ANNUAL SUMMARY REPORT

P72: Moisture Susceptibility of Cement Treated Materials – Phase 1 (2017–2019)

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Summary

Unbound granular pavement layers are known to be susceptible to moisture-induced damage. The Queensland Department of Transport and Main Roads therefore aims to control the moisture content of these pavement layers during construction by specifying a maximum allowable degree of saturation (DoS) prior to sealing the road. Unbound granular materials with moisture contents greater than the allowable degree of saturation limits can be prone to rapid deterioration, including potholes and rutting.

During construction, the DoS is controlled by allowing the granular material to dry out (also known as 'dry-back') to within the specified limits prior to placing the overlying pavement layers or wearing course. However, to avoid DoS compliance requirements, there have been instances where the granular material was treated with relatively small quantities of a cementitious binder without any accompanying mix design or dry-back. It is understood that these practices have resulted in rapid pavement failures on some projects.

A National Asset Centre of Excellence (NACOE) project was therefore established to investigate the moisture sensitivity of granular materials modified with small quantities of a cementitious binder. The project comprised a literature review of current local and international practice regarding the moisture control of pavement materials during construction, followed by laboratory testing of 3 granular materials treated with varying quantities and at different moisture contents.

The laboratory assessment showed that the crushed rock materials performed poorly in the repeat load triaxial test at moisture contents above 65% of the DoS, even when treated with enough cementitious binder to achieve a 7-day UCS of greater than 1 MPa. The ridge gravel did however show significant improvement in performance when treated with higher quantities of binder, even at higher moisture contents. This indicates that treating granular materials with a small percentage of binder without any associated mix design may not necessarily reduce the risk of premature moisture-related damage occurring. It is therefore recommended that the moisture content (i.e. DoS) of granular materials modified with small quantities of cementitious binders without any accompanying mix design be controlled during construction, similar to the requirements for unbound pavement layers in MRTS05.

Limited testing undertaken in Stage 1 indicated that the use of 'modified' instead of a 'standard' compaction energy significantly improved the permanent deformation resistance measured in the repeat load triaxial test of the materials modified with a small quantity of cement, even at high moisture contents. However, this finding should be further investigated through additional laboratory testing on a variety of different granular material sources.

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1 Introduction

1.1 Background

Unbound granular pavement layers underneath sprayed seal or asphalt surfacings can be susceptible to moisture-induced damage. The Queensland Department of Transport and Main Roads (TMR) therefore controls the moisture content of these pavement layers during construction by specifying a maximum allowable degree of saturation (DoS) for the material prior to placing subsequent pavement layers or sealing the road.

The DoS of a material is defined as the ratio of volume of moisture to the volume of voids in a compacted material. Unbound granular materials with moisture contents greater than allowable DoS limits are prone to rapid deterioration, including potholes and rutting. High moisture contents can also lead to poor bonding between the base layer and overlying bituminous surfacing, as well as embedment of the sprayed seal aggregates into the moisture-softened base layer. During construction, the DoS is controlled by allowing the unbound granular material to dry out (also known as 'dry-back') prior to placing the overlying pavement layers or wearing course.

Achieving adequate dry-back in wet environments (e.g. northern Queensland) can be challenging and TMR regularly adopts cement stabilisation in these environments to overcome the DoS requirements for unbound granular materials. This can either be specified by the designer or requested as a variation during construction. Often only a small amount of cement (without any accompanying mix design) is incorporated into the granular material with the expectation that dry-back will not be required and that that the layer will still act as a flexible unbound pavement.

However, there is anecdotal evidence to suggest that granular materials treated with small quantities of a cementitious binder can still be moisture sensitive. There have been instances on TMR projects where granular materials were treated with small quantities of a cementitious binder (e.g. approximately 1% or less) with no accompanying mix design to avoid the requirement to achieve the DoS limits in the specification prior to sealing the road. These materials would typically not meet the minimum 28-day unconfined compressive strength (UCS) specified by TMR for lightly bound materials and the materials are therefore more representative of a cementitiously modified (also known as 'modified') material in accordance with the Austroads *Guide to Pavement Technology Part 4D: Stabilised Materials* (Austroads 2019). In some cases, the modified material would be trafficked within 1–2 days after construction with limited time available for any dry-back to occur. Consequently, there have been reports throughout Queensland where these modified materials have not performed as intended, and it is suspected that not adequately controlling the moisture content (i.e. DoS) prior to sealing the layer led to the premature pavement failures. Some examples of these moisture-related failures observed in the tropical parts of Queensland are shown in Figure 1.1.

Figure 1.1: Suspected moisture-related failures of a cement modified basecourse on the outskirts of Ravenshoe, Far North Queensland

Source: TMR (circa 2015).

It is important to note that TMR is not aware of any moisture-related failures occurring in lightly or heavily bound pavement layers that were designed and constructed in accordance with the appropriate TMR technical guidelines and specifications. This study therefore only focussed on the moisture sensitivity of granular materials treated with small percentages of a cementitious binder (i.e. modified materials) without any associated mix designs.

1.2 Project Scope and Objectives

The project was aimed at assessing the moisture sensitivity of granular materials treated with small quantities of a cementitious binder (i.e. modified materials) in the laboratory. The objectives of the study comprised the following:

- a literature review of current local, national and international practice regarding the moisture control of granular materials modified with small percentages of cementitious binder
- laboratory testing of 3 granular materials treated with varying quantities of cement to determine their moisture sensitivity in the repeat load triaxial (RLT) test
- laboratory testing to assess the effects of different levels of compactive effort (i.e. 'modified' and 'standard' compaction) on the performance of 2 materials in the RLT test
- documenting the findings of the study in an Annual Summary Report (this report).

1.3 Report Structure

Section 2 of the report documents current jurisdictional practices to control the moisture content of granular and modified pavement materials, as well as summarising potential failure mechanisms for these pavements due to the presence of high moisture soon after construction. Section 3 documents the results of the laboratory testing undertaken on 3 different granular materials treated with varying quantities of cement. Section 4 provides interim conclusions and recommendations for the subsequent phases in this project.

2 Literature Review

A targeted literature review was undertaken of the moisture sensitivity of unbound granular, modified and lightly bound materials. The review also identified current practice (both in Australia and internationally) regarding the moisture control of modified materials during construction.

2.1 The Behaviour of Bound, Lightly Bound and Modified Materials

Cementitiously bound (also referred to as heavily bound) pavement materials are granular materials that are stabilised with sufficient quantities of a cementitious binder to produce a material which has tensile strength. The bound material acts like a beam in the pavement structure and has a significantly higher structural capacity compared to the untreated granular material. However, cementitiously bound pavement layers can be prone to shrinkage and fatigue cracking if not properly designed and constructed (Austroads 2019).

Lightly bound materials are granular materials treated with relatively small quantities of a cementitious binder to have higher strength and modulus values compared to modified materials, but not to achieve the same degree of cementation (stabilisation) required for heavily bound materials (Austroads 2019). Depending on the level of tensile strength developed, lightly bound materials can still be susceptible to fatigue and shrinkage cracking, but the size of the cracks are typically smaller compared to cementitiously bound materials.

Modified pavement materials are granular materials treated with small amounts of a cementitious binder to improve rut resistance and modulus, or to correct other deficiencies (e.g. a high plasticity) without significantly increasing the tensile strength of the material (Austroads 2019). These materials would typically have a UCS value of less than 1 MPa and are therefore considered to behave similar to an unbound granular material. The main failure mechanism of modified materials is therefore permanent deformation (e.g. rutting or shear deformation).

