Smart Pavements Australia Research Collaboration

SPARC HUB

Submission

Inquiry into the implications of severe weather events on the national regional, rural, and remote road network

House of Representatives Standing Committee on Regional Development, Infrastructure and Transport

8 May 2023

SPARC HUB Smart Pavements Australia Research Collaboration

ARC Smart Pavements Hub
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Executive Summary

An efficient and sustainable road network is essential to Australia's social, economic, and cultural vibrancy. However, this vital asset is facing unprecedented challenges, including (i) extreme weather events; (ii) rapidly growing digitalisation and automation; (iii) increasing traffic volumes and loads; (iv) the need to reduce the carbon footprint of road construction; (v) increasing number of road fatalities; (vi) frequent reworks due to poor quality of construction; (vii) effective and optimal use of recycled materials; and (viii) the requirement to upskill and align the workforce to meet these challenges. These challenges require government, industry, and university collaboration to provide innovative solutions and use available funds optimally. This harmony is essential due to the deeply entrenched, age-old practices that must be reimagined in response to these challenges. The SPARC Hub research program has contributed to improving road infrastructure resilience to severe weather events by developing innovative test, design and construction approaches that take into account climatic effects. However, further targeted R&D is needed to transform these outcomes into practical solutions.

Recommendations

- Horizontally integrate the processes involved in road materials testing, design, construction and condition assessment to modernise these processes, fully leverage the advantages of digitalisation and big data analytics and ensure effective maintenance and rehabilitation of road structures.
- Modernise unbound pavement testing and design beyond the dependency of age-old data, and incorporate advanced hydrological modelling and climatic effects in road pavement testing and design. SPARC has developed a preliminary validated model for simulating past climates and incorporating climate effects into pavement design.
- Incentivise the use of sustainable solutions such as innovative materials (e.g., foamed bitumen, recycled materials) and technologies (e.g., intelligent compaction) in road construction and maintenance through funding and procurement policies to improve the resilience, durability, and sustainability of the Australian road network. However, while using sustainable materials, the most up-to-date techniques to engineer these materials and blends must be utilised to make pavements resilient.
- Advance pavement construction with intelligent compaction technology to minimise rutting, complying with designed performance requirements.
- Construct and maintain good-quality seals with low permeability and good ductility/environmental resistance. These seals must be resilient against traffic loading and increased temperature and moisture.
- Enhance the unsealed roads in flood-prone areas that do not have alternative routes to improve access to essential services and support economic growth in regional, rural, and remote areas.
- There is a need for greater collaboration between government agencies, industry, universities and research institutions to enhance the development and implementation of best practice approaches to enhance road infrastructure resilience and use resources optimally.
- The provision of skill enhancement, knowledge transfer, and training is crucial for the sector's future success in addressing the emerging challenges in the transport infrastructure. In this regard, industry-based PhD research is also pivotal for breaking boundaries and innovating processes and products suited to the Australian context. The use of overseas technologies may not be always optimal for Australian conditions.
- Given the urgent need for climate-resilience roads, there is an opportunity for a Commonwealth-funded National Centre for Transport Infrastructure to link universities, peak bodies, contractors, road authorities, and local councils to future-proof the Australian transport pavements, making them cost-effective, climate-resilient, safe, and sustainable, addressing digitalisation, climate action and resilience.

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1. About SPARC

SPARC (Smart Pavements Australia Research Collaboration) is Australia's first university-led industry-based research program on transport pavements. It is a collaborative Hub that was established in June 2019 through the Australian Research Council's Industrial Transformation Research Hub (ITRH) Scheme in partnership with some 20 industry partners. The collaborative partners include NTRO/ARRB, Austroads, EIC Activities of CIMIC Group and several road authorities. Seven Australian universities are involved, with Monash as the lead university.

SPARC Hub has become the focal point and 'think tank' for university-industry-based transport pavements research in Australia. Our vision is to transform the transport pavement industry to make transport pavements smarter, longer-lasting, safer and more economical with a lower environmental footprint. We aspire to realise this vision through targeted skill enhancement and innovation with an R&D strategy that is balanced in both Research and Development. We are passionate about leading this collaboration to future-proof the Australian transport pavement industry and provide lasting benefits to the community.

SPARC is a five-year research program that will conclude in June 2024 with the completion of ARC funding.

1.1. Relevant scientific and technological advancements, and economic benefits

The SPARC program has made significant scientific and technological advancements that have the potential to make much-needed paradigm shifts in the transport pavement industry. Further targeted R&D is needed to transform these research outcomes to advance the practice.

Some of the key advancements to date include:

- Development of a smart, cheaper, more rational test method for unbound road material ranking and characterisation for road design. This method can effectively be used for testing new road materials, including recycled materials.
- A new design method for unbound and subgrade layer rutting, which can be incorporated into the current pavement design superseding empirical design method based on 1960s data.
- Incorporation of climate effects into pavement design, which is not considered in the current Australian road design. The method can be easily extended to incorporate predicted anthropogenic climate change effects.
- A new laboratory test method and design approach for flood-resilient foamed bitumen pavements.
- A practical design method for optimising the use of geosynthetics for very soft subgrades.
- Extension of the use of Ground Penetration Radar (GPR) for automated real-time layer thickness estimation and moisture content determination.
- A technique for proximal measurement of road material density in real-time during compaction. When fully developed, this technique, along with proximal moisture measurement, can realise the aspiration level of intelligent compaction Level 5 developed by US FHWA, making Australia a leader in this technology.
- Development of an Intelligent Compaction Analyser – a novel, versatile platform for automating and digitalising road materials compaction.
- An innovative microwave technology (at the early stage of development) for speeding up the dry back process of road pavement layers during construction to achieve performance-based construction.
- Practical approaches to maximise the benefits of current intelligent compaction technology for Australian road construction.
- Investigation of the use of geopolymer from wastes such as bricks and glass to produce cement for constructing and rehabilitating resilient and sustainable road bases.
- An approach to horizontally integrate primary pavement processes: testing, design, construction and asset management, to create digital twins of roads to realise the full benefits of digitalisation as in Industry 4.0.

1.2. Much-needed skill enhancement

SPARC's commitment to skills enhancement is a critical contribution to the transport pavements sector. By providing opportunities for PhD graduates and young researchers to work with experienced practitioners from the industry, they gain valuable insights and practical skills that will help them become competent engineers and champions of future challenges. Through secondments, seminars, and workshops, SPARC is creating a culture of collaboration and knowledge-sharing between academia and industry, which will be crucial for the sector's future success. The 37 PhD graduates and 12 young research engineers/fellows from SPARC will bring a wealth of knowledge and expertise to the transport pavements industry, making it more locally and globally competitive.

1.3. Consultations and knowledge dissemination within the national and international road sectors

To date, SPARC organised over 25 webinars, 35 masterclasses, 30 brainstorming sessions, 40 invited talks and technical presentations with local and overseas industry and academic experts for the road sector. In addition, SPARC delivered the following workshops and showcase events to disseminate the technological innovations/advancements and new knowledge generated in the research program.

