FINAL REPORT

P54: Effective Expansive Subgrade Treatments Across Queensland (2016/17)

Project No: PRP16030

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AN INITIATIVE BY:

SUMMARY

A significant proportion of the road network in Queensland is constructed over natural soils that may be prone to moisture-induced strength loss and volumetric change. When inundated by moisture, these pavements have historically exhibited pavement distresses including structural deterioration, surface irregularities due to shrink/swell cycles and severe cracking.

A range of treatments have been adopted over the last several decades, including the addition of granular cover material, chemical stabilisation, mechanical stabilisation, geosynthetic layers and the replacement of unsuitable material with select fill. Over this time, only limited research has been conducted into the background and the relative success of these treatments, despite significant project budget being allocated to the treatment of subgrades.

The objective of this project was to investigate the optimal approach to the selection, design and construction of the best value-for-money moisture-sensitive soil treatment alternatives for road pavement applications. The adoption of a standardised approach to treating expansive subgrades could potentially reduce conservatism, cost and long-term performance risks. It is imperative that fit-for-purpose and value-for-money solutions are adopted across the network.

The overall aim of this research project was to investigate the optimal approach to the selection, design and construction of the best value-for-money moisture-sensitive soil treatment alternatives for road pavement applications. A targeted literature review and a survey of the most heavily-impacted Districts across Queensland revealed that the issue of expansive subgrades affects a wide area of the State. It also highlighted that expansive subgrades are responsible for many pavement failures. However, the approaches to treating these materials varies widely across the State. While District personnel have generally found solutions that have a reasonable success rate, there is recognition that much is still not known about the distribution of treatments and their relative performance.

A review of design and treatment methodologies applicable to reactive soils showed that there are a variety of options for treating and maintaining pavements constructed over expansive subgrades. These may be optimised across the State through increased knowledge sharing, the development of a more sophisticated treatment selection procedure, and through targeted funding of the most appropriate treatments for each location (with accompanying funding for maintenance and resealing).

A series of key recommendations are offered which, if adopted, will help to reduce conservatism, reduce treatment costs and minimise long-term performance risks.

ACKNOWLEDGEMENTS

The project team would like to acknowledge the contributions of the personnel from the Department of Transport and Main Roads North West District, Central West District, Darling Downs District and South West District, particularly with respect to the regional consultation and obtaining data on case studies.

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1 INTRODUCTION

Expansive subgrades are a major source of premature pavement failure across Queensland. A significant proportion of the road network is constructed over natural soils that may be prone to moisture-induced strength loss and volumetric change. This has historically led to pavement distresses, including structural deterioration, surface irregularities due to shrink/swell cycles and severe cracking.

A range of treatments have been adopted over the last several decades, including adding granular cover material, chemical stabilisation, mechanical stabilisation, geosynthetic layers and the replacement of unsuitable material with select fill, each with varying degrees of success.

Over this time, there has been only limited research into the extent, distribution and relative success of each of these treatments. With a significant portion of project budgets being allocated to the treatment of subgrades, it is imperative that fit-for-purpose and value-for-money solutions are adopted across the network.

The objective of this project is to investigate the optimal approach to the selection, design and construction of the best value-for-money moisture-sensitive soil treatment alternatives for road pavement applications. This has involved a review of literature from Australian and international sources, and a review of standard practice through both a regional consultation and targeted data analysis. A standardised approach to treating expansive subgrades could potentially reduce conservatism, cost and long-term performance risks.

It should be noted that this study is focussed primarily on pavements, with other road infrastructure only covered to the extent that some treatments may overlap in their application.

1.1 Benefits of this Research

While there have been efforts in the past to bring together research on this topic from Queensland regions and elsewhere, gaps in the knowledge base still appear to exist. This project has sought to facilitate a range of benefits to the Queensland Department of Transport and Main Roads (TMR), regional practitioners and road users, including:

- the identification of opportunities for improving current Queensland practice without extensive additional investigation – through a review of national and international best practice
- the adoption of location-specific and application-specific treatments – leading to cost savings in construction and maintenance through reduced conservatism and improved performance predictions
- the identification of treatments that may help to reduce the volume of unbound granular material used for cover over expansive subgrades – leading to a reduction in material and haulage costs
- the development of a well-documented performance history of the rural road network – to facilitate peripheral benefits
- the identification of benefits to local road asset owners, who can take advantage of a greater knowledge base and improved design methodology
- capability development – given the loss over time of knowledgeable practitioners who traditionally managed the risks associated with these works through their own personal experience.

1.2 Report Outline

This report covers four key sections that each contribute to the investigation of expansive subgrades across Queensland.

Section 2 summarises the regional consultation undertaken at the beginning of this project, with issues and experiences categorised into key themes.

Following this, Section 3 will explore current and alternative approaches to dealing with expansive subgrades, including Austroads and TMR documentation as well as guidance from South Africa and North America (Texas). While not intended to comprise a comprehensive summary of every alternative, this provides insight into the potential for reaching amenable solutions through multiple pathways.

Section 4 details six of the most common treatments employed across Queensland, and outlines case studies for these treatments where available. Limited performance history is available on these case studies; however, there is potential for these sections to be designated for long-term performance monitoring.

Several of the major outcomes from this project are discussed in Section 5, with conclusions and recommendations outlined in Section 6.

2 REGIONAL CONSULTATION

2.1 Introduction

A series of informal discussions were conducted in November 2016 between the National Asset Centre of Excellence (NACOE) project team and TMR District personnel. The Districts contacted were Toowoomba (Darling Downs), Roma (South West), Barcaldine (Central West) and Cloncurry (North West), as well as the Engineering and Technology branch in Brisbane.

These Districts were chosen based on their level of exposure to expansive subgrades (see Table 2.1 and Figure 2.1). The 12 TMR Districts all have areas that contain expansive subgrades; however, for the purposes of this study, it was considered most efficient to focus on those regions that deal with expansive materials on a routine basis. Outcomes of the study will be shared more widely to provide guidance for all Districts, even where the extent of reactive subgrades is less common.

Table 2.1: Breakdown of TMR Districts by exposure to expansive subgrades

Minimal expansive subgrades	Moderate extent of expansive subgrades	Widespread expansive subgrades
Far North District	Mackay/Whitsunday District	North West District
Northern District	North Coast District	Central West District
Wide Bay / Burnett District	Metropolitan District	Darling Downs District
	South Coast District	South West District
	Fitzroy District	

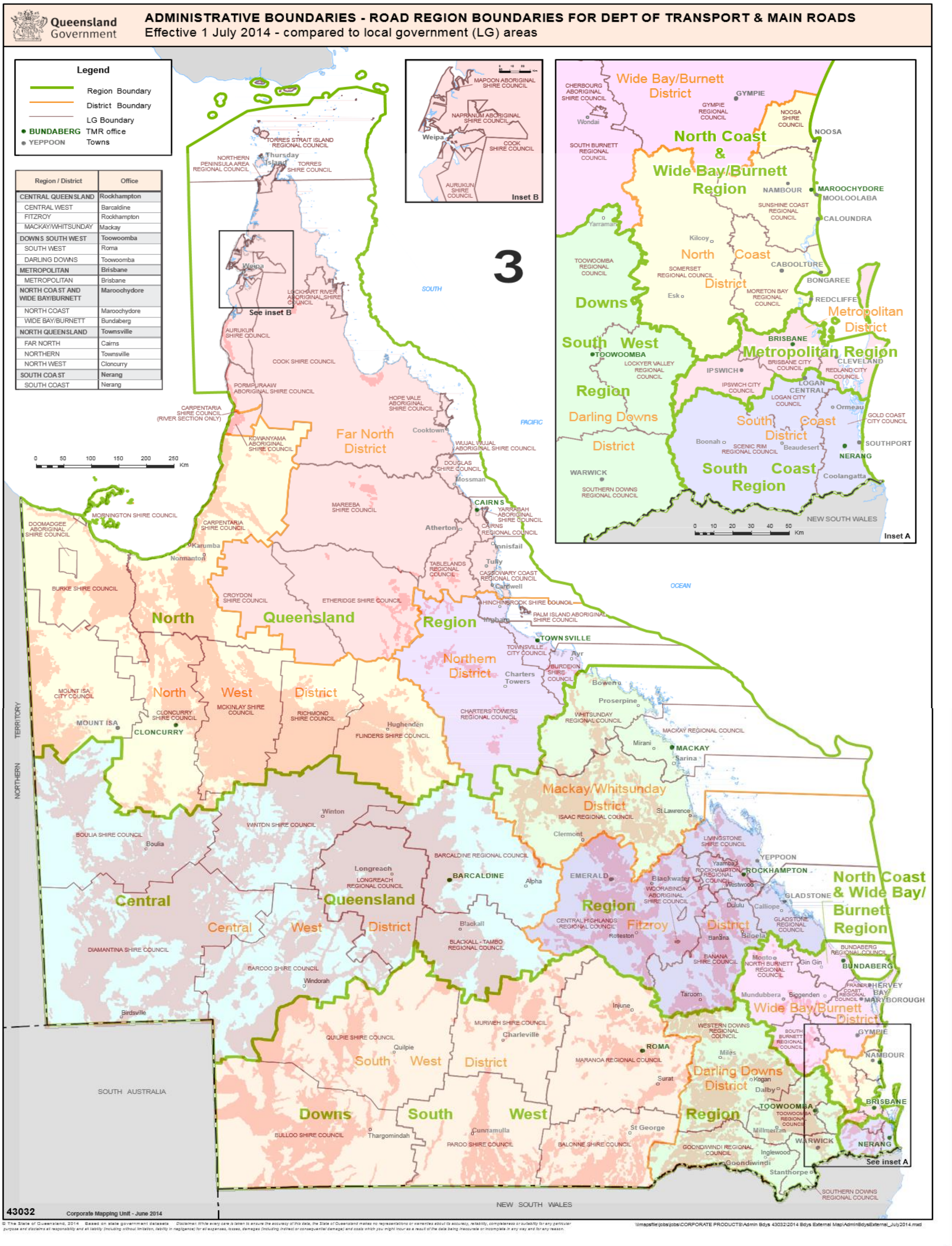
2.2 Summary of Responses

The responses have been summarised in Table 2.2, categorised based on the following most prominent recurring themes:

- lime stabilisation
- testing/materials
- construction practices
- foam bitumen with lime-stabilised subgrade
- fabric seals/geotextiles
- innovative practices
- granular overlays
- upcoming projects.

A summary of these discussions has been disseminated to the participating Districts for feedback, and any applicable feedback has been reflected in this report.

Figure 2.1: Administrative map of Queensland overlaid with map of expansive subgrades



Source: Queensland Government (2014).

Table 2.2: Summary of responses from regional consultation, categorised by theme

Theme	Region	Comments
Common usage of lime stabilisation	Darling Downs	▪ Undertake 300 mm in situ lime stabilisation (increase up to 500 mm at times – example Toowoomba-Cecil Plains Rd – possible because of issue with slow setup before construction).
	Darling Downs	▪ No seal provided over lime-stabilised layer.
	Darling Downs	▪ No permeability testing of lime stabilisation is typically undertaken; however, anecdotally it is believed to be highly impermeable. No measurement of the actual moisture contents in situ appears to have been made.
	Darling Downs	▪ Based on experience, cracking of the lime-stabilised layer is not an issue. Have photos of lime layer that was excavated 10 years after placement to rectify issues where the overlying unbound pavement was saturated and failed.
	Darling Downs	▪ Historically where not enough lime has been used, failures have occurred. However, this has generally been addressed in recent works/design approaches. ▪ Use of quicklime to stabilise subgrades on slopes/hills has been problematics due to run-off during slaking. ▪ Drainage of pavement layers over the lime-stabilised layer can be a concern. Design detail worth considering further. ▪ There may be some case studies in Darling Downs where lime stabilisation effects on the subgrade might be able to be investigated in situ away from the main alignment.
	Darling Downs	▪ Lime stabilisation requires the lime demand test, which often comes back with a value of 3–8 %. To this, 1–2% is added during design to allow for loss during construction. It has been found through experience to 'err on the side of caution' and add a little more lime rather than not enough. Adding a little extra water is also usually beneficial (obviously this has limits).
	Darling Downs	▪ Lime stabilisation of subgrades is the most common treatment, and it is usually very successful. The exception is in very specific circumstances such as on slopes where it is difficult to compact.
	Darling Downs	▪ Lime stabilisation has also been used on high-traffic roads in combination with an improved base layer with an asphalt or seal as wearing course. Dosage rates need to be carefully considered on improved layers: too much cement leads to too stiff of a base layer; this can cause problems if subgrade is undertreated
	Darling Downs	▪ One design note is that a higher modulus can probably be used for lime-stabilised subgrades due to experience with relatively high strength gain with lime in subgrades. We are likely understating the performance of these layers with lime added (if done properly).
	Roma	▪ Lime stabilised is the preferred treatment, and was recently used on the National Hwy. ▪ These designs are done in Roma and passed by E&T before progressing.
	Barcaldine	▪ Some use of lime in black soil on the National Hwy; suspected poor construction led to rutting and general failure. Due to high percentages of lime required (as determined by testing) the cost is generally prohibitive compared to other treatments.
	Engineering & Technology	▪ Winton–Hughenden section used subgrade as base layer with lime, then sealed. Material was marginal but might not be much worse than material from borrow pits which is also very marginal in some western regions.
Testing/materials	Darling Downs	▪ 14% swell is typical in the Darling Downs black soils. However, often it can be less than this.
	Darling Downs	▪ Typical tests include grading, Atterberg Limits Tests & CBR. When CBR is low (<3), swell percentage is also tested.
	Darling Downs	▪ Design requirements are based primarily around traffic rather than around swell of the subgrade.
	Cloncurry	▪ Expansive soils are present to the north and east of Cloncurry, most are moderately expansive (not extreme).
	Cloncurry	▪ Swell is not typically tested, more about standard suite of tests and applying standard treatments. Treatments do not appear to be tailored to test results to any great degree.
	Cloncurry	▪ WG35 is rarely used in the region. Locally-available materials are not high quality, with Type 2.2 and 2.3 materials needing long haul distances.

Theme	Region	Comments
	Roma	▪ Do not test for volume change, but generally do Atterberg tests (plasticity is particularly important).
	Roma	▪ For CBR swell values, the lab has advised that a typical CBR swell value is in the range of 4–5% for expansive subgrade materials.
	Barcaldine	▪ Patchy distribution across District, with eastern area having more black soil than the western part of the District.
	Barcaldine	▪ Not much testing is typically done, little information gathered from local labs, etc.
Foam bitumen with lime stabilised subgrade	Darling Downs	▪ The Toowoomba-Cecil Plains Road rehab included lime stabilisation in combination with a foamed bitumen base. One small section used cement instead of foamed bitumen due to cost reasons, but it is showing early signs of failure. The foamed bitumen sections are performing well. This project did see some longitudinal cracks form, but is suspected that this was a construction issue.
	Cloncurry	▪ Foamed bitumen has been used once on the Flinders Highway 14D (chainage 71-85) during TNRP. This involved stabilising 300 mm of the subgrade, then foamed bitumen over that. Total formation height was 0.5-0.7 metres. There were some failures, particularly the wide crack down the centreline which was likely a construction issue
	Cloncurry	▪ One major advantage of foam bitumen is that it can be re-treated in 10-20 years by just re-blending more bitumen and extra material. With cement-stabilised pavements it is much more difficult to do this.
	Cloncurry	▪ Some push to use plant-mixed foam bitumen but needs re-think of design approach.
Fabric seals, geotextiles	Cloncurry	▪ Fabric seals have been used over shoulders.
	Cloncurry	▪ The Kennedy Development Road 99C was rehabilitated after a major flood in 1999/2000, with a lime-stabilised subgrade and fabric seal.
	Roma	▪ A few locations have required fabric seals or CRM sprayed seals.
	Roma	▪ Geogrids used but only in isolated ‘tricky’ sites.
	Darling Downs	▪ Limited experience with geogrids to address highly-reactive subgrades.
Innovative practices	Barcaldine	▪ Old treatment on National Hwy was to build up a 2–3 metre embankment with black soil to increase pavement height near creeks or low points.
	Barcaldine	▪ In lower traffic areas (<50 AADT), 3.5 metre seals have been used to save money (e.g. Winton–Boulia and Boulia–Mt Isa). This has channelised traffic and led to some accelerated failures. The 6-metre seal allows for more wander and less damage is evident.
	Barcaldine	▪ When constructing new alignments, practice is to leave the road unsealed for around 2 years. This allows the District to understand the potential problems before locking them under a seal. Any issues may be alleviated before sealing.
	Darling Downs	▪ Through Dalby town centre, subgrade replacement is the preferred approach as the contractor and TMR personnel did not want to use lime in close proximity to the town centre. There could be issues getting suitable material for this site, and material/haulage costs will be high (only short length of road though).
	Roma	▪ Sometimes major projects don’t treat subgrades much at all – this is innovative in its own right. ▪ TNRP works on Mitchell Highway (overlay only, no subgrade works) has performed well, although some sections show signs of cracking and minor shape loss
	Engineering & Technology	▪ In NSW, they use temporary side tracks during harvest season to avoid heavy machinery damaging the road.
	Engineering & Technology	▪ Upside-down pavements can be used BUT sealing and maintenance is critical to avoid water sitting at top of cemented layer and causing debonding or shear failure.
	Engineering & Technology	▪ Reduced thickness actually may reduce damage, as the water front is further from critical locations (reference paper on this matter from Ed Baran).
Granular overlays	Barcaldine	▪ Generic pavement design is done in almost all situations – 150 mm of gravel (of variable quality, best available) on top of natural soil, which can be borrowed from side of road if need be. – Pavement is left alone for unsealed roads but almost all are sealed afterwards. – General idea is to target WQ35 spec with material; usually meets this but can add some percentage of better material. This roughly doubles the cost of materials.