Modified and lightly bound materials are therefore expected to behave differently in service, depending on the amount of cementitious binder added and the strength achieved. However, the UCS value at which a material transitions from a modified to lightly bound material is not necessarily well defined. TMR specifies an upper 28-day UCS limit of 2.0 MPa to manage the risk of cracking and a lower UCS limit of 1.0 MPa to ensure sufficient material strength is developed to meet the intended load capacity of the pavement (TMR 2022a). This strength range has proven to be successful in Queensland and the Department has extensive experience with successfully using lightly bound materials (particularly in northern Queensland).

Table 2.1 provides a comparison between bound, lightly bound and modified pavement materials.

Table 2.1: Comparison between bound, lightly bound and modified materials

Stabilisation category	Indicative UCS(1)	Benefits	Disadvantages	Expected failure mechanism
Cementitiously bound	> 2 MPa	• Increased pavement modulus • Low moisture sensitivity	• Increased risk of shrinkage cracking • Can be prone to fatigue cracking • Increased cost	• Fatigue cracking
Lightly bound	1–2 MPa	• Improved deformation resistance compared to modified material • Less moisture sensitive compared to modified material	• May be susceptible to fatigue and/or shrinkage cracking • Transition to a fully bound or modified material not well defined • May be susceptible to erosion at low binder contents where cracks are present	• Expected failure mechanism not well defined and will depend on level of stabilisation achieved.
Modified	< 1 MPa	• Improved deformation resistance compared to untreated material • Improved modulus compared to untreated material • Less moisture sensitive compared to untreated material	• Moisture content prior to sealing still needs to be controlled • May be susceptible to erosion where cracks are present	• Rutting or shear deformation

1. After 28 days curing.

Source: Adapted from Austroads (2019).

2.2 Moisture Control in Pavement Layers – Australian Practice

The literature review considered current practices in Queensland, New South Wales and Western Australia to control the moisture content in pavement layers during construction.

2.2.1 Queensland

Unbound granular and cement stabilised pavement layers in Queensland are typically specified to one of the following TMR technical specifications:

- MRTS05 *Unbound Pavements* (2022b)
- MRTS07B *Insitu Stabilised Pavements Using Cement or Cementitious Blends* (2022c)
- MRTS08 *Plant-mixed Heavily Bound (Cemented) Pavements* (2022d)
- MRTS10 *Plant-mixed Lightly Bound Pavements* (2022a).

Importantly, TMR does not currently have a specification that applies to the construction of modified pavement layers.

MRTS05 *Unbound Pavements*

MRTS05 applies to unbound granular pavement layers (i.e. granular pavement layers without any stabilising agent). Importantly, the specification states the following:

> This Technical Specification assumes that the pavement is not excessively exposed to water and that protective measures are taken to assure this. Where exposure to moisture is expected, additional controls over and above the requirements of this Technical Specification may be warranted or the use of bound pavement materials should be considered in the pavement design.

In addition to the material properties specified in MRTS05, the specification also provides requirements for controlling the moisture content of the materials during construction and up to the time when the material is covered by a pavement layer or bituminous surfacing. The specification sets a maximum DoS limit for each material type prior to the placement of an overlaying pavement or surfacing layer, or any trafficking occurring (refer Table 2.2). The DoS of the material is determined in accordance with test method Q146 *Degree of Saturation of Soils and Crushed Rock.*

Table 2.2: MRTS05 prescribed maximum DoS limits

Material	Maximum degree of saturation	
Compaction standard	Modified	Standard
Type 1 (HSG)	60	Not applicable
Type 2	70	65
Type 3	70	65
Type 4	Not applicable	65

Source: TMR (2022b).

MRTS05 also notes that the premature failure of newly constructed unbound granular pavements is known to occur due to excess moisture in the pavement base prior to the application of the surfacing layer. The specification therefore states that materials with a DoS above the limits specified in Table 2.2 can lead to:

- rapid pavement failure (including blow-outs and rutting)
- lifting of the surfacing due to positive pore pressures in the basecourse
- embedment of sprayed sealing aggregate due to a soft basecourse.

It should be noted that the DoS limits are not applicable when placing and compacting the unbound materials. The materials should ideally be placed at or near the optimum moisture content (OMC) of the material as the higher moisture content aids with workability and compaction of the material. Once the material has been placed and compacted, ‘dry-back’ is required to reduce the moisture content to below the DoS limits specified in Table 2.2.

MRTS07B *Insitu Stabilised Pavements Using Cement or Cementitious Blends*

MRTS07B applies to in situ materials stabilised with a cementitious binder to form a lightly bound or heavily bound pavement layer that achieves the project-specific strength requirements.

For the final in situ stabilisation pass, the relative moisture ratio (i.e. the ratio of the in situ moisture content to the OMC of the material) must be between 90% and 105%. Similar to MRTS05, the higher moisture content aids with workability and compaction of the material, as well as assisting with the cementitious hydration reaction. The completed stabilised material must also be cured in a damp condition until the layer is covered by an overlying pavement layer or a sprayed bituminous surfacing with cover aggregate.

Importantly, MRTS07B does not specify any DoS limits for lightly or heavily bound pavement layers.

MRTS08 *Plant-mixed Heavily Bound (Cemented) Pavements*

MRTS08 applies to the construction of pavement layers using a plant-mixed stabilised material to form a bound layer. The specification requires that the moisture content of the stabilised material be within ±1% of the OMC of the material at the time of construction. The compacted material must also be cured using water or a bituminous curing coat until the layer is covered.

Similar to MRTS07B, MRTS08 does not specify any DoS limits for heavily bound materials.

MRTS10 *Plant-mixed Lightly Bound Pavements*

MRTS10 specifies the requirements for plant-mixed lightly bound pavements and includes guidance and specification limits for both lightly bound basecourses and lightly bound improved layers (previously known as working platforms). As mentioned previously, TMR requires lightly bound materials to have a 28-day UCS value of between 1.0 MPa and 2.0 MPa which is intended to produce a material that provides sufficient structural capacity while minimising the risk of cracking generally associated with heavily bound pavement materials.

The contractor is responsible for nominating the upper and lower moisture content limits to achieve the specified level of compaction during construction. The specification also requires that the moisture content of the lightly bound material must not exceed the OMC of the unbound pavement material prior to stabilisation. Once the material has been compacted, the lightly bound layer must be cured in a damp condition until the material is covered by an overlying pavement or surfacing layer.

MRTS10 does not specify any DoS limits for lightly bound layers, but importantly, the lightly bound material is not allowed to be covered within 48 hours after placement or after rainfall occurring.

An important difference between MRTS05 for unbound pavement layers and the specifications for lightly bound and bound layers (i.e. MRTS07B, MRTS08 and MRTS10) is the control of moisture during material placement, compaction and subsequent sealing. Moisture is required to allow for lubrication of the granular particles to achieve optimal compaction; however, only unbound granular layers have a dry-back requirement to achieve the specified DoS limits. This would suggest that TMR considers cementitiously treated materials that meet the requirements in MRTS07B, MRTS08 and MRTS10 to be less sensitive to higher in-service moisture contents compared to unbound granular materials.

2.2.2 New South Wales

Transport for New South Wales (TfNSW), previously known as Roads and Maritime Services (RMS), specifies the construction of unbound granular, modified and cement stabilised layers in accordance with the following specifications:

- R71 *Construction of Unbound and Modified Pavement Course* (2018)
- R73 *Construction of Plant Mixed Heavily Bound Pavement Course* (2015a)
- R75 *Insitu Pavement Stabilisation Using Slow Setting Binders* (2015b).

R71 *Construction of Unbound and Modified Pavement Course*

R71 specifies the requirements for unbound and modified pavement layers, where modified materials are defined as granular materials mixed with small amounts of binder to improve the material's properties (e.g. to adjust plasticity or prevent material breakdown) without significantly increasing the tensile strength of the material.

