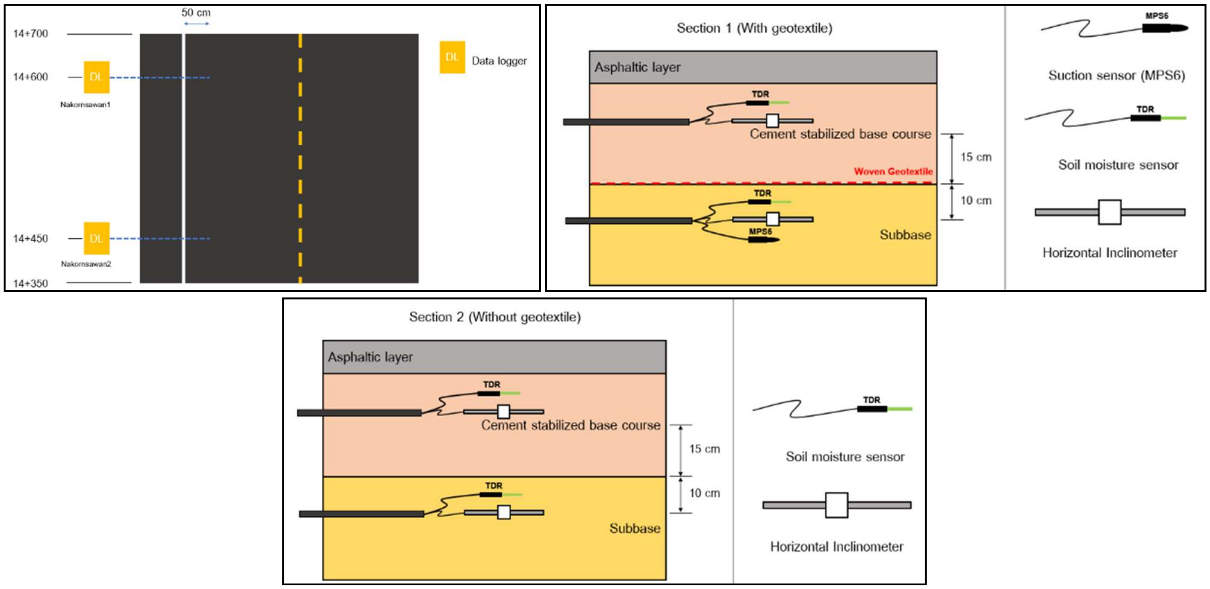


Figure 3: Layout of field monitoring instrumentation

Construction of Trial Pavements

The existing asphalt surface and basecourse, a thickness of 400 mm, were removed by a milling machine. The soil-aggregate subbase was then placed and compacted to meet the designed thickness. The field instrumentation for pavement performance monitoring and the woven geotextile TenCate Mirafi® H2Rx for mechanical stabilization, moisture management, and layer material separation were then installed as shown in Figure 4 and Figure 5 respectively.

Figure 4: Installation of field monitoring instrument

Figure 5: Installation of woven geotextile TenCate Mirafi® H2Rx

After the installation of the field monitoring instrument and the woven geotextile, a loose crushed rock layer 50 mm thick was placed for the purposes of base levelling and mixture modification. The new crushed rock and cement powder were then placed and mixed using a recycling machine to form the cement-modified crushed rock or cement-stabilized base. The target Unconfined Compressive Strength (UCS) of the cement-stabilized material was 2.4 MPa (DH-S 213/2000). To avoid any damage to the woven geotextile sheet, the mixing process using the recycling machine was performed on a section with no geosynthetic reinforcement. The machine was then hauled to a section which included the geosynthetic reinforcement. The mix was uniformly compacted to achieve the design thickness of 250 mm and the target compaction level of at least 95% of modified Proctor density. A sample of the mix was collected during the construction and subsequently compacted for laboratory UCS testing in accordance with DH-T 105/1972. After the compaction levels of both the cement-modified crushed rock base sections had been met, a prime coat was applied and the asphalt surface was placed. Photos of the construction process are shown in Figure 6.

Figure 6: Construction process

Performance Evaluation

Core Sampling

A 100 mm diameter cylindrical sample was collected from the site after construction was complete as shown in Figure 7. Examination of the cored sample showed that it had good continuity and uniformity throughout the 340 mm thick cement-stabilized base. This reflected the efficiency of the construction process and the quality management in this project.

Figure 7: Extraction of 100 mm diameter core

Field Data

Field data was collected for the purpose of in-service performance evaluation as shown in Figure. The moisture content of the subbase layer in Section 1 (with woven geotextile, Figurea) was relatively constant regardless of the rainfall, while the moisture contents of both the subbase and base layers in Section 2 (without woven geotextile, Figureb) exhibited an abrupt change approximately 1-2 days after each rainfall event. The moisture content of the base in Section 1 only slightly increased by 1% following the rainfall. The horizontal inclinometer data also indicated consistent response. Larger movement was observed in Section 2 (without woven geotextile, Figure 8), while the movement in Section 1 (with woven geotextile, Figure) was much smaller during the rainfall event.

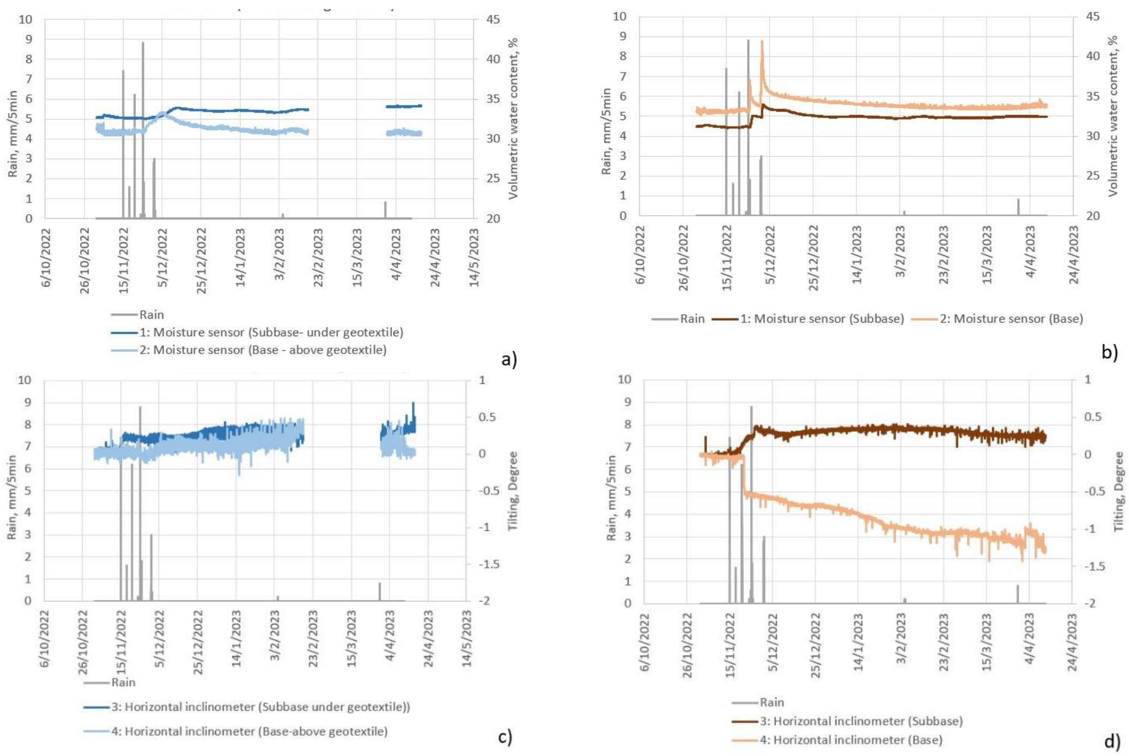


Figure 8: In-service performance evaluation using field monitoring data

Surface deflection measurements using the Falling Weight Deflectometer (FWD) were conducted ‘before’ and ‘after’ rehabilitation and the results are compared in Figure 9. It can be seen that, after the rehabilitation, the deflections reduced by approximately 30%. A pavement evaluation conducted two months after construction suggested that there was no sign of pavement distress. Clearly, the rehabilitation method adopted resulted in high structural integrity and good in-service performance.

Figure 9: Comparison of FWD surface deflection data before and after rehabilitation

Conclusions

After major traditional rehabilitation in 2021, National Highway No. 117 has been experiencing severe damage, including common pavement distresses such as longitudinal cracking, block cracking, alligator cracking, rutting, etc. The highway was also subjected to flooding and high traffic volumes. To address these issues, and to make it more resilient to water- and traffic-related impacts, a hybrid design approach was proposed to improve resilience and to improve pavement performance by: (1) enhancing structural integrity by controlling layer stiffness, homogeneity, and uniformity, (2) incorporating layer reinforcement and/or drainage capacity using innovative or modified materials, and (3) providing a good separator between new stabilized layers and the existing or problematic materials. The use of such a hybrid approach can reduce the impact of extreme events, minimize moisture damage, prevent pumping of underlying fine-grained material, and increase the load-carrying capacity to cater for heavy vehicles and high traffic volumes.

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Development of a New Test Method Applying Pore Water Pressure for Evaluating Interlayer Bonding Properties of Asphalt Pavements[18]

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Shigeki Takahashi, Nippon Expressway Research Institute Co. Ltd, Japan

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Introduction

The total length of expressway network managed by the three NEXCO companies in Japan (East Nippon Expressway, Central Nippon Expressway, and West Nippon Expressway Company Limited) exceeded 9,000 km in 2019; approximately 5 million vehicles use the network daily. Many of the Japanese expressways were constructed during the period of Japan's rapid economic growth and they are now aging. More specifically, by 2020, approximately 4,700 km and 700 km of the network had been in service for over 30 years and 50 years, respectively (see Figure 1).

It has been observed that damage to expressway pavements is occurring in the deeper layers underneath the surface course, necessitating repair to both the surface course and upper basecourse.

No detailed surveys of the condition of expressway pavements had been performed until 2012. Since then, however, nationwide surveys involving trenching and examination of the pavement have been conducted (NEXCO RI 2019; Takahashi 2017).

In the surveys, the pavement was cut, using a drum cutter, into blocks for use as test specimens. As shown in Figure 2, the section of the block taken from a damaged area of pavement showed delamination between layers and very small horizontal cracks running in the horizontal direction between the binder course and upper basecourse. These cracks were only observed in the wheelpaths (see Figure 3).

[18] This paper was awarded a Katahira Award for the best paper at the 16th REAAA Conference, Manila, Philippines, in March 2021.