Theme	Region	Comments
		– Material variation makes the process somewhat reliant on local knowledge; testing results cannot always be relied upon as the stockpiles can have a range of properties from sample to sample. – Generic design has performed well in a variety of conditions; change has been considered but no reason to change something that is working well. – Pavements carry less than 150 AADT so this makes the design a little easier. – Only failures are on relatively old pavements (15+ years).
	Darling Downs	▪ On current rehab project at Jingi Jingi (Warrego Highway 18C), there is a granular overlay on an expansive subgrade. This treatment uses Type 2 material, from 2.5 at the bottom up to 2.1 at the top. The treatment has minimal disturbance of the subgrade.
	Roma	▪ Overlay design for treated subgrades, this doesn't disturb existing pavement.
Construction practices	Roma	▪ Important to be careful with over-compaction, as moderate compaction allows some future swell from the subgrade.
	Engineering & Technology	▪ Long haulage of materials is generally avoided for various reasons but, for example, was done on several occasions during TNRP to bring in superior materials. This should be considered in locations where better materials would be worthwhile (weigh up risk vs. reward and economics of options)
	Engineering & Technology	▪ Beneficial to compact at above the OMC (closer to equilibrium moisture content) such that the pavement does not over-compact – this has led to issues with excessive movement as the pavement reaches equilibrium moisture at some future date.
Upcoming projects	Barcaldine	▪ National Hwy job south of Barcaldine has been designed and tested, construction in 2017.
	Barcaldine	▪ Dingo Creek on 13F National Hwy will get a full geotechnical investigation before fixing failed areas and widening the alignment. $25 million project for 2018 (most likely).
	Darling Downs	▪ More work upcoming on the Warrego Highway, small sections are gradually being rehabilitated and the treatments vary by location, budget and contractor.
	Cloncurry	▪ More sections of the Flinders Highway will likely be treated in the next few years, but treatments on this road are very expensive compared to the level of traffic.
	Roma	▪ Miles to Roma is using lime-stabilised subgrades generally, with modified cement-stabilised base.

The information in Table 2.2 can be used to prepare a summary of common, occasional and rarely-used treatments in each of the surveyed Districts (Table 2.3). This has been used as a basis for targeting and summarising treatment types and case studies as discussed in Section 4 of this report.

Table 2.3: Summary of treatments by region

Treatment / District	Cover requirements	Lime stabilisation	Other stabilisation	Remove and replace	Granular overlay	Geogrids/ geotextiles
SEQ						
Toowoomba		Most rehab & new pavements	Some foamed bitumen	Through populated areas	e.g. 18C at Jingi Jingi	In trouble spots only
Roma		Most rehab & new pavements	Some cement stabilisation		To avoid disturbing subgrade	In trouble spots only
Barcaldine		On National Hwy, very expensive	Some cement treated pavements	In trouble spots only	Sometimes includes cement stabilisation	In trouble spots only
Cloncurry			Stabilise subgrade with cement		To avoid disturbing subgrade	Some fabric seals, looked at geogrids

Legend:

Common/standard treatment in region	Occasional/isolated treatment in region	Rarely/never utilised in region

2.3 Experience during Transport Network Reconstruction Program

Between 2010 and 2013, a series of natural disaster events occurred across Queensland, with heavy rain reaching inland areas that typically have low-moderate annual rainfall totals. This led to severe damage across the local and state-controlled road network. In response to this flooding, the Transport Network Reconstruction Program (TNRP) was established to manage the recovery and reconstruction works.

While pavement work comprised the bulk of the total program, works also included bridges, culverts and earthworks, with the total program value being in excess of $6.4 billion. An ongoing research project is underway through NACOE to document the work undertaken, evaluate the effectiveness of various treatments employed, and to enable long-term monitoring of selected projects (Lee et al. 2016; Lee & Noya 2016). Ultimately, it is envisaged that this improved understanding and stronger analytical approach will lead to a reduction in construction costs and risks, and improved resilience to future rain and flood events across Queensland. A map of TNRP treatments across the State is shown in Figure 2.2.

The distribution of major reconstruction works across the State during TNRP reveals that the presence of expansive subgrades strongly correlated with major pavement damage (as can be seen in Figure 2.2). This should not be particularly surprising, as a lot of small towns and regional centres are in expansive subgrade regions, due to the superior agricultural conditions present with those soil types. Therefore, the roads linking these communities often pass through expansive subgrade regions. It is also not coincidental that these areas are in close proximity to major rivers and floodplains, which makes the surrounding roads especially vulnerable in the event of sustained heavy rain in the catchment areas.

A workshop was held at the start of the NACOE TNRP project. Representatives from several of the major Regional Project Offices (RPOs) provided input on the processes involved, challenges faced, lessons learnt and guidance on prioritising facets of the NACOE study. One notable finding of the workshop was a general agreement that the majority of pavement failures occurred (at least in part) due to saturated subgrades. Failures were most severe in locations with low-strength and/or highly-reactive subgrades, with treatments in areas of non-expansive subgrades usually only involved re-sheeting (i.e. nothing to do with the subgrade, just damage from the flow of water over the surface).

Figure 2.2: Map of works during TNRP against expansive subgrades

Source: Lee et al. (2016); Lee & Noya (2016).

Other factors considered to be contributing to the extensive failures across the network included the lack of sealed shoulders, flat or low-lying terrain allowing for prolonged saturation, and inadequate or poorly maintained drainage. The representatives at the workshop identified early on that relatively simple solutions such as sealing the full pavement width and maintaining drainage infrastructure were key to reducing the probability of pavement failure. Furthermore, more extensive treatments such as raising the pavement profile and stabilising the subgrade would also likely be beneficial.

During TNRP, there was a trend that the more resilient treatments with 20-year design lives were usually constrained to only higher-order strategic routes, with lower volume roads usually receiving less robust treatments. Some of these lower-order roads are, however, strategic and/or critical links to remote communities. The use of lower-cost treatments will often not lead to any improvement to resilience in the longer term.

The most common treatments employed, as illustrated in Figure 2.2, were cement-modified (lightly bound) pavements (either on top of a granular layer or in an 'upside-down pavement' configuration with a granular layer above), gravel re-sheeting and granular overlays. In some cases, subgrades were also treated but it was not always clear that these treatments were documented in ARMIS as comprehensively as the primary structural layer treatments.

The NACOE TNRP project included analysis of treatment performance over the several years since reconstruction works were conducted. Early indications (as of the end of 2016) are that most pavement works are performing well to date, with 90% considered in 'good' condition or better, as measured by the TMR Pavement Condition Index (PCI) (Lee et al. 2016; Lee & Noya 2016). Approximately 7% of the pavement works are considered to only be in 'fair' condition after just a short period of service, while around 2.5% (approximately 100 km in total) have deteriorated rapidly and are in poor condition. Sections in fair to poor condition will be the subject of ongoing monitoring in the future.

Some of the factors that contributed to successful outcomes during TNRP included:

- Early and comprehensive laboratory testing of materials at regular intervals, in order to refine treatments before construction commences.
- Taking advantage of local knowledge wherever possible, particularly given that several of the Regional Project Offices were led by contractors based in south-east Queensland or interstate who may not have possessed a comprehensive knowledge of local materials and practices.
- Planning and coordination of programs of work, both within and across regions to ensure the most efficient scheduling and best allocation of construction resources.
- Thorough documentation and information sharing, both within the Districts and on a state-wide basis with personnel in the TMR Engineering and Technology branch in Brisbane.

3 CURRENT AND ALTERNATIVE APPROACHES TO EXPANSIVE SUBGRADE TREATMENTS

The regional consultation highlighted that although there is a wide range of treatments and philosophies employed across the State, the focus in each District appeared to be more targeted at one or two primary options. Thus, this section will explore current and alternative approaches to dealing with expansive subgrades, including Austroads and TMR documentation. It will also include a review of guidance from South Africa and Texas, in order to summarise the current state of practice and allow designers to explore a ‘first principles’ approach when developing solutions in practice.

3.1 Austroads

The Austroads *Guide to Pavement Technology Part 2: Pavement Structural Design AGPT02-12* (Austroads 2012) contains guidance on the appropriate approach to pavement design and construction on expansive subgrades. It recognises that shrink/swell and shape loss due to changes in moisture content of the subgrade can be a major factor in pavement failure and the requirement for rehabilitation. Soils are divided into four categories based on a range of characteristics, all of which are relatively easy to measure through laboratory testing (see Table 3.1).

Table 3.1: Guide to classification of expansive soils

Expansive nature	Liquid Limit (%)	Plasticity index	PI x (% passing 425 μm sieve)	Swell (%)[1]
Very high	> 70	> 45	> 3200	> 5.0
High	> 70	> 45	2200–3200	2.5–5.0
Moderate	50–70	25–45	1200–2200	0.5–2.5
Low	< 50	< 25	< 1200	< 0.5

Note 1: Swell at OMC and 98% MDD using Standard compactive effort; four day soak. Based on 4.5 kg surcharge.

Source: Austroads (2012).

AGPT02 notes that volume changes in the subgrade, and subsequent damage that this may cause, can be minimised through strategies including:

- Construction with expansive materials taking place at a time when the soil suction of the material is at or near the long-term equilibrium value.
- Using a low-permeability lower subbase or capping layer above the expansive material (roughly 150 mm depth) and extending into the shoulder, to reduce moisture-induced movement of the pavement.
- Adopting minimum cover requirements using low-expansive materials, with the required thickness increasing with increasing traffic loading (due to higher expectations of ride quality on higher order roads).
- Providing separation between pavement drainage and expansive materials to reduce the impact of moisture fluctuations from drains.
- Restricting vegetation close to the edge of the pavement.
- Sealing shoulders and providing impermeable shoulder and verge material to reduce the risk of moisture changes affecting the outer wheel path.
- Utilising stabilisation technologies, including lime stabilisation, to reduce plasticity and lessen the expansive nature of the soil.

3.2 Department of Transport and Main Roads

3.2.1 Pavement Design Supplement

The latest TMR Pavement Design Supplement (Supplement) provides practitioners with additional guidance on top of the information provided in AGPT02 (Department of Transport and Main Roads 2017a).

With respect to the treatment and management of expansive subgrade materials, the Supplement also acknowledges the risk presented by volume change in the subgrade, with damage possible through several mechanisms, including:

- deformation at the surface, causing poor ride quality for motorists and ponding of water in low spots
- pavement deformation, leading to reduced density in structural layers and loss of strength
- cracking, which can allow water infiltration and further deterioration and strength loss.

The Supplement recognises that a range of factors are relevant when determining the approach to treatment, including:

- availability of materials
- tolerance for future maintenance interventions to correct minor shape loss or cracking
- cost of various treatment alternatives
- improvement in service
- project constraints, including equipment, personnel, time and traffic management.

The Supplement also recommends a geotechnical assessment in areas with material known for being highly expansive, in order to determine the optimal mitigation strategy. This would typically include testing the material for:

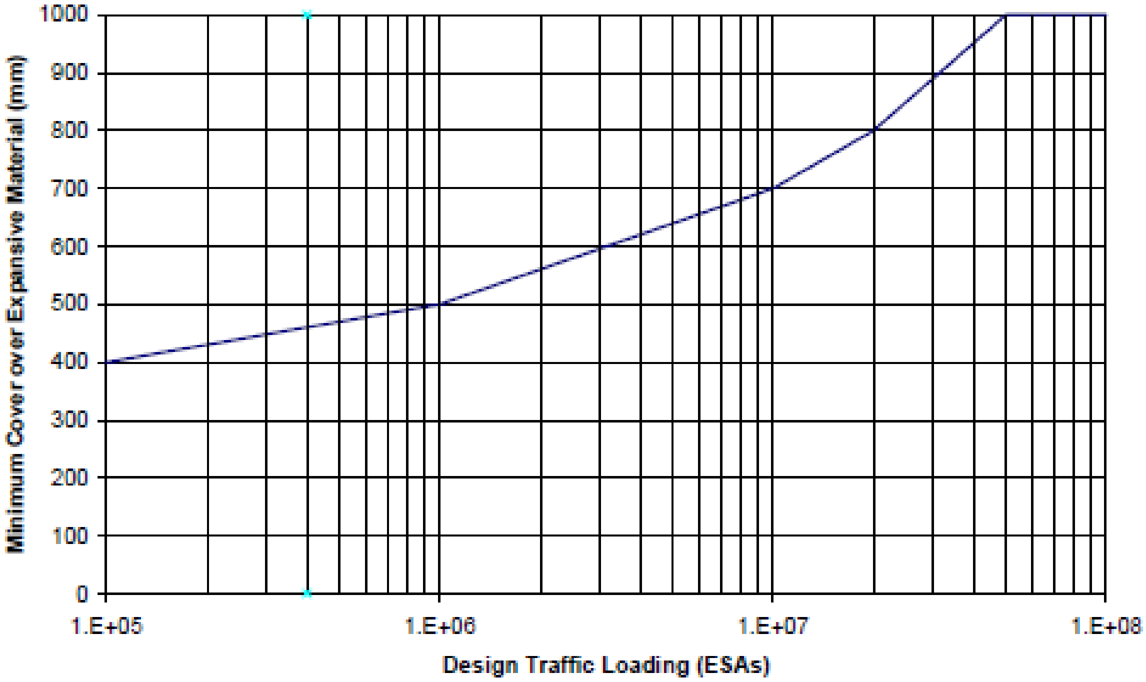
- Atterberg limits
- grading
- shrink-swell index
- moisture content at various depths
- soil suction
- clay type (using x-ray diffraction techniques).

The assessment would also include an analysis of the condition and maintenance history for the section, an assessment of the likely fluctuations in moisture content (taking seasonal and localised weather conditions into account) and TMR performance expectations for the pavement. The Supplement also recommends considering other methods of estimating surface movement, such as AS2870-2011 (see Section 3.6) and van der Merwe (1964) (see Section 3.5).

In cases where a full geotechnical assessment is not possible or not considered necessary, but the area is known for highly-expansive materials, the recommendation is to follow the cover requirements in Figure 3.1. For materials with low to moderate expansive properties, the pavement thickness itself is considered adequate to control and volume change in the subgrade.

It is important to note that documentation within Austroads or the TMR Pavement Design Supplement is broad guidance only, and that due to the challenges involved in building pavements over expansive subgrades, each situation may require a different approach.

Figure 3.1: Typical cover thickness over highly expansive materials for flexible pavements



Source: VicRoads (2010) in Department of Transport and Main Roads (2017a).

If a subgrade's expansive nature is classified as 'high' according to the classification in Table 3.1, then the Supplement includes the option of following the subgrade cover requirements outlined in Figure 3.1. This graph originated with VicRoads research in the early 1990s that considered expansive subgrades with moderate to high expansive nature and a review of best practice in the field (including the work undertaken in Texas – see Section 3.4). The original requirement only addressed higher-traffic roads; however, it was refined to also include cover requirements for lower-traffic pavements, which are considered to have a higher terminal roughness value compared to higher-trafficked pavements (personal communication, Geoff Jameson, December 2016).

The Supplement does not provide any specific guidance for cover requirements when the expansive nature of the subgrade is 'very high' as defined in Table 3.1. For very highly expansive subgrades the necessary cover is to be determined based on a geotechnical assessment. As this involves a significant element of engineering judgement, TMR has observed different approaches across various projects, ultimately resulting in different outcomes for similar scenarios. To improve consistency across similar project scenarios, it is recommended that Figure 3.1 be updated to also include cover requirements for very highly expansive subgrades.

Application of AS2870 method to determine cover over very highly expansive subgrades

While there may be some limitations to the AS2870 method as a first principles calculation method, it is considered reasonable to use the method to inform the expansion of Figure 3.1 to also include cover over very highly expansive subgrades. This view appears to be shared by a number of experienced geotechnical design engineers who have adopted this approach on recent projects.

This is achieved by benchmarking the input variables and outcome with existing cover thicknesses in Figure 3.1 for highly expansive subgrades. The calculations are then repeated, with the only change being to the properties of the subgrade material from highly expansive to very highly expansive.

The methodology for these changes is detailed in Appendix A.

This recommendation considers traffic loading only, due to the expectation of better ride quality for higher-trafficked pavements.

According to the TMR Supplement, other additional strategies may also be appropriate to minimise volume changes, including:

- minimising the extent of expansive materials in embankments
- maintaining the moisture content of the upper layers of subgrade as close as possible to its equilibrium moisture content
- ensuring correct geometric alignment and drainage provisions to move water away as far as practically possible (5+ metres) from the pavement formation
- allowing for drying back and re-compacting subgrades that are above equilibrium moisture content (despite the potential construction delay this may cause).

Overall, the TMR Supplement adds Queensland context to assist practitioners in preparing their design to best account for expansive subgrades.