- A Showcase Event (sparcshowcase2023.org.au) was held in March 2023 at Monash College (750 Collins St, Docklands), where the Federal Minister for Infrastructure, Transport, Regional Development and Local Government, the Hon Catherine King MP, attended the event as the chief guest. The interactive event showcased transformational research outcomes in transport infrastructure, highlighting innovations, technological advancements and skill enhancements achieved through university-industry collaborations in 42 SPARC projects (the event was a resounding success, with over 150 participants from industry, universities and government organisations). A mini showcase event was held in Queensland Main Roads (TMR) and QUT in April 2023 and similar events are being planned in Sydney and Perth.
- A technical workshop on 'Intelligent Construction of Road Pavements – Recent Theoretical and Technological Advancements in Australia' was delivered at the ISIC International Conference on 'Trends on Construction in the Post-Digital Era' held in Portugal in Sept 2022 (icisic2022.com). Seven of our research scholars and SPARC Director attended the conference, ran the workshop and delivered technical presentations.
- SPARC delivered an international symposium on 'Towards the Performance-based Specifications for Unbound Flexible Pavements' in Melbourne in Sept 2022 (over 70 participants from 10 countries, sparchub-unbound-pavements-symposium-2022.org.au).
- SPARC ran an international workshop on 'Intelligent Compaction' in Melbourne in Sept 2021 (over 50 participants from 9 countries).
- Regular presentations to Pavements Task Force in Austroads represented by road authorities and councils.

2. Our response to the terms of reference

2.1. Road engineering and construction standards required to enhance the resiliency of future road construction

Table 1. Road pavement types used in Australia and associated climatic effects

Road pavement type*	Description
Unbound pavements with a thin seal or without a seal (unsealed roads)	Unbound granular pavements with thin bitumen seals are the most economical and amount to about 90% of the sealed road network. These pavements are more susceptible to moisture ingress from prolonged rainfall on top of the impact of increased traffic loads. The load-carrying capacity of these pavements significantly decreases when the moisture content in the unbound layer increases, leading to excessive rutting and cracking and, in turn, potholes in the bitumen seals.

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	During significant rainfall, water will ingress easily through a poorly built or maintained seal, causing progressive failure of the pavement. Our recent international symposium on 'unbound pavements with thin seal' held in Melbourne highlighted that unbound pavements will continue to play a major role in Australia due to their economic viability. In addition, about 50% of the total Australian road network is unsealed roads built with unbound materials *without* a bitumen seal. Unsealed roads (dirt or gravel roads) are more vulnerable to erosion and corrugations in addition to rutting. These roads can become muddy or slippery when wet, making them impassable and substantially reducing road users' safety and comfort. When these roads are in a dry state, they can generate significant amounts of corrugations and dust, creating visibility hazards for drivers, reducing air quality, and creating health issues for nearby residents. Local councils mainly manage these roads.
Asphalt pavements	This pavement type is generally used for heavily trafficked areas. In addition to the bituminous materials, additives such as polymers are used in asphalt to enhance the pavement's performance, durability and longevity. The average CO_2 emissions during the production of 1 tonne of hot mix asphalt can range between 150 kg to 300 kg CO_2, depending on the specific production processes and technologies used. The temperature significantly affects the performance of asphalt pavements under heavy traffic loads. The stiffness and viscosity of bitumen (the binder in asphalt), a key component of asphalt pavement, are highly dependent on temperature. When the temperature increases, the bitumen becomes soft and less viscous, which can cause the asphalt pavement to be susceptible to damage. Asphalt pavement can become brittle and lose flexibility due to oxidation caused by exposure to sunlight and can be prone to cracking. These cracks can lead to water ingress into the asphalt layer. The presence of water in an asphalt layer can reduce the strength and durability of the asphalt mix as the bond between bitumen mastic and the fine/coarse aggregate weakens during repeated heavy traffic loading, causing potholing and surface damage.
Stabilised pavements	These pavements use cementitious (cement) or bituminous materials (foamed bitumen, bitumen emulsion), along with recycled materials (fly ash, crushed concrete/brick, crumb rubber) to stabilise the base of the road, making it more durable and resistant to deformation. Foamed bitumen stabilised pavements have shown significant resilience to flooding. The foamed bitumen pavements managed by TMR Queensland could reopen to traffic shortly after the floodwater subsided. Further, foamed bitumen materials are cost-effective (often less expensive than cement), eco-friendly, less moisture susceptible and immediately trafficable after construction. For other types of stabilised pavements, water entering into stabilised layer generally lose its strength and durability and can make the pavement more susceptible to damage from shrinkage cracking and heavy traffic loads.
Concrete pavements	Concrete pavements are classified as rigid pavements. These pavements can be prone to cracking due to shrinkage caused by temperature and (or) moisture changes. Cracks can allow water to penetrate the pavement, which can cause further damage to the subgrade (compacted ground) that supports the concrete layer. Joints are used to connect sections of concrete pavement and allow for movement due to temperature changes or settlement. If the joint is not formed correctly or sealed, water and debris can infiltrate the pavement, leading to increased distress and potential failure. The quality of construction practices significantly impacts the performance of concrete pavements.
Problematic ground conditions	
Reactive subgrades	The subgrade is the prepared ground over which the road pavement is constructed. Australia has significant areas of reactive (shrinking/swelling due to moisture changes) subgrade, which causes pavements to experience extensive distress, requiring special measures.

**This submission mainly focuses on unbound pavements, asphalt pavements and some stabilised pavement types only.*

2.1.1. Road material testing

Rutting (or excessive permanent deformation) is the primary failure mechanism of unbound granular materials in sealed unbound pavements, resulting from deformations in unbound material layer and subgrade. Rutting is evaluated primarily through the repeated load triaxial (RLT) test locally and globally for unbound materials. However, it is well-recognised that this test is inaccurate, cumbersome and expensive to use commonly, and these difficulties lead to suboptimal and problematic use of unbound materials.

Subgrade rutting is not commonly evaluated, but the California Bearing Ratio (CBR) test (invented during World War I in California and no longer used in the USA) is still used locally to measure the CBR value to use in pavement designs as an indirect measure of subgrade stiffness.

Recognising this pressing need, SPARC Hub has been working on an innovative, cost-effective, easy-to-use, yet more rational test method called Constant Radial Stiffness Triaxial Test or CRST, as shown in Figure 1. It can be used for the rutting assessment of any unbound granular material, including recycled materials and blends. Furthermore, it can be used to assess the subgrade materials, including reactive soils. Hence, it can replace RLT and CBR with one rational test providing rutting assessment and parameters needed for unbound pavement design (i.e., rutting and resilient modulus).