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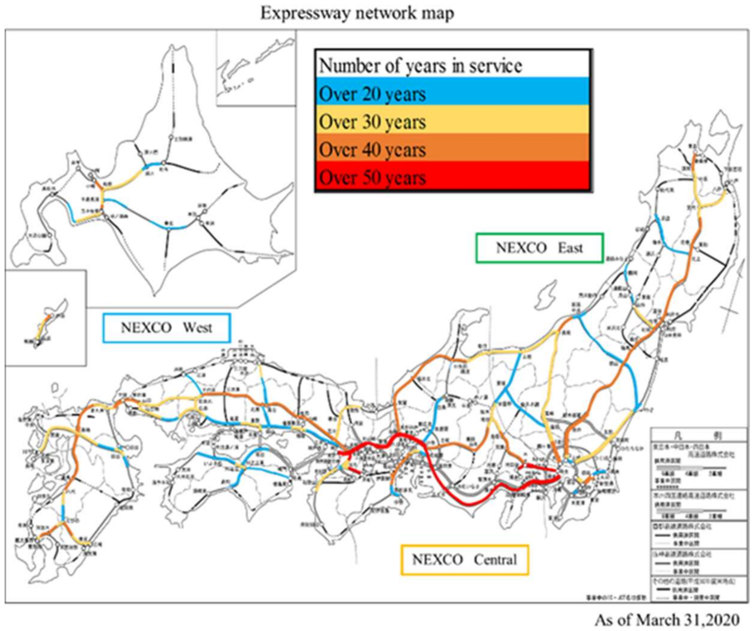


Figure 1: Japanese expressway network and number of years in service

Figure 2: Block of pavement separated into two (upper and lower) layers

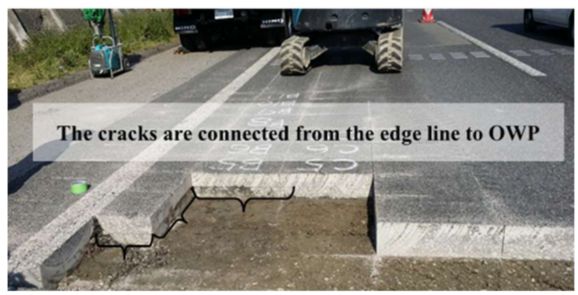


Figure 3: Horizontal cracks developed between binder course and upper basecourse

In addition, where an area of a pavement having alligator cracks was cut out, some horizontal cracks were observed between the binder course and the upper basecourse in the wheelpath, despite the fact that no repair work had been performed there.

An example of a survey conducted at a site where it had rained the day before is shown in Figure 4. Although a dry cutter was used, it was observed that rainwater had penetrated into the pavement through the cracks which had developed vertically along the boundary between a lane line and the pavement. The water was then spreading along the interface between the binder course and upper basecourse.

Figure 4: Rainwater penetrated into pavement through a crack

In terms of the directions of the crack formation on the cross-section of the pavement where a wide crack extending in the vertical direction developed on the road surface (see Figure 5, it was observed that the crack initiated at the road surface and, soon after running through the first and second layers, horizontal cracks developed between the second and third layers. The (wide) crack then extended through the third layer and cracking developed between the third and fourth layers.

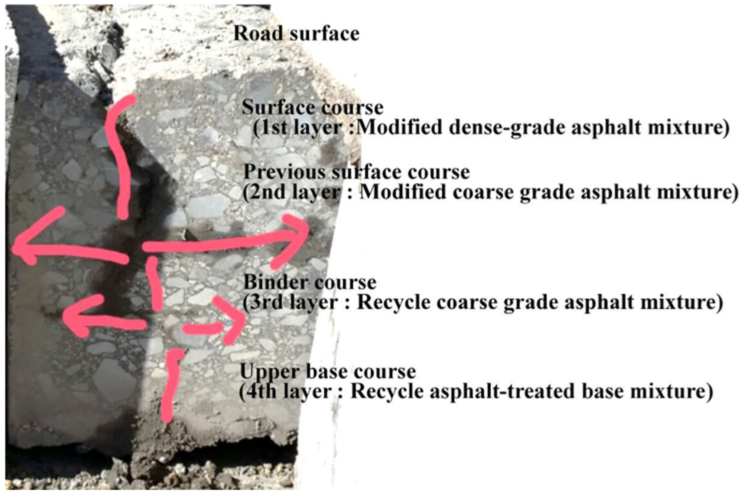


Figure 5: Progress of crack formation and horizontal cracks

The field surveys showed that seepage water, when pressurized by traffic loads, can result in deterioration at the interlayers of the asphalt pavement over decades.

A conventional method used to bond the interlayers is to apply a tack coat. To test the bonding strength, tests are carried out, such as the tensile or shear test, to evaluate the bonding strength. However, these tests do not consider the effect of water which was observed in the field. Therefore, a new test was developed which repeatedly applies pore water pressure between the layers of the asphalt mix.

Evaluation of Adhesiveness of Tack Coats Between Interlayers

Overview

As a way of evaluating the adhesiveness of tack coats between asphalt interlayers, a test that applies loads to the mix, such as the tensile adhesion test or shear test, is often used (e.g. see Al-Qadi et al. 2012; McDaniel, Shah & Lee 2018; Bahia et al. 2019). However, in the case of a mix containing a binder with a low softening point, if the test temperature is high, a cohesive failure of the mix itself may occur, especially during the summer. It is therefore difficult to assume that the tack coat's adhesive strength has been properly evaluated. Taking this into consideration, test equipment and methods that repeatedly apply water pressure between the layers of asphalt mixes and reproduce the adhesion to evaluate the adhesiveness of the tack coat applied between the interlayers were developed. The test is hereinafter referred to as the 'Repeated Pore Pressure for Interlayer' test.

Repeated Pore Pressure for Interlayer Test

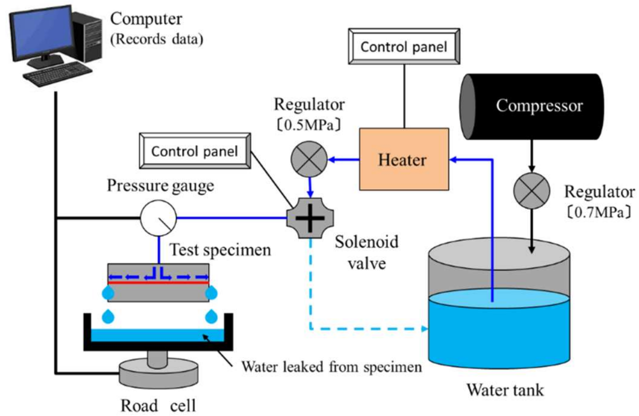
Overview of testing apparatus

A conceptual diagram and view of the test apparatus is shown in Figure 6. The apparatus was designed to generate pore-water pressure by intermittently injecting pressurized water between the layers of test specimens by opening and closing a solenoid valve.

The main parts of the test apparatus are as follows.

- Compressor for applying pressure to water stored in the tank.
- Tank that stores water for applying water pressure to the specimen.
- Regulator for regulating the pressure in the water tank.
- Heater for adjusting water temperature.
- Regulator for adjusting the water pressure applied to the specimen.
- Solenoid valve for switching the supply of water to repeatedly apply pressure to the specimen.
- Test specimen.
- Load cell for measuring the amount of water leaked from the specimen.

- Pressure gauge for measuring the water pressure applied to the specimen.
- Control panel for controlling each device and a computer for storing data.



(a) Conceptual diagram

(b) External view

Figure 6: Conceptual diagram and external view of new test apparatus

The specification for the test equipment is shown in Table .

Table 1: Specification for test equipment

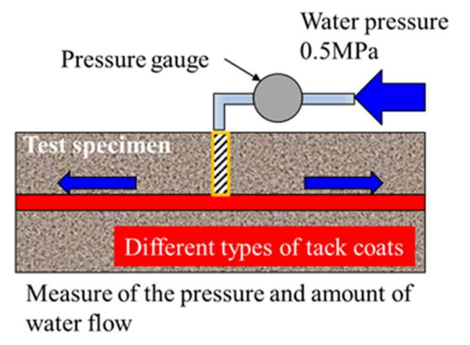
Item	Specification
Water pressure	0 – 0.6 MPa
Water tank capacity	30 L
Water temperature	23 – 60°C
Range of leaked water measurement	0.001 – 10 kg

The test procedure is as follows:

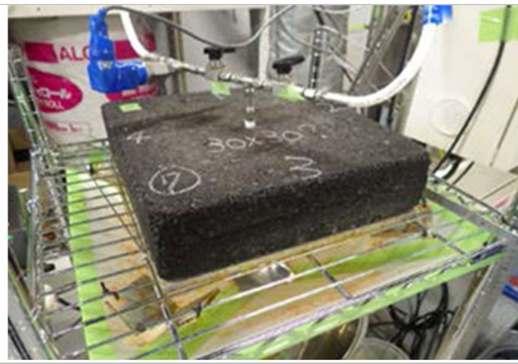
1) Set the specimen in place.
2) Put water in the water tank and use the regulator to adjust the pressure (0.7 MPa) in the tank so that it is higher than the pressure applied to the specimen.
3) Turn on the various control panels and set test conditions (water pressure, pressurization cycle, etc.).
4) Turn on the operation switch of the solenoid valve control panel and start the test.
5) Check if the data recorded by the measurement software looks appropriate.

During the test, the time, the number of pressure cycles, the volume of water leakage, and the measured values of the pressure applied to the specimen are recorded.

The conceptual diagram of the test specimens and the state of the test specimen placed in the equipment is shown in Figure . The test intermittently injects water into the interface of the asphalt layers, which causes a breakage of the adhesion between them; eventually the water leaks out from a side surface of the test specimen. For the test, a solution that emits light when irradiated with black light was added to the water to make its flow path more visible.



Conceptual diagram



State of test specimen placed

Figure 7: Set up of test specimens

Specimen preparation

The test specimen was prepared as follows:

- A water pipe (inner diameter: 15 mm) for water injection was installed at the centre of a block of asphalt (hereinafter, referred to as the ‘mixture’),which was 300 mm long x 300 mm wide x 40 mm thick. This was the upper layer.
- Before stacking the upper layer mixture on top of the lower layer, various types of tack coats were applied.
- A 40 mm thick block was laid as the lower layer.

Note that, to make sure that both the upper and lower layers maintained a high water-tightness, NEXCO’s mixture for the surface course used in snowy regions (finer-graded dense-graded asphalt) was used.

As the binder of the mixture was a modified asphalt for very heavy loads used in port applications (hereinafter referred to as ‘super heavy load type’), a type of SBS base binder was used. The test was initially carried out using commonly-employed modified asphalt. However, this mix significantly deformed during testing, as shown in Figure 8.

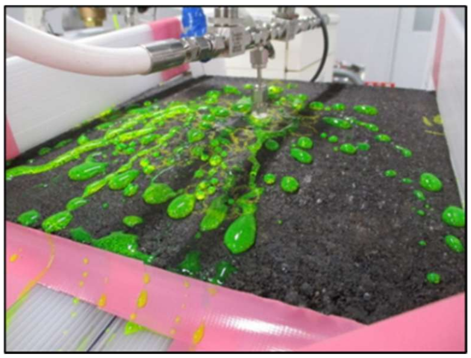


Figure 8: Deformation of test specimen (modified Type II binder)

Since it was thought that the adhesive strength of the interlayers could not be properly evaluated if such deformation occurred, it was decided to use the super heavy load type of mix. The specification for the super heavy load type binder is shown in Table 2.

Table 2: Specification for super heavy binder used in testing

Test item	Super heavy load type	Test item
Penetration (25°C)	1/10 mm	Penetration (25°C)
Softening point	°C	Softening point
Ductility (15°C)	cm	Ductility (15°C)
Flash point	°C	Flash point
Rate of thin-film mass change by heating	%	Rate of thin-film mass change by heating
Residual penetration ratio after heating the thin film	%	Residual penetration ratio after heating the thin film
Toughness (25°C)	N.m	Toughness (25°C)
Tenacity (25°C)	N.m	Tenacity (25°C)
Fraas breaking point	°C	Fraas breaking point
Stripped area ratio of coarse aggregate	%	Stripped area ratio of coarse aggregate
G*/sin δ	kPa	1.5 or more

Interlayer adhesive to be evaluated

The different types of tack coats used as adhesives between the layers, and the amount of each tack coat applied, are shown in Table . Three types of tack coats, namely PK-4, SBS modified asphalt emulsion (PKM-T), and a quick-breaking type of SBS modified asphalt emulsion (PKM-T-Q), were selected for the test. The test was performed using four different scenarios, more specifically, three cases with these tack coats and one case with no tack coat application.