The contractor's mix design must note the OMC of the unbound or modified material and develop a target moisture envelope to ensure that:

- there is adequate moisture in the material to achieve binder hydration and the specified level of compaction
- the pavement is capable of carrying the traffic loads without shoving or ravelling on completion of compaction.

R71 requires that unbound and modified basecourse layers be dried back to less than 70% OMC of the material prior to placing the surfacing layer. Importantly, R71 requires the same moisture control regime for both unbound granular and modified materials.

R73 *Construction of Plant Mixed Heavily Bound Pavement Course and R75 Insitu Pavement Stabilisation Using Slow Setting Binders*

R73 and R75 specify the requirements for plant-mixed heavily bound and in situ stabilised pavement layers, respectively. Both these specifications will result in a cementitiously bound material with a 7-day UCS value of at least 3 MPa and a minimum stabilising agent content of 4%.

The contractor is required to develop a target construction moisture content envelope for the bound material. The stabilised layer must also be cured in a moist condition until the material is covered with a subsequent pavement or surfacing layer.

TfNSW, similar to TMR, does not specify any moisture content requirements for heavily bound pavement materials prior to placing the overlying pavement or surfacing layer.

2.2.3 Western Australia

Main Roads Western Australia (MRWA) specifies the construction of unbound granular, modified and cement stabilised layers in accordance with the following specifications:

- Specification 501 *Pavements* (2022)
- Specification 515 *In Situ Stabilisation of Pavement Materials* (2021).

Specification 501 *Pavements*

Specification 501 specifies requirements for the supply and construction of unbound and modified granular pavement layers. The specification does not provide a definition for modified granular pavement layers, but nonetheless, it does require the basecourse and subbase layers to be dried back to between 60% and 85% of the OMC of the material, depending on the pavement layer, material type and final surfacing type.

Specification 515 *In situ Stabilisation of Pavement Materials*

Specification 515 specifies requirements for the supply and application of in situ stabilised granular pavement layers (including the use of chemical and bituminous stabilising agents). The 7-day and 28-day UCS values of the stabilised material should be limited to a maximum of 1 MPa for cement and lime, respectively. These materials would therefore likely behave similar to modified materials in accordance with Austroads (2019). The specification requires that the in situ stabilised (i.e. modified) basecourse or subbase layers be dried back to 85% OMC of the material. A lower moisture ratio may also be considered for heavily trafficked roads.

2.3 Moisture Control in Pavement Layers – International Practice

The literature review also considered current practices in New Zealand and South Africa to control the moisture content in pavement layers during construction.

2.3.1 New Zealand

Gray (2017) noted that it is difficult in New Zealand to achieve the very low cement contents required for a modified material and that any variability in the cement content, water content or grading of the material can lead to lightly bound or even more heavily bound pavement layers.

The New Zealand Transport Agency (NZTA) specifies the requirements for unbound granular, modified and cementitiously bound pavement layers in accordance with:

- TNZ B/2 *Specification for Construction of Unbound Granular Pavement Layers* (2015)
- TNZ B/5 *Specification for In-situ Stabilisation of Modified Pavement Layers* (2008)
- NZTA B/6 *Specification for In-situ Stabilisation of Bound Sub-base Layers* (2012a)
- NZTA B/7 *Specification for the Manufacture and Construction of Plant Mixed Modified Pavement Layers* (2012b)
- NZTA B/8 *Specification for the Manufacture and Construction of Plant Mixed Bound Sub-base Pavement Layers* (2012c).

TNZ B/2 *Specification for Construction of Unbound Granular Pavement Layers*

TNZ B/2 specifies requirements for the construction of unbound granular subbase and basecourse pavement layers. The specification does not provide any specific moisture requirements during the placement and compaction of the granular materials but does provide maximum DoS limits prior to sealing the basecourse layer. A maximum DoS value of 80% is specified prior to sealing; however, the specification also notes that the rut resistance of unbound granular materials improves with decreasing DoS levels. A DoS limit of 60% is therefore recommended for pavements carrying more than 5 x 10^6 million equivalent standard axles.

TNZ B/5 *Specification for In-situ Stabilisation of Modified Pavement Layers* and NZTA B/7 *Specification for the Manufacture and Construction of Plant Mixed Modified Pavement Layers*

TNZ B/2 and NZTA B/7 specify requirements for the in situ and plant-mixed stabilisation of modified pavement layers, where modified materials are defined as materials to which small quantities of stabilising agent are added to improve the properties of the material whilst still behaving as an unbound granular pavement layer. The specifications are aimed at reducing the moisture sensitivity and improving the shear resistance of granular materials. TNZ B/2 also notes that using modified materials reduces the risk of excessive shrinkage and/or fatigue cracking which are typically associated with heavily bound pavement layers.

The contractor must add sufficient water during the stabilisation process, but care should be taken to avoid excessive wetting of the material. The moisture content should be between 90% and 100% of the material's OMC. The stabilised layer must be protected and cured in a damp condition until the next pavement or surfacing layer is placed. Importantly, the DoS of the basecourse should be less than 80% prior to sealing the road.

NZTA B/6 *Specification for In-situ Stabilisation of Bound Sub-base Layers* and NZTA B/8 *Specification for the Manufacture and Construction of Plant Mixed Bound Sub-base Pavement Layers*

NZTA B/6 and NZTA B/8 apply to the construction of in situ and plant-mixed cementitiously bound subbase layers. The specifications require that the stabilised material must be within 90% to 100% of the material's OMC during compaction, without excessively wetting the material. The stabilised material must also be cured in a damp condition or covered with an impermeable sheet or curing compound until the overlying layer is placed. Construction traffic (except the traffic required for curing) is not allowed on the completed stabilised layer for at least 7 days.

Similar to TMR and TfNSW, NZTA does not specify any DoS or moisture content limits for heavily bound pavement layers.

2.3.2 South Africa

TRH13 *Cementitious Stabilizers in Road Construction* distinguishes between modified and cemented pavement materials (South African Department of Transportation 1986). The specification states that at low cement quantities, a material's properties (such as California Bearing Ratio (CBR) and plasticity index (PI)) may be improved without significantly increasing the compressive or tensile strength of the material. Materials treated with small percentages of cement (without significant increases in the material's tensile strength) is referred to as modified materials. Importantly, TRH13 also notes that there is no clear boundary between modified and bound materials.

Cementitiously bound stabilised materials in South Africa are divided into 4 categories as shown in Table 2.3. The South African C3 and C4 materials are similar to lightly bound materials used by TMR, albeit with slightly different UCS limits.

Table 2.3: South African UCS limits for cementitiously bound materials

Test conditions	C1 – Cemented crushed stone or gravel		C2 – Cemented crushed stone or gravel		C3 – Cemented natural gravel		C4 – Cemented natural gravel	
	Min	Max	Min	Max	Min	Max	Min	Max
Laboratory-design, UCS at 7 days, 100% Mod AASHTO density	6	12	3	6	1.5	3	0.75	1.5
Laboratory-design, UCS at 7 days, 97% Mod AASHTO density	4	8	2	4	1	2	0.5	1

Source: South African Department of Transportation (1986).

TRH13 also states that modified materials are not required to be bound, and therefore, the specification allows for materials that do not meet the requirements for an unbound granular pavement layer to be modified using small quantities of cement to meet the requirements in Table 2.4.