Our research showed that the CRST test is more effective in simulating the pavement loading conditions in the field more closely. The relevant supporting international journal publications are provided in Section 3. *Once this method is fully developed and validated, road authorities and agencies can use it for optimal pavement material selection, design and construction.*

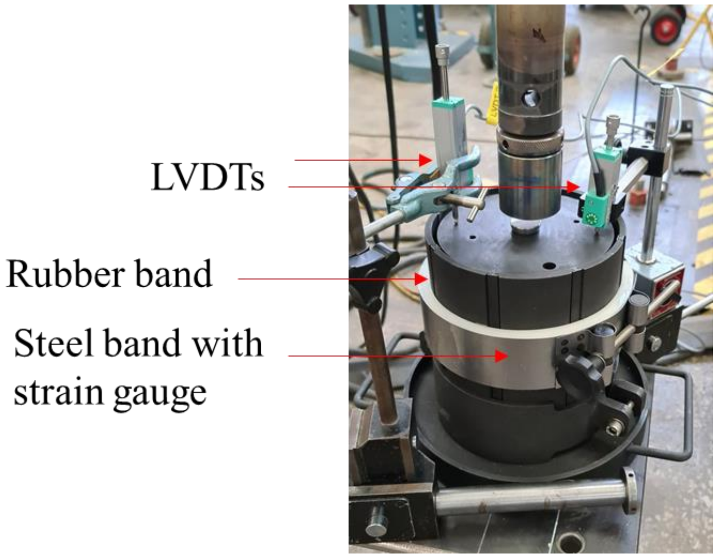

Figure 1. Constant Radial Stiffness Triaxial (CRST) Device

2.1.2. Road pavement design

Unbound granular pavements: The Australian mechanistic-empirical design approach uses the empirical design chart (Figure 8.4 of Austroads Design Guide for empirical pavement design) to assess the rutting behaviour of any unbound granular material. For advanced computer-based pavement design, the data in this chart is presented as a rutting equation. This empirical design chart was established based on age-old empirical data dating back to the 1960s, which are not representative of new road materials, current traffic loads and changing climate. Hence, it can produce suboptimal designs. These aspects were well highlighted in the SPARC International Symposium on Unbound Pavements held in September 2022. *Therefore, there is a clear need to reimagine the design process directly considering rutting performance integrated with testing and construction.*

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The empirical design chart for rutting unbound granular materials (Figure 8.4 of Austroads Design Guide for empirical pavement design) was initially developed to design unbound granular layers *with thin seals only*. However, the Australian mechanistic-empirical design approach uses a formula developed directly using this empirical design chart for *any road pavement structure* consisting of multiple layers to determine layer thickness of any unbound material required over subgrade (compacted ground). Moreover, the terminal condition of the pavement structure is not explicitly considered in this approach, as it does not analyse the ultimate rutting of each layer in the unbound pavement system for the design traffic. Therefore, this approach cannot be considered foolproof or optimal since the field scenarios for which the empirical evidence is applicable are limited as materials and their density, moisture and stress conditions vary significantly. In addition, new materials and blends of recycled materials are being increasingly introduced, for which this empirical evidence is not directly applicable. SPARC has developed a practical approach for rutting analysis and design of any unbound granular pavement addressing these issues (Publication No. 1, Section 3). Further work is needed to make it acceptable to the broader road sector.

Moisture content in unbound granular layers and subgrade can change due to environmental conditions of rainfall and evaporation, water infiltration into shoulders, water table fluctuations, vapour movements inside pavement due to thermal gradients, etc. *The current Australian pavement design approach does not consider the climate effects in sufficient detail (Section 4.0 Environment), as reflected by the significant road damage we face due to extreme weather conditions.* A workable model is unavailable for Australia to predict temporal moisture variations in unbound pavements after construction. This is particularly important for more vulnerable road sections where problematic soils such as highly reactive soils exist in flood-prone areas or locations with high-temperature variations. Following the USA approach, SPARC has developed a preliminary validated model for simulating past climates and incorporating climate effects into pavement design (Publication No. 3 to 5, Section 3).

Asphalt pavements: A recent USA study in 'Nature Climate Science' highlighted that with warming temperatures, maintaining the standard practice of material selection for road asphalt seal layers can add to A$30 billion by 2040 (Underwood et al., 2017). Currently, asphalt pavements are designed using *a single design temperature* called the Weighted Mean Annual Pavement Temperature (WMAPT). The asphalt pavements in hot climates are built with a larger layer thickness than those in cooler climates. *The WMAPT approach does not consider the temporal temperature variations in asphalt pavements during their operation, particularly during extreme weather events such as excessively hot weather and the associated traffic distribution throughout each day.*

Figure 2 shows the variation of temperature measured within an asphalt pavement on a summer day in Karratha, Western Australia. As shown in this figure, the temperature closer to the asphalt surface (at a depth of 45 mm from the asphalt surface) peaks at 63℃ between 2 pm and 4 pm, where the traffic on the road is expected to be higher. It should be noted that the estimated WMAPT for Karratha based on climate data is 40 ℃ (WARRIP, 2019). The stiffness and viscosity of bitumen (the binder in asphalt), a key component of asphalt pavement, are highly dependent on temperature. When the temperature increases, the bitumen becomes soft and less viscous, which can cause the asphalt pavement to be susceptible to damage. *To address this issue, we proposed an incremental-recursive model considering the variation of asphalt temperature and the corresponding traffic loads to evaluate the cumulative damage to the asphalt pavement (Publication No. 6, Section 3).*

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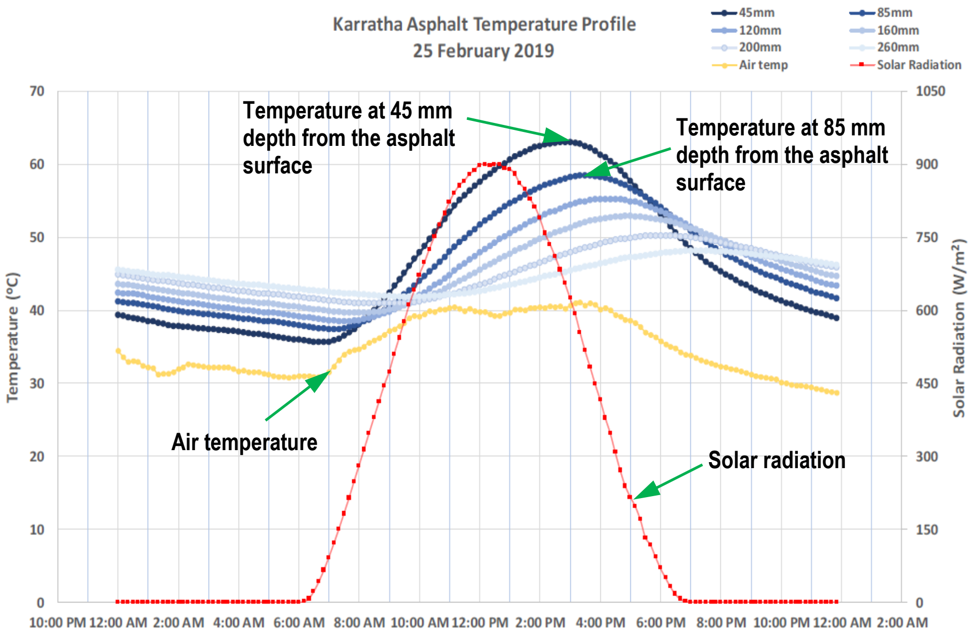

Figure 2. Temperature variation measured within an asphalt pavement on a summer day, test site: Karratha, WA (WARRIP, 2019)

2.1.3. Road construction

Quality control (QC) and quality assurance (QA): "Our roads in the past have been resurfaced, but in no time, the potholes appear" (Submission 3 by Kay Wilson). Although the testing and design are advanced, the sustained functionality of roads heavily depends on the QC and QA during the construction of the road structure. Significant delays in the construction phase have been reported due to frequent reworks, owing to the limitations in the current QC/QA processes. Current practice involves using discrete measurements using a nuclear density gauge (NDG) or by disruptive sample collection. While the NDG can be inaccurate and the sample collection is time-consuming and disruptive, a major issue is that they do not consider the inherent spatial variability of density and moisture content of materials in the construction corridor.