Table 3: Type of tack coat and application rates

Type	Application rate (L/m^2)
Plain	0 (no tack coat)
PK-4	0.4
PKM-T	0.4
PKM-T-Q	0.8

In general, the standard amount of PK-4 and PKM-T applied is 0.4 L/m^2 and this application rate was used in the testing. PKM-T-Q has the same basic properties as PKM-T (Japan Road Association 2019). In addition, a feature of PKM-T-Q is that the construction time is short. For the PTM-T, an application rate of 0.8 L/m^2 was adopted for the purpose of reducing the penetration of water from surface ponds and surfaces where porous asphalt is used as the surface course. In this situation, PKM-T-Q is considered to have advantages over other tack coats.

Test conditions

The test conditions are shown in Table 4. The water pressure was set to 0.5 MPa with reference to the conditions of the Water Resistance test II. The value of 0.5 MPa is based on the tyre mounting pressure of heavy vehicles (Japan Road Association 2007). The pressure application cycle was set to 1 cycle/second, while the loading time was set to 0.3 seconds, the shortest possible time the tester can provide 0.5 MPa based on its performance capability, and 0.7 seconds with no pressure application mechanically.

Table 4: Test conditions

Item	Specification
Water temperature	23°C
Pressure	0.5 MPa
Pressure application cycle	1.0 seconds (0.3 seconds with pressure application) (0.7 seconds, reset time interval without pressure application)

Method of evaluating interlayer adhesiveness

The tensile adhesion test, or shear test, are methods used to evaluate the adhesion of a specimen after testing. However, if the layers are broken, the adhesive strength of the interlayers will be lost and these tests cannot be performed. Therefore, the following three methods were used in the evaluation:

- the relationship between the number of repetitions and the amount of water
- the relationship between the number of repetitions and the pore water pressure
- the presence, or absence, of flow paths in the test specimen.

In this test, it is possible to measure the amount of water flow – induced by the number of times pore water pressure is applied – from the test specimen layers. The relationship between the number of repetitions and the amount of water flowing from the interface between the test specimen layers (hereinafter, referred to as the ‘amount of water flow’) is shown in Figure a.

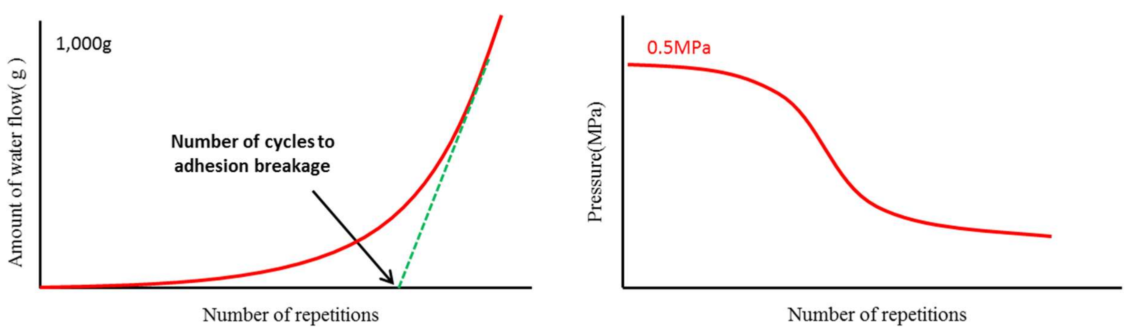
The test commences when there is no water leaking from the layer, then water starts to leak from the layer and gradually increases. The leaking eventually develops into a large flow of water. In the preliminary confirmation testing, when the water flow rate from the layers reached 1,000 g, a large amount of water was flowing due to the lack of adhesive force.

The point where a tangent line on the graph at the point where the amount of water flow reached 1,000 g intersects with the axis of the horizontal line (abscissas) (Figure a) was defined as the ‘number of cycles to adhesion breakage’. Resistance to the breaking of the adhesion between the interlayers was evaluated based on the differences in the number of cycles to adhesion breakage.

Pore water pressures at different elapsed times were also measured. The relationship between the number of repetitions and pore pressure is shown in Figure b.

When the interlayers are completely adhered, the pressure does not decrease because there is no way for the pressure to escape. However, when water begins to flow between the layers, a pressure escape is created and the pressure drops. When water begins to leak outside the specimen, the pressure drops significantly.

Whether this pore pressure could be used as an evaluation item was examined, and whether the level of adhesiveness could be evaluated by the presence, or absence, of flow paths in the test specimen, i.e. whether the interlayers split after the test was completed, was also examined.



(a) amount of water flow **(b) pore water pressure**

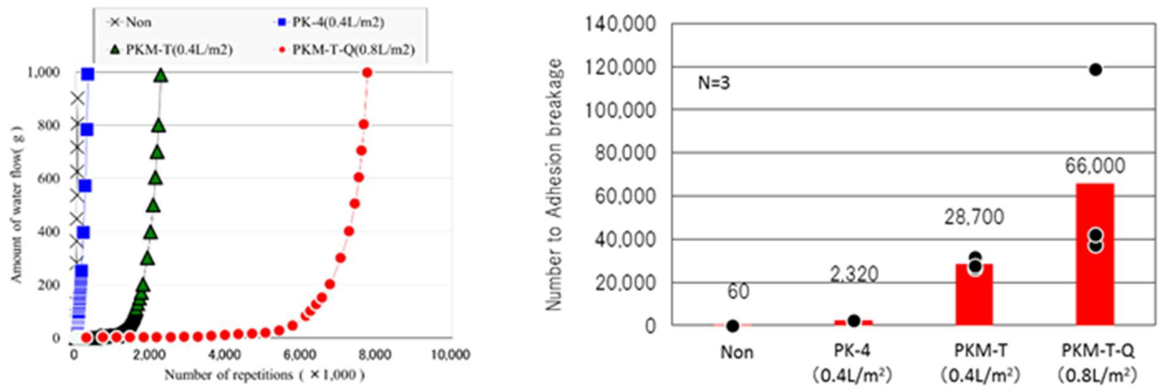
Figure 9: Relationship between number of repetitions and amount of water and pore water pressure

Results

Relationship between Number of Repetitions and Amount of Water Flow

An example of the relationship between the number of repetitions and the amount of water flow obtained in the tests is shown in Figure a. In the case of no tack coat and PK-4, water leakage started from the layers within 30 minutes of applying pressure, and the amount of water flow increased sharply after water leakage began. On the other hand, with PKM-T and PKM-T-Q, except for some specimens, water leakage from the layers commenced when the load was applied tens of thousands of times or more, and then water flow increased sharply.

The number of cycles required for adhesion breakage was the smallest in the case of no tack coat application, followed by PK-4 and PKM-T. PKM-T-Q took the longest number of repetitions (Figure b). PKM-T and PKM-T-Q had high adhesive strengths, and in the current tensile adhesion test, they aggregate fractures in the mixture. As a result, the interlayer adhesive strength of the tack coat could not be evaluated (Hiraoka, Iitaka & Sawa 2018). By using this test equipment and method, it was possible to confirm the differences in the levels of adhesiveness depending on the type of tack coat.



a) Amount of water flow   b) Adhesion breakage

Figure 10: Relationship between the number of repetitions and: (a) amount of water flow, and (b) adhesion breakage

Relationship Between Number of Repetitions and Pore Water Pressure

An example of the relationship between the number of repetitions and pore water pressure is shown in Figure 11. The number of repetitions until the pressure started to drop was shorter in the no tack coat application, PK-4, PKM-T, and PKM-T-Q.

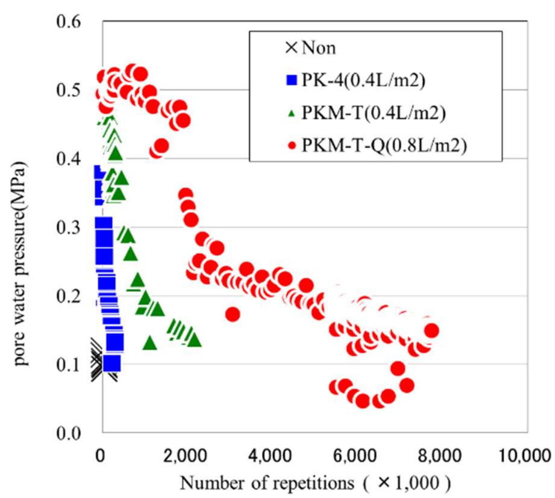
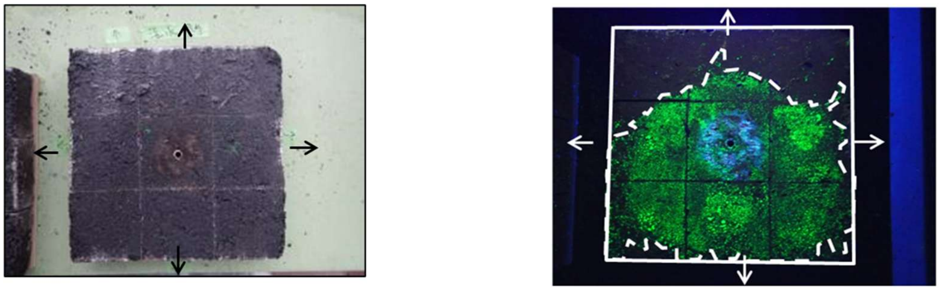


Figure 11: Relationship between number of repetitions and pore pressure

Confirmation of Flow Path Results

The flow path results were confirmed by splitting the specimen between interlayers after the completion of the test. Figure 12 shows a situation where the split surface is irradiated with black light. There were some tests when the flow path of the water to the edge of the specimen could not be confirmed, even though the water was flowing out from the side of it. This indicates that the test water that passed through the layers passed through the inside of the mixture instead of between the layers, resulting in water leakage from the side of the specimen.



a) **After splitting** b) **During black-light irradiation**

c) d)

Figure 12: Results from review of water flow path (PK-4; 0.4 L/m^2)

Conclusions

This paper has described new test equipment and a test method which reproduces adhesion breakage caused by water in the field. The adhesiveness of the tack coat used between the construction layers has been evaluated using this equipment and test method. Different results were obtained depending on the type of tack coat used. It was difficult to evaluate the difference in adhesion by confirming the flow path after the test. However, from the number of cycles to adhesion breakage obtained from the relationship between the amount of water flow and testing time, it was confirmed that the adhesive strength of interlayers differs due to differences in the materials.

Plans are in place to improve the test method to reduce inconsistencies in the results. The next step will be to determine the optimal material and amount of application under different test conditions, including temperature and the degree of surface roughness of the mixes on which the tack coat is applied.

An effective way to extend the life of asphalt pavements is to increase the interlayer adhesive strength (Chabot et al. 2016; Molenaar 2016; Partl 2016). Work will continue to define what properties are needed to obtain a sufficient adhesive strength of interlayers and to develop an optimal method which takes this into consideration.

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Reformation of Bridge Slab Maintenance: Development of Specialized Waterproofing Materials for Manual Pavement Work

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Overview

Many minor pavement repairs are required as a result of the deterioration of concrete slab bridge decks. When repairing the slabs, vulnerable portions of deteriorated concrete are removed and new concrete placed, and then waterproofed. However, the waterproofing of small repair areas by hand has posed challenges in terms of work quality, efficiency, and safety. To address these challenges, interviews were conducted with members of the paving industry and the manufacturers of bridge slab waterproofing materials. However, optimal material could be identified. It was therefore decided to develop a new waterproofing material, specialized for small-scale manual pavement work, in collaboration with a resin manufacturer.