Table 2.4: PI limits for modified materials

Material groups	Material designation	Maximum liquid limit	Maximum PI	Minimum CBR
Graded crushed stone	G1	–	Not permitted*	–
	G2	25	6	80 (@ 98%)
	G3	25	6	80 (@ 98%)
Natural gravel	G4	25	6	80 (@ 98%)
	G5	30	10	45 (@ 95%)
	G6	–	12**	25 (@ 93%)
Gravel-soil	G7	–	–	15 (@ 93%)
	G8	–	–	10 (@ in-situ density)
	G9	–	–	10 (@ in-situ density)
	G10	–	–	10 (@ in-situ density)

Notes: * Some rock fines may be plastic, in which case a maximum liquid limit of 25 and a PI of 4 are permissible.

** For coarse materials, the maximum PI can be increased based on grading.

Source: South African Department of Transportation (1986).

Additionally, TRH13 recommends that the PI of modified pavement materials be reduced to below the values shown in Table 2.5.

Table 2.5: PI limits for modified materials

Pavement layer	Maximum PI after modification
Base	4
Subbase	6
Selected subgrade	10

Source: South African Department of Transportation (1986).

Although using modified materials can improve the PI of a material and the low stabilisation contents limit the effect of shrinkage, additional guidance is given regarding the moisture content used during compaction. TRH13 states that shrinkage is proportional to the amount of moisture lost during drying of the material. It also suggests that the compaction moisture should be close to the OMC and not be unnecessarily high as this would contribute to shrinkage cracking.

2.4 Summary of Findings

Modified pavement materials are granular materials treated with small amounts of a cementitious binder to improve the properties of the material without significantly increasing tensile strength of the material. These materials would typically have a UCS value of less than 1 MPa. Lightly bound materials are granular materials treated with relatively small quantities of a cementitious binder to have higher strength and modulus values compared to modified materials, but without the same degree of cementation achieved for fully bound materials. Modified and lightly bound materials are therefore expected to behave differently in service, depending on the amount of stabilising agent added and the strength achieved. Currently the UCS value at which a material transitions from a modified to lightly bound material is not well defined.

TMR has detailed procedures and specification requirements for granular, lightly and heavily bound pavement layers using cementitious binders. However, the Department does not have any specification or mix design requirements for modified materials where only a small amount of cement is added to improve the properties of a granular material.

A literature review of current practices elsewhere found that New South Wales, Western Australia, New Zealand and South Africa have requirements for modified pavement layers. All 4 jurisdictions require that the moisture content of modified materials be controlled prior to sealing, which suggests that these jurisdictions consider these materials still to be moisture sensitive.

3 Laboratory Testing and Analysis

TMR currently uses the capillary rise test method (Q125D *Capillary Rise of Stabilised Materials)* to assess the moisture susceptibility of stabilised materials in the laboratory. Test method Q125D requires measuring the height of the wetting front on the surface of a cylindrical cement stabilised specimen for 72 hours.

The UCS test is widely used to assess the strength of cementitiously stabilised materials. TMR requires that the UCS of lightly and heavily bound materials be determined in accordance with test method Q115 *Unconfined Compressive Strength of Stabilised Materials.*

In Australia, the repeat load triaxial (RLT) test is often used to assess the permanent deformation resistance of unbound granular materials. There are several different RLT test methods available; however, TMR developed an in-house procedure (Q137 *Permanent Deformation and Resilient Modulus of Granular Unbound Material*) that determines the plastic strain and modulus in 3 specimens over a range of DoS values and at a constant stress ratio of 750/125 kPa.

Capillary rise, UCS and RLT testing were therefore undertaken to assess moisture sensitivity of unbound granular materials treated with relatively small percentages of a cementitious binder.

3.1 Materials and Testing Schedule

The laboratory testing program comprised testing 3 different granular materials treated with varying cement contents. Control samples (without the addition of cement) were also included in the study. The 3 materials that were tested included a ridge gravel sourced from Emerald and 2 crushed rock materials (Material A and Material B) sourced from commercial hard rock quarries in Southeast Queensland. The ridge gravel met the specification criteria for a Type 2.3 material in MRTS05 and are typically used in the subbase layer of unbound pavements. The crushed rock materials met the criteria for a Type 2.1 material typically used as a basecourse in unbound pavements.

The stabilising agent used for the laboratory testing was a general blend (GB) cement with 75% general purpose (GP) cement and 25% fly ash. The cement contents used in the samples that were prepared for the RLT testing were determined after the completion of the UCS testing to ensure that the testing covered a range of UCS values either side of 1 MPa.

The laboratory testing program shown in Table 3.1 included basic material characterisation tests, as well as some more performance-related tests (including capillary rise, UCS and RLT testing).

Table 3.1: Laboratory testing program

	Test parameter	Test method	Binder content (%)	Total number of tests
Characterisation	Particle size distribution	Q103A	N/A	3
	Moisture content	Q102A	N/A	3
	Atterberg limits	Q104A, Q105, Q106	N/A	3
	Apparent particle density	Q109	N/A	3
	Moisture density relationship	Q142A	Extrapolated based on 0 (untreated), 0.7 & 1.5	9

	Test parameter	Test method	Binder content (%)	Total number of tests
Performance	Capillary rise	Q125D	0 (untreated), 0.5, 0.7, 0.9, 1.1, 1.3 & 1.5	21
	Unconfined compressive strength	Q115	0 (untreated), 0.5, 0.7, 0.9, 1.1, 1.3 & 1.5	21
	Repeat load triaxial	Q137	0 (untreated) and 3 different binder contents (2 points for each test)	24

3.2 Type 2.3 Ridge Gravel – Test Results and Analysis

The results of the material characterisation testing undertaken on the ridge gravel are summarised in Table 3.2.

Table 3.2: Type 2.3 ridge gravel material properties

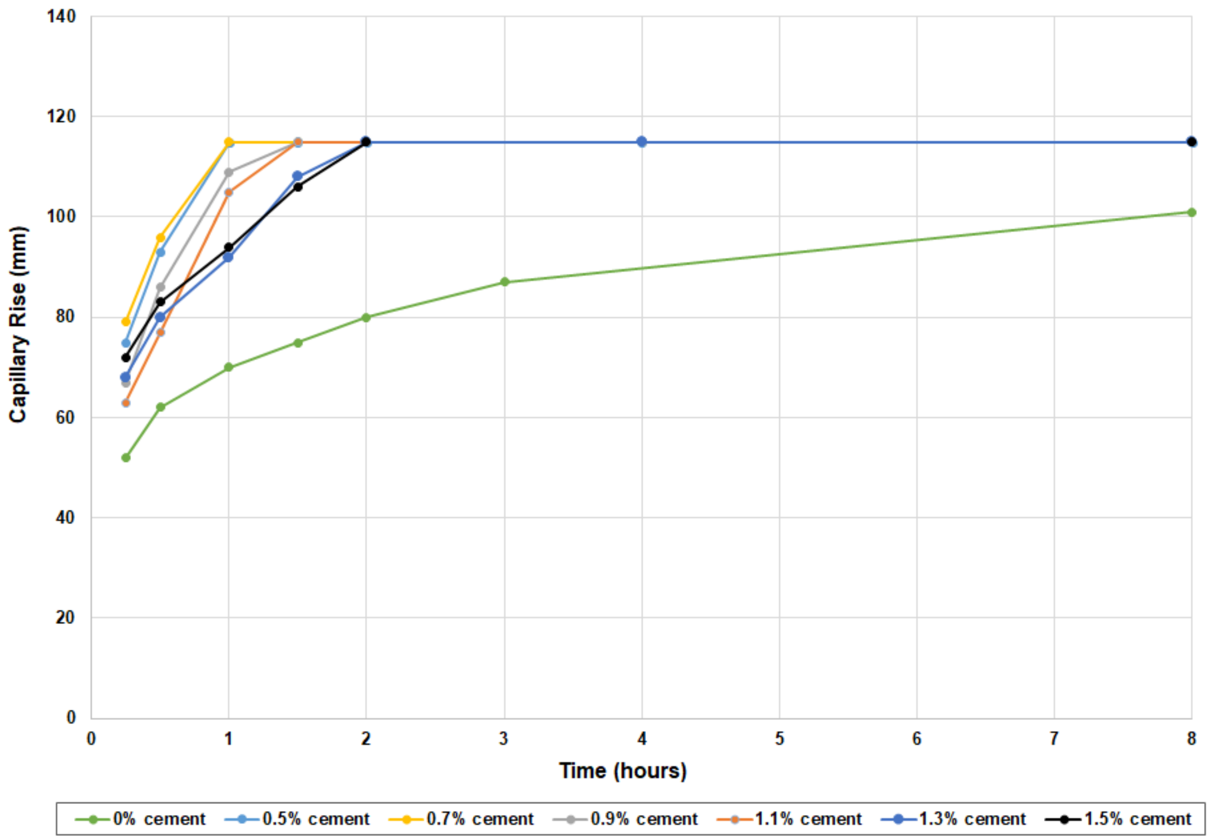
Test parameter	Test method	Result	Specification limit
Fines ratio	Q103A	0.32	0.30–0.65
Liquid limit (%)	Q104A	23.0	28 (max)
Plastic limit (%)	Q105	19.0	Not specified
PI (%)	Q105	4.0	8 (max)
Weighted PI (%)	Q105	98	200 (max)
Linear shrinkage (%)	Q106	3.8	4.5 (max)
Weighted linear shrinkage (%)	Q106	93	110 (max)
Apparent particle density of soil (t/m^3)	Q109	2.64	Not specified