Intelligent compaction (IC) technology is advanced to monitor and digitally document the entire compaction area in real-time to overcome these issues. Such digital recording would also be part of the infrastructure digital twins pursued in the Industry 4.0 revolution. 'Intelligent Construction' broadly refers to constructing a transport pavement, primarily using advanced sensing and automation that achieves the target performance over its design life. *The pavement construction industry in Australia is slow in implementing this technology in practice for several reasons. These reasons include a lack of understanding of the benefits of IC and not having a common approach to appreciate bids that are not of the lowest cost but have used innovative technology. This is highlighted in the document by Australian Constructors Association (ACA) named "Disrupt or Die" to address the industry's significant productivity laggard.* The recent international workshop on intelligent compaction organised by SPARC highlighted that countries like the US and China had implemented IC technology in practice as a mandatory requirement for contractors almost seven years ahead of Australia. To maximise the benefits of current IC technology for Australian contractors, SPARC has developed more practical IC specifications addressing some critical issues in the current technology while taking into account the limitations in the field. SPARC has also developed an innovative technique where the density can be continually monitored proximally in real-time during unbound materials compaction for targeted performance (Patent Application: PCT/AU2021/051505). *When fully developed, this technology can potentially transform the unbound materials compaction globally to the highest level (Level 5 – a roadmap for IC by FHWA, 2017).*

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To implement the IC specifications and novel proximal density measurement technique, SPARC has developed a versatile platform from the ground up (Intelligent Compaction Analyser – Figure 3) to monitor, record and analyse road materials compaction in real-time. The functionality of this platform has been tested and validated in some road construction projects.

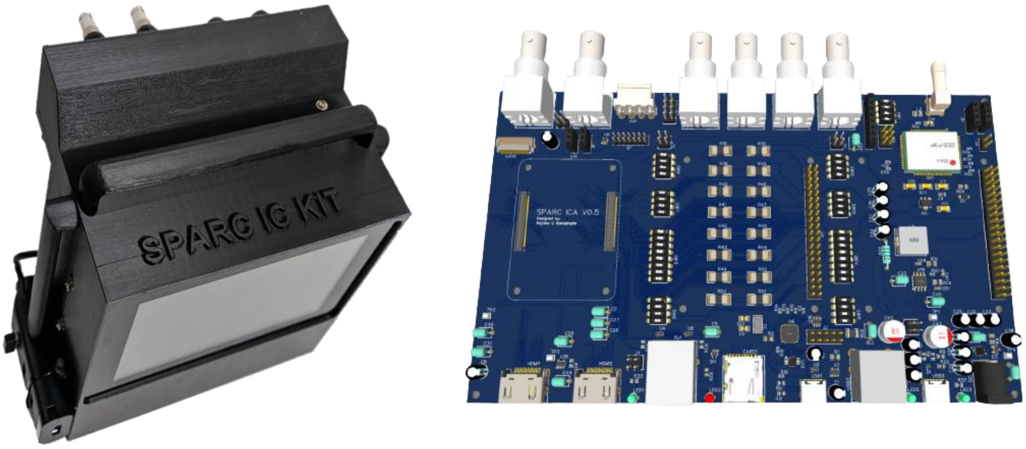

Figure 3. SPARC Intelligent Compaction Analyser

Lack of integration of pavement design and construction: pavement design is undertaken by estimating layer thickness for the selected elastic modulus of the unbound granular material in linear-elastic analysis. The construction is carried out by specifying density at a particular moisture content. This lack of integration does not directly address the main performance requirement of limiting rutting and heavily relies on the proper construction to achieve the targeted performance.

Pothole repairs: Potholes are fixed using a throw-and-roll repair method, where asphalt patch material is placed inside a pothole and then compacted using a heavy vehicle. This method provides a temporary solution and has a high failure rate. It is recommended to undertake rehabilitation of the failed sections of the pavement after accessing the current structural condition of the underlying structure of the road pavement using a suitable condition assessment method. The data collected during the condition assessment is vital for the optimum design of rehabilitation work.

2.1.4. Road condition monitoring and maintenance: horizontal integration of pavement processes

Currently, the pavement processes (testing, design, construction and maintenance) are mainly considered disparate tasks without much integration. In addition, there are no consistently used standards for Australian road maintenance data, resulting in data that is often siloed, poor quality, held in varied, disparate systems and collected intermittently (Submission 10, Austroads). To fully leverage the advantages of continuous digitalisation and ensure effective maintenance and rehabilitation of road structures, it is essential to establish national standards that can document and integrate the data collected from various pavement processes. Such advancement is essential for developing digital twins for roads with feedback loops to update the digital structure based on the (big) data gathered in different pavement processes. *It is worth noting here that developing digital twins for underground structures such as roads is more complex than for above-ground structures and is lagging behind the above-ground infrastructure hence a special effort is needed. Figure 4 schematically shows an example integration of processes in pavement testing, design, construction and condition assessment to benefit from digitalisation and the AI revolution.*