An epoxy-based resin was developed to bond the deck plate and asphalt on steel bridges in China. The product developed has solved the concerns of quality, work efficiency, and safety. The product has passed the strict waterproofing standard prescribed by the Nippon Expressway Company Limited (hereafter referred to as NEXCO). Subsequently, the product was used on the Higashi-Meihan Expressway. This paper describes the developmental efforts conducted to date. Some photos are shown in Figure 1 and Figure 2.

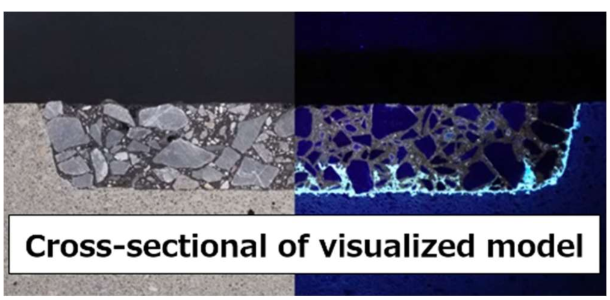

Figure 1: Blue paint is new material

Figure 2: Packing component

State of Japan's Expressways and the Waterproofing of Slabs

The total length of Japan's expressways has reached approximately 9,000 km since the first route opened to traffic in 1963. About 40% (about 3,700 km) of these bridge sections have been in service for more than 30 years. Meanwhile, bridges constructed before 2002 were not waterproofed. Even if waterproofing was implemented, many bridges have already been damaged and are no longer functional. Rainwater and anti-icing agents spread on the roadway penetrate through cracks into the deck slabs, causing corrosion of the steel bars inside, resulting in deterioration of the slabs and development of potholes (Figure 3 and Figure 4).

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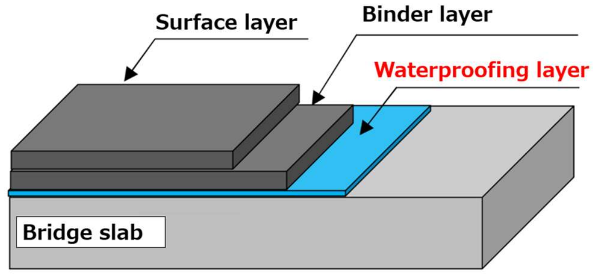

Figure 3: Pavement structure on bridge

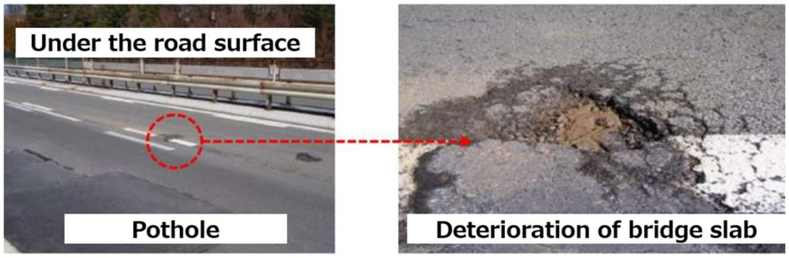

Figure 4: Examples of pavement damage caused by concrete slab deterioration

Issues Concerning Slab Waterproofing

The conventionally-implemented sheet waterproofing method used in NEXCO's maintenance jobs is classified as the 'asphalt heating type of waterproof layers, which focuses on the following:

(1) Quality – Due to the lack of electric pots available for small-scale manual pavement work, gas burners are used to melt materials. As a result, proper temperature control is difficult.

(2) Work efficiency – When working at low temperatures in winter, it takes a longer time to dry and cure the organic solvent in the primer.

(3) Work safety – There is a risk of fire when transporting heated materials and accidents may happen during the loading or unloading of heavy materials.

Survey of Waterproofing Materials in Use Overseas

In order to address these problems, NEXCO consulted with some major Japanese manufacturers of waterproofing materials, but no existing materials were identified which best suited extremely small-scale, manual pavement work. Slab waterproofing methods in use on expressways overseas were therefore investigated. It was found that epoxy resin was used to waterproof steel decks and to prevent anti-rutting in heavily-trafficked sections. The use of epoxy resin eliminates the use of fire to heat and melt materials. In addition, it is possible to control curing time by designing the resin composition appropriately. The development with a resin manufacturer was therefore initiated, based on the condition that a waterproofing material best suited for manual pavement work could be incorporated using simple equipment and without special techniques or hazardous work (Figure 5).

Figure 5: Overseas practice – using steel deck adhesive and epoxy-based material

Establishment of Development Goals

Since the waterproofing material for manual pavement work is used at expressway maintenance sites, it was assumed that the material would pass the tests specified in the Japan Society of Civil Engineer's Guidelines for Pavement Construction Management[22] (*Required performance Grade I for waterproof layers for slabs).* The four challenges facing job sites are shown in Table 1.

Table 1: Development goals

Premise: Passing the tests of six items as per the Required Performance Grade I
1. Reduction in work time for waterproof layers
2. Simplification of tools used
3. Improvement in construction safety
4. Capability to re-bond damaged waterproof sheets

The development was carried out by enhancing the adhesive used on steel decks in China with additional waterproofing and flexibility agents. Laboratory testing was conducted on multiple prototypes, with a chemical composition that would significantly change the characteristics of the existing product.

Evaluation and Verification of Development Goals

Since the results of the laboratory testing satisfied the criteria of the six items in accordance with the *Required performance Grade I for waterproof layers for slabs*, a third-party was approached for verification. The new materials were officially confirmed to pass the criteria, as specified in Table 2

Table 2: Results of third-party testing

Test item	Pavement laying load	Pass/fail guideline	Test result	Pass/fail
Waterproofness test Ⅱ	Ⅰ	No leaks	None	Pass
	Ⅱ		None	Pass
Crack follow-up performance test Ⅱ	None	0.3mm or more	4.1mm	Pass
Tensile bond strength test	Ⅱ	0.6N/mm^2 or more	1.7N/mm^2	Pass
	Ⅲ	0.6N/mm^2 or more	1.7N/mm^2	Pass
Shear test	Ⅱ	0.15N/mm^2 or more	0.87N/mm^2	Pass
	Ⅲ	0.15N/mm^2 or more	0.58N/mm^2	Pass
Water immersion tensile bond strength test	Ⅱ	50% or higher tensil bond strength compared to before water immersion	59%	Pass
Chemical resistance test	None	No abnormalites	No abnormalites	Pass

Reducion in Working Time for Waterproof Layers

The conventional method, as shown in Figure 6, requires a total of about 3 hours for the application work and primer-drying under low temperatures in winter. Drying by a heater is attempted to shorten the curing time, but this approach is problematic because the primer can be ignited and the surface of the repair mortar could crack due to rapid drying. On the other hand, the new method does not need a curing time because the heat from the asphalt mixture after application accelerates the curing of the epoxy, and the time required for waterproofing work is only 10 minutes.

22 Performance requirement I is a standard for bridge waterproofing material for highway repair as determined by NEXCO.

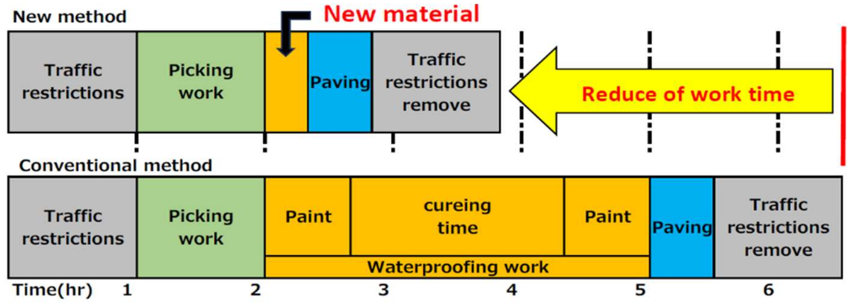

Figure 6: Comparison of work times between new method and conventional methods

Simplification and Safety

The conventional method requires waterproofing materials to be melted on site, which limits time and labour for transporting many tools such as melting furnaces and gas burners and unloading them on site. However, with the new method, waterproofing work can now be performed using only rechargeable agitators and brushes. The weight of the tools used has been reduced by 95%, and the labour involved in preparation greatly reduced. The paving workers also commented positively that the work became much safer with no risk of heavy lifting, fire, or accidents (Figure 7).

Figure 7: Comparison of tools

Capability to re-bond existing damaged waterproof sheets

A bond verification test was conducted to re-bond peeled waterproof sheets using the new method. The bond strength between the waterproof sheet and the concrete was 1.20 N/mm^2 or higher, the specimen fracture surface remained on the sheet interface, and the bond strength exceeded the sheet strength. This confirmed that the new method could be substantially used as an adhesive to bond existing damaged deck slabs (Figure 8).

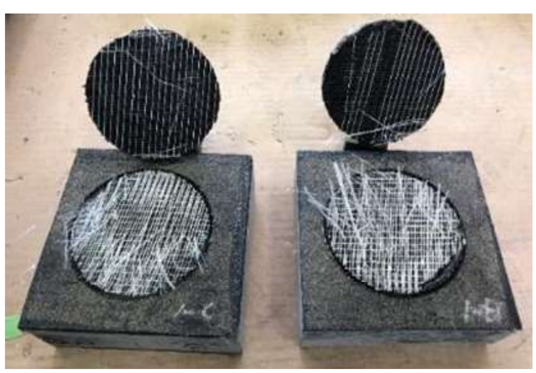

Figure 8: Bond verification test of waterproof sheets and deck slabs

An initial test construction was conducted on 4 April 2022. Although the construction was conducted at a low temperature of 10 °C for both the outside air and concrete slabs, it was possible to verify that all the problems associated with the conventional method had been sufficiently addressed (Figure 9). NEXCO has conducted over 400 repairs using this material, and no damages has been caused by the waterproofing material (Figure 10).

Measurement **Mixing** **Painting**

Waterproofing complete **Paving**

Figure 9: Construction procedure

Figure 10: Appearance 60 days after repair work

Final Remarks

For over 20 years, NEXCO has been engaged in small pavement repairs, and they have long wanted to make a waterproofing layer safe, easy to handle, and durable during limited manual pavement work. The newly-developed material has passed the NEXCO standard and achieved substantial results in the actual field. This product has led to the realization of an extended pavement and bridge lifespan. It is hoped that this new remedy will be utilized worldwide.

Foamed Asphalt Pavement Recycling in Canberra, Australia[23]

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Davina Smith, Stabilised Pavements of Australia Pty Ltd (SPA), Australia[25]

Introduction and Background

Northbourne Avenue is one of the busiest arterial roads in Australia's Capital City, providing main access to traffic entering and exiting Canberra. Northbourne Avenue has two carriageways running north-south and both carriageways have three lanes for motorised traffic and one lane for bicycles. Vehicle traffic counts exceed 14,000 veh/day. The carriageways are separated by a large median strip containing a light railway line, which was constructed in 2019 about a year prior to road being rehabilitated.

The majority of the existing pavement showed signs of having reached the end of its serviceable life in both carriageways, with extensive pavement defects evident. Despite a routine resurfacing program to reseal the road surface and enhance waterproofing to slow the rate of deterioration, some parts of the existing pavement were assessed as being in 'very poor' condition, exhibiting significant rutting, potholes and cracking in many locations with depressions (see Figure 1). The road was becoming a safety concern for road users, as well as an increasingly urgent and constant maintenance task for Roads ACT.

Figure 1: Typical pavement failures in Northbourne Avenue

Investigations carried out by the Roads ACT Maintenance Department revealed that structural improvement of the pavement was necessary to restore the pavement and prevent further damage to the underlying foundations, which would result in more costly full depth pavement reconstruction. There were clear indications that major rehabilitation was urgently needed and the implementation of a long-term solution was imminent.