3.2.2 Western Queensland Best Practices Guidelines WQ35

The Western Queensland Best Practices Guidelines (Department of Transport and Main Roads 2014) are a series of guidelines based on an analysis of design, construction and performance records and follow-up structural analysis of many road sections in Western Queensland. WQ35: *Paving Materials and Type Cross Sections for Roads on Expansive Soils in Western Queensland* was developed to provide guidance on the selection of paving materials and type cross-sections for roads with relatively low traffic volumes, in areas with typically low average rainfall. It is noted that, in some situations, it may not be possible to comply with all of the requirements in the guidelines.

A key principle of WQ35 involves giving priority to keeping moisture out of the pavement, rather than assuming it will enter and providing measures to remove it. Whilst some moisture will inevitably enter the pavement, its effect can be minimised through a combination of moisture control, pavement material properties, adequate drainage and cross-sectional design.

Moisture control

Moisture control is especially important when dealing with expansive material. To ensure pavement and subgrade strength is maintained and to reduce subgrade shrink/swell, WQ35 recommends typical permissible moisture contents for each pavement layer (zone) (see Table 3.2).

Table 3.2: Typical moisture content for pavement layers in WQ35

Zone	Typical moisture content range (% of optimum moisture content (OMC) based on standard compaction)	
	Before covering/sealing	Equilibrium (post-construction)
Base	< 70	35–50
Subbase	< 70	35–65
Embankment (top 300 mm above top of subgrade)	Total layer: 60–85 Upper 150 mm: < 70	70–95
Embankment (> 300 mm below top of subgrade)		70–95

Source: Department of Transport and Main Roads (2014).

WQ35 provides in-depth guidelines regarding moisture contents, which are summarised below:

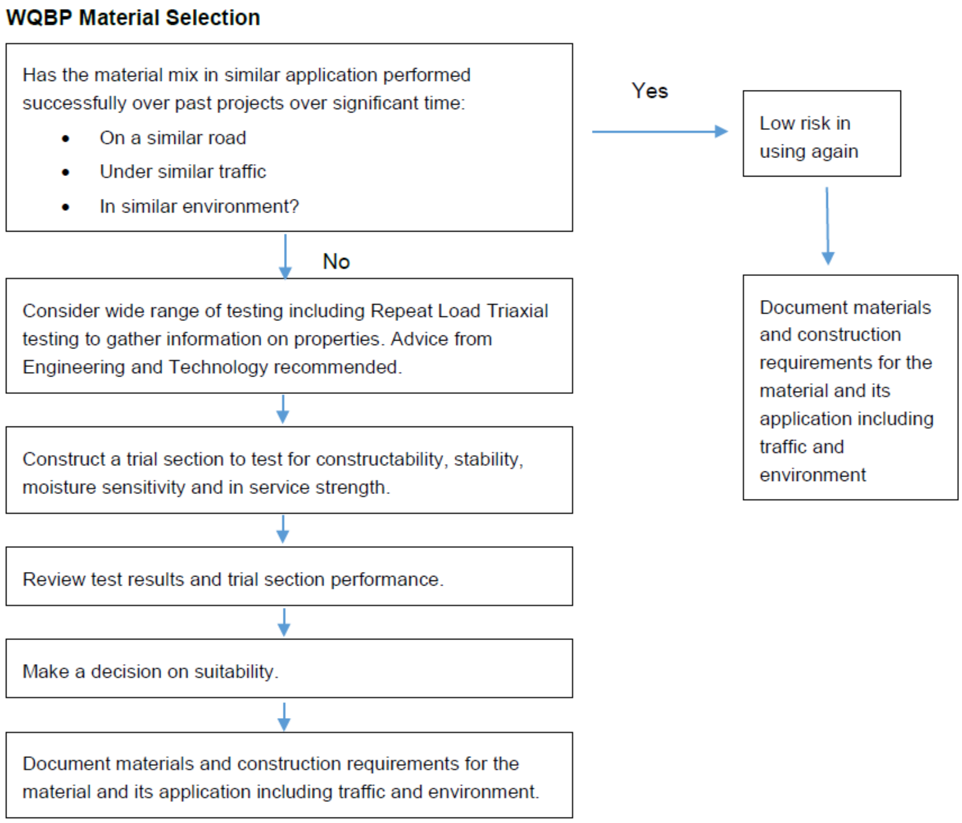
- After construction of a pavement, the total moisture content of the top 300 mm of the subgrade should be in the equilibrium range specified in Table 3.2.
- Moisture contents above the equilibrium can be tolerated under specific conditions.
- Moisture contents higher than that specified in Table 3.2 may be required to achieve compaction during construction.
- For Type 4 materials, it is acceptable to measure pavement construction moisture contents relative to OMC rather than the degree of saturation.
- In some cases, time for drying back may be necessary before the layer is covered.
- If significant rainfall events occur, moisture contents should be checked and, if required, allow time for drying – use mechanical methods to assist drying or treat the subgrade with quicklime.
- Soil drying with lime will significantly increase the permeability of the subgrade, resulting in a subsequent reduction of the expected pavement life.
- If the seal is applied with excess moisture trapped in the pavement and subgrade, then damage to the seal is likely to occur, particularly on higher-trafficked roads.
- It is vital that the road structure is insulated from the environmental effects of wetting and drying to protect the pavement.
- Shrink/swell cycles of expansive materials can lead to rutting and longitudinal cracking in the pavement, creating paths for water entry, possibly resulting in premature failure. The use of low-permeability materials and type cross-sections can mitigate this risk.

Pavement Materials

Due to the difficulties associated with obtaining good quality pavement materials in remote areas of western Queensland, it is often necessary to use the material available on site. A selection tree is available to assist in this process (Figure 3.2). To reduce the risk of these materials causing moisture-related issues during service, some of the following considerations from WQ35 may be worth noting:

- lower-quality materials may be successfully used if additional measures are considered (e.g. greater width of shoulder protection)
- high permeability materials should be avoided as they allow moisture entry and create edge effects up to 2.5 metres under the seal
- for materials with excess plastic fines, measuring CBR values at moisture contents below OMC or at modified compaction can be misleading and must not be used
- materials can be treated with cement, fly ash, lime or bitumen if appropriate and economical. For treated materials to perform successfully, a low permeability material of adequate strength is required.

Figure 3.2: Western Queensland Best Practice (WQ35) – material selection decision tree



Source: Department of Transport and Main Roads (2014).

Cross-Sectional Design

As mentioned previously, the key principle of constructing an embankment with expansive soils is to keep moisture out during the service life of the pavement. WQ35 gives guidance on the type of cross-section that can minimise moisture entry into the pavement. Guidance includes the following:

- The best performance will be achieved by providing at least 1 metre of sealed pavement outside the edge of the wheel path.
- Large exposed areas on the batters will allow moisture ingress, even when using low-permeability materials. To prevent this, the pavement batter should be cut to 1 in 2 at the seal edge, excess pavement material should be removed and the pavement encased with embankment at a 1 on 4 slope. Good compaction of the embankment and at the edge is also critical.
- Positive encasement has been shown to reduce moisture infiltration and evaporation. This can be achieved by adding 300 to 500 mm of embankment on both sides of the formation. Spraying bitumen on the top 300 mm of the pavement batter before encasing can also improve performance.
- Thin unbound granular pavements have been shown to absorb less moisture than thicker unbound granular pavements. Many pavements 150 to 250 mm thick have performed well. Pavements as thin as 100 mm are not recommended due to construction tolerances, compaction difficulties and the risk of damage from heavy or overloaded vehicles.
- The use of sealed pavement batters used in conjunction with very permeable base materials can result in improved performance by reducing the severity of moisture entry in the short term. However, it will not eliminate it. This approach is not recommended as a long-term measure; however, it could be used as a corrective treatment on existing permeable pavements.

- Using flat embankment batters (1 in 4 or flatter) with low-permeability materials and low formation height reduces the risk of shoulder and pavement edge cracking and deformation. Wherever possible, flat embankment batters and low formations heights should be used. However positive formation height above the surrounding terrain should be achieved (say 300 to 500 mm at the top of formation).
- Effective drainage is of particular importance. Table drains should never be constructed in flat country as they will hold water for extended periods of time. Table drains may be used where there is positive drainage and if erosion is not an issue. The invert of the table drain should be 300 mm below the top of the subgrade.
- Constructing on the existing alignment can be an advantage, provided sufficient formation height is achieved.

3.3 Other Australian Documents

3.3.1 VicRoads Code of Practice RC 50022

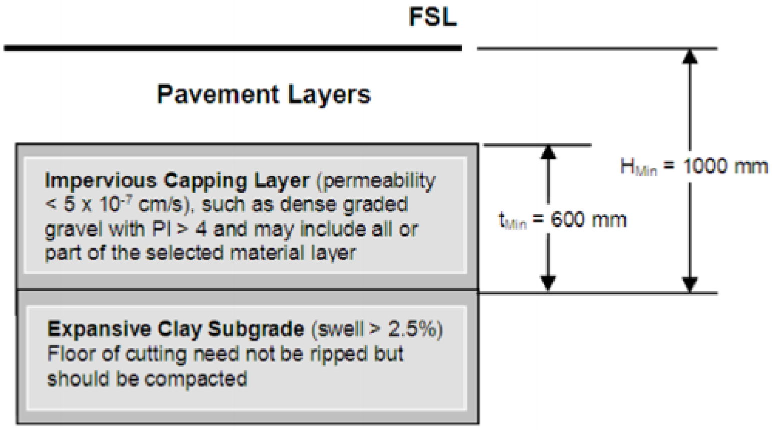
VicRoads classifies an expansive material as any material that has a swell of greater than 2.5% (VicRoads 2013). In conjunction with guidance provided by Section 5.35 of Austroads (2012), VicRoads continue to use the same cover requirements as presented in Figure 3.1 when an expansive subgrade is encountered. The use of material with a swell of greater than 1.5% is not permitted in the cover material. A key component of the cover material is the capping layer placed immediately above the expansive subgrade which is made up of a superior quality fill 'Type A' material. The minimum thickness of this layer is 150 mm or 2.5 times the maximum particle size. Advice is also provided for subsurface pavement drains, landscaping, and footways and bicycle paths.

Similar to the practice in Queensland, VicRoads do consider the strength benefits of lime stabilisation of the subgrade. The Austroads procedures are used for the mechanistic design of pavements on lime-stabilised subgrades, with the lime-stabilised subgrade characterised in the same manner as for a selected subgrade material. A higher modulus is assigned by Transport and Main Roads where a comprehensive mix design methodology is used to ensure the higher strength is achieved and retained in the longer term.

3.3.2 Roads and Maritime Services - Part 2 Pavement Structural Design

Roads and Maritime Services (RMS) New South Wales provides adequate cover of at least 1000 mm including the pavement layers to treat an expansive subgrade (defined as having swell over 2.5%) (RMS 2015). As shown in Figure 3.3 a minimum of 600 mm of this cover material must be an impervious capping layer below the lowest pavement layer. This material must have a CBR > 8% and a swell of less than 1% as determined by Test Method T117 (RMS 2012). It should also be noted that unlike TMR and VicRoads, RMS does not consider that lime stabilising an expansive subgrade provides any strength benefits for the subgrade. If lime stabilisation is conducted, it is primarily for construction expediency as a working platform, to reduce moisture sensitivity and to improve the compaction of overlying layers (RMS 2015; Austroads 2013).

Figure 3.3: RMS treatment for expansive clay subgrades



Source: RMS (2015).

3.4 Guidelines for Subgrade Stabilisation in Texas

Texas has some of the most expansive soils in the United States. A significant portion of pavement construction in Texas is the rehabilitation of existing roads that often have subgrade or base material failures. Good-quality aggregate sources are becoming scarcer and additives such as lime, bitumen, cement and fly ash are being used to achieve the required subgrade properties (Texas Department of Transportation 2005).

Due to these issues faced by the Texas Department of Transportation (TxDOT), a three step methodology was developed by Dallas Little and Tom Scullion (TxDOT). The methodology considers many variables for subgrade treatment, particularly when long-term performance is required. This approach appears to be more comprehensive than the practices used in Australia. The flowchart in Figure 3.4 shows the steps required for a successful subgrade treatment.

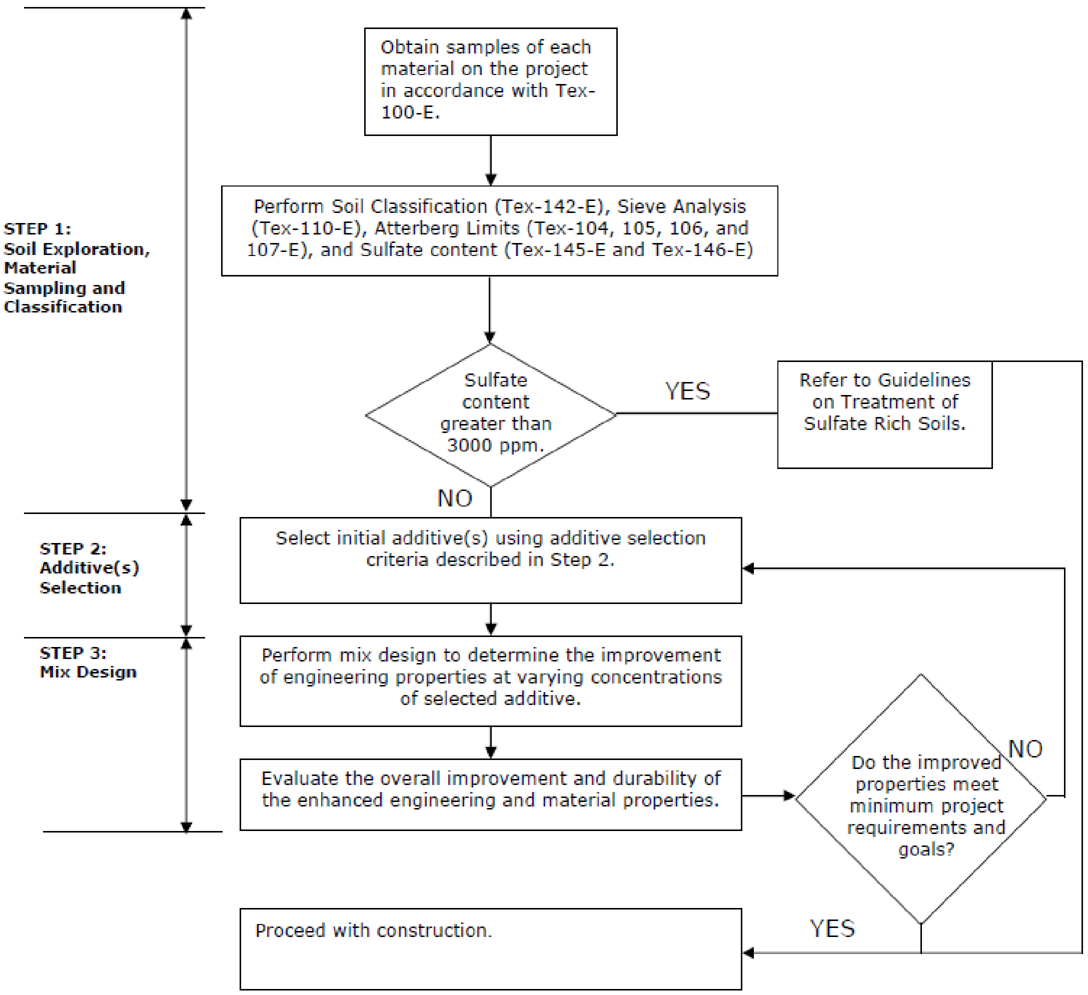
3.4.1 Step 1 – Soil Exploration, Material Sampling and Classification

Soil exploration is a vital step in determining the properties of the subgrade. Conditions in the underlying strata can also be recorded such as soil mineralogy, water-table proximity and soil strata variation. As a ‘rule of thumb’ the methodology recommends that ten 50 lb. (22 kg) samples of each soil type be collected as a minimum. Soil investigation, classification and characterisation are referenced in the TxDOT Pavement Design Manual.

3.4.2 Step 2 – Additive Selection Criteria

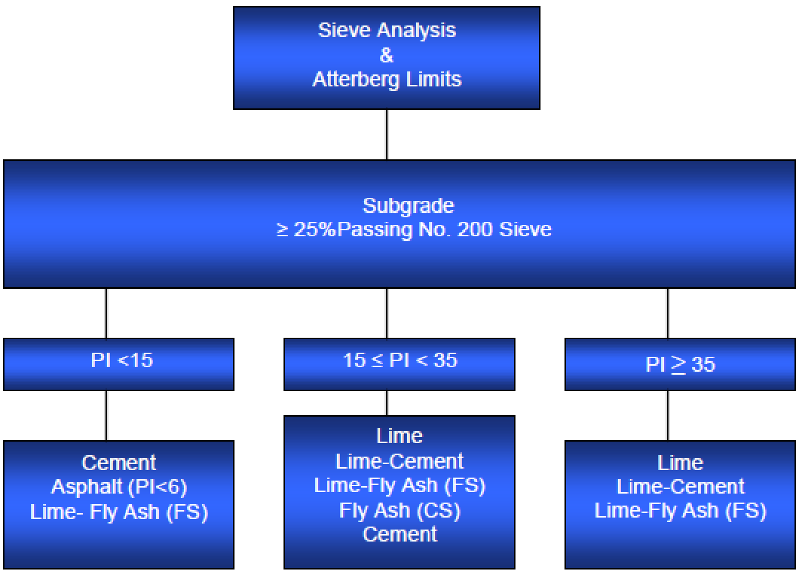
Selecting an appropriate additive is another key component in stabilising an expansive subgrade material. TxDOT (2005) established the flow chart in Figure 3.5 from charts developed by Currin et al. (1976), Little (1995) and Smith & Epps (1975) (in TxDOT 2005). The flow chart applies to most, but not all cases and validation testing must be performed to verify whether the modified subgrade achieves the required properties. Economics, availability, construction costs and construction time should all be considered during the selection of the additive.