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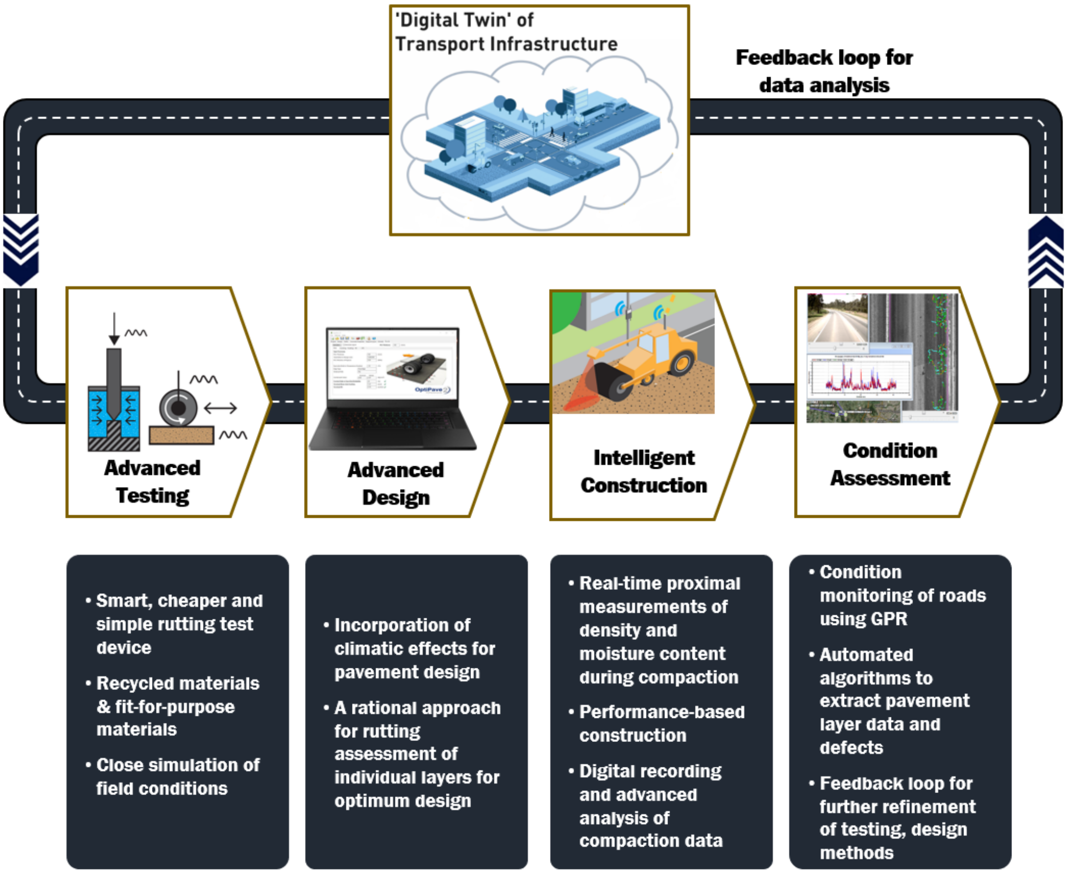

Figure 4. Horizontal integration of pavement processes

2.2. Identification of climate-resilient corridors suitable for future road construction projects

Freight vehicles are a key resource during and immediately after flooding events for managing disaster recovery operations to support the community and economic recovery. Most unbound road pavements are susceptible to significant damage due to flooding, which may make them unable to carry heavy traffic loads. Therefore, the first step is to identify a less vulnerable route to extreme weather events (i.e., areas vulnerable to severe flooding and prolonged droughts) based on past and future (predicted) climate data. When selecting climate-resilient corridors, it is also essential to assess the nature of the existing ground to avoid expansive soil regions, which are more problematic for road structures during extreme climate events. Proximity to robust pavement materials is another prerequisite. If such a route is impractical due to road network connectivity and cost, then climate-resilient materials (for example, foamed bitumen as a flood-resilient material or any other stabilised material) must be used to build the road structure for sections of the route that are susceptible to flooding. For these vulnerable road sections, flood estimates considering future extreme events are crucial for adapting suitable drainage design practices. *However, pavement drainage design is also based on old practices and must be reimagined in light of advanced science, particularly in unsaturated soil mechanics.* "Anecdotally, what previously was considered to be a 1:100 storm now is occurring at a 1:10 frequency, which means roads must now be designed and built to that standard" (Submission 12, Shire of Pingelly).

Various modern techniques will enhance pavement drainage. For example, wicking drains could drain water before the pavement becomes saturated. Road drainage and geometry design are crucial in directing the stormwater away from the road surface and using drainage features such as crown and cross slope to handle the increased water runoff. Advanced hydrological modelling using the future rainfalls (predicted) could be undertaken to estimate the peak flood levels for designing and constructing road infrastructure to suit the future climatic conditions that are likely to happen. Considering the social and economic benefits to the community, a comprehensive cost-benefit analysis should be undertaken for the conservative engineering design and future maintenance requirements of the structure related to extreme weather events. This is particularly critical for roads in remote areas that do not have alternative routes.

During the operation of these critical road infrastructures, frequent maintenance of road drainage is particularly important to prevent debris blockage. In several recent flood events, it is reported that debris blockage has resulted in full or partial blockage of drainage structures (including major culverts and even bridges) where major flows were diverted, causing significant damage to infrastructure and the local community (Submission 10, Austroads).

2.3. Opportunities to enhance road resilience through the use of waterproof products in road construction

2.3.1. Resilient seals

Above, we highlighted methods to test, design and construct unbound pavement layers to minimise rutting. For the longevity of the unbound pavements, however, it is vital to construct and maintain good-quality seals having low permeability and good ductility/environmental resistance. During heavy rainfall, water will ingress through poorly built/maintained seals (or high permeable seals) and wet the base layers, leading to significant rutting and potholes in the seal. These seals need to be resilient against traffic loading and increased temperature and moisture. Regular maintenance of the seals (i.e., retreatment of sprayed seals) to prevent extensive cracks on the road surface is desirable and more economical. *In addition to inventing more effective seal materials, we will need to reimagine an optimal seal thickness, possibly increasing it from the current thickness values to keep using unbound pavements as our economically viable but resilient choice.* It may be possible to invest in developing an automated crack-sealing machine to undertake this activity expeditiously, cost-effectively and safely.

Polymer-modified binders improve pavement properties such as reduced temperature susceptibility, increased elasticity, improved cohesion, and enhanced bond strength. When used in sprayed seals, these binders provide significant long-term performance benefits, including reduced bleeding, improved crack resistance, better aggregate retention, and less deformation at high temperatures (Submission 10, Austroads).

Crumb rubber-modified binders have also improved performance in sprayed seals and asphalt, particularly in severe and challenging locations (Submission 10, Austroads). Recent research conducted by RMIT has shown that adding crumb rubber, combined with the right mix of bitumen and other compounds, can slow down the ageing trend of the seal. This can effectively act as a sunscreen for roads, doubling the surface's lifespan compared to regular bitumen (Jamal et al., 2022).

Polymer-modified bitumen emulsion is a cost-effective and environmentally friendly surface treatment for unsealed roads, providing a low permeable layer that suppresses dust emissions and possibly reduces rutting and corrugation formation. This treatment offers improvements in performance and durability, as well as reduced life cycle costs, compared to unmodified bitumen emulsions or hot mix asphalt surfacing (John and Gayle, 2008).

2.3.2. Foamed bitumen and asphalt materials

Foamed bitumen stabilised (FBS) pavements have shown significant resilience due to flooding. The FBS pavements, managed by TMR Queensland, were able to reopen to traffic shortly after the floodwater subsided. Foamed bitumen materials are cost-effective (often less expensive than only cement-based), eco-friendly, less moisture susceptible and immediately trafficable after construction.

Fatigue cracking is the primary failure mechanism of FBS road bases under repeated heavy traffic loading. However, without a bespoke fatigue relationship for FBS materials, the current Australian pavement practice relies on using the asphalt laboratory fatigue relationship *directly* to estimate the design life of FBS road bases. In collaboration with ARRB, we have conducted a meticulous laboratory investigation and analysis on the structural

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performance of FBS materials under various conditions, including different temperatures and after specimens were soaked. Based on an analysis of the experimental data, we have developed a rigorous practical design approach for FBS road bases that considers variations in temperature, bitumen content, moisture content and density of the FBS mixtures (Publication No. 6 to 10, Section 3).