Preliminary Project

A section of the northbound carriageway was selected as the start of the pavement rehabilitation. A consulting engineering company was appointed to carry out all pavement investigations and prepare the rehabilitation designs. Challenges were encountered during the investigations due to the presence of various underground services that ran along the Northbourne Avenue corridor, as well as the light railway operations in the median. The presence of the underground services restricted the investigations as they were not able to be relocated

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[23] This paper is based on a paper presented at the Australian Flexible Pavement Association's 'International Flexible Pavements Symposium, 'Roads going full circle', in 2021.

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due to the major disruptions .to all adjacent properties along the section of works and massive traffic disruptions.

It was decided to adopt a traditional method of construction involving two pavement types that required the removal of the existing pavement and the placement of conventional deep lift asphalt. Extensive subgrade replacement was also required in five separate locations along the length of the project. However, in order to construct in line this this design, it would have been necessary to change pavement types at eight points along the project. In addition, only one lane could be rehabilitated at a time. This restrictive approach, combined with the interchanging pavement designs and the extensive excavation and replacement activities, limited speed of construction and resulted in an estimated construction period of 26 weeks, not including potential delays caused by weather and other unforeseen conditions or issues encountered. The traditional method involving two pavement types as shown in Figure 2.

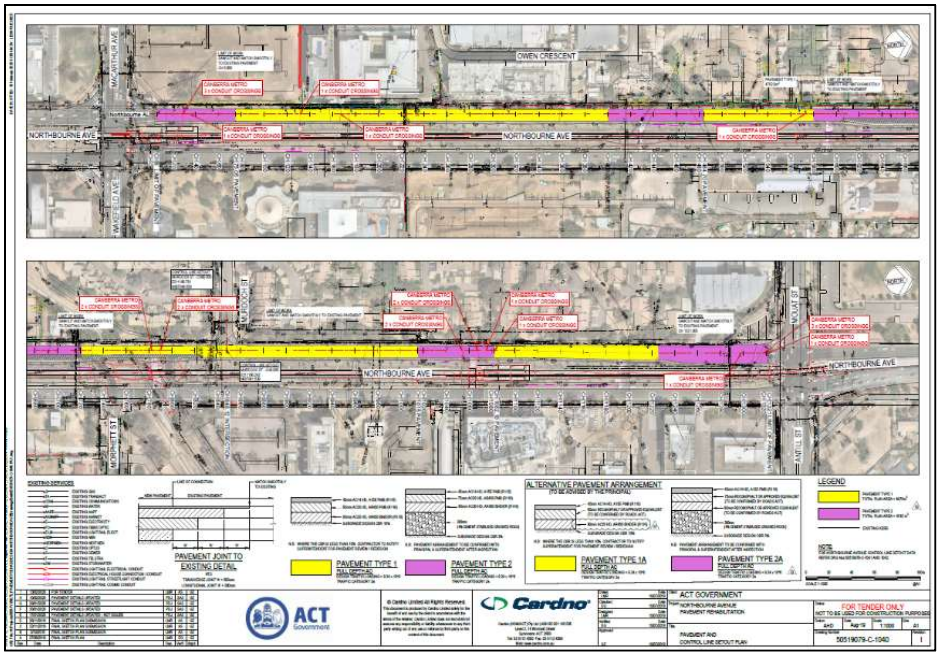

Figure 2: Preliminary project pavement designs for Northbourne Avenue rehabilitation

Innovative Pavement Recycling – Foamed Asphalt

Foamed asphalt pavement recycling is a new innovation in sustainable pavement maintenance and recycling technology. It was introduced into the Australian market in 2020. Foamed asphalt combines the proven and recognised pavement treatment technology of in situ foamed bitumen – currently used to recycle and rejuvenate pavements – with a custom-built paver-laid placement process similar to conventional asphalt. This paver-laid placement is a key point of difference in the foamed asphalt process compared to any other in situ recycling method; it enables an advanced, single-pass, forward-moving ‘train’ method of construction.

The in situ foamed bitumen technology at the core of the recycling process involves a mixture of air, water, foaming agent, hot bitumen and supplementary binder. When the hot bitumen (160-200°C) is injected with a small quantity of cold water (typically 1.5% quantity at 15-25°C) this causes the bitumen to instantly expand up to 15 times its original volume to form a fine mist. In this foamed state, the bitumen has an extremely low viscosity (Kendall et al. 1999).

The foamed bitumen is incorporated into the existing pavement materials in the mixing chamber of the recycling plant. The foamed bitumen droplets are attracted to, and coat, the finer particles of the pavement material, forming a mastic that effectively binds the mixture together. Lime or cement (commonly lime in the form of hydrated lime or quicklime) is added as a secondary binder to assist with adhesion of the bitumen, reduce the plasticity of the host material, harden the bitumen, and promote early strength for trafficking (Smith 2015). Foamed asphalt pavement recycling was introduced by the Australian-owned company Stabilised Pavements of Australia (SPA). An example of foamed asphalt combining foamed bitumen treatment with an asphalt paver-laid process is shown in Figure 3.

Figure 3: Example of foamed asphalt combining foamed bitumen treatment with an asphalt paver-laid process

Northbourne Avenue Alternative Proposal

Design

The foamed asphalt pavement recycling option was designed for an equivalent design life period (20 years), and performance outcomes, as the traditional designs in the preliminary project. This allowed fair comparison of sustainability benefits discussed later in this paper. The design of the alternative foamed bitumen asphalt pavement recycling solution was based on site-specific information obtained during the preparation of the preliminary project. The alternative proposal retained the same design parameters as the original designs, including:

- Design traffic loading: 9.34 x 10^6 Design Equivalent Standard Axles (for a 20 year design life).
- Design subgrade Californian Bearing Ratio (CBR): 3% (lowest laboratory 4-day soaked CBR, result of 15 samples).

Laboratory mix design testing was undertaken to confirm that the design requirements would be achieved. The nominated mix design of 2.5% bitumen and 1.5% hydrated lime (by mass) was also approved as appropriate. A revised pavement design with a single pavement type consistent throughout the site was administered. Details are shown in Table 1.

Table 1: Foamed asphalt pavement design for Northbourne Avenue

Layer	Thickness (mm)	Material
Wearing course	45	AC14
Intermediate course	45	Reconophalt (asphalt product with high quantities of recycled material)
Sprayed seal	10	C170 bitumen, single coat
Foamed asphalt	200	In situ foamed asphalt
Total rehabilitated pavement thickness	300	
Subgrade/existing foundation layer		Natural subgrade with design subgrade CBR of 3%

Construction

The pavement construction method adopted for the project was unique and, most critically, needed to allow for continuous traffic whilst roadworks were underway. Another requirement was that two lanes had to be opened at the end of each shift at 3 PM for the afternoon peak hour traffic commuting north out of Canberra.

The construction program consisted of two stages which divided the site lengthways in two sections. The wide paving widths of the paver's interchangeable screed-board allowed more than one lane to be rehabilitated at a time and the overall job to be completed in only two continuous runs. This approach also allowed for one lane of traffic to be opened during works. The advantage of foamed bitumen recycling is its fast curing time, which allowed the rehabilitated pavement to be opened at the end of each shift with two lanes available for the afternoon peak hour.

A summary of the construction program for each stage is as follows:

1. Milling of 50 mm of existing asphalt wearing course This was intended for later use as reclaimed asphalt pavement (RAP) in the wearing course layers.
2. Milling of material to allow for two 45 mm layers of imported asphalt wearing courses. This accounted for approximately 10% bulking of the treated existing material due to the incorporation of recycling binders and material handling.
3. Foamed asphalt pavement recycling of 200 mm of the existing pavement layers, which included considerable asphalt from the wearing course and patches, as well as various unbound granular materials such as sands and gravels which made up the base and subbase. The process involved the simultaneous milling, blending and processing of the existing pavement materials with the recycling binders – 2.5% bitumen and 1.5% hydrate lime (by mass).
4. Application of a C170 bitumen single coat sprayed seal to assist with the cohesion of the overlying asphalt wearing course layer. Although the pavement could be immediately trafficked without a seal, having the seal helped protect the newly-rehabilitated pavement from vehicle damage (particularly at turning/braking points at driveways) given it was almost a week until the asphalt wearing courses were applied.
5. Placement of 45 mm of Reconophalt. In addition to the RAP described in dot point 1, the recycled asphalt contained soft plastics, crushed glass bottles and toner cartridges sourced through community programs involving the collection soft plastic collected from schools, councils and businesses in NSW.
6. Laying of traditional 45 mm AC14 wearing course and line-marking before the road was fully opened to traffic.

Sustainability Benefits

General

The construction of infrastructure such as roads is invaluable to society; however, it is imperative to deliver and maintain such infrastructure without inducing immediate or future detrimental impacts. This can be achieved by striving for sustainability when implementing engineering practices. While there is no one correct definition of 'sustainability', it is generally accepted as a term that encompasses environmental, social and economic concepts in an interconnected relationship.

Environmental

Greenhouse Gas Emissions

A greenhouse gas is any gas in the atmosphere that absorbs and re-emits heat, thereby keeping the planet's atmosphere warm. The main greenhouse gases in the atmosphere are water vapour, carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O) and ozone (Brander 2012).

Although greenhouse gases naturally occur in the atmosphere, excess release of greenhouse gas emissions into the Earth's atmosphere is currently widely recognised for the potential future negative impacts on the Earth's climate. As such, there is generally a global initiative to either reduce or modify human-related activities that burn fossil fuels and generate greenhouse gas emissions.

Most processes related to road construction or rehabilitation, such as quarrying, manufacturing materials, transportation, excavation and so forth, are energy consuming processes that require the burning of fossil fuels and contribute emissions to the atmosphere. Furthermore, greenhouse gas emissions can be used as a good metric of sustainability as they also represent a broader range of environmental considerations such as the usage of finite resources, burning of fuel, power and energy expenditure, and the general effort invested.

The quantity of greenhouse gas emissions for each option was estimated using an Environmental Calculator. The Environmental Calculator was first developed by Stabilised Pavements Ltd, which is a UK based company belonging to the Stabilised Pavements group of companies. The calculator has been progressively modified accordingly to suit Australian conditions and expanded upon over the course of seven years. The Environmental Calculator is suitable not only for this case, but for other road rehabilitation options beyond the scope of this paper.

The Environmental Calculator measures the carbon dioxide equivalents ($CO_{2\text{-}e}$), which is a metric measurement used to encompass different greenhouse gases with different global warming potentials under a single and distinct unit. The $CO_{2\text{-}e}$ for a gas is derived by multiplying the tonnes of the gas by the associated global warming potential. Global warming potential is the heat absorbed by any greenhouse gas in the atmosphere, as a multiple of the heat that would be absorbed by the same mass of CO_2. Such as, the global warming potential for CO_2 is 1, and for other gases it depends on the gas and the time frame assessed (20, 50, or 100 years for example).

For each option, the Environmental Calculator quantified CO_{2}-$_{e}$ emitted for:

1. manufacturing of materials (cradle-to-gate analysis)
2. transportation of materials and plant
3. on-site construction processes.

CO_{2}-$_{e}$ emitted for each option is quantified in Table 2. In addition to a total, the sub-categories described above have also been included.

Table 2: Estimated tonnes of CO_{2}-$_{e}$ emissions for road rehabilitation options

Option	Total	Manufacturing of materials	Construction activities	Transport
Foamed asphalt pavement recycling	716	666	16	34
Conventional pavement types	1815	1686	68	61
Savings/difference by using foamed asphalt	1099	1020	52	26
	61%	61%	76%	44%

Recycling of Existing Materials

In essence, road rehabilitation is all about the management of road pavement materials. Whether the materials are old and redundant or brand new for the purpose of a serviceable road pavement, all pavement materials possess a potential asset value if handled efficiently by asset managers.