Figure 3.4: Flowchart of Texas DOT approach to subgrade treatments



Source: TxDOT (2005).

Figure 3.5: Texas DOT stabilisation additive selection methodology



Source: TxDOT (2005).

3.4.3 Step 3 – Mix Design

A mix design is necessary to determine the optimum level of additive to be used and thus optimise the material properties of the subgrade. Information gathered during this process can dictate construction requirements and mitigate distresses associated with material behaviour such as cracking. Improvements are dependent on soil type, as varying soils have varying chemical properties and compositions. TxDOT (2005) developed the following six-step procedure to ensure variables affecting expansive soils are considered during the mix design.

Step 1: Sulphate and organic testing

Materials are to be tested to ensure that sulphate and organic levels in the materials are not at detrimental levels. High organic content may require additional additives.

Step 2: Moisture/density curve

The next step is to determine the moisture/density relationship in order to control density and compaction in the field.

Step 3: pH of material

Particularly when stabilising with lime, it is critical to understand the pH of the soil, as basic soils will produce a better reaction between lime and minerals in the soil. This helps to determine the quantity of lime required for adequate stabilisation.

Step 4: Plasticity index

Plasticity index (PI) is commonly used as a measure of the expansive nature of a material, as well as providing as indication on constructability at various moisture contents.

Step 5: Strength testing

Strength testing, when required, is to be undertaken in line with the test procedures of the local authority. This provides an indication of the bearing capacity of the material, and helps in determining the design of structural layers.

Step 6: Modifier percentage selection

The final step is to select the lowest additive content in order to satisfy the project requirements.

3.4.4 Summary and Key Lessons

The Texas approach provides an in-depth methodology for the appropriate selection and design of stabilised subgrade materials. Key learnings from the Texas method include the following:

- The Texas guidelines outline a specific set of material sampling tests that must be conducted in order to classify the material. It also recommends a minimum quantity of samples (ten at 22 kg) that would be required to adequately characterise the subgrade.
- The Texas guidelines outline specific criteria for the appropriate selection of an additive using the results from the sieve analysis and Atterberg limits.
- The Texas guidelines also consider cement and fly ash mixtures as genuine stabilisers for expansive subgrades, with provision to be used in combination with lime for materials with a higher plasticity index.
- A minimum thickness and maximum presumptive modulus for the stabilised subgrade layer are not specified in the Texas guidelines.

3.5 South African Method

In the early 1980s the South African Department of Transport (SADoT) investigated the design, construction and maintenance methods with respect to minimising the impact of expansive soils (SADoT 1982). The investigation confirmed that moisture content is of the utmost importance when working with expansive materials (particularly clays) and that it is essential to realise that swelling is necessarily time dependent.

The key findings and recommendations of the investigation fit into four broad categories:

1. Expansive soils require higher moisture content prior to compaction:
   - The investigation found that a higher moisture content of the expansive material resulted in higher strength and cohesion properties with reduced swelling. It was recommended that the moisture content should be 2-3% higher than the modified AASHTO OMC prior to compaction.
   - Higher moisture content will likely result in compaction issues during construction. To address these issues, judgement is required to allow for possible deviations from density requirements and lighter construction equipment may be required to allow a higher moisture content.
2. Embankments are susceptible to shrink/swell for several years:
   - In general, the moisture content at the centre of an embankment reaches equilibrium after approximately five years. At this stage, swelling of the expansive material will cease.
   - The material at the edge of the embankment is still susceptible to repeated cycles of wetting and drying. To address issues that could arise from this, the width of the embankment should be extended 3–4 metres or beyond. As such, cracking and defects should occur on the side slopes of the embankment and not beneath the pavement structure.
   - Maintenance will be required for the first few wet and dry seasons to repair the cracks and prevent water ingress through the side slopes to the subgrade. It was recommended that longitudinal side drains at the toe of the embankment be avoided where possible.
3. Some locations will require removal of expansive material:
   - Removal and replacement of expansive materials may be considered where shallow depths of the material occur. If material is removed, it should be covered immediately to prevent moisture loss.
   - Issues most commonly arise at culverts as the subgrade is most susceptible to moisture ingress in these areas. It is often found that the expansive material is not deep and therefore it could be economically viable to excavate and replace with a less expansive material. To minimise issues, any excavations should be kept covered or irrigated appropriately during construction. It is important to ensure moisture from the culvert does not leak into the soil beneath and ponding at the inlets and outlets is prevented.
   - In some cases, expansive material will need to be used as fill. If so, it was recommended that it is placed at the base of the fill, and contained within the embankment, not less than 3 m from the edge. This will minimise moisture variation.
4. There are alternative treatments to reduce the risk of damage:

— Swelling of expansive material can be reduced by lime stabilisation, either in situ or added to the material used to build the embankment. Although expensive, there are cases where material has been stabilised with lime to depths of over 1 metre.

— For greenfield sites, removing plant and organic growth and placing a 150 mm layer of permeable material (i.e. coarse sand) over the expansive material are simpler and more cost-effective techniques which can be employed to reduce swelling. Ideally, the permeable layer should be laid 12 months prior to construction. It can also be helpful to lay the final pavement layers shortly after the end of the wet season, to maximise the moisture content of the expansive material.

3.5.1 Methods of Assessment

The methods of assessing the expansive nature of the soils used in this study included Weston's method and van der Merwe's method. The van der Merwe method gives conservative, preliminary indications of swelling potential based on routine testing. The study noted that there had been considerable argument about methods of predicting swelling. As such, the results of these methods should be viewed in a qualitative sense, rather than as absolute quantitative predictions.

The basis of the van der Merwe method is that expansive clay is classified into four grades of Potential Expansiveness (PE) by the relationship between the Plasticity Index (PI) and the clay fraction. It is important to note that this fraction is defined as the percentage less than the 2 μm size and therefore will require hydrometer or other specialist testing to determine. It should also be noted that it is the clay fraction of the whole sample, not only of that portion passing the 425 μm sieve, which means that the percentage less than 2 μm must be multiplied by the percentage less than 425 μm to obtain the clay fraction of the whole sample. This can make a considerable difference to the assessment of the heave potential (SADoT 1982). The expected swell for each classification is presented in Table 3.3.

Table 3.3: Grades of potential expansiveness (PE)

Classification	Heave (mm per metre of profile)
Very high	80
High	40
Medium	20
Low	0

Source: van der Merwe (1964).

Due to the increase in pressure from the overburden, the potential expansiveness (PE) decreases with depth. A depth factor (F) is introduced to account for this and it is presented in Table 3.4. Therefore, the PE multiplied by F gives the swell of the material.

Table 3.4: Relationship between depth factor (F) and depth

Depth (m)	0–1	1–2	2–3	3–4	4–5	5–6	6–7	7–8	8–9
Mean F	0.85	0.60	0.40	0.27	0.20	0.12	0.08	0.06	0.04

Source: van der Merwe (1964).

Weston's method was, at the time a relatively untried method and differed from the van der Merwe method as the designer could take into account the moisture changes that are likely to occur. As with the van der Merwe method, the total potential heave of the soil profile is calculated as the sum of the potential expansiveness of each layer, with allowance for overburden pressure. It should be noted that the investigation recommended that Weston's method be used in conjunction with the van der Merwe method.

3.5.2 Summary and Key Lessons

This investigation confirmed that effective management and understanding of the moisture content is of the utmost importance when working with expansive clays. This importance is echoed throughout the Austroads and TMR approaches, particularly in the *Western Queensland Best Practice Guidelines* (WQ35) (Department of Transport and Main Roads 2014). There are a number of similarities in the design and construction recommendations made by WQ35 and the SADoT, including the:

- widening of embankments to reduce the effects of repeated wetting and drying cycles
- use of embankments with wide, flat batters
- removal of plant and organic growth from the shoulders
- installation of effective drainage.

A key difference in approach is that the SADoT method recommends that the moisture content should be 2% to 3% higher than the modified AASHTO OMC prior to compaction. However, Austroads and TMR prefer to hold the moisture content as close as possible to the equilibrium. WQ35 tolerates moisture contents above the equilibrium but only under specific conditions.

3.6 Swell Index for House Foundations

Look et al. (1992) developed a design strategy for embankments constructed with expansive materials.

The method proposed by Look et al. comprised the following major steps;

- identification of the hazard (expansive soil) from index tests
- quantification of the associated distress

Identification of the hazard (expansive soil), from index tests

Methods for classifying potential swell and the classification of embankment material are available in Snethen (1979) and Queensland Department of Main Roads (1991).

In 1991, the proposed methodology was applied to a field study at an upgrade to the Bruce Highway near Cooroy (details provided in Queensland Department of Main Roads 1991). The material was classified as a high swell-potential. Trenches were excavated in embankments, probes were installed for monitoring of moisture changes and laboratory CBR testing was performed on the proposed material. In situ CBR, density and moisture content was measured and the OMC and MDD of the material determined. A summary of the relevant results is presented in Table 3.5 and Table 3.6.

Table 3.5: Classification of potential swell

Liquid limit (%)	Plasticity index (%)	Natural soil suction (kPa)	Potential swell classification
> 60	> 35	> 380	High
50 – 60	25 – 35	140 – 380	Marginal
< 50	< 25	140	Low

Source: Snethen (1979).

Table 3.6: Classification of embankment material

Class	Plasticity index (%)	Potential for expansion
A	< 12	Low
B	12 – 22	Medium
C	22 - 32	High
D	> 32	Very high

Source: Queensland Department of Main Roads (1991).

Quantification of the associated distress

The quantification of the associated pavement distresses involves the evaluation of

1. in-service moisture and density conditions
2. depth of the active zone
3. soil suction changes between wet and dry states
4. prediction of movement
5. evaluation of the risks associated with the movements and design alternatives.

1. In-service moisture and density conditions

The in-service performance of a pavement is controlled by its longer term moisture-density equilibrium conditions within its environment, as well as traffic loading and constructed properties. These equilibrium conditions are typically achieved about three to five years after construction. Historically, Queensland's roads have been constructed with moisture contents at approximately 80% to 90% of OMC and a relative dry density (RDD) at or greater than 95% (Look et al. 1992).

Haupt (1981) developed various models for predicting equilibrium moisture content based on OMC, MDD, liquid limit and particle size distribution. Equation 1 provides a method of predicting equilibrium moisture content for when the OMC is less than 13%; however, it does not account for seasonal variations at the surface and the pavement edge.

$$PEMC = 0.38 * LL^{0.7} * (\% - 0.425)^{0.3} - 1.5 \qquad 1$$

where

$PEMC$ = predicted equilibrium moisture content (%)

LL = Liquid limit (%)

$\% - 0.425$ = % passing the 425 µm sieve

However, a more site-specific approach involving an evaluation of existing roadway performance under conditions of similar road construction with similar materials from the area would usually yield more accurate results. At the Cooroy project, time domain reflectivity (TDR) was used to monitor moisture changes of an in situ pavement.

2 Depth of the active zone (cracked and uncracked if possible)

The depth of the active zone is evaluated using the TDR. The results are compared with the rainfall events from the nearest rainfall station, noting that there can be a time delay between the 'wetting up' of the embankment and the rainfall event. If possible, the probes should be installed at different depths prior to the wettest months of the year, so that the worst conditions that may occur at the site can be identified. Long-term monitoring would involve recording values over at least a full year cycle.

The depth at which the probes 'wet up' can indicate the depth of the cracked and uncracked zones. If deeper material wets up before the materials closer to the surface, then this could indicate that water is infiltrating through the cracks to this depth before rising upwards. In the case of the Cooroy project, probes installed at depths of 1.15 metres and 1.25 metres wetted up prior to the probes installed at a depth of 0.6 metres. Readings taken at a depth of 1.8 metres indicated that this was the bottom of the active zone.

One-dimensional odeometer swelling tests can also be used to determine the depth of the active zone. Tests can be conducted on samples from trenches as part of the determination of the shrink/swell index and to evaluate the relationship between overburden pressure and swelling strain. When the results show zero swelling strain, this indicates that, at this depth, the soil is in an equilibrium condition. The results can also be used to predict the expected movement.

3. Soil suction changes between wet and dry states

Soil suction is measured on samples collected from trenches. Snethen (1979) investigated a relationship between that of the (matrix) soil suction and (gravimetric) moisture content. The relationship is given by Equation 2:

$$log\tau_m = A - B * w \tag{2}$$

where

τ_m	=	soil suction (kPa)
A, B	=	constants
w	=	water content (%)

However, Look et al. proposed modifications to Snethen's moisture suction relation (Equation 2), using water content as volumetric (θ_v), rather than gravimetric (w), as this produced a better correlation. In addition, an even better correlation was observed when the depth (z) at which the sample was taken was included in the regression analysis (Look et al. 1992; Look 1995).

4. Prediction of movement (total movement since construction, and movement differential due to seasonal variations), by adapting existing predictive models to suit roadway embankment conditions

AS2870-2011 provides methods of calculating surface movement with respect to residential slabs. It defines the predicted surface movement as a criterion for assessing the reactivity at a site and for subsequent foundation design. Methods of calculating the surface movement is based on the instability index and a generalised suction profile. The surface movement is predicted using Equation 3 (from AS2870):

$$y_s = \sum I_{ss} * \Delta z * \alpha * \Delta u \tag{3}$$

where

y_s	=	predicted surface movement (mm)
I_{ss}	=	shrink swell index
Δz	=	thickness of expansive layer (mm)
α	=	restraint factor
Δu	=	change in soil suction

O'Neill and Poormoayed (1980) developed another method to determine surface movement (heave) for a given foundation. The method relies on the swelling pressure of the sample and the measure of swell on inundation. As such, the swelling strain corresponding to the overburden pressure is determined. This method uses complete inundation and considers one dimensional swell throughout the active zone.

The surface movement (for a given surcharge pressure) is given by Equation 4:

$$y = \sum s * h_j * 0.1 \qquad (4)$$

where

y	=	heave for the given surcharge pressure
s	=	swell in layer *i* for the surcharge (%)
h_j	=	thickness of the soil layer (mm)

The final method considered by Look et al. was developed by Richards (1967), which uses soil suction curves to predict moisture content changes in soils. The equilibrium suction is determined from correlations with a climatic rating. This method assumes that volume change in the soil is equal to the moisture change, and that equal volume changes occur in the vertical and horizontal directions. The vertical surface movement is given by Equation 5:

$$\frac{\Delta H}{H} = \frac{1}{3} * \frac{\Delta V}{V} = \frac{1}{3} * \frac{(w_f - w_i)G_s}{100 + w_i G_s} \qquad (5)$$

where

$\frac{\Delta H}{H}$	=	vertical heave (mm)
$\frac{\Delta V}{V}$	=	volume change
w_i	=	initial water content (%)
w_f	=	final water content (%)
G_s	=	specific gravity

However, as these methods were primarily developed for the design of foundations and structural slabs, Look et al. (1992) proposed the modifications presented in Table 3.7 to provide a more accurate assessment of potential surface movement of an embankment.

From preliminary analysis using the results obtained from the Cooroy project, Look et al. found that, when subject to specific serviceability criteria, a 10 mm seasonal differential movement could be tolerable, while 20 mm would be unacceptable. A total ‘heave’ of approximately 15 mm showed no pavement distress. However, further investigation and application of this method would be required to verify these values.

Table 3.7: Modifications applied to existing methods of movement prediction.

Description of method	Adaptation	Reference
Shrink/swell index	▪ Active zone ▪ Cracked/uncracked zone ▪ Suction profile	Equation 3
Swell pressure	▪ Use 1/3 heave in cracked zone and full heave in uncracked zone	Equation 4
Moisture change	▪ Nil	Equation 5

5. Evaluate the risks associated with the movements and design alternatives to minimise these risks

The key to constructing a quality embankment using reactive materials is to have suitable limiting moisture content criteria. However, moisture content impacts on construction controls. Common controls are density and moisture content. Usually, achieving a minimum specified density has been the governing criteria for compaction control. For expansive material, the moisture content should be the governing criteria.

Upper and lower moisture content limits should be determined for the expansive material. The lower limit prevents excessive swelling over the range of moisture contents expected in service (a movement criterion). The upper limit is a strength criterion, ensuring the material does not become difficult to work with, place or compact. Between these limits, an appropriate moisture content can be selected, taking into account economics and design requirements.

Care should be taken to avoid an upper limit that is too high, as this could result in increasing the pore water pressure during compaction. If a higher upper limit is required, then smaller or lighter compaction equipment may be required.

4 TREATMENTS FOR EXPANSIVE SUBGRADES AND CASE STUDIES

The regional consultation also led to the identification of a number of case studies to document and track in order to have a better understanding of a 'typical' subgrade treatment in those regions. Several of these cases are specifically focused on treatments that may be considered innovative.