The results in the table above indicate that the ridge gravel used in the study complied with the requirements for a Type 2.3 material in accordance with MRTS05.

3.2.1 Capillary Rise Testing

The capillary rise testing was undertaken on specimens with a nominal height of 115 mm in accordance with test method Q125D. The moisture front in the untreated specimen reached the full 115 mm specimen height after 24 hours, whereas the moisture front in each of the stabilised specimens reached the full specimen height within 2 hours. Interestingly, the waterfront in the specimens prepared at the lower cement contents (i.e. 0.5% and 0.7%) reached the full specimen height by the end of the first hour of testing (refer Figure 3.1). The reason for the shorter rise times observed for the specimens treated with lower cement contents were not further investigated but could be due to the cement lowering the plasticity of the granular material resulting in a more permeable soil structure.

Figure 3.1: Type 2.3 ridge gravel capillary rise at different cement contents



3.2.2 UCS Testing

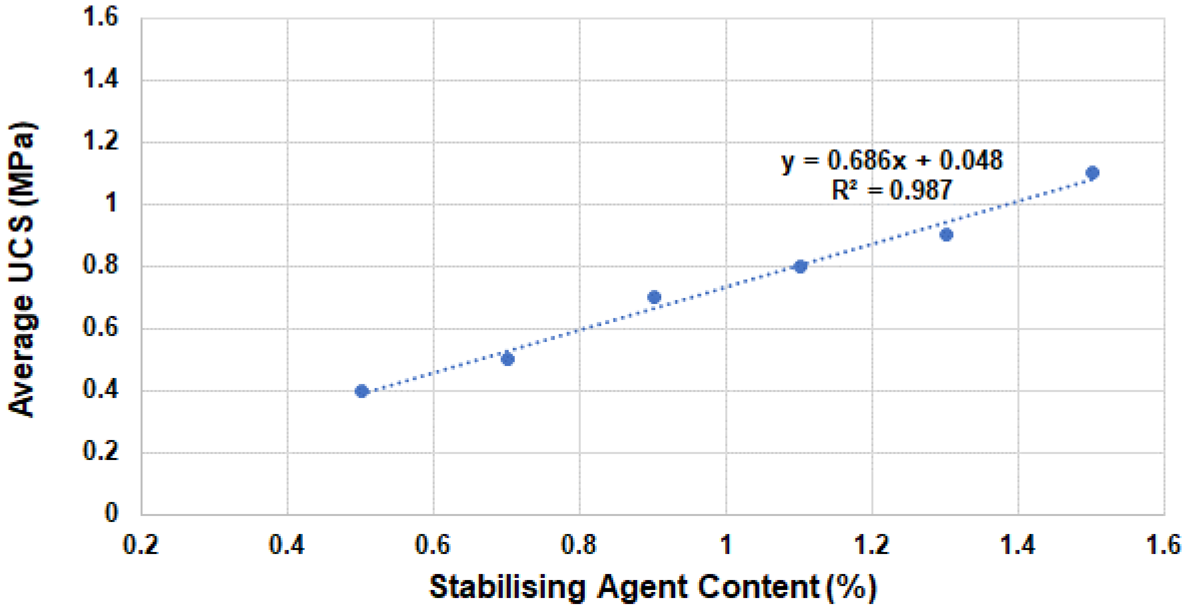
The UCS testing was undertaken in accordance with test method Q115 on specimens prepared at different cement contents ranging between 0.5% and 1.5%. The UCS results are summarised in Table 3.3 and shown in Figure 3.2.

Table 3.3: Summary of Type 2.3 ridge gravel UCS test results

Target moisture content (%)	Average moisture content (%)	Target dry density (t/m^3)(1)	Average dry density (t/m^3)(1)	Stabilising agent content (%)	Average UCS (MPa)(2)
6.3	6.0	2.200	2.210	0.5	0.4
6.3	6.1	2.200	2.209	0.7	0.5
6.3	6.4	2.200	2.204	0.9	0.7
6.3	6.2	2.200	2.206	1.1	0.8
6.2	6.4	2.201	2.202	1.3	0.9
6.2	6.2	2.201	2.206	1.5	1.1

1. Dry density based on standard compaction effort.
2. After 7 days curing.

Figure 3.2: Type 2.3 ridge gravel UCS values at cement contents



The UCS increased linearly with an increase in cement content, with a minimum of 1.4% cement required to achieve a UCS of 1 MPa.

3.2.3 RLT Testing

As mentioned previously, 3 cement contents were selected for the RLT testing. These contents (i.e. 0.7%, 1.3% and 1.5%) were chosen to have test specimens with UCS values either side of 1 MPa. An untreated (control) specimen set was also included in the testing program.

Each specimen set was prepared and tested at 2 different moisture contents, including:

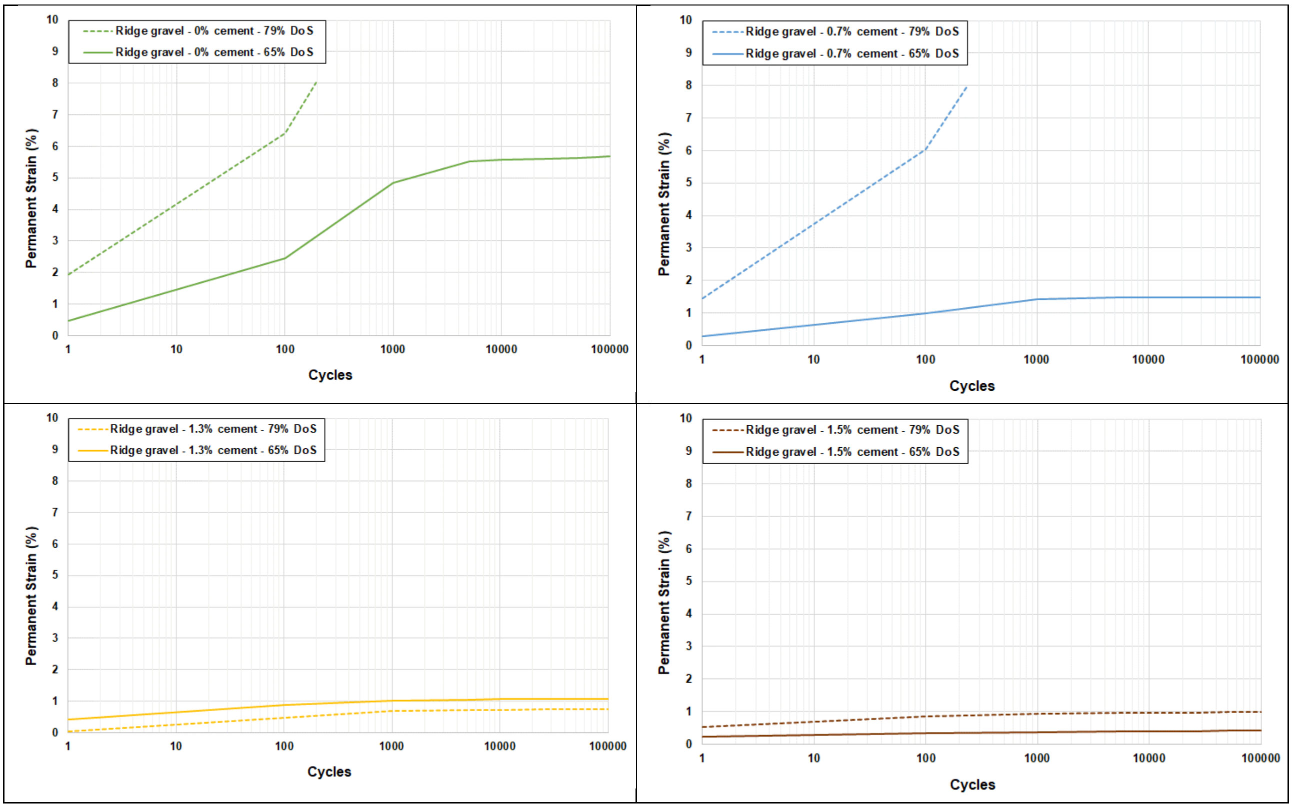
- at 79% of DoS (i.e. 5.7% moisture content and 100% of OMC)
- at 65% of DoS (i.e. 4.7% moisture content and 82% of OMC).

MRTS05 allows for higher levels of DoS during construction if the material has a permanent strain value of less than 1.5% after 1,000 cycles and less than 4.0% after 50,000 cycles in the RLT test when tested at the higher DoS value.

The permanent strain results of the RLT testing undertaken are shown in Figure 3.3. The untreated (control) specimens failed rapidly, reaching 4% strain in less than 1,000 cycles at both moisture contents. The rapid failure indicates that this material would typically not be suitable for use in the basecourse of sealed pavements. The untreated specimen prepared at the lower moisture content did, however, exhibit improved deformation resistance compared to the specimen prepared at 100% of OMC, suggesting the performance of the untreated material is likely to change as the moisture content changes.

The specimen treated with 0.7% cement (i.e. achieving a UCS of 0.5 MPa) and compacted at 79% of DoS (i.e. 100% of OMC) also failed rapidly, whereas the same material performed significantly better at a lower DoS value of 65% (i.e. 82% of OMC). This suggests that the performance of the ridge gravel is still likely to change based on changes in the moisture content at relatively low cement contents. However, the specimens treated with the higher cement contents (i.e. 1.3% and 1.5% corresponding to UCS values of 0.9 MPa and 1.1 MPa, respectively) performed significantly better at both the moisture contents tested and passed the 4% permanent strain criteria after 50,000 cycles specified in MRTS05.

Figure 3.3: Permanent strain at different moisture and cement contents – ridge gravel



The RLT test results indicate that the changes in performance of the ridge gravel tested as part of the study is likely to be less sensitive to changes in moisture content if the material is stabilised with sufficient quantities of a cementitious binder to achieve a minimum 7-day UCS of 0.9 MPa in the laboratory.

3.3 Type 2.1 Crushed Rock (Material A) – Test Results and Analysis

The results of the material characterisation testing undertaken on Material A are summarised in Table 3.4.

Table 3.4: Material A properties

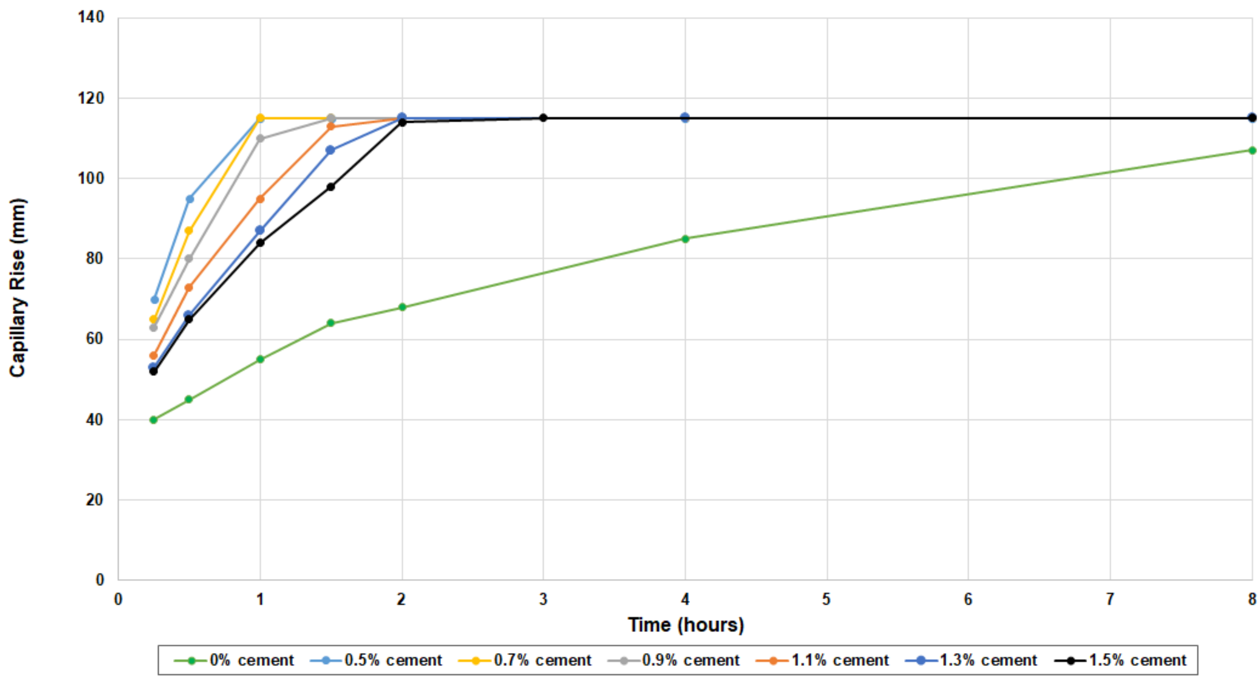
Test parameter	Test method	Result	Specification limit
Fines ratio	Q103A	0.49	0.30–0.55
Liquid limit (%)	Q104A	19.4	25 (max)
Plastic limit (%)	Q105	15.6	Not specified
PI (%)	Q105	3.8	6 (max)
Weighted PI (%)	Q105	58	150 (max)
Linear shrinkage (%)	Q106	1.8	3.5 (max)
Weighted linear shrinkage (%)	Q106	28	85 (max)
Apparent particle density of soil (t/m^3)	Q109	2.72	Not specified

The results in the table above indicate that Material A complied with the requirements for a Type 2.1 material in accordance with MRTS05.

3.3.1 Capillary Rise Testing

The results of the capillary rise testing undertaken on the specimens prepared with Material A are shown in Figure 3.4. The waterfront in the untreated specimen did not reach the full 115 mm specimen height until approximately 9 hours after the start of the test. However, the waterfront in each of the stabilised specimens reached the full specimen height within 2 hours. Similar to the ridge gravel tested, the waterfront in the specimens prepared with the lower cement contents (i.e. 0.5% and 0.7%) reached the full specimen height in less than one hour. The capillary rise time also increased with an increase in cement content.