The consequence of discarding existing road pavement materials and importing materials is not only the requirement for new products, but the displacement of the existing road pavement materials, which still have an asset value to some degree. In 2018, it was reported that Australia generated a total of 67 million tonnes of waste per year, with construction and demolition waste comprising 20.4 million tonnes or approximately 70% (Commonwealth of Australia 2018) Therefore, the recycling of existing pavement materials should possibly be one of the priority considerations and form part of responsible, long-term decision-making when planning road rehabilitation projects.

At Northbourne Avenue, the preliminary project involved two pavement types that required the complete importation of road pavement materials. Although RAP was available from the existing wearing course, and it was later reused in new asphalt wearing courses, the material still required exportation, processing, and then importing back into the project. None of the existing road pavement materials were recycled in situ and only this relatively small quantity of RAP was to be reused in the new pavement.

In contrast, the foamed asphalt pavement recycling option recycled and reused 100% of the existing road pavement materials to create the rehabilitated pavement in situ. This excluded the new asphalt wearing courses that were the same as the preliminary project with the traditional design/pavement types.

This was made possible by the foamed bitumen technology. Based on geotechnical engineering principles, the bitumen and lime additives react with, and alter, the existing pavement materials to essentially create an improved road pavement asset. As well as maximising the recycling potential of existing pavement materials, this approach greatly reduced the amount of existing pavement materials excavated and removed off site.

Foamed asphalt pavements also have the capability to be recycled and rejuvenated again using the same foamed bitumen technology, leading to longer-term benefits for future generations.

To demonstrate the benefits of recycling the existing pavement materials using foamed asphalt pavement recycling, three areas regarding material management were assessed:

1. recycled material – including existing pavement materials recycled in situ and any recycled materials used in asphalt products, such as RAP and recyclates (plastics, toners, etc).
2. new material – included materials required to be manufactured from primary sources

3. exported material – included any material taken away from site, even if it was later brought back to site as RAP in asphalt products.

Before estimating the quantity of materials recycled, imported or exported from site, it was important to firstly establish how materials were classified according to each area listed above for both options. This is outlined in Table 3.

Table 3: Material management for road rehabilitation options

Option	Recycled material	New material	Exported material
Foamed asphalt pavement recycling	Existing pavement materials, RAP and any recyclates used in asphalt products	Binders, asphalt materials excluding RAP and recyclates, sprayed seal	Existing material to allow for asphalt wearing courses and seal Approximately 10% treated material to account for bulking due to binders and material handling
Conventional pavement types	RAP and any recyclates used in asphalt products	Asphalt materials excluding RAP and recyclates, crushed rock and cement for subgrade replacement	Existing materials to allow for new pavement layers

The results derived from the benefits of recycling existing materials are shown in Table 4.

Table 4: Recycled, new and imported, and exported materials for road rehabilitation options

Option	Recycled material	New material	Exported material
Foamed asphalt pavement recycling	6173	2214	3392
Conventional pavement types	2114	7042	8296
Savings/difference by using foamed asphalt	4059	4828	4904
	66%	69%	59%

An example of a foamed asphalt pavement consisting of 100% recycled existing pavement materials undergoing final compaction is shown in Figure 4.

Figure 4: Foamed asphalt pavement consisting of 100% recycled existing pavement materials undergoing final compaction

Community Impact and Streamlined Construction

With the Northbourne Avenue project characterised as a high-profile, heavily-trafficked pavement, a large area to be rehabilitated across multiple lanes, and a length of almost 1.5 km, the efficiency advantages of foamed asphalt pavement recycling were well suited to the situation. These advantages included:

- Continuous, single-pass construction with all recycling occurring in just one pass of the 'train' without reversing.
- The ability to recycle multiple road lanes at a time, enabled by the paver screed-board placing material at extensive widths greater than the 3.8 m working width of pavement recycler.
- Treatment and placement of substantial layer thicknesses of up to and over 200 mm, which was greater than conventional asphalt and enabled single-layered construction.
- The material being treated in situ and mixed separately four times prior to placement, This excluded the need for separate pre-milling to either export material for treatment and/or effectively achieve uniform blending of pavement layers prior to incorporating the treatment additives.

- Paver-laid treated material had an initial compaction upon placement and controlled levels, eliminating the need for a grader and requiring only one roller for final compaction.

Due to these advantages, the quantified points listed in Table 5 demonstrate the main reasons for the selection of foamed asphalt pavement recycling as the best option in terms of a streamlined construction whilst minimising disruption to the community:

Table 5: Comparison of construction methods

Feature	Preliminary Project	Foamed Asphalt
Construction program time	26 weeks total, not accounting for delays	8 weeks total, with pavement rehabilitation taking only 6 weeks including a week intermission between stages
Staging	Works undertaken one single lane at a time	Two stages comprising of two longitudinal segments or 'runs' that covered multiple lanes
Pavement types	Two pavement types implemented and requiring alternation eight times along the project	One pavement design implemented along the project, excluding any isolated areas requiring additional subgrade treatment as identified during works

In the final stages of planning it was still necessary to engage a combination of consultation and ingenuity to devise a construction program that was accommodating to the unique restrictions presented by the Northbourne Avenue project. It was imperative these stipulations were not compromised. The foamed asphalt recycling during the second stage of the project all in a single pass of the 'train' is shown in Figure 5.

Figure 5: Foamed asphalt recycling during the second stage of the project all in a single pass of the 'train

In order to gain an insight into some of the tailored approaches adopted for Northbourne Avenue that arose once the alternative project was approved for proceeding, some of the project constraints and solutions incorporated into the construction approach are shown in Table 6.

Table 6: Northbourne Avenue project constraints and solutions

Project constraints	Solutions
Road works had to avoid the afternoon peak hour traffic travelling north out of Canberra and minimise any traffic congestion during this time	Road works were completed in shifts starting at 6.30 am and finishing before 3 pm; two lanes were opened at the end of each shift, including with the rehabilitated pavement that was able to be trafficked at the end of each shift
Strict Road Occupancy Licence time period for permitted road works	Dedicating allowable time purely to construction by conducting, where possible, inductions and toolboxes in the afternoon prior to a shift or earlier before the Road Occupancy Licence commenced for each shift to prevent any delays
The road had to remain open at a minimum capacity of one lane during construction shifts	One lane remained opened at all times during road works
Vibration from plant had to be minimised due to nearby pedestrian pathway, light railway corridor and residential buildings	Use of a specialised HD+140 Tandem Roller with oscillation system for final compaction that could achieve compaction without vertical vibration

The pavement rehabilitation works were fully completed, inclusive of line marking, and open to traffic within six weeks of commencement (Figure 6).

Figure 6: Completed pavement

Direct Costs

There are several basic elements under a life-cycle-analysis model that could be considered as economic costs related to road assets. These include:

1. initial (or direct) costs
2. pavement life
3. maintenance costs
4. salvage value of pavement (Wilmot 1991).

The scope of this paper includes the first element only, which is the direct cost of road rehabilitation options. With regard to the second to fourth points, the road rehabilitation options proposed were intended for equivalent design life periods and performance outcomes and therefore these can be considered equal. Also in keeping with the aims of this paper, the complexities of considering these approaches, along with the realistic influence of political and financial pressures, dictate that the direct cost is the value most significant in the decision-making in determining road pavement rehabilitation options (Smith & Vorobieff 2007).

A direct cost saving of approximately 25% was achieved by implementing foamed asphalt pavement recycling as opposed to the traditional deep lift asphalt and subgrade replacement approach. This direct cost saving was easily determined by comparing the costs submitted for the preliminary project with the costs of the implemented foamed asphalt pavement recycling component of works.

The most significant cost saving was the removal of the need to import material for pavement sub-layers into the site. This is not only due to the recycling of existing materials serving as a far less expensive alternative to purchasing new materials, but also the expedited construction program. Further explained, the foamed asphalt pavement recycling process was able to rehabilitate the full 200 mm pavement depth both in situ and in one layer. In comparison, the traditional method involved subgrade replacement and the use of conventional asphalt, both requiring exportation and importation activities to displace existing materials and make way for new material. Additionally, the placement thickness of a layer of conventional asphalt must be between 3 to 5 times the nominal mix sizes and therefore must be placed in multiple layers. (Transport for New South Wales 2020).

Challenges

Not uncommon to large-scale and important projects that require detailed planning, a theme of ‘delay’ arose early during the planning of the preliminary project and continued to pose a significant threat to successful rehabilitation, even during the actual construction of the alternative foamed asphalt pavement recycling methodology.

Arguably caused by a mix of factors, the underlying cause was likely the involvement of too many and separate stakeholders who were specialised in their particular field but not broadly across all required facets required to tie the project together. This caused difficulties in finding unity on issues surrounding the project, such as design and best construction process. Furthermore, understanding was limited given the process was a recently-introduced innovation and similar in situ recycling methods were not being practised in the ACT.

To overcome this challenge, the actual delivery of the project required extensive and continuous collaboration between stakeholders to ensure all aspects were thoroughly addressed, due to the high-profile and critical nature of this essential infrastructure project. Such aspects covered a range of topics including design, construction logistics and methodology, specifications, additional testing implemented, and workplace safety.

The collaboration process occurred over the course of two months prior to, and throughout, the duration of the project. In particular, the challenges that arose were with external consultants/superintendent who were lacked knowledge of this new recycling process or construction experience. These hurdles were overcome and the site works continued. It is a demonstration of the commitment of the key stakeholders to the success of the project and overall innovation and progression regarding sustainable infrastructure solutions.

Conclusions

Foamed asphalt pavement recycling for the rehabilitation of Northbourne Avenue was a historical project that not only formed part of major holistic infrastructure renewal occurring in Canberra, but also showcased the successful implementation of a revolutionary new innovation in road asset management.

With a preliminary project using traditional methods established, it was possible to effectively and quantitatively compare the sustainability benefits of the new foamed asphalt pavement recycling option. This paper has addressed the three pillars founding sustainability: environmental, social and economic considerations. By using sustainability as the primary criteria, this allowed a complete assessment of these important and interrelated influences.

It is encouraging that the decision-making surrounding critical and infrastructure renewal was based on pursuing the best options that offered sustainability benefits. The project at Northbourne Avenue using foamed asphalt pavement recycling is a key example of the rewards that are possible by investing and committing to new innovation.

Acknowledgements

A team of specialist contractors worked together to deliver the project, including Pavement Recyclers, Woden Contractors and Cardno consulting engineers. Thanks also to Warren Smith, David Berg, Ben Helmers and Gerard Zafico for the support they provided to achieve the outcomes of the project.

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Improved Design and Construction Methodology for Urban Local Roads in Flood Prone Areas[26]

Scott Young, Technical Manager, Stabilised Pavements of Australia[27]

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Introduction

River Terrace is a local road located in the town of Mullumbimby in northern NSW, which is approximately 20 km northwest of Byron Bay (Figure 1). Both towns are part of the Byron Shire Council (BSC) jurisdiction.