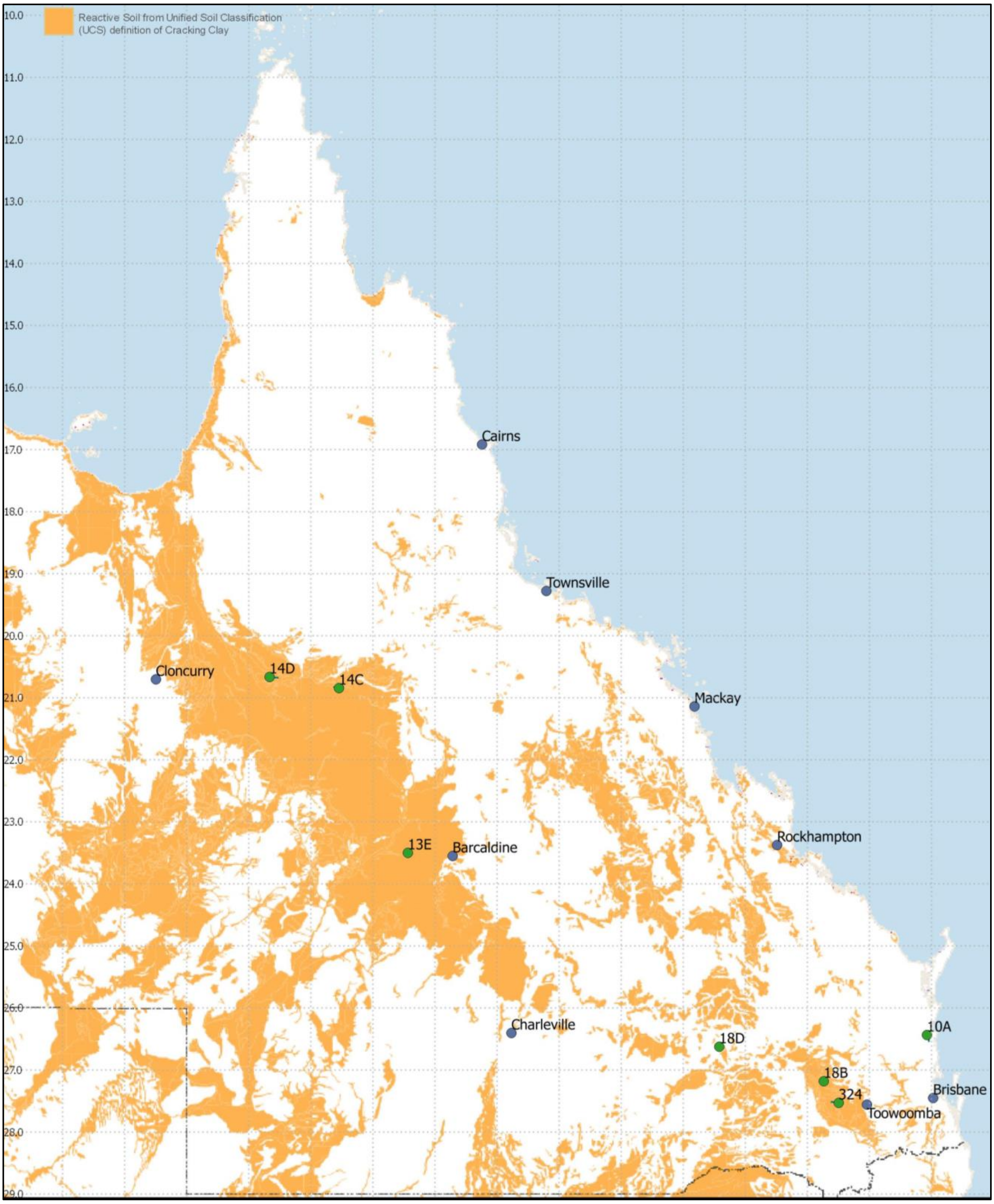
This section details some of the more common treatments undertaken for expansive subgrades across Queensland; the case studies in Table 4.1 are noted within the applicable treatment type. It is the intention that these form a useful reference to track over coming years. It is envisaged that tracking the relative performance of treatments for expansive subgrades could lead to improved treatment selection, better performing pavements, and more resilient pavements over expansive subgrades.

Table 4.1: Proposed case studies on typical expansive subgrade treatments

Treatment	District	Road		Chainage	Comments	Year of treatment
Cover requirements / remove and replace	North Coast	10A	Bruce Hwy (Yandina-Cooroy)	89.3–100.7	Major project – design advice provided by E&T at the time of design/construction	2001
Remove and replace	Toowoomba	18B	Warrego Hwy (Dalby town)	81.36–84.56	Sensitive location near residents, difficult to use lime	2017
Lime stabilisation and foam bitumen	Toowoomba	324	Toowoomba – Cecil Plains Rd	43.5–55.5	Lime stabilised with foam bitumen, some longitudinal cracks (Ch. 47.1)	2013
Lime stabilisation	Roma	18D	Warrego Hwy	58.1–61.13	Hydrated lime and triple blend	2015
Other stabilisation	Cloncurry	14C	Flinders Hwy	80.8–87.8	Stabilise subgrade with cement, reinstate granular layer	2016
Other stabilisation	Cloncurry	14D	Flinders Hwy	71.7–86.14	Foamed bitumen (insitu)	2014
Granular overlay	Barcaldine	13E	Landsborough Highway	75–77.5	Granular overlay during TNRP	2014

Seven of the more common treatments for expansive subgrade treatments employed across Queensland are summarised in Sections 4.1 through Section 4.7.

Figure 4.1: Map of case studies across expansive subgrade regions in Queensland



4.1 Cover Requirements

This treatment involves providing cover over an expansive subgrade to negate the effects of swell, as outlined in Section 3.1. This cover is intended to both reduce the potential for moisture to enter the subgrade and the mass of the cover material is intended to resist and movement of the underlying subgrade should it tend to shink or swell. This is one of the most common practices utilised in Queensland, particularly in urban areas (Department of Transport and Main Roads 2017b).

The successful provision of adequate cover also has the following additional benefits:

- improved ride quality due to increased thickness
- reduced number of defects seen on the overlying layers.

The traffic volumes and serviceability requirements of the road determine the amount of cover required with a minimum of 400 mm required for lightly-trafficked flexible pavements and up to 1 000 mm for heavily-trafficked flexible pavements. The cover material depth includes the depth of the structural pavement layers, with the remainder made up from low-swell material. The top 300 mm of the pavement should have CBR swells of less than 1.5% and less than 2.5% for the remainder of the pavement (Austroads 2012).

Providing adequate cover over an expansive subgrade is a technique that is typically used in the Metropolitan and South Coast Districts due to a reduced appetite for premature pavement deformation, the availability of adequate cover material, and the limitations of undertaking alternative treatments in constrained urban areas.

A typical rehabilitation treatment by providing adequate cover would involve a number of steps:

- Remove the existing granular material and place in windrows along the shoulder.
- Compact the subgrade at the equilibrium moisture content.
- Place and compact the non-expansive material in ‘lifts’ between 100 mm and 200 mm to the required depth.
- Place and compact the structural layers.
- Seal with a rubberised or polymer modified binder seal.

It may also be possible to achieve this treatment by importing new material to add as cover on existing pavements, with the existing untreated granular pavement considered as part of the cover.

Providing adequate cover over an expansive subgrade may be an appropriate treatment option when:

- adequate cover material is readily available
- it is economically viable to move large amounts of material
- there is effective drainage for the embankment or the subgrade is protected from moisture ingress
- heavy traffic loading is expected (pavements with high importance).

Providing adequate cover over an expansive subgrade may be not be an appropriate treatment option when:

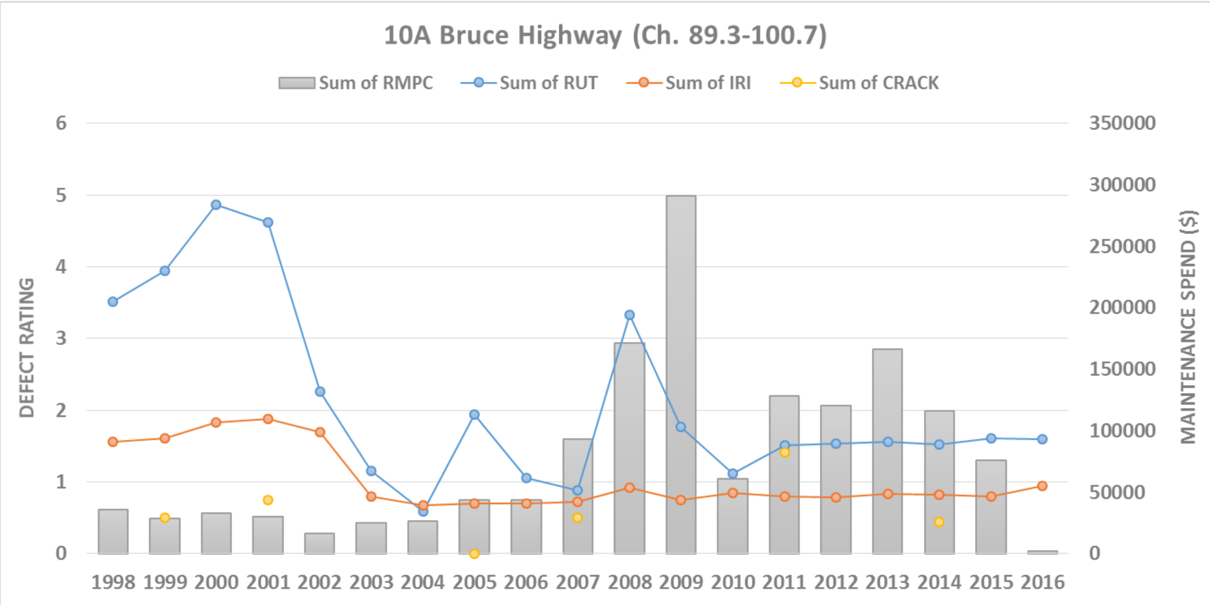
- very low traffic is expected, as it may not be economically justifiable to move large amounts of material

- height restrictions prevent adequate cover being achieved, i.e. kerb and channel, side access, bridges.

Upgrades of the Bruce Highway between Yandina and the Blackall Range required significant cover to be added at some locations with high to very high expansive nature, with part of the design calling for 1.5–1.8 metres of cover with a low-swell material. The cover consisted of various layers of gradually increasing quality and strength as the construction moved upwards through the layers. Subsoil drainage was also a focus during the design phase, in order to further reduce the risk of moisture-related distress. As this section is a critical north-south route through south-east Queensland, the extra cost of importing large quantities of material could be justified.

Figure 4.2 compares performance over the last few years and maintenance expenditure. It can be seen that there was a large drop in rutting and a significant drop in roughness after the completion of the works in 2001. Maintenance spending has progressively increased over the last decade, although with very heavy traffic on this route, high maintenance spending is not unexpected. As there has not been a significant increase in roughness (IRI) or cracking for a period of almost 15 years, it is concluded that the expansive subgrade cover adopted for this project was sufficient, and possibly even conservative, to inhibit detrimental impacts on the pavement. The key benefit of the extensive cover requirements was that it allowed the final structural (asphalt) layers to be paved on a stable working platform that would only experience limited seasonal movement. In areas of poor subgrade strength, using controlled subgrade material can also reduce the structural pavement thickness.

Figure 4.2: Rutting, roughness, maintenance spending: Warrego Highway (10A)



Source: TMR ARMIS database (2017c).

4.2 Remove and Replace

The removal and replacement of an expansive subgrade is a technique that is very successful at mitigating the effects of expansive material. This technique has been successfully used in Queensland, and in the past has been recommended as the optimum treatment for expansive materials. However, due to the significant excavation, haulage and material costs, it is usually not economically viable to construct roads of lower strategic value using this approach. As a result, the technique is typically used in the Metropolitan and Darling Downs Districts (i.e. in areas with higher population and traffic loading).

In many ways, the treatment is achieving the same effect as cover requirements – increasing the distance between the expansive material and the top of the pavement layer. However, removal and replacement of material may be better suited in some situations, including where the expansive subgrade is only relatively thin. In these cases, it would likely be more economical to remove the expansive material rather than import a very large quantity of higher-quality material to achieve the cover requirements. It is also preferable where the formation height is limited.

This treatment involves the excavation, removal and replacement of the expansive material with fill that is less expansive. A typical rehabilitation treatment would involve:

- Removal of the existing granular layer and placing in windrows along the shoulder.
- Excavation and disposal of the expansive material, typically to a minimum depth of 600 mm and up to 1.8 metres (noting that the cost of removing 1.8 metres would be extremely high).
- ‘Wetting up’ the subgrade above OMC and compacting.
- Placement, compaction and trimming of the required amount of less expansive fill.
- Placement, compaction and trimming of the granular structural layers, recycling the previous material if appropriate.
- Sealing with a rubberised or polymer modified binder seal.

Removing and replacing expansive material may be an appropriate treatment option when:

- adequate fill material is readily available
- it is economically viable to move large amounts of material
- high traffic loading is expected
- the total height of the pavement is restricted.

Removing and replacing expansive material may not be an appropriate treatment option:

- in environmentally sensitive areas, including the presence of acid sulphate soils
- in cuttings or flood prone areas due to the possibility of the ‘swimming pool’ effect
- when low traffic loading is expected
- there are constructability constraints such as shallow services or traffic management.

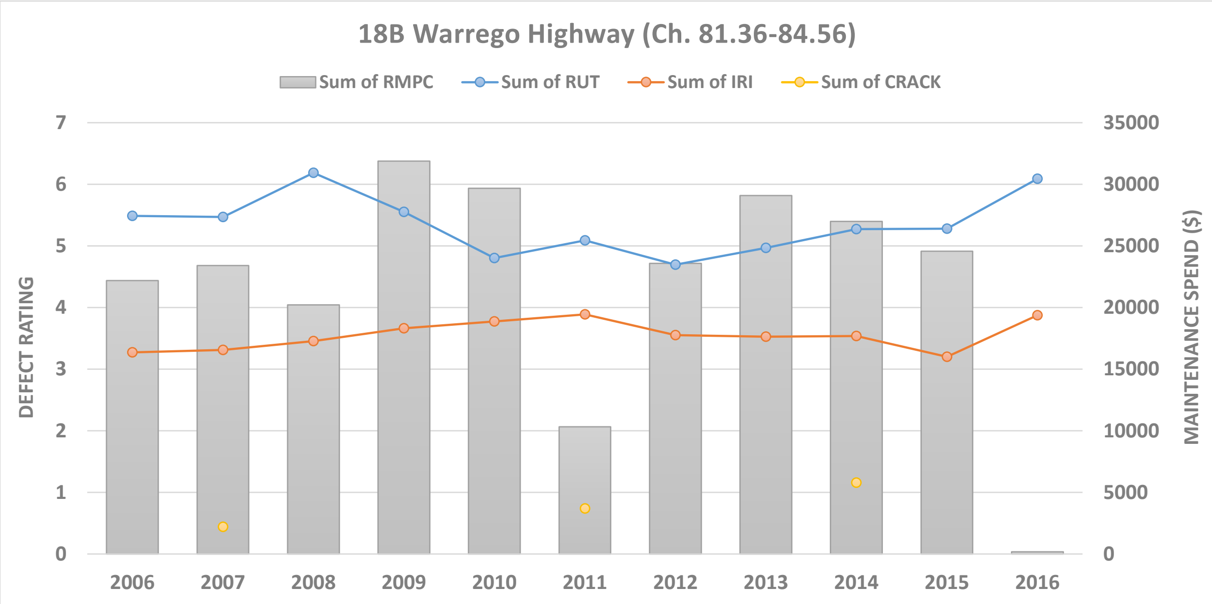
The successful removal and replacement of expansive material has the following key benefits:

- very effective at reducing the effects of expansive materials.
- proven record of success in Australia, US and South Africa.
- it could be used in wet or dry climates (depending on the depth of the excavated material).

An upcoming project on the Warrego Highway (18B) through the town of Dalby will adopt a removal and replacement strategy for an expansive subgrade. While this section of road had been subject to moderately high routine maintenance costs, it had performed reasonably well in previous years, with rutting and roughness remaining relatively constant between 2010 and 2015 (Figure 4.3). Interestingly, roughness and rutting increased sharply in 2016 in comparison to previous years. Due to the proximity to the township, vehicle speeds are lower and this subsequently adds to the traffic-induced strains imparted to the pavement.

Due to the proximity to local residents, it was thought preferable to not adopt chemical stabilisation for this project. The solution was to remove the subgrade material to at least 600 mm depth, add a geocomposite then 200–300 mm of Type 1 material as subgrade replacement. This was covered with another geocomposite and improved lightly bound granular layer, 150 mm thick, followed by an emulsion prime and 350+ mm of asphalt in multiple layers. This is certainly a very comprehensive solution and is only possible because of the relatively short treatment length and high-profile location through the town of Dalby. However, it does highlight the potential to essentially avoid future issues by removing the expansive material entirely. One issue associated with this approach was that, in some areas, expansive material was found at depths of 2 metres or more; the cost of removing and replacing this much material may prove prohibitive, even in short lengths.

Figure 4.3: Rutting, roughness, maintenance expenditure: Warrego Highway (18B)



Source: TMR ARMIS database (2017c).