Figure 3.4: Material A capillary rise at different cement contents



3.3.2 UCS Testing

The UCS testing on the specimens prepared with Material A was undertaken at cement contents ranging between 0.5% and 1.5% (Table 3.5).

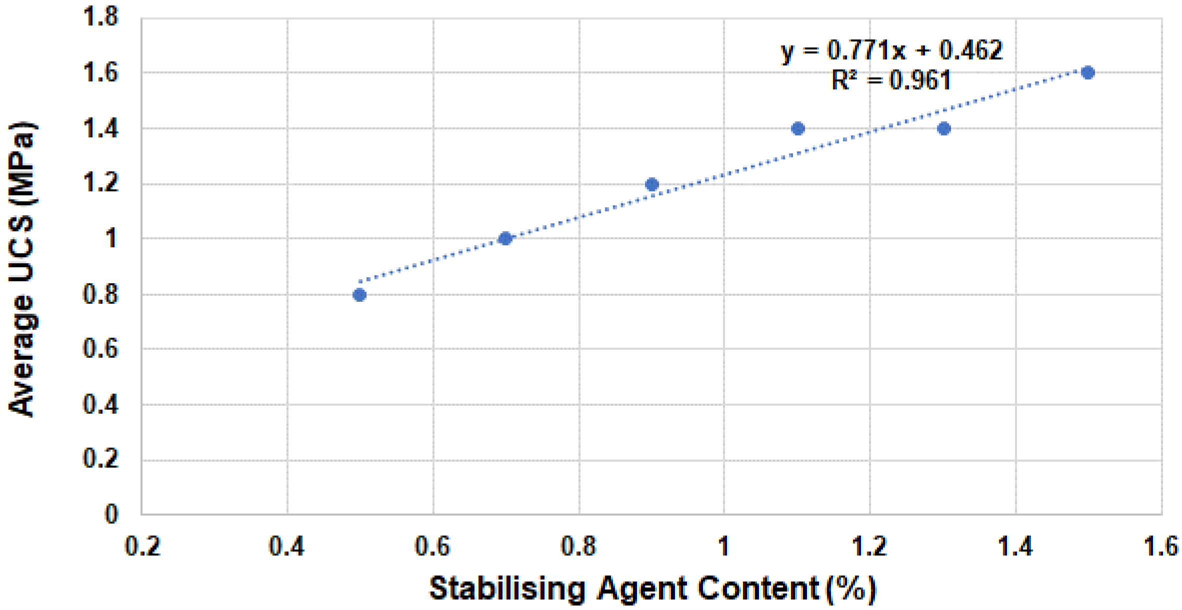
Table 3.5: Summary of Material A UCS test results

Target moisture content (%)	Average moisture content (%)	Target dry density (t/m^3)(1)	Average dry density (t/m^3)(1)	Stabilising agent content (%)	Average UCS (MPa)(2)
8.4	8.4	2.165	2.165	0.5	0.8
8.4	8.8	2.168	2.160	0.7	1.0
8.3	8.2	2.171	2.176	0.9	1.2
8.3	8.1	2.174	2.183	1.1	1.4
8.2	8.6	2.177	2.169	1.3	1.4
8.2	8.2	2.181	2.185	1.5	1.6

1. Dry density based on standard compaction effort.
2. After 7 days curing.

Similar to the ridge gravel, a linear relationship was observed between the UCS values and cement content (Figure 3.5). However, the UCS of Material A appears to be less sensitive to a change in cement content compared to the ridge gravel. A minimum of 0.7% cement was required to achieve a UCS of 1 MPa.

Figure 3.5: Material A UCS values at different cement contents



3.3.3 RLT Testing

Three cement contents (i.e. 0.5%, 0.9% and 1.5%) were selected for the RLT testing to achieve UCS values either side of 1 MPa. An untreated (control) specimen set was also included in the testing program. Each specimen set was prepared and tested at 2 different moisture contents, including:

- at 96% of DoS (8.5% moisture content and 100% of OMC)
- at 65% of DoS (5.8% moisture content and 68% of OMC).

The results of the RLT testing are shown in Figure 3.6.

Figure 3.6: Permanent strain at different moisture and cement contents – Material A

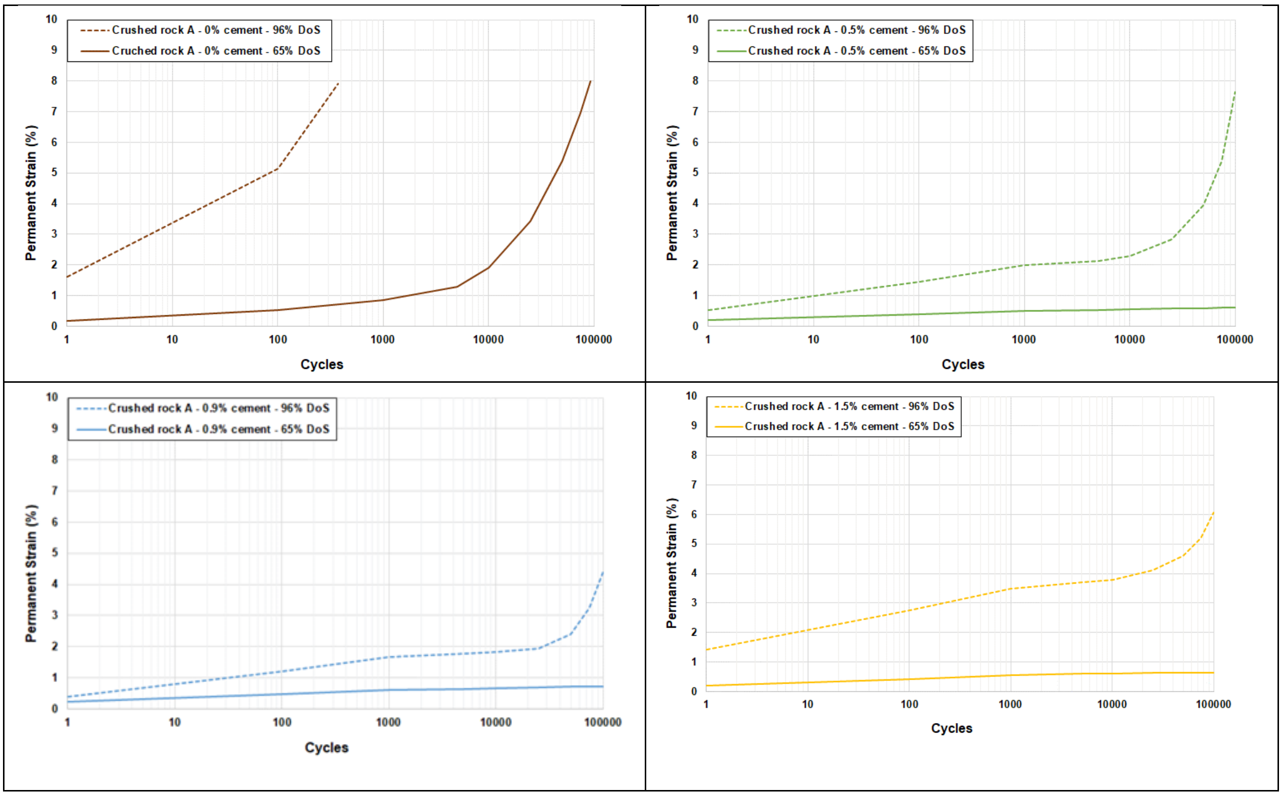


Figure 3.6 shows that the untreated specimens prepared at 96% of DoS (i.e. 100% of OMC) failed rapidly and did not meet the minimum permanent strain criteria specified in MRTS05. However, the untreated specimens performed significantly better at a lower moisture content (i.e. 65% of DoS) and only reached a 4% permanent strain level after approximately 30,000 cycles. The test results therefore indicate that the permanent deformation resistance of Material A (without any cement) is likely to be sensitive to changes in the moisture content.