Our fatigue experiments revealed that FBS specimens soaked in water for 48 hours had similar fatigue life to unsoaked specimens at operational stress levels. This finding is consistent with the field performance of FBS road bases after flooding. FBS materials comprise bitumen as the primary binder (2 to 4%) and cement or lime as the secondary binder. The bitumen content in FBS materials enhances moisture resistance and flexibility, resulting in ductile behaviour (see Figure 5). In contrast, the cement/lime content increases strength and stiffness against permanent deformation (see Figure 5). Increased strength/stiffness and ductility are ideal material characteristics for road construction. *Following this innovative concept, it is possible to innovate new resilient materials that utilise blends of recycled materials, such as crumb rubber, plastic, crushed glass and concrete. However, further work is needed to learn from the observed superior performance of foamed bitumen pavements and exploit it for enhancing other materials.*

The recent Austroads publication on foamed bitumen materials (Austroads Publication No. AP-R666-22) references the critical findings of our foamed bitumen research project.

In addition, other asphalt materials can be investigated to achieve resilience. One such material is EME2, which was first introduced in France in the early 1990s. This material exhibits high stiffness, high impermeability to moisture ingress, less susceptibility to moisture, and superior resistance to permanent deformation and fatigue, with low maintenance costs. International and Australian experiences indicate that considerable pavement thickness reductions can be achieved using EME2 (WARRIP, 2018). Recycled materials such as reclaimed asphalt pavement (RAP) can be used in EME2 to reduce carbon emissions and enhance sustainability.

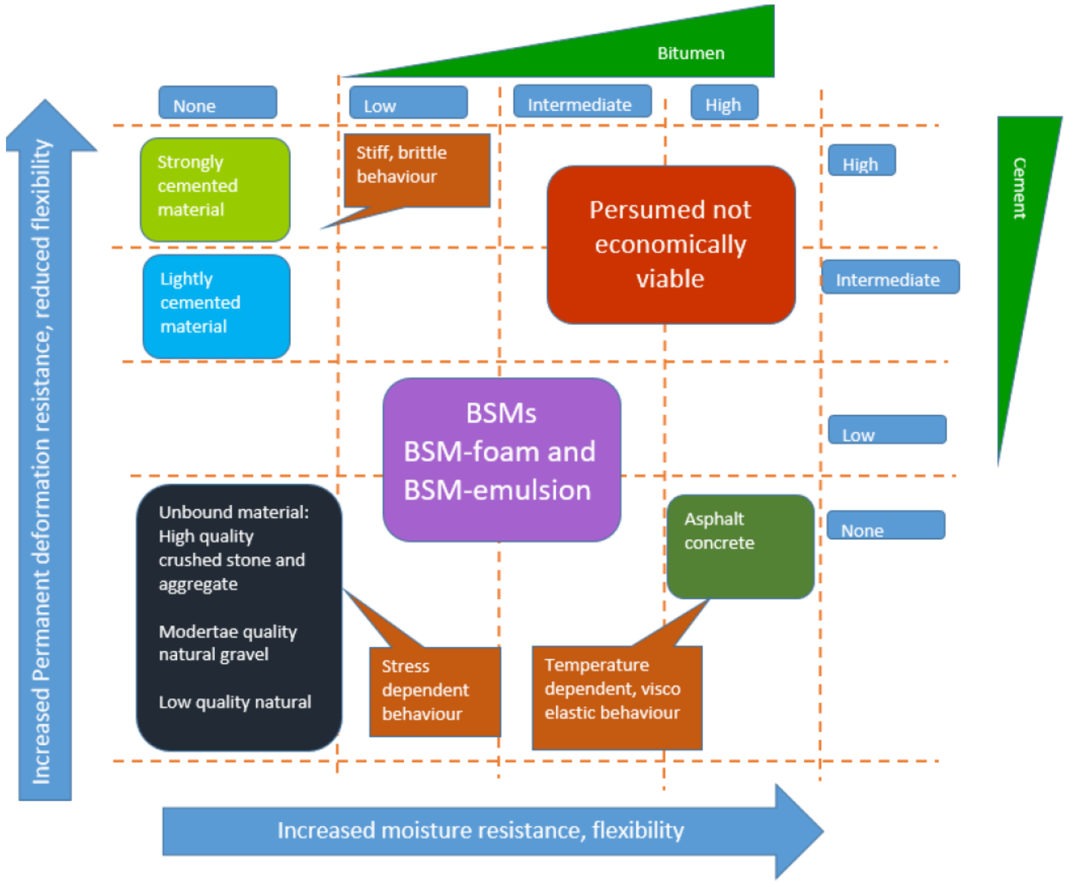

Figure 5. Classification of Road Materials based on bitumen and cement contents (developed using the scheme published by the Asphalt Academy)

2.4. The Commonwealth's role in road resilience planning

Australia spends approximately $30.25 billion annually on roads (BITRE, 2019), with up to $7 billion annually spent on maintaining its 900,000 km road network, the world's highest per capita maintenance expenditure. Over the next decade, the Australian Government has committed $120 billion to transport infrastructure nationwide. In this context, the Commonwealth could play a direct role in road resilience planning. Hence, there is an opportunity to establish a Commonwealth-funded centre for addressing transport pavement needs nationally. The case for this commonwealth role is also justified because 50% of the road network is unsealed and primarily managed by local councils.

Commonwealth can create a dedicated national centre for transport infrastructure linking the entire value-chain of universities, peak bodies (such as Austroads, NTRO and AfPA), contractors, road authorities and local councils to future-proof the transport pavements industry, making transport pavements (roads, rail, airport and min-haul pavements) cost-effective, climate-resilient, safer, with a lower environmental footprint and adaptable to future transport demands and climate changes. Skill enhancement, knowledge transfer, and training can also be core activities of the centre.

2.5. References

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3. Relevant SPARC research articles and technical reports

No	Article Title	Publication Year/Publisher	Highlights
New test method for pavement rutting			
1	Evaluation of unbound/subgrade material rutting and resilient behaviour based on initial density and saturation degree	2022 *(Transportation Geotechnics)*	This study performed a test called the constant radial stiffness triaxial (CRST) test on a silty sand, which better replicates the stress on the materials from traffic loading. Rutting prediction models were developed to control compaction in the field towards performance-based construction.
Incorporation of climatic effects into pavement design			
2	Review of Soil Compaction: History and Recent Developments	2018 *(Transportation Geotechnics)*	Soil compaction is a major construction activity in civil engineering. This paper discusses the history and development of soil compaction, and their associated field specifications. Areas for further advancements in theory and practice are identified including the incorporation of climatic effects.