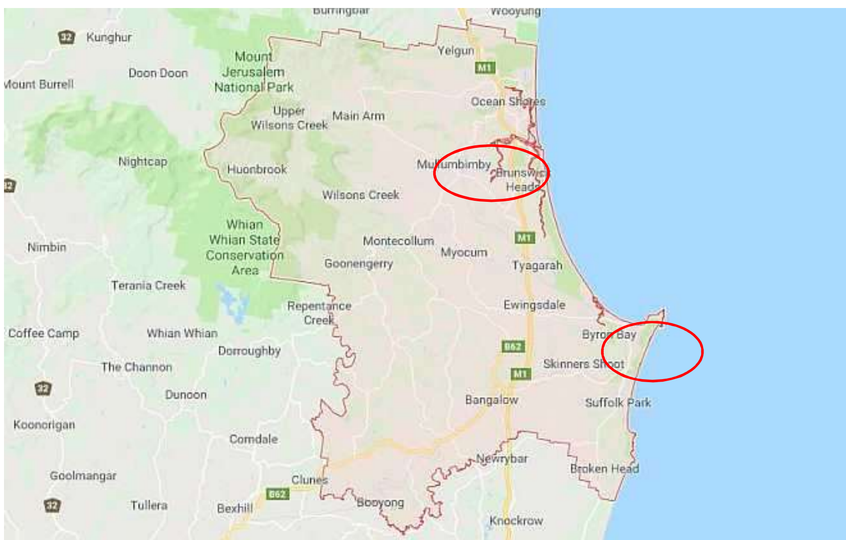

Figure 1: Location of Byron Shire and Mullumbimby

BSC identified that River Terrace was in need of repair due to the significant degradation observed in the wearing surface which showed signs of being caused by loss of integrity and structural capacity in the base course. BSC engaged an external consultant (Civil Consult) in the first half of 2023 to undertake a geotechnical investigation, supplemented by material sampling and laboratory testing. This work was to ultimately inform a series of pavement design options in a pavement rehabilitation report for BSC to consider. Their intent was to implement the rehabilitation works in the 2024 financial year. After BSC reviewed the report, they concluded that their budgeted funds for the project were unable to support any of the pavement rehabilitation design options.

At this juncture, BSC engaged another external consultant (SP Design) in August 2023 to provide advice on what other options may be available, with a specific reference to in situ stabilisation techniques. BSC's overarching objective remained which was provision of a rehabilitation solution to satisfy two key parameters,

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26 This paper was awarded the Katahira TC prize at the 17th REAAA Conference, held in Goyang, Korea, in October 2025.

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being a 20-year design period and the allocated budget. SP Design provided BSC with a proposal which involved review of the previous pavement design report and development of a new pavement design report.

Site Overview

River Terrace is located in the town of Mullumbimby, close to the central business district (Figure 2). The site is bounded by Burringbar Street to the north and Whian Street to the south. It is classified as an urban collector road on a bus route. The site is approximately 240 m in length and has one lane in each direction with no line marking. The site also has an unsealed shoulder/parking bay on the western side between property number 14 and 17. Kerb and channel drainage exists in the northern end of the site on both sides of the road.

Figure 2: Mullumbimby (L) & River Terrace (R)

The limit of proposed pavement rehabilitation works was approximately 2,500 m^2. The project also included some minor civil works (i.e. drainage) and additional asphalt surfacing on the northern end and in the parking lane adjacent to the industrial business accesses. Mullumbimby Creek runs adjacent to the western side of River Terrace. The Brunswick River is slightly west of Mullumbimby Creek. The eastern side of River Terrace is flanked by industrial and commercial premises (Figure 3).

Figure 3: River Terrace features

The weighted mean annual pavement temperature (WMAPT) is 31°C (for Byron Bay which has the closest weather station to the site), and the long-term annual mean rainfall for Byron Bay is 1735.7 mm. Not only does Mullumbimby receive rainfall on average almost half of the year (measured by days), but also River Terrace is located in an area that is liable to become inundated when Mullumbimby Creek breaks its banks and flood-waters make their way towards the CBD. Hence, the site is classified as a flood zone, which means that BSC does not permit any increases to the level of the existing road whenever rehabilitation or resurfacing works occur. This is illustrated n Figure 4.

Figure 4: Mullumbimby fill exclusion zone

Site Condition

The images shown in Figure 5 were reproduced from the Civil Consult report, indicating the condition of the pavement in mid-2023.

Figure 5: Condition of River Terrace pavement

Site Geology and Existing Material Properties

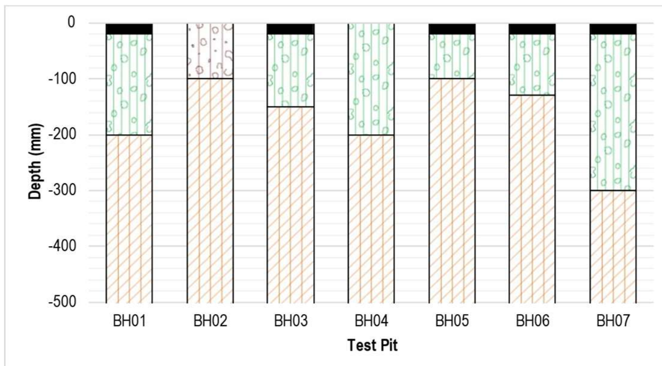
River Terrace and the surrounding area of Mullumbimby is concentrated with alluvial floodplain deposits, comprising silt, very fine to medium-grained lithic, to quartz rich sand and clay. This geological form is illustrated in Figure 6.

Figure 6: Geology mapping at and around River Terrace

The client engaged Civil Consult to undertake the initial geotechnical field investigation in June 2023. Seven boreholes were excavated, two of which (BH02 and BH04) were excavated in the unsealed shoulder. Dynamic Cone Penetrometer (DCP) testing was undertaken on the subgrade at each borehole location. The site plan showing the borehole locations from the Civil Consult report is shown in Figure 7.

Figure 7: Test pit locations [2]

The pavement profiles from each location are shown in Figure 8.



Bituminous Surfacing	Silty Gravel	Gravelly Silt	Silty Clay

Figure 8: Existing pavement profile

Excluding BH02 and BH04 (shoulder profiles), there was barely 200 mm of material above the silty-clay subgrade. This was validated when SP Design undertook an independent material sampling exercise in December 2023. Typical materials are shown in Figure 9.

Figure 9: River Terrace: typical materials

The base layer materials had an average of 17% fines and a plasticity index ranging from 4.0% to 12%. The subgrade samples exhibited variable CBR's as low as 4.5% with low to moderate swell being recorded. All samples were soaked for 4 days, though it was noted that a 10-day soaking period would have been more representative of the site conditions. The soaked samples were not fully saturated after the 4-day soaking period when the moisture content of the top 30 mm was compared to the entire sample, suggesting that the CBR results may have been slightly over-estimated.

Original Pavement Design

The Civil Consults report provided two pavement design solutions for BSC to consider. The first was a granular remove-and-replace design, whilst the second was similar to the first, but included a stabilised subgrade. The design traffic was based on 1,000 vehicles per day with 10% heavy vehicles. The design details are shown Table 1.

Table 1: Civil Consult pavement designs

Layer	Details
Spray Seal	Double/Double (14mm/7mm aggregate)*
Priming Treatment	Cutback primer, AMC0 or AMC00
Base Course – DGB20	150 mm - CBR 35%
Subbase Course – DGS20 or DGS40	300 mm - CBR 25%
Natural Subgrade - Silty CLAY (CH)	CBR 4%
* A 40 mm thick asphalt seal (AC10) may also be acceptable as a seal if preferred by Council.	

Layer	Details
Spray Seal	Double/Double (14mm/7mm aggregate)*
Priming Treatment	Cutback primer, AMC0 or AMC00
Base Course – DGB20	150 mm - CBR 35%
Subbase Course – DGS20 or DGS40	150 mm - CBR 25%
Lime Stabilised Subgrade Insitu – 5% Lime Content	200 mm - CBR 10%
Natural Subgrade – Silty CLAY (CH)	CBR 4%
* A 40 mm thick asphalt seal (AC10) may also be acceptable as a seal if preferred by Council.	

BSC's cost estimate to construct the cheapest of the above two designs was AUD810,000. They did not have adequate funds to implement either of these design options, as both required significant excavation, disposal and material import costs. Further, both of these solutions did not address Council's desire to achieve optimum sustainability outcomes. As a result, BSC engaged SP Design to provide additional advice.

Alternate Pavement Design

Discussions between BSC and SP Design revealed that a design solution to incorporate as much of the existing pavement as possible was desired. A design subgrade of 4.0% was adopted in line with the Civil Consult report, along with a design traffic loading (DESA) of 3.60E+05 for a 20 year design period. The key challenges identified that were to be addressed in the design phase were:

- flood zoning of the area, mandating no increase in surface level being permitted
- a thin existing pavement comprising around 200 mm of gravelly-silt
- variable materials throughout the site, particularly where the shoulders on the eastern side of the road were identified by BSC to be included in the scope
- limited funds for the rehabilitation.

One of the design solutions was to excavate the basecourse material, stockpile it, and then remove some of the subgrade to effectively lower its position. Whilst this strategy is a robust and sustainable solution, this was not seen as an economical or practical solution, as a high frequency of rain events were occurring and predicted to occur in the area at the time. The emphasis was therefore placed on not doing any major excavation and attempting to recycle the pavement materials.

The design solution presented to BSC was a process involving a double stabilisation treatment. The first process was to mix lime into a mix of the existing pavement base and subgrade (i.e. basegrade stabilisation). The intent of this process was to lower the position of the subgrade to a depth of 300 mm below the existing surface level, but without any excavation. All of the existing wearing course was incorporated into the mix. A minimum curing period of 3 days was nominated to enable the lime-treated materials to ameliorate. The top 50 mm of treated material would then be removed to accommodate the placement of the final wearing course. The strengthening process would then take place, whereby a second stabilisation treatment to the design thickness of 200 mm would occur to generate a lightly-bound basecourse layer, defined as having a UCS in the range of 1-2 MPa. The design cross-section and basic construction process is illustrated in Figure 10 and Figure 11.

Figure 10: Pavement design cross section

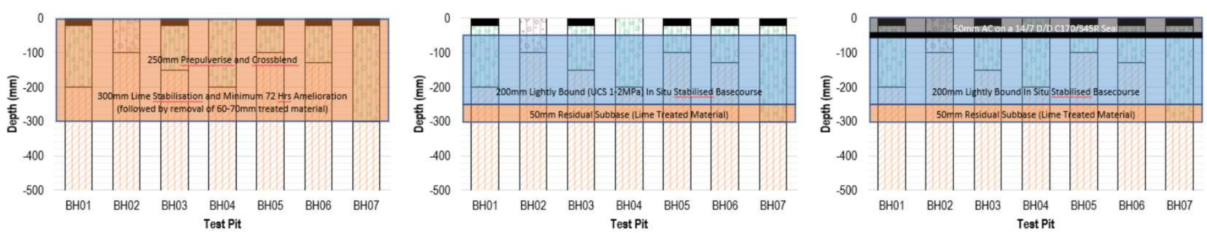


Figure 11: Construction process

BSC's cost estimate to implement this treatment was AUD337,000, which became the project budget. This was almost 60% less than the cost estimate for the granular replacement solution. Further, the cost of the alternate design satisfied the budget allocation.

Stabilisation Mix Design

Stabilisation mix design trials were designed to replicate the design and the construction methodology. The process of stabilizing the same material twice with an amelioration period in between needed to be captured, with specific details provided to the testing laboratory to supplement the existing test method for unconfined compressive strength testing. The mix design trial methodology was as follows.

a) Conduct a Lime Demand (LD) test on the subgrade clay.
b) Adopt a lime content of LD+1%.
c) Break down all samples together to ensure that accurate proportions of the bituminous wearing course, base gravel and subgrade are contained in the mix to reflect the initial pre-pulverising and cross-blending phase.
d) Determine the OMC/MDD relationship of the mix with LD+1% hydrated lime.
e) Mix hydrated lime at LD+1% into the material at OMC.
f) Prepare UCS cylinders.
g) Cure the samples whilst in the cylinders at 25 C for no less than 72 hours.
h) Break down the samples to reflect the second stabilisation mixing process.
i) Determine the MDD/OMC relationship of the mix with 60/40 slag/lime.
j) Undertake UCS testing at 3%, 4% and 5% 60/40 slag/lime.