The treatment is too recent to incorporate post-construction performance data, however, performance will be monitored over coming years to determine the effectiveness of the treatment.

4.3 Cement Stabilisation

Cement stabilisation is a technique that can be used to treat mildly expansive subgrades. However it is often found that, due to the increased stiffness, the subgrade can become more prone to cracking after stabilisation. In Queensland, cement-stabilised subgrades have been utilised in the North West District and occasionally in the Central West and South West Districts.

The use of cement stabilise a subgrade has the following key benefits:

- increase subgrade stiffness/strength
- cost savings compared to lime stabilisation
- forms a water-resistant layer
- constructability – provides a temporary construction platform for civil works.

Guidance for the use of cement stabilisation in pavements is presented in Austroads (2006) and Austroads (2011).

A typical rehabilitation treatment with cement stabilisation would involve a number of steps:

- Adding cement to the subgrade, mixing with a stabiliser and compacting (being careful not to over-compact).
- Placing the remaining pavement layers, compacting and trimming.

- Sealing with rubberised or polymer modified binder seal.

Using cement to stabilise the subgrade may be an appropriate treatment option for the following scenarios (AustStab 2011):

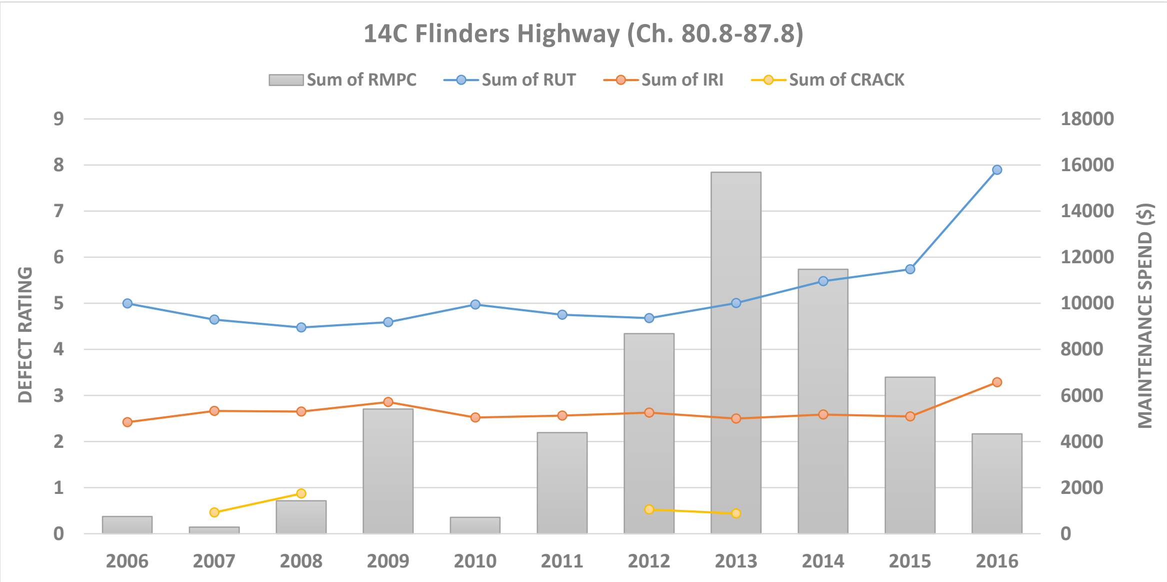
- when the plasticity index (PI) is less than 20, liquid limit (LL) is less than 40 and plastic limit (PL) is less than 20
- when the material being stabilised is well graded and has a low volume of voids when compacted
- in wet conditions, due to the rapid reaction of the binders.

Using cement to stabilise the subgrade may not be an appropriate treatment option for the following scenarios (AustStab 2011):

- when there is reactive organic compounds present in the subgrade materials as this has a detrimental effect on the reaction
- when the material is classified as having very high expansive properties, due to the tendency of cement stabilised material to crack, thus causing reflective cracking in the overlying pavement layers.

In late 2014, cement stabilisation was used to treat an expansive subgrade along the Flinders Highway (14C) between chainages 80.8 km to 87.8 km. A granular layer was placed over the cement stabilised subgrade. While this section of road had been subject to increasing routine maintenance costs, it had performed reasonably well in previous years with rutting and roughness remaining relatively constant. Interestingly, after rehabilitation using cement stabilisation of the subgrade, the roughness and rutting levels increased sharply compared to previous years (see Figure 4.4).

Figure 4.4: Rutting, roughness, maintenance expenditure: Flinders Highway (14C)



Source: TMR ARMIS database (2017c).

4.4 Lime Stabilisation

Lime-stabilised subgrades were trialled extensively by TMR in the 1970s and several Councils, most notably Ipswich City Council, were using lime to stabilise subgrades as early as 1961. No further treatments occurred until the mid-1990s because its use fell out of favour following some high-profile failures that occurred in the late 1970s (Crone 2009).

In the mid-1990s, a committee was established to review a design procedure for lime-stabilised subgrades developed from research conducted by Dallas Little for TxDOT (Evans et al. 1998; Little 1995). Following the committee outcomes, two trial projects were constructed in the Warwick region on Killarney Rd and at the Freestone Creek to Eight Mile intersection. The two trial projects performed very well, leading to further research and trials. Based on the outcomes of this work, TMR released technical specification *MRTS07A: In situ Stabilised Subgrades using Quicklime or Hydrated Lime;* the latest version was published in 2017.

Lime-stabilised subgrades are commonly utilised in the Darling Downs and South West Districts and occasionally in the Central West District; however in the latter case, it has been found to be more expensive compared to other options due to the limited availability of lime and the processes required.

Guidance for the use of lime stabilisation in pavements is presented in Austroads (2006) and Austroads (2011).

Using lime to stabilise a subgrade has the following key benefits:

- increase in subgrade stiffness
- forms a water-resistant layer
- reduces the PI of the material
- constructability – provides a temporary construction platform for civil works
- improves the ability to achieve compaction of the overlying pavement layers. This reduces the number of defects normally seen on the overlying base layers
- overlying pavement thicknesses are considerably reduced due to a stronger subgrade

Using lime to stabilise the subgrade may be an appropriate treatment option for the following scenarios (Austroads 2006):

- when the PI is higher than 15, indicating a high clay content in the subgrade
- when there is a high number of pozzolans in the material – this will facilitate a successful chemical reaction between the silica, alumina and the calcium hydroxide
- when there is limited organic carbon or soluble sulphate present in the subgrade materials as this has a detrimental effect on the reaction
- when there is effective drainage for the embankment or the subgrade is protected from moisture ingress
- when heavy traffic loading is expected
- when a working platform is required during construction
- when wet, plastic clay subgrades are present.

Using lime to stabilise the subgrade may not be an appropriate treatment option for the following scenarios:

- in low-lying, flood-prone areas or areas where significant moisture ingress is possible, and the impermeable lime stabilised layer may hinder pavement drainage
- in environmentally sensitive areas, due to the possible leaching of the lime into the surrounding environment
- where unacceptably high levels of sulphate are present.

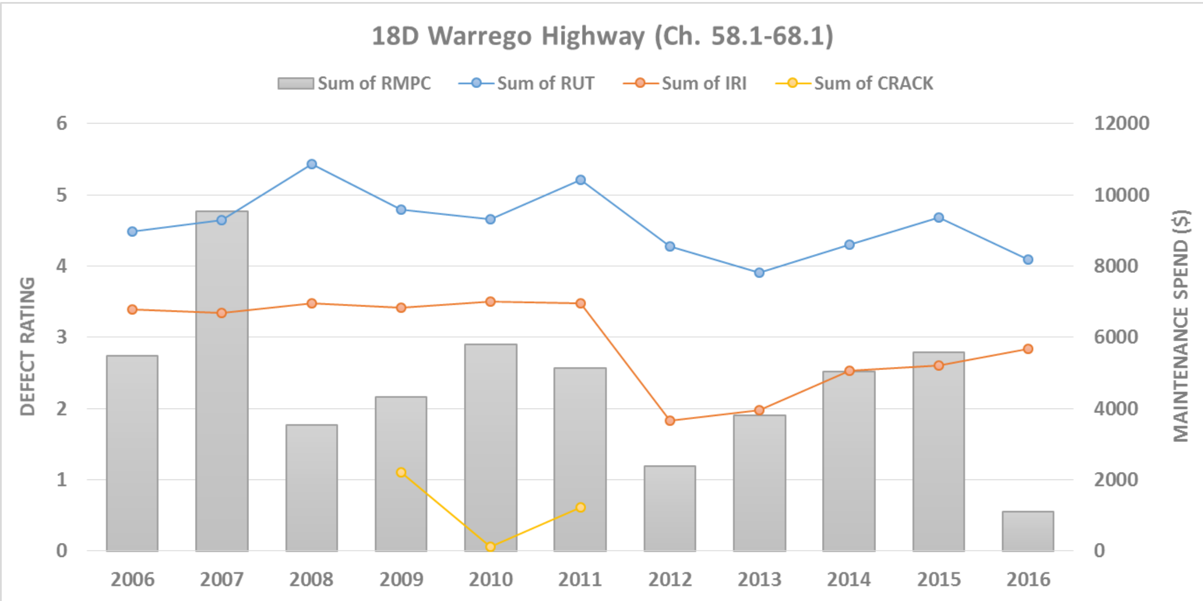
Lime stabilisation of expansive subgrades involves in situ mixing of quicklime or lime that has been previously hydrated into the subgrade to increase strength and reduce expansiveness. A pozzolanic reaction between the silica and alumina in the clay minerals and the calcium hydroxide in the lime must occur to achieve long lasting strength. It is critical that adequate soil testing of the subgrade is conducted to correctly classify the subgrade.

A typical rehabilitation treatment with lime stabilisation would involve a number of steps:

- Firstly, removing the existing granular layer and placing in windrows along the shoulder.
- Stabilisation is carried out over two days. On the first day, half the required amount of lime is added and mixed with a stabiliser. On the second day, the remaining lime is added and mixed with a minimum of two mixing passes required.
- Compaction and trimming should be completed within the allowable working time, measured from the start of mixing on the second day.
- Replacing the granular material, adding extra material of the same quality where required and compacting.
- Sealing with rubberised or polymer modified binder seal.

In 2015, lime stabilisation was used to treat an expansive subgrade along the Warrego Highway (18D) between chainages 58.1 to 68.13 (Figure 4.5). This section of road had been subject to moderately high routine maintenance costs as well as significantly increased heavy vehicle traffic, almost doubling between 2006 and 2014. It is too early to make any definitive conclusions regarding the performance since the treatment but it can be seen from Figure 4.5 that there has been a slight decrease in rutting, a slight increase in IRI but minimal maintenance expenditure in 2016.

Figure 4.5: Rutting, roughness, maintenance expenditure: Warrego Highway (18D)



Source: TMR ARMIS database (2017c)

4.5 Bound Bituminous Layers with Lime-Stabilised Subgrade

While rarely a treatment for expansive subgrades directly, bound layers, including foamed bitumen, have been used in conjunction with lime stabilisation of the subgrade to constitute a 'complete' solution designed to increase pavement life and improve performance. The stabilisation of the pavement subgrade reduces volume change, and any minor expansive behaviour can be tolerated by the flexible foam bitumen base. This combination of structural capacity and flexibility means that reflective cracking is minimised, while the high structural capacity ensures a long fatigue life under heavy trafficking.

The treatment has the following key benefits:

- moisture resistance – low permeability means that there is a reduced risk of major failure if the pavement is inundated by floodwaters
- good fatigue resistance – better than cement-stabilised bases
- reduced risk of shrinkage cracking, assuming good construction practices and the correct additive content
- improved stiffness and load-bearing capacity compared to granular bases
- lime as the secondary additive provides longer working time and increased early strength.

A typical rehabilitation treatment with foam bitumen would involve a number of steps (Ramanujam 2015):

- Firstly, removing the existing granular layer and placing in windrows along the shoulder.
- Adding hydrated lime or quicklime to the subgrade, mixing with a stabiliser and compacting (being careful not to over-compact).
- In situ stabilising the base material with foam bitumen and additional lime, then compacting:
  - alternatively, the existing base material can be transported to a foam bitumen plant and processed (with some added material if necessary to improve grading), then taken back to the site and placed and compacted.
- Sealing with a rubberised or polymer modified binder seal.

Anecdotal evidence suggests that the combination treatment of foamed bitumen and a stabilised subgrade has been successful in a number of regions

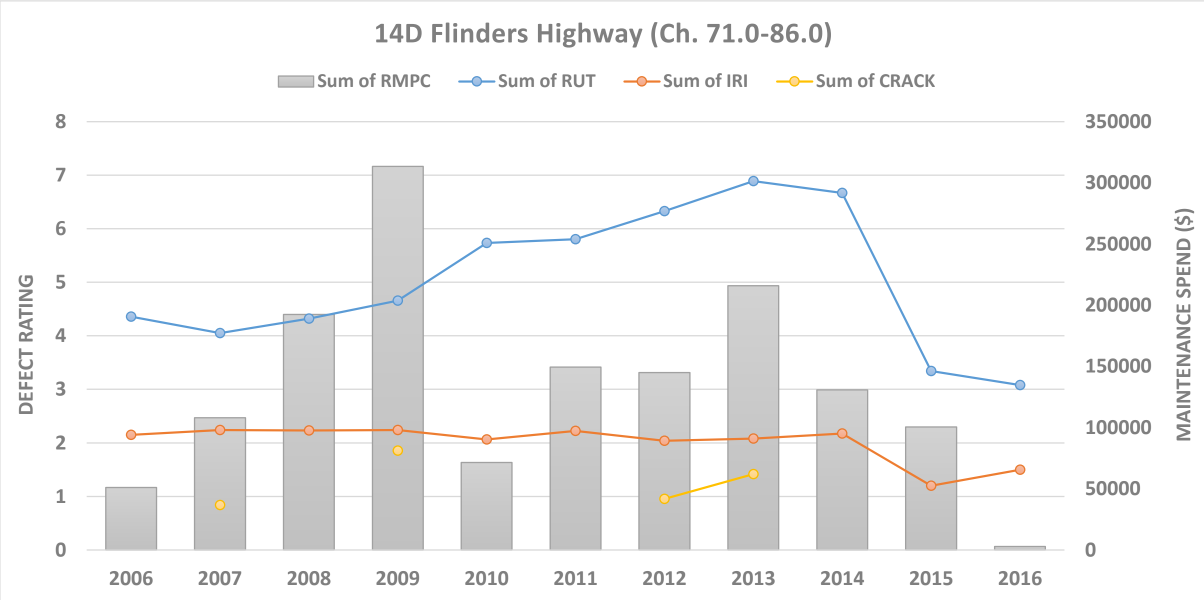
Many trials and demonstration projects have been completed over the last 20 years, with foamed bitumen now a common treatment type in many areas of the State. It was noted that there has been some major rutting and high routine maintenance costs along some sections of the Flinders Highway (14D), including chainages 71–86 km (see Figure 4.6). In addition, this region of the State has been subjected to higher volumes of heavy vehicle traffic. The major flooding events in 2010-12 led to further deterioration.

In order to restore structural performance and reduce ongoing maintenance costs of this section of the Flinders Highway, a comprehensive treatment of lime-stabilised subgrade and foamed bitumen base was proposed. While this treatment is more expensive than the alternative of cement stabilisation or a granular overlay, the intention was that, by increasing service life, lowering road user costs and reducing maintenance expenditure, the overall costs over the pavement life cycle would decrease.

The design underwent an optimisation process to reduce costs, including reducing the bitumen content from 3.0% to 2.5% (saving approximately $26 000/km) and reducing the lime content required for subgrade stabilisation from 8% to 5% (saving approximately $48 700/km).

It should be noted, however, that the overall design of the pavement is poor (e.g. too little lime in the subgrade or too much cement in the base granular layer) there can be issues associated with cracking of the foam bitumen pavement. This has occurred in some isolated locations on highways west of Toowoomba.

Figure 4.6: Rutting, roughness, maintenance expenditure: 14D Flinders Highway



Source: TMR ARMIS database (2017c).

4.6 Granular Overlay

This treatment type is likely to be most appropriate in regions with the following environmental, material and traffic characteristics (Department of Transport and Main Roads 2011):

- arid environment with rainfall of around 500 mm per annum (this describes the majority of the North West, Central West and South West Districts).
- subgrades with predominantly sandy loam or black soil
- pavement materials that would fit within the WQ35 specification (best locally available).

It is not clear that thin granular overlays are effective in higher rainfall regions, and there are limitations to the quality of material that would be suitable for such treatments. In areas with sub-standard materials, it may be possible to blend in situ material with some imported gravel, but this would likely add significantly to the total cost.

In many cases, the higher costs associated with treatments such as lime stabilisation and foamed bitumen, and the large volume of material required to fulfil cover requirements of 0.5 metres or more, means that in some areas it may be preferable to treat a greater extent of their network with less expensive designs that require less virgin material.

One such approach adopted in the Central West region is a generic unbound granular overlay, placed either directly on the subgrade or as a two-part process with the existing road base blended and compacted followed by an overlay (Department of Transport and Main Roads 2011). In the majority of cases, this will be followed by a sprayed seal (using polymer modified or rubberised bitumen if the budget allows). The overlay involves 150 mm of the best, locally-available material. Another option for higher-order roads, or in specific locations such as floodways, incorporates approximately 3% of cement to form a 200 mm thick lightly bound layer, in place of, or in addition to, the 150 mm unbound granular overlay.