3	Numerical evaluation of temporal moisture variations in unbound pavements with thin seals	2022 *(Transportation Geotechnics)*	The moisture condition of pavements is critical to their performance. To predict possible temporal moisture variation during service life, a model was developed in this study. The model was validated against field data.
4	Evaluation of the Temporal Moisture Variations in Flexible Pavements with Thin Seals Under Melbourne Climate	2022 *(Proceedings of ISIC conference)*	This paper discusses the development of a model to predict moisture variations in pavement layers of unbound pavements with thin sprayed seals under Melbourne's climate. The accurate prediction of moisture variations in pavements throughout their service life can lead to more economical and safer pavement design.
5	Experimental and Numerical Investigation of Moisture Variation in Unbound Pavements with Sprayed Seals During Drying and Wetting	2023 *(Transportation Geotechnics)*	This study investigates how moisture moves through road surfaces with sprayed seals using laboratory and numerical techniques. It was found that once moisture entered the unbound base, it was harder for it to dry out, but the drying rate depended on the base layer's saturation condition.
Foamed bitumen			
6	Characterisation of fatigue performance in foamed bitumen stabilised materials for pavement design	2020 *(PhD thesis, Monash)*	This thesis examines the behaviour of foamed bitumen stabilised road pavements through laboratory and field testing. Based on the experimental observations, it develops analytical procedures for more rational foamed bitumen pavement design.
7	Advanced characterisation of flexural fatigue performance of foamed bitumen stabilised pavement materials	2022 *(Construction and Building Materials)*	This study found that the flexural fatigue life of the foamed bitumen stabilised (FBS) beams increases with increasing density and bitumen content, but decreases with increasing temperature and moisture content. This study also developed analytical models for predicting the flexural fatigue life of FBS mixtures based on variations in temperature, bitumen content, moisture content, and density.
8	Flexural behaviour evaluation on foamed bitumen stabilised pavement beams using fibre optic sensors	2020 *(International Journal of Pavement Engineering)*	This paper evaluates the accuracy of distributed fibre optics sensors (DFOs) and fibre Bragg grating sensors (FBGs) in measuring the flexural strain of foamed bitumen stabilised (FBS) beams under different loading conditions. Additionally, the study found that DFOs were able to detect crack initiation and propagation during the tests.
9	Experimental Characterisation of Fatigue Damage in Foamed Bitumen Stabilised Materials Using Dissipated Energy Approach	2019 *(Construction and Building Materials)*	Foamed bitumen stabilisation (FBS) of degraded pavements has become popular in recent times. This study investigates the flexural fatigue performance of FBS beams using dissipated energy (DE) approach.
10	Characterisation of Laboratory and Field Foamed Bitumen Stabilised Beams from Accelerated Pavement Testing Trial	2020 *(Proceedings of 6th APT Conference)*	This study compared the properties of field-constructed and laboratory-manufactured foamed bitumen stabilised (FBS) beams. The results revealed that the field extracted beam samples showed lower sensitivity to temperature and frequency compared to the laboratory-manufactured FBS specimens.
11	Mechanistic Design of Foamed Bitumen Stabilised Pavement Bases	2018 *(GeoMEast International Congress and Exhibition)*	This paper discusses the limitations in current pavement design and testing methods of foamed bitumen stabilised (FBS) materials and proposes a detailed study to characterise their flexural fatigue behaviour under laboratory and field conditions.
Recycled materials (Geopolymer concrete, Waste clay bricks, Crumb rubber)			
12	Investigation of waste clay brick as partial replacement of geopolymer binders for rigid pavement application	2021 *(Construction and Building Materials)*	This study investigated the use of waste clay brick (WCB) as an alternative to ordinary Portland cement in producing geopolymer binders. The study found that WCB-slag blends had higher compressive strengths and achieved up to 96.8 MPa at 28 days, while reducing carbon emissions by up to 78% and energy consumption by up to 85% compared to ordinary Portland cement.
13	Waste Clay Bricks as a Geopolymer Binder for Pavement Construction	2022 *(Sustainability)*	This study reviews recent research on WCB-based geopolymers, including the properties of raw materials, curing conditions, and mechanical properties. Further studies on the durability and field performance of geopolymer concrete are recommended.
14	Investigation of waste clay brick as partial replacement in geopolymer binder	2023 *(Construction and Building Materials)*	This study investigated using waste clay brick (WCB) as a replacement for some of the binding materials in geopolymers made with fly ash and/or slag. The WCB-based geopolymers showed good compressive

			strength, low water absorption, and enhanced resistance to sulphate attack when compared to ordinary Portland cement.
15	Waste Clay Brick as a Part Binder for Pavement Grade Geopolymer Concrete	2023 *(International Journal of Pavement Research and Technology)*	Geopolymer concrete (GPC) was created using waste clay brick powder, fly ash, and slag as binders. The concrete's strength and durability were tested under different curing conditions, particle sizes, and environmental exposures. The results showed that the GPC met the basic strength requirements for use in pavement construction and was resistant to wear, water absorption, and cyclic wetting and drying.
16	Thermal-based experimental method and kinetic model for predicting the composition of crumb rubber derived from end-of-life vehicle tyres	2022 *(Journal of Cleaner Production)*	This study investigated the chemical composition of recycled tires that are turned into crumb rubber for use in construction. The composition of the crumb rubber can vary depending on the source of the end-of-life tires. The researchers developed a thermal model that can predict the rubber content of the crumb rubber, allowing for faster screening of the product for engineering applications.
17	Comparative life cycle assessment of reprocessed plastics and commercial polymer modified asphalts	2022 *(Journal of Cleaner Production)*	This study investigates the environmental benefits and burdens of using reprocessed plastics (RPs) as binder modifiers in asphalt mixtures compared to commercial polymers. The study shows that while the use of RPs increases the environmental burden of the manufacture of asphalt mixtures, it offers an environmentally friendly alternative to commercial polymers.
18	Sustainable pavement construction: A systematic literature review of environmental and economic analysis of recycled materials	2021 *(Journal of Cleaner Production)*	This article discusses the potential of using recycled materials in pavement construction as a solution to waste management and sustainability issues. The study reviews the environmental and economic impacts of various recycled materials, such as recycled concrete aggregates, lignin, waste plastic, recycled glass, crushed brick, and crumb rubber.
Cement-stabilised road materials			
19	An Advanced Experimental Investigation of Size Effect on Flexural Fatigue Behaviour of Cement-Bound Granular Materials	2022 *(International Journal of Pavement Engineering)*	This paper examines the impact of specimen size on the flexural fatigue behaviour of two pavement materials stabilised with 3% general purpose cement. The research proposes an empirical relation to determine the flexural strength of any given beam size and a stress-based fatigue model to predict the flexural fatigue life of cement-stabilised pavement materials in service.
20	Early-Age Fatigue Damage Assessment of Cement-Treated Bases Under Repetitive Heavy Traffic Loading	2018 *(Journal of Materials in Civil Eng)*	This study investigates preventing early-age fatigue damage in cement-treated bases (CTBs) due to heavy traffic loading. This study also discusses the limitations and simplifications in current pavement design and testing methods.
21	Experimental and Numerical Investigation of Flexural Behaviour of Cemented Granular Materials	2018 *(Journal of Materials in Civil Eng)*	This study investigates the flexural behaviour of two different cement-stabilised granular materials at various curing ages. The study proposes that the flexural properties of these materials should be determined at 28 days curing age for use in pavement structural designs, and a numerical model was developed that accurately predicted the flexural behaviour of the materials at various curing ages.
22	Evaluation of Flexural Behaviour of Cemented Pavement Material Beams Using Distributed Fibre Optic Sensors	2017 *(Construction and Building Materials)*	This study evaluated a technique for measuring the flexural strain in cemented pavement material (CPM) beams using a distributed fiber optic sensing (DFOS) technique. The study also demonstrated that DFOSs can detect crack initiation and propagation in CPM beams.
23	Effect of Cement on the Engineering Properties of Pavement Materials	2016 *(Materials Science Forum)*	This paper discusses the importance of characterising cement-stabilised granular materials for highway construction. The results suggest that the flexural modulus and flexural strength ratios depend on various factors, including the material, age, and testing practices.
Intelligent Construction			
24	Advancement of current intelligent compaction technology for asphalt pavement layers	2023 *(PhD thesis, Monash)*	Intelligent compaction (IC) provides real-time feedback to the roller operator by displaying colour-coded maps to ensure uniform compaction. This study aims to advance the current IC technology for asphalt to maximise its benefits for quality assurance and quality control (QA/QC) of asphalt compaction.
25	In-situ spot test measurements and ICMVs for asphalt pavement: Lack of	2023 *(International Journal of*	This paper analysed the performance of different intelligent compaction measurement values (ICMVs) for asphalt pavement and compared them with spot test measurements. A correction method was also