The lime demand test yielded a result of 2.0%, with a lime content of 3.0% being adopted. The results of the UCS trial with the cementitious mix design trials are shown in Figure 12.

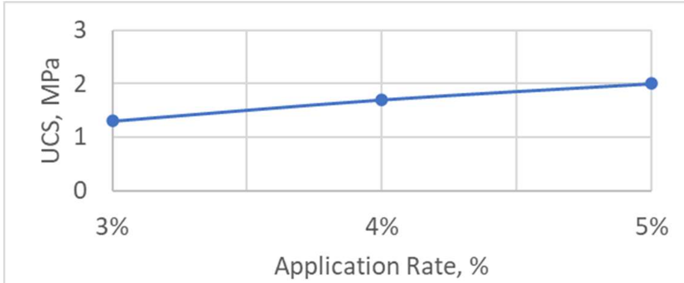


Figure 12: Trial Mix Design UCS Results

Given the target UCS was 1.5 MPa, an application rate of 4.0% was adopted. The targets were used for construction are shown in Table 2.

Table 2: Adopted mix designs

	Application Rate (%)	MDD (t/m^3)	Field Target Spread Rate (kg/m^2)
Hydrated Lime (1st Treatment)	3.0	1.96	18.0
60/40 Slag/Lime (2nd Treatment	4.0	1.94	15.5

Construction

The stages of construction that were specified are shown in Figure 13.

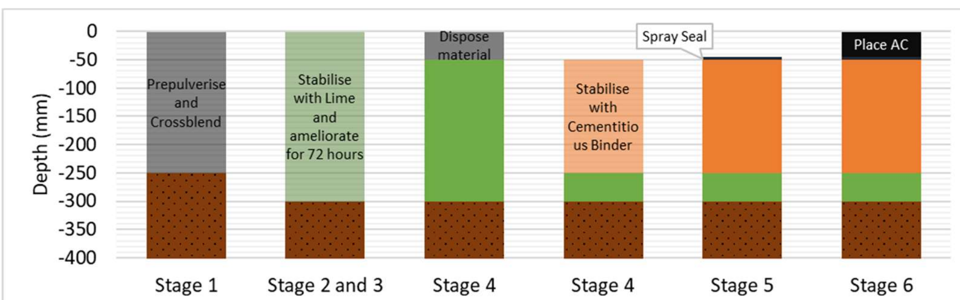


Figure 13: Stages of construction

The intent of the initial construction process requiring the material to be pre-pulverised and cross-blended in line with AustStab (2006) was to improve the uniformity of the material to be stabilised so that uniform strength gain could be achieved as much as possible. A detailed description of each stage of the construction process follows.

a) Pre-pulverise and cross-blend the existing pavement material to a depth of 250 mm to improve the consistency of the pavement material type and thickness along the length and width of the site.
b) Stabilise the pre-pulverised material with hydrated lime to a depth of 300 mm. Compact and trim to enable the road to be trafficked.
c) Allow the lime-treated material to ameliorate for a minimum of 72 hours.
d) Remove and dispose of 50 mm of the lime-treated material.
e) Stabilise the lime-treated material with a suitable cementitious binder to a depth of 200 mm.
f) Place a SAMI sprayed seal.
g) Place 50 mm of AC14 (Class 450 bitumen).

Although the total project time was 21 days, only 6 days were required where construction activities took place. After the initial lime stabilisation treatment was completed, there were two areas that exhibited deformation. The first was at the corner of River Terrace and Whian St, the lowest point of the site. Council noted this location had previously been subjected to numerous repairs. A soft subgrade replacement was undertaken by

BSC which constituted less than 20 m^2. The second area was slightly east of the previously-noted location, in Whian St, where a shallow domestic water service that traversed across the road was damaged during the recycling process. This caused an increase in moisture filtering into the subgrade in the immediate area. The placement of the SAMI seal was also delayed due to wet weather conditions. Photos of the construction are shown in Figure 14.

Spreading and mixing lime

Lime-treated pavement during amelioration period

Mixing 60/40 Slag/Lime

Bitumen sealing

Post-asphalt placement (1 May 2024)

Figure 14: Photos of construction

Post-construction Testing

The following four approaches to the post construction testing were undertaken on River Terrace:

- density testing
- Unconfined Compressive Strength (UCS) testing
- Clegg Hammer testing
- Falling Weight Deflectometer (FWD) testing.

The density testing was performed on sampled retrieved from 6 locations along the length of the site. Although the density ratios were observed to be favourable, the key indicator of success was the low coefficient of variation of the maximum dry density (MDD) and the optimum moisture content (OMC) determined from each sample extracted from behind the stabiliser that had mixed in the 60/40 slag/lime. This is illustrated in Figure 15 (chainage zero was at the southern end of the site).

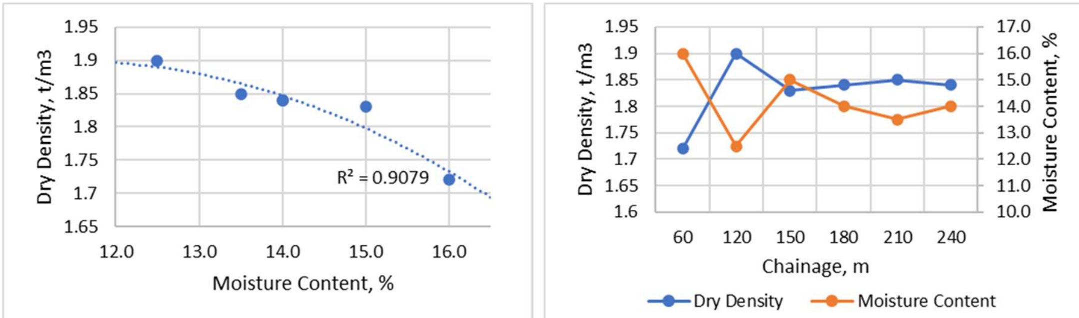


Figure 15: Dry density v moisture content post-lime stabilisation

The UCS test results were considered unreliable due to a curing regime error. The prepared samples were subjected to load in the UCS testing apparatus after 7 days of curing in a 25 C temperature-controlled environment. This curing regime was a blend of the test methods typically used in New South Wales and Queensland, which are 7 days of accelerated temperature curing and 28 days at 23 C respectively. The average dry density and moisture content was 1.83 t/m^3 and 14.2% respectively. Both sets of data had a coefficient of variation less than 9%, indicating material uniformity.

A digital 4.5 kg Clegg Hammer was also used to observe the level of uniformity within the pavement. The Clegg Hammer typically provides Clegg Impact Values (CIV) based on the response to a dropped mass (similar to the mass in a CBR testing apparatus) on the surface, with a zone of influence of around 150 mm. An illustration of the Clegg Hammer being used on River Terrace on 17 April 2024 prior to the slag/lime stabilisation phase is shown in Figure 16. The same test was carried out prior to the site being sealed on 26 April 2024.

Figure 16: Clegg Hammer testing

The photos shown in Figure 17 illustrate how uniform the material appeared from a visual perspective after the slag/lime stabilisation phase. This was attributable to the initial pre-pulverisation and cross-blending phase, which considerably improved the uniformity of in the situ materials.

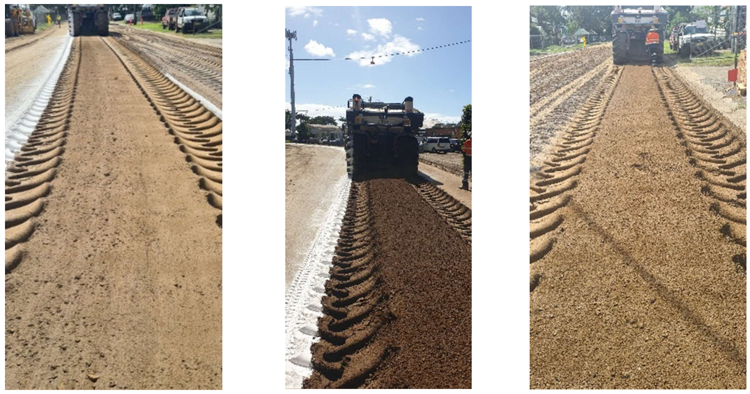


Figure 17: Material uniformity

After the project construction activities were completed, FWD testing was undertaken on the pavement at 5 m intervals in the left wheelpath in both directions. The results of the deflection survey are shown in Figure 18. The high deflection between CH200 and CH240 was caused by the soft subgrade that was repaired at the corner of River Terrace and Whian St. The deflections in Whian St were generally higher than those in River Terrace; this is likely to be related to the slower dry-back period after the rain event that occurred prior to the pavement being sealed. This was because Whian St has significantly more shady conditions compared to River Terrace. Further deflection testing in the future will likely produce more realistic indications of pavement stiffness.

Figure 18: Maximum Deflection and curvature results

Project Economics

As already discussed, BSC's original budget was AUD337,000 which was nearly 60% less than the traditional remove-and-replace alternative that was originally designed and proposed. After the project was completed, BSC provided all of the costs associated with the project as shown in Table 3.

Table 3: Project costs

Item	Qty	Unit	Rate (AUD)	Total cost (AUD)	% of total
Project management	1	item	19,191.67	19,191.67	6%
Geotechnical investigations/designs	1	item	16,080.00	16,080.00	5%
Site establishment/prelims	10	days	3,131.51	31,315.10	9%
Traffic control	12	days	1,604.89	19,258.68	6%
Initial seal	3720	m^2	6.14	22,840.80	7%
40 mm AC10 asphalt	3185	m^2	32.57	103,735.50	31%
Pavement stabilisation	2475	m^2	39.11	96,797.25	29%
Earthworks/drainage	1	item	21,721.97	21,721.97	7%
			Total	**330,940.90**	

With about 80% of the project costs being the actual pavement works, it is clear that the stabilisation element (at only 29% of the project total) provides a significant cost-benefit, given it provides the structural component of the pavement system. The average unit cost of the project was approximately AUD110/m^2.

Conclusions

The rehabilitation of River Terrace in Mullumbimby initially presented multiple challenges to Byron Shire Council. These challenges are not unique to this Council, where restrictions on finished surface levels, flood zoning, thin pavements and variable existing pavement are encountered. A unique solution was implemented involving a double stabilisation strategy. This enabled the aforementioned challenges to be overcome by initially improving the non-uniform nature of the road through the use of pre-pulverisation and cross-blending. This activity is recommended to be adopted on any pavement stabilisation project where existing materials are not considered highly uniform.

Secondly, the thin pavement challenge was overcome by lowering the position of the subgrade through the first lime stabilisation treatment of the pavement. The strengthening treatment was then able to be implemented onto a pavement that had not just uniform materials, but with adequate depth of cover. The reason for the double stabilisation strategy, as opposed to a traditional single stabilisation treatment, was to position the depth of the subgrade beneath the strengthened base layer and to provide additional resistance during time of flooding and/or high moisture. The 'additional resistance' would be found from having a 'buffer' between the subgrade and the strengthened base, as well as enabling a higher probability of achieving higher densities in the strengthened base due to being compacted onto a subbase, rather than the subgrade.

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Oscorp Engineering provided a valuable service to undertake FWD testing on the finished pavement. Their flexibility in accommodating schedules is always appreciated.

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