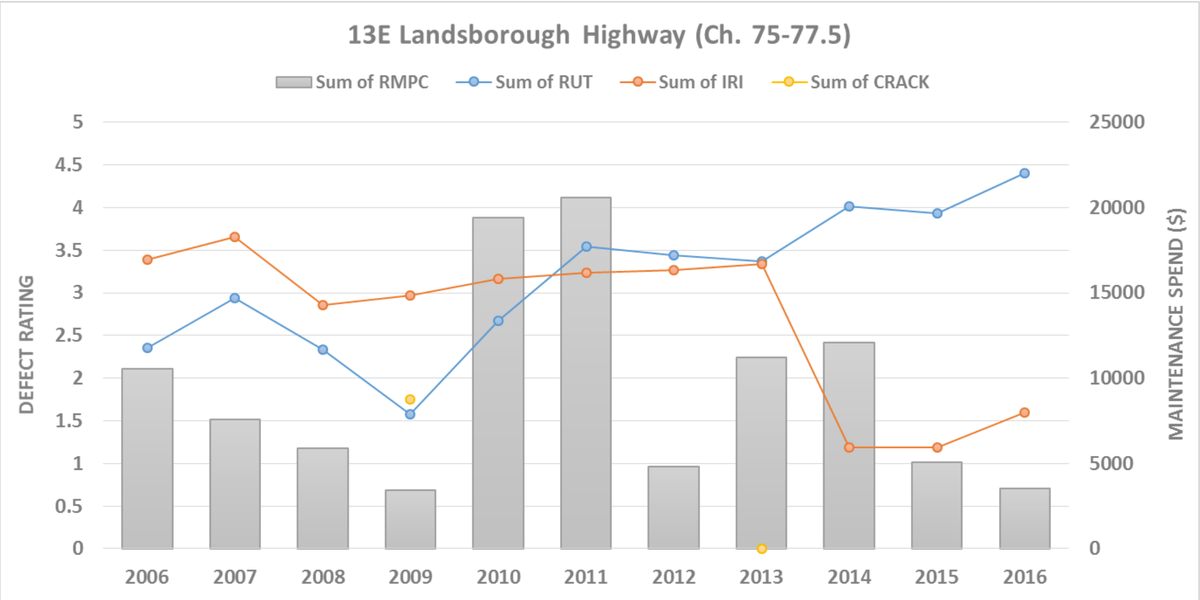
Using unbound granular overlays as a treatment for expansive subgrades can be an effective cost-saving measure. However, the money saved should be invested in a robust seal and appropriate maintenance. Robust seals that could be considered include polymer modified and rubberised bitumen.

This treatment has been standardised as a ‘generic pavement design’ for low volume roads in the Central West region. This design could be applied to all but the National Highway portion of the Central West network. The good performance of thin granular overlays has been well documented. For example, Baran (1999) provided details of the experience gained over 20 or more years in arid and semi-arid environments, including notes on 26 trial sections on the Landsborough Highway. Pavement thickness was not found to be a significant indicator of performance, and thinner pavements often performed satisfactorily in the field.

In developing this generic design, it was recommended that the District maintain documentation of the history, performance and evidence behind the design, make note of any departures from the standard approach, and take specific project criteria into account (climate, subgrade properties, local materials, etc.).

An example is the Landsborough Highway, which was heavily impacted in the 2010-11 flood events, with many sections needing major repairs and reconstruction. Section 13E (Barcaldine to Longreach) was one such section, with increased rutting and high maintenance costs in 2010 and 2011 (see Figure 4.7). The initial repairs and maintenance works conducted were sufficient to reopen the road, and rehabilitation was not undertaken until 2014. This treatment included a granular overlay; the treatment led to a large decrease in roughness but little change in rutting. It would be valuable to monitor sections such as this over the next decade to determine their effectiveness, particularly in light of the increased traffic volumes and heavier axle loads likely across rural Queensland.

Figure 4.7: Rutting, roughness, maintenance expenditure: Landsborough Highway (13E)



Source: TMR ARMIS database (2017c).

4.7 Other Treatments

Other treatments that have been implemented in the past, but not considered in detail as part of this project, include:

- The use of geosynthetic and geofabric materials either above the subgrade or between structural layers to limit reflective cracking. These materials are often used in conjunction with other treatments such as minimum cover or stabilisation.
- Manufactured stabilisation aids (e.g. polymers, oils, emulsions) that may be specifically suited to a particular material or application. TMR has limited experience with these products having tended to adopt more standardised treatments.

- Various innovative construction techniques (particularly focused on maintaining the material at equilibrium moisture content during construction and during its early life). These treatments are heavily reliant on experience civil contractors with thorough process and quality assurance controls.

4.8 Summary

A summary of the information presented in this Section, including the key benefits and disadvantages of each of the most common treatments is presented in Table 4.2. This may eventually form the basis of a more detailed treatment selection matrix as proposed in Section 6 of this report.

Table 4.2: Treatment options for expansive subgrades

Treatment option	Advantages	Disadvantages	Other notes
Cover requirements (including 'remove and replace')	▪ Simple treatment ▪ Does not require cover material to be of a high quality	▪ Material and haulage costs may be high in some regions ▪ Increased pavement thickness, increased cost in batters and road safety risks	Cover requirements seem inconsistent and arbitrary in some cases
Cement-stabilised (or cement blends)	▪ May be cheaper than lime stabilisation ▪ Cement is readily available and easy to use ▪ Effectively reduces the water sensitivity of the subgrades	▪ Generally not suitable for very highly expansive subgrades ▪ Only suitable for moderately plastic materials (PI<10-15) ▪ Is still susceptible to heave ▪ May be prone to cracking	Slow-setting cement with additives should be used where possible to prevent shrinkage cracking, but care needs to be taken during the mix design process as these blends may make the pavement stiffer in the long term
Lime-stabilised subgrade	▪ When treated with correct quantity, proven to reduce reactivity of subgrades ▪ Well suited to high-profile or heavily-trafficked pavements ▪ Effectively reduces the water sensitivity of the subgrades	▪ Too little or too much lime can be detrimental (need lime demand test) ▪ Construction practices are important ▪ Is still susceptible to heave ▪ May not always be practical – particularly in urban areas	
Lime stabilised subgrade with bound upper layers (e.g. foam bitumen)	▪ Robust treatment ▪ Very little material wastage ▪ Reduces moisture sensitivity of material over lime stabilised subgrade without using cement – hence reducing the propensity of cracking	▪ Stabilisation with bitumen is typically more expensive than cement ▪ Requires transportation and handling of bitumen ▪ Requires a more experienced contractor to supply and place the bound upper layer ▪ May not always be practical – particularly in urban areas	See case studies from TMR E&T – can be done relatively affordably In heavily trafficked applications, dense-graded asphalt bases may also be constructed over the lime stabilised subgrade treatment
Thin granular overlay	▪ Typically local material can be used ▪ Lower material costs and less haulage (local materials) ▪ Less disruptive to construct ▪ Simple treatment that does not disturb subgrade ▪ Leaving unbound pavement above allows for some movement in the subgrade	▪ Relies on good construction practices ▪ Local material must be of reasonable standard; otherwise need to bring in higher-quality material from elsewhere ▪ Needs accompanying drainage improvement ▪ May be susceptible in major flooding events ▪ Maintenance of sprayed seal surfacing is critical to the performance of this treatment.	A version of this is used as a standard treatment in Barcaldine
Geosynthetics over subgrade	▪ Potential for cost savings ▪ May be used in conjunction with other treatments to expand their suitability	▪ Not a lot of research into economic benefits ▪ Exact mechanism of improvement is not certain	Need to extend geosynthetic/geocomposite to shoulder to deliver full benefit
Manufactured stabilisation aids (e.g. polymers, oils)	▪ Usually requires smaller quantities of additive (less haulage) ▪ Reduced dependence on lime ▪ Can use product specifically tailored to region and soil type	▪ Potentially quite expensive compared to traditional products ▪ Limitations in construction and technical expertise ▪ TMR has limited experience with the use of these materials and their suitability would need extensive investigation prior to use	Many stabilisation products are targeted at improving granular base layers, with subgrade treatment being a secondary application

5 DISCUSSION

This study has highlighted a number of important issues and observations that are discussed in further detail in the following sub-sections.

5.1 Applicability of Expansive Soil Classification Table

This study highlighted that the many subgrade materials in Queensland are classified as being of a ‘very high’ expansive nature based on the expansive soil classification table contained in Austroads (2012) and referenced in the TMR supplement (refer to Table 5.1 below). In practice, it may be better to introduce further classification for materials that are currently classified as ‘very high’.

Table 5.1: Guide to classification of expansive soils

Expansive nature	Liquid limit (%)	Plasticity index	PI x (% passing 425 µm sieve)	Swell (%)
Very high	> 70	> 45	> 3200	> 5.0
High	> 70	> 45	2200–3200	2.5–5.0
Moderate	50–70	25–45	1200–2200	0.5–2.5
Low	< 50	< 25	< 1200	< 0.5

Source: Austroads (2012).

This would potentially allow for more standardised treatments at swells of greater than 5%, and reserve more comprehensive assessment of materials for those areas with subgrade soils possessing swells closer to 10% (or more). The Districts have demonstrated that they are capable of appropriately treating subgrades on the lower end of the ‘very high’ category; resources and extra finances could be optimised through focussing on those well above the indicative 5% swell level.

It is recommended that the ‘very highly’ expansive material category be capped at a swell of 10%, with a new category introduced for material with an ‘extreme’ expansive nature, with swell greater than 10%. This would allow standard treatments for very highly expansive subgrades to be introduced, while extreme cases would still require more specialised assessment. The updated table is shown in Table 5.2.

5.2 Range of Preferred Treatments across Regions

The foremost observation during the regional consultation and subsequent scoping of case studies was that despite there being significant overlap in the traffic, material types and climate, the TMR Districts have preferences for different approaches to the common issue of expansive subgrades. The reasons for this are varied, including:

- Management and design professionals in a District have extensive experience with a particular treatment. They have found that its application has been reasonably successful. As a result, their ‘default’ treatment is used in the majority of cases.
- While issues with sourcing quality pavement material are increasingly common across the State, some Districts have more funding available or a greater willingness to haul new material long distances while others prefer to spend their limited resources on using local materials as best they can (which may in turn limit the range of treatment options available).

The generic TMR guidance available to the Districts is often not tailored to rural applications, and the specific guidance for Western Queensland (e.g. WQ35) does not seem to be utilised heavily; if it is adopted, it is with non-WQ35 materials or with some of the methodology altered.

5.3 Expansive Subgrades in Different Environments

The discussion and case studies fit into one of the following three general categories:

- Moderate/heavily-trafficked routes where sufficient funding is available to perform bottom-up treatment of expansive subgrades (e.g. Darling Downs treating most of their network with lime).
- Low-traffic and remote roads where heavy stabilisation and cover requirements are prohibitively expensive (and/or the material is not available), and low-cost treatments are adopted.
- Isolated trouble spots such as cuttings, culverts, floodways and embankments, where the shorter treatment lengths allow for more extensive or innovative solutions including geotextiles, rock fill, or remove and replace (can also be appropriate through town centres).

Each approach or treatment is best suited to one of these general categories, and matching these is critical. These scenarios can be characterised by the level of acceptable risk, with higher risk generally being acceptable on low-volume roads, which would allow greater freedom in designing a suitable treatment. This may require an understanding from asset managers and funding sources regarding the trade-off between risk and treatment cost.

It is generally not be appropriate to attempt to treat expansive subgrades with a ‘one size fits all’ approach. Thus, taking into account treatments best-suited to the road type or road function will allow for more targeted and cost-effective outcomes. This could form a matrix for the assessment and design of treatments for roads with expansive subgrades, with generic designs prepared to facilitate the adoption of such a matrix. The matrix may also have to include consideration of the percentage of swell of the material (or other material properties), and the environment (including average rainfall and major flood recurrence interval).

5.4 Maintenance

This study has demonstrated the potential for the use of treatments characterised as ‘low-cost’, such as the granular overlays employed in Barcaldine. Under the South African approach outlined in Section 3.5, it was noted that performance issues may arise within the first two to three cycles of wet and dry seasons and that maintenance is critical in the early pavement life.

While significant up-front cost savings can be realised from utilising low-cost treatments, optimising whole-of-life costs appears to be linked to maintenance spending early in the life of the new treatment. In cases where a district has employed a low-cost treatment, consideration could be given to increase early maintenance funding accordingly. This may include crack-sealing and more regular drainage maintenance.

This approach could encourage the use of robust seals on these pavements. If the granular bases are somewhat more vulnerable to moisture-induced damage and cracking through shrink/swell, it is imperative that the water is kept out of the pavement. While proper drainage design and regular drainage maintenance can contribute, there would be advantages to implementing more robust seals (including crumbed rubber and polymer-modified seals), and widening the sealed pavement to increase the seal distance from the edge line.

5.5 Alternative Approaches

Section 3 outlined the range of approaches to addressing expansive subgrades across Queensland, as well as some of the more prominent approaches adopted in other jurisdictions (Australian and international). While some common themes are evident, each approach may have advantages in certain circumstances.

For example, the South African methodology includes some hybrid metrics for material testing and evaluation, which could provide more information than measures such as swell percentage alone. Also, the treatment selection matrix in the Texas approach could be beneficial (using a decision tree), particularly if it is eventually developed into an automated program.

Further consultation may be required with Districts to ensure that any proposed changes are beneficial and do not conflict with each other.

5.6 Long-term Performance Monitoring

With the exception of some sites utilising foam bitumen or other relatively recent innovations, very few sites were identified that included long-term performance monitoring.

Through NACOE, ARRB and TMR maintain a long-term pavement performance (LTPP) database which includes a range of trials, demonstration projects and other projects including innovative or alternative approaches. It would be ideal if a range of projects could be identified to add to this database for long-term performance monitoring. The examples noted for each treatment in Section 4

It was also noted that, while the TMR ARMIS database has flexibility for documenting structural and surfacing layer information, if does not appear to be used as widely when detailing works undertaken on subgrades for projects. Even in cases where subgrades are not modified in any way, it would be beneficial to document the condition and materials within the subgrade to assist in future pavement design; it would also aid in the prediction of pavement deterioration over time and in the event of flooding.

5.7 Challenges and Limitations

A common thread throughout this project has been that, while there have been some promising developments and a lot of success with treating expansive subgrades around the State, it remains a greatly challenging area, with a number of significant limitations preventing a comprehensive solution. The reality being faced by the Districts is that there are so many factors which influence the relative success or failure of an individual project. As a result, it is difficult to isolate the factors that could be controlled.

Some challenges being faced include:

- Each project has unique materials that change regularly along the project length.
- The environment has a large impact on pavement design and performance, not only from the perspective of rainfall and general climatic factors but also because of topography, roadside vegetation and the impact of agriculture.
- Recent traffic data is generally available across the network, but traffic projections remain a source of uncertainty into the future.
- Construction techniques vary according to District, contractor and the individual operators of equipment. They may have to be adjusted based on the time of year, weather, etc.
- Maintenance is critical to maintain the integrity of treatments and reduce risk of inundation.
- Ongoing monitoring and routine maintenance of the network is critical to the longevity of treatments.

Additionally, many of the recommendations in this report may be applicable to the majority of situations faced by Districts, but may not necessarily apply equally to non-pavement subgrade treatments, e.g. around culverts and other structures, at floodways, and near river crossings.

6 CONCLUSIONS AND RECOMMENDATIONS

6.1 Conclusions

The overarching aim of this research project was to investigate the optimal approach to the selection, design and construction of the best value-for-money moisture-sensitive soil treatment alternatives for road pavement applications. A targeted literature review and a survey of the most heavily-impacted Districts across Queensland revealed that the issue of expansive subgrades effects a wide area of the State. It also highlighted that expansive subgrades are responsible for many pavement failures. However, the approaches to treating these materials varies widely across the State. While District personnel have generally found solutions that have a reasonable success rate, there is recognition that much is still not known about the distribution of treatments and their relative performance.

A review of design and treatment methodologies applicable to reactive soils showed that there are a variety of options for treating and maintaining pavements constructed over expansive subgrades. These may be optimised across the State through increased knowledge sharing, the development of a more sophisticated treatment selection matrix, and through targeted funding of the most appropriate treatments for each location (with accompanying funding for maintenance and resealing to the extent required).

6.2 Recommendations

Table 6.1 outlines the key recommendations for this project. These recommendations are intended to help facilitate the selection of fit for purpose subgrade treatments in areas where there are expansive subgrade soils across Queensland.