	Correlations and the effect of underlying support	*Pavement Engineering)*	developed in this study to decouple the influence of underlying support on the one of the ICMVs, vibratory modulus.
26	Prediction of average in-depth temperature of asphalt pavement using surface temperature measured during intelligent compaction	2022 (*International Journal of Pavement Engineering)*	This paper presents a novel equation to predict the average in-depth temperature of asphalt layers in real-time during compaction. This equation was validated in a field test, and further numerical simulations demonstrated the applicability of the equation in different field scenarios.
27	A state-of-the-art review of compaction control test methods and intelligent compaction technology for asphalt pavements	2021 *(Road Materials and Pavement Design)*	This paper investigates the current state of knowledge of the existing compaction testing methods for asphalt and identifies the limitations of these methods in using them during asphalt pavement compaction. The effects of asphalt mat temperature and underlying support on ICMVs measured by IC rollers are identified as the potential causes of the poor correlation between ICMVs and spot density measurements.
28	An Intelligent Compaction Analyser: A versatile platform for real-time recording, monitoring and analysing of road material compaction	Preprint *(Under review)*	This study presents the development of the Intelligent Compaction Analyser (ICA), which can be retrofitted to existing conventional rollers. This study provides the basic design concepts of the ICA, outlines its functionalities and capabilities, and presents initial field validation results demonstrating its effectiveness.
29	Using a Novel Instrumented Roller to Estimate Soil Dry Density During Compaction	2022 (*Proceedings of ISIC conference)*	This study developed and validated a new framework for estimating density evolution during compaction of soils and unbound granular materials. Real-time deformation measurements were used to estimate density using a machine-learning artificial neural network (ANN) model, with high accuracy compared to conventional methods.
30	Proximal Sensing of Density During Soil Compaction by Instrumented Roller	2023 *(Australian Geomechanics Journal)*	This study developed a new way to estimate the density of soil during road construction in real-time. This new approach allows for non-destructive and accurate measurement of density during compaction, which can lead to expedited construction, reduced failures, and maintained uniformity.
31	Moisture-permittivity relationship of unbound granular materials for GPR application	2022 *(19th International Conference on Ground Penetrating Radar)*	In this study, a free-space methodology has been used to investigate the moisture-permittivity relationship for unbound granular materials (UGM). This has important implications for accurately assessing moisture levels in UGM pavement layers.
Condition assessment of roads			
32	Automated Segmentation Framework for Asphalt Layer Thickness from GPR Data Using a Cascaded k-Means-DBSCAN Algorithm	2022 *(Journal of Environmental and Engineering Geophysics)*	This study proposes a non-destructive technique for monitoring pavement sub-surface layer thickness and condition evaluation using ground-penetrating radar (GPR). The study presents an automated segmentation framework that providing cost-effective and robust analysis.
33	Adaptive Fuzzy Inference System for Automated Pavement Condition Evaluation of Large Pavement Sections from Ground Penetrating Radar (GPR) Thickness Data	2022 *(Proceedings of ISIC conference)*	In this study, an automated fuzzy inference system was proposed to evaluate pavement conditions using data collected by a 1.5 GHz GPR system, and the output was a pavement condition classification rating that could help engineers plan rehabilitation and maintenance.
34	Smart Sensing and Analysis of ALF Test Pavement Subjected to Accelerated Trafficking	2020 *(SPARC Technical Report)*	A pavement testbed was built indoors to study the performance of thin seals over unbound granular layers under accelerated trafficking. The pavement structure consisted of two adjacent sections, each was instrumented with distributed fibre optic cables for continuous strain monitoring at different vertical positions.
Geogrid strengthening of weak subgrades			
35	Evaluate the performance of geosynthetic reinforced subgrades under monotonic loading	2022 *(PhD thesis, QUT)*	A series of large-scale pavement model tests were conducted in a laboratory environment to investigate the effect of geosynthetics in improving the modulus of weak subgrades. The outcomes of this study promote the use of geosynthetics in road construction to make economical, environmentally friendly, climate resilient, and sustainable road infrastructure.
36	Small-Scale Cyclic Loading Test to Investigate the Rutting Performance of	2022 *(International Journal of*	This study presents the results of small-scale cyclic load tests on unreinforced and geogrid-reinforced unpaved roads using a circular mould. This research could help reduce the required amount of

	Geogrid-Reinforced Unpaved Pavements	*Pavement Research and Technology)*	materials, cost, and effort for future pavement research by optimising the number of tests required.
37	Predicting California Bearing Ratio (CBR) value of a selected subgrade material	2021 *(Proceedings of 12th International Conference on Road and Airfield Pavement Technology)*	This study aims to develop a model to predict subgrade California Bearing Ratio (CBR) based on moisture content and compacted density. The study involved performing CBR tests under different moisture and density combinations and developing a statistical model to predict the CBR value.
38	Monotonic Loading Test to Investigate the Benefits of Composite Geogrids for Subgrade Improvement		This study compared the performance of an unreinforced model section to a composite geogrid-reinforced model section under monotonic loading and found that the ultimate bearing capacity of the subgrade was increased by 53% in the composite geogrid-reinforced section.
39	Development of design guidelines for composite-geogrid reinforced unpaved pavements		This study aimed to develop guidelines for designing unpaved granular pavements/working platforms reinforced with composite geogrids (CGGs) at the base-subgrade interface. Design guidelines were developed based on the rut depths of both the reinforced and unreinforced pavement models obtained after repeated loading. The adoption of these guidelines could lead to both economic and environmental benefits.