Table 6.1: Recommendations from NACOE P54 research

Recommendations	Detail
1. Refine the expansive soil classification table	▪ Include an additional level above 'very high' and refine the existing levels to better differentiate between very high swell scenarios (5-10%), and extreme sites where the swell may be more than 10%. ▪ As shown in Table 5.2. (proposed new line in graph)
2. Specify treatments based on relevant scenario	▪ Develop matrix for treatments based on problem and location characteristics, including consideration of the local environmental and rainfall conditions, and the material swell percentage (or a hybrid material evaluation as in the South African methodology). ▪ Embed this selection matrix into pavement design guidelines, technical notes and/or Western Queensland best practice documentation.
3. Improve guidance and knowledge sharing across regions	▪ Produce new TMR guidance which focusses on treatments for expansive subgrades – to assist in the selection of the most efficient selection of treatments. ▪ Encourage knowledge sharing across Districts through a workshops or symposia on the treatment of expansive subgrades.
4. Provide early maintenance funding and additional funding for high-quality seals	▪ Maintenance funding for crack sealing, drainage works and so on needs to be specifically allocated in the early stages of operation for projects constructed in areas of expansive subgrades. This will ensure that the works are in good condition when they reach equilibrium moisture contents after the first few wet/dry cycles. ▪ Allowance should be made to construct highly-robust seals over areas of expansive subgrades to prevent moisture ingress where it is most critical to the long-term performance of the pavement, particularly where large capital cost savings have been made due to the use of proven low-cost treatments.
5. Incorporate elements of alternative approaches	▪ Look to incorporate alternative approaches (as discussed in Section 5.5) in TMR pavement design guidance where appropriate. ▪ Alternative approaches can form part of the matrix for treatments
6. Improve database to better represent the network	▪ Add selected sites to LTPP database and monitor over time (look at adapting existing LTPP database) ▪ Consider extending the capabilities of ARMIS to capture more detailed subgrade information.
7. Update Figure 3.1	▪ Update Figure 3.1 to include very highly expansive cover requirements, as detailed in Section 3.6.1

6.3 Changes to TMR Pavement Design Supplement

In early 2018, a series of changes were made in the TMR Pavement Design Supplement, in part to reflect the recommendations made through this research. The following updates are recommended to the Transport and Main Roads Pavement Design Supplement:

1. Introduce an “extreme” category of expansive subgrade material
2. Increase the cover requirement over highly expansive subgrades for low to moderately trafficked pavements
3. Provide more specific guidance for cover over very highly expansive subgrade materials.

These changes, as documented in the Pavement Design Supplement, are provided in Appendix A.

The proposed changes were circulated to the Districts for feedback, with two notable items of feedback relating to specific sections in the Pavement Design Supplement:

1. A request to clarify whether WPI and swell both apply in classifying the expansive nature of the soil. It was subsequently proposed to add the following text to Section 5.3.5 to clarify “Where CBR swell and weighted plasticity index (WPI) on the same material indicate different classifications, the CBR swell should take precedence.”
2. A comment that the CBR swell values given in Table 5.3.5 for high to very high expansive soils appear to be very high, with some lower values suggested (for example, the extreme category is for swell >5%). However, the lower values that were suggested may not adequately cover the range of materials we get in Queensland, which include many projects where the swell is measured at 10% or more.

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APPENDIX A RECOMMENDED CHANGES TO TMR PDS

Expansive subgrades – Recommended changes to the TMR Pavement Design Supplement, 13/02/2018, updated 04/06/2018

The following updates are recommended to the Transport and Main Roads *Pavement Design Supplement*:

1. Introduce an "extreme" category of expansive subgrade material
2. Increase the cover requirement over highly expansive subgrades for low to moderately trafficked pavements
3. Provide more specific guidance for cover over very highly expansive subgrade materials.

Each of these is discussed in more detail below.

Recommendation 1: Introduce an "extreme" category of expansive subgrade material

The existing Austroads Guide (AGPT02) classification for expansive materials includes a "very highly expansive" category which is for materials with swell exceeding 5%. However, in Queensland it is not unusual for materials to have swells of 10% or more. Using the AGPT02 classification, these materials are considered the same as materials with much lower swells of 5%. Hence, the AGPT02 categorisation does not adequately distinguish between materials with vastly different swell potentials.

It is therefore recommended to introduce an "extreme" category to better distinguish between common materials in Queensland. In this case the "very highly expansive" category is amended to materials with swells of 5 to 10%, and materials with swell greater than 10% are considered "extreme". The new classification recommended is shown in Table 1.

For practical reasons, it is also recommended to allow swell testing at 95% maximum dry density (MDD) (standard compaction) rather than requiring it at 98% MDD as detailed in AGPT02. As 95% MDD is the most common condition used on TMR projects for testing CBR of subgrade materials, testing swell at 95% MDD would avoid the need to undertake swell testing at a different density to CBR testing. As swell testing is part of the CBR test, this essentially halves the number of CBR tests required.

Table 1 Recommended guide to classification of expansive soils

Expansive nature	Weighted Plasticity Index (WPI) (PI x % < 0.425 mm)	CBR Swell (%)[1]
Extreme	> 4200	> 10.0
Very high	3200-4200	5.0-10.0
High	2200-3200	2.5-5.0
Moderate	1200-2200	0.5-2.5
Low	< 1200	< 0.5

1. Swell at OMC, 95% to 98% MDD (standard compactive effort), four-day soaked, and using 4.5kg surcharge.

Recommendation 2: Increase the cover requirement over highly expansive subgrades for low to moderately trafficked pavements

Options to improve the guidance in the *Pavement Design Supplement* for cover over expansive subgrades were considered and discussed at a meeting between key ARRB and TMR engineers on 30 August 2017. From this meeting, and based strongly on significant experience in investigating and rehabilitating distressed pavements, it is recommended to adjusted the required cover over highly expansive subgrades (swells of 2.5 to 5%) for traffic in the range of 1E5 to 1E7 ESA. For traffic loadings in this range it is not unusual to adopt pavements with bound layers, which are more expensive to repair if subgrade related problems arise. The recommended adjustment is to provide a minimum of 700 mm cover for traffic between 1E6 and 1E7 ESA, reducing to 500 mm at 1E5 ESA.

The slight increase to the cover requirements for these low to moderate traffic situations is consistent with the risk-based philosophy inherent in the existing cover over expansive subgrades chart.

The recommended cover compared to the existing *Pavement Design Supplement* is as shown in Figure 1.

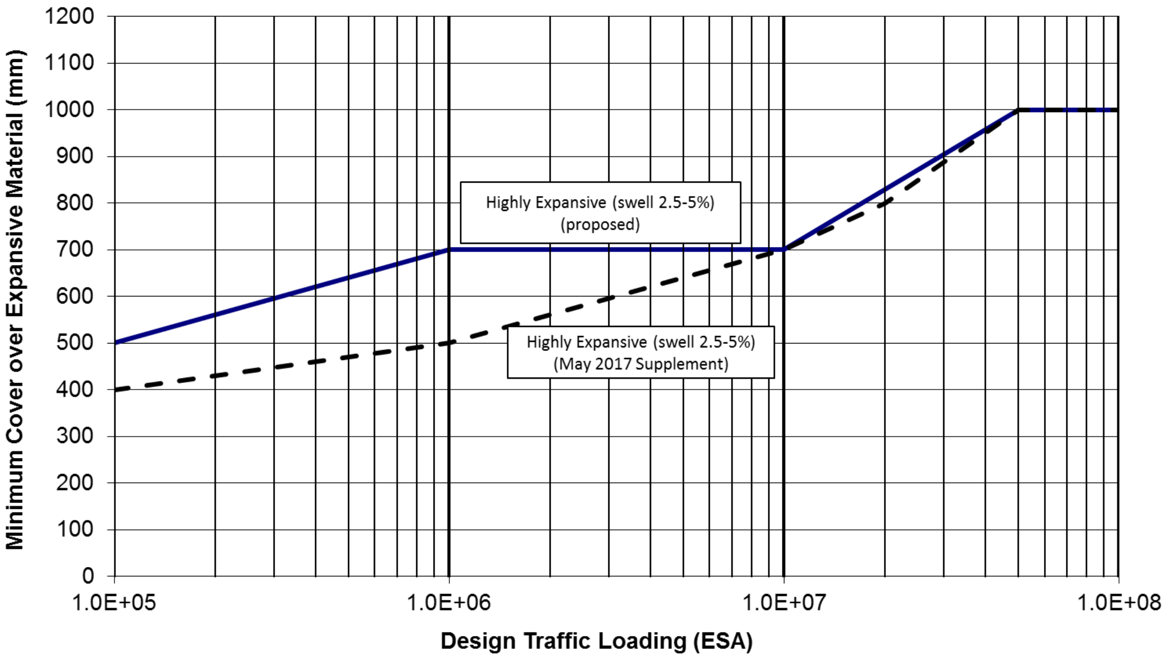

Figure 1 Recommended updates to cover over highly expansive subgrade

Recommendation 3: Provide more specific guidance for cover over very highly expansive subgrade materials.

At the meeting on 30 August 2017, provision of specific guidance in the *Pavement Design Supplement* for cover over very highly expansive subgrades (swells 5 to 10%) was also discussed. Materials in this category are often encountered, and as the existing supplement does not provide specific guidance for treatment of these, individual designers have tended to develop their own approaches to determine cover thickness. This has led to inconsistencies between projects for relatively similar conditions. It was therefore decided that a cover thickness over these materials should be included to ensure a consistent approach is adopted for similar situations in the future.

The principles of AS 2870-2011 were adopted to determine the cover requirements. The cover requirements had been determined prior to the meeting on 30 August 2017, but have since been adjusted and refined following updates to the cover over highly expansive subgrade requirements detailed in recommendation 2. The latest calculations are detailed in the following paragraphs.

The principles of AS2870-2011 were applied by bench-marking the estimated characteristic surface movement (y_s) over a very highly expansive subgrade with that calculated for a highly expansive subgrade (with all other variables remaining unchanged).

Calculations were undertaken for a range of depths of design suction change (H_s), and depths of the cracked zone. These ranges were restricted to values expected in wetter areas (climatic considerations are further detailed below). However, the difference in results within the ranges selected was not considered significant for the exercise being undertaken. Hence, the results were simplified to a single case as shown in Figure 2.

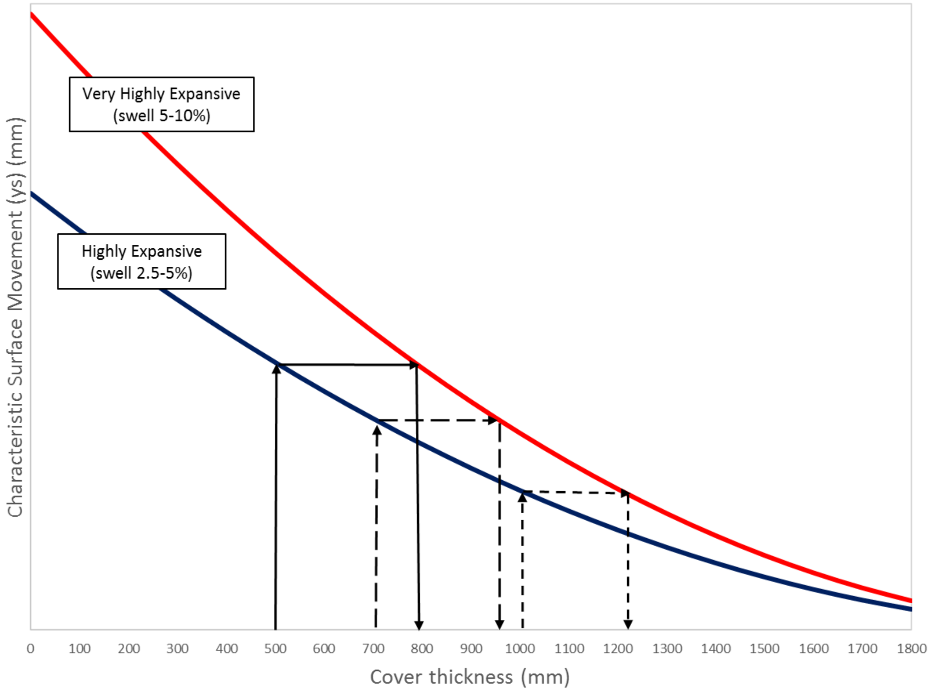

Figure 2 Benchmarking of characteristic surface movement

In Figure 2, no scale is shown for characteristic surface movement on the vertical axis. This is intentional as the cover thickness required to achieve a pre-determined y_s was not the goal of this exercise; as the link between y_s and pavement performance has not been established. Instead, the procedures of AS 2870-2011 were adopted to provide an estimation of cover required so that y_s does not change when changing from a highly expansive subgrade to a very highly expansive subgrade.

For example, Figure 1 recommends 1000 mm cover over a highly expansive subgrade for traffic exceeding 5E7 ESA. Using Figure 2, at 1000 mm cover over a highly expansive subgrade, to achieve the same y_s over a very highly expansive subgrade a cover of 1200 mm is necessary.

This process was used to determine the recommended cover over very-highly expansive subgrades at all traffic/risk levels. The resulting chart is shown in Figure 3 and is recommended for inclusion in the *Pavement Design Supplement*.

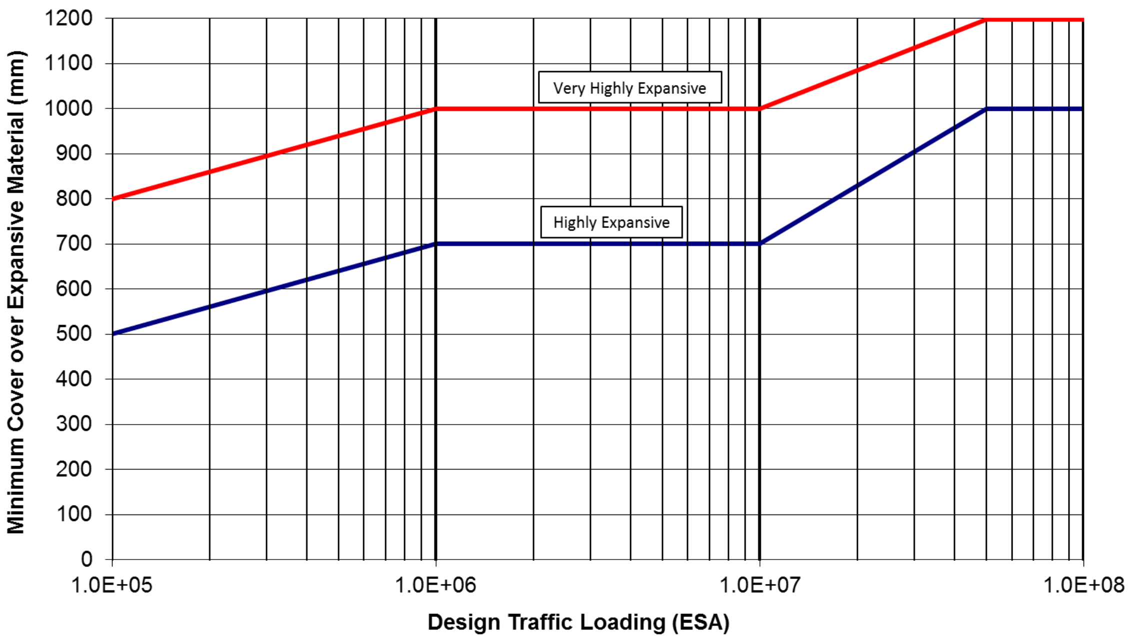

Figure 3 Recommended cover over highly and very highly expansive subgrades for flexible pavements

As part of the updates to the cover over expansive subgrade chart, it was considered necessary to also clarify the applicability of the cover thicknesses to different climatic zones. AS2870-2011 deals with the influence of climate, with more detailed discussion included in Fox (2000 and 2002).

In dry temperate, semi-arid and arid areas the depth of soil suction change is greater than in wetter areas, meaning that even greater thickness of cover may be required to address expansive subgrade issues. Other treatment types, such as lime stabilisation, are likely to be more economic and practical in these areas.

Therefore, the following text is also recommended for inclusion in the *Pavement Design Supplement*:

Where expansive subgrades are present, a geotechnical assessment is typically required to determine the appropriate mitigation strategy, particularly where the depth of design soil suction change is very high and/or the expansive nature of the soil is extreme (as defined in Table 5.3.5).

Fox (2000 and 2002) defines the relationship between the depth of design soil suction change and six climatic zones in Queensland: wet coastal, wet temperate, temperate, dry temperate, semi-arid and arid. The depth of design soil suction change is considered to be very high in dry temperate, semi-arid and arid areas. In these areas, providing a minimum cover of material over expansive soil is not typically economic as substantial thicknesses of cover are required. In these areas, other treatments are typically adopted and these are selected and designed in accordance with local practice (for example, lime stabilisation).

The thicknesses in Figure 3 only apply in wet coastal, wet temperate and temperate locations where the depth of design soil suction change is 2.3 metres or less (corresponding to locations with Thornthwaite Moisture Index of -15 or greater). In dry temperate, semi-arid and arid locations, where the depth of design soil suction change is greater than 2.3 metres (corresponding to Thornthwaite Moisture Index less than -15), a project-specific geotechnical assessment is recommended. Refer to AS 2870 and Fox (2000 and 2002) for further guidance.

Inclusion of a map of Queensland that illustrates the location of the different climatic zones (based on Thornthwaite Index) is currently being investigated.

Other discussion

At the meeting on 30 August 2017, use of geo-composites was also discussed.

It was agreed that guidance on reducing the cover where a subgrade geo-composite is used should not be included in the *Pavement Design Supplement* at this time as this is still an area of research.

Consultation of recommended changes

The recommended changes detailed above were consulted with industry representatives and TMR districts during December 2017 to February 2018. This included 6 face-to-face workshops, 1 skype workshop and release of draft updates to the *Pavement Design Supplement* for review.

Changes resulting from the consultation are detail in Section 6.3 of this report.

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