The addition of small quantities of cement did improve the deformation resistance of Material A; however, the test results indicate that performance of the material may still change with changes in moisture content at the different cement contents assessed. As shown in Figure 3.6, the permanent strain continued to progress rapidly in the cement stabilised specimens prepared at OMC, whereas the permanent strain remained stable throughout the test at the lower moisture content (i.e. 65% of DoS).

Interestingly, the specimen prepared with 1.5% cement and tested at OMC exhibited a higher rate of permanent deformation in the triaxial test compared to the specimens treated with quantities of cement contents. The reason for this behaviour was not further investigated and could potentially be due to a testing error or an anomaly in the results. The implications of undertaking RLT testing on materials with higher cement contents and UCS values are also unclear at this stage.

3.4 Type 2.1 Crushed Rock (Material B) – Test Results and Analysis

The results of the material characterisation testing undertaken on Material B are summarised in Table 3.6.

Table 3.6: Material B properties

Test parameter	Test method	Result	Specification limit
Fines ratio	Q103A	0.47	0.30–0.55
Liquid limit (%)	Q104A	20.0	25 (max)
Plastic limit (%)	Q105	17.8	Not specified
PI (%)	Q105	2.2	6 (max)

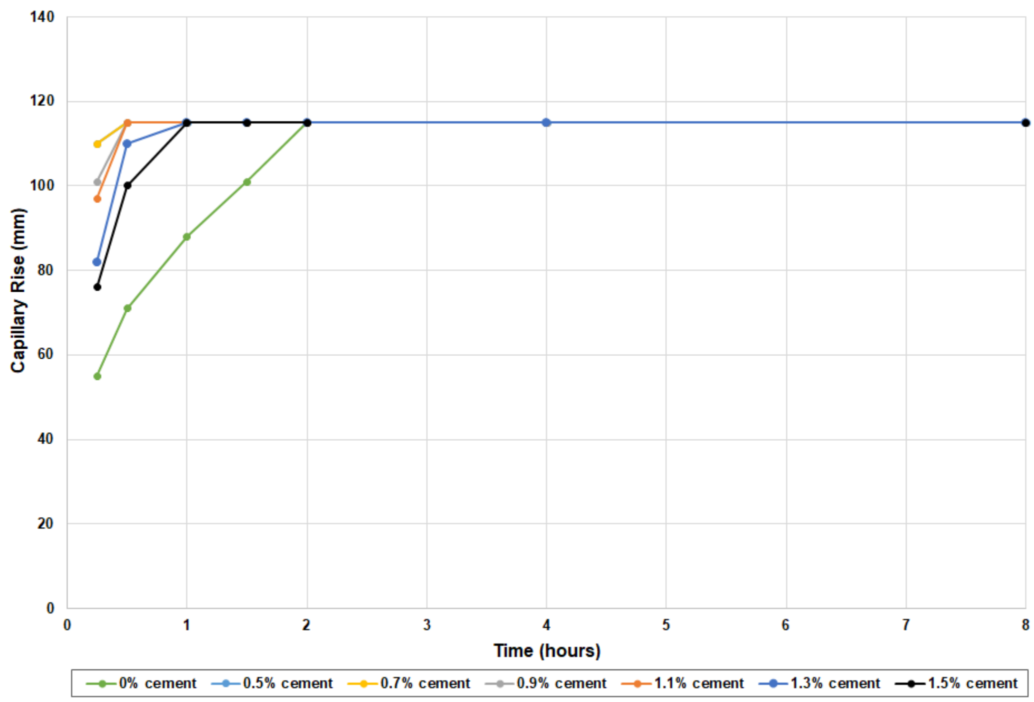
Test parameter	Test method	Result	Specification limit
Weighted PI (%)	Q105	28	150 (max)
Linear shrinkage (%)	Q106	1.8	3.5 (max)
Weighted linear shrinkage (%)	Q106	23	85 (max)
Apparent particle density of soil (t/m^3)	Q109	2.97	Not specified

The results in the table above indicate that Material B complied with the requirements for a Type 2.1 material in MRTS05. The material had a lower PI compared to Material A but had similar fines ratio and linear shrinkage values.

3.4.1 Capillary Rise Testing

The results of the capillary rise testing undertaken on Material B are shown in Figure 3.7.

Figure 3.7: Material B capillary rise at different cement contents



The waterfront in the untreated specimen reached the full 115 mm specimen height after only 2 hours. However, the waterfront in each of the stabilised specimens reached the full specimen within one hour, irrespective of the cement content. Only the specimens with cement contents of 1.3% and 1.5% took longer than 30 minutes for the waterfront to reach the full height of the specimens. Similar to Material A, there is a correlation between the capillary rise time and cement content of the material.

3.4.2 UCS Testing

The UCS testing on the specimens prepared with Material B was undertaken at cement contents ranging between 0.5% and 1.5% (Table 3.7).

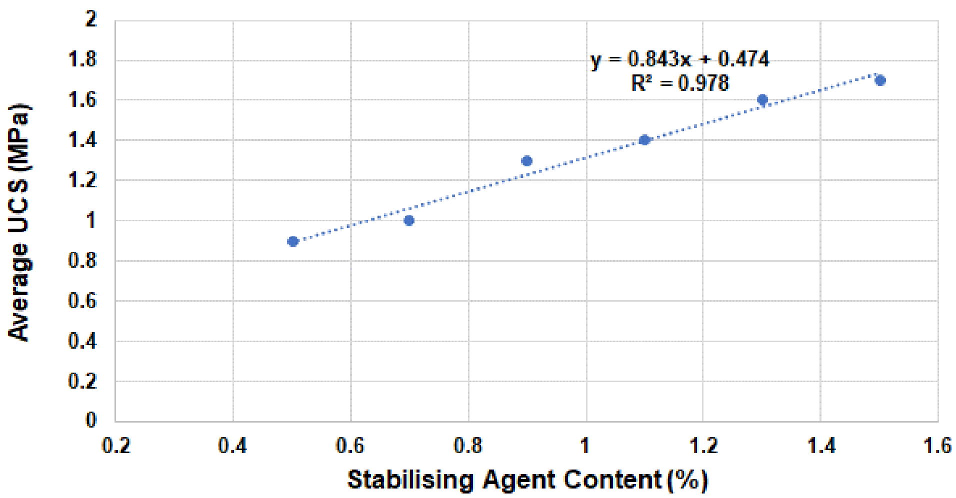
Table 3.7: Summary of Material B UCS test results

Target moisture content (%)	Average moisture content (%)	Target dry density (t/m^3)(1)	Average dry density (t/m^3)(1)	Stabilising agent content (%)	Average UCS (MPa)(2)
8.2	7.9	2.352	2.363	0.5	0.9
8.5	7.7	2.343	2.359	0.7	1.0
8.4	7.9	2.348	2.348	0.9	1.3
8.3	7.8	2.353	2.355	1.1	1.4
8.3	7.8	2.359	2.367	1.3	1.6
8.2	7.9	2.364	2.362	1.5	1.7

1. Dry density based on standard compaction effort.
2. After 7 days curing.

Figure 3.8 shows that Material B exhibited a similar linear UCS-cement content relationship when compared to Material A. A minimum of 0.7% cement was also required to achieve a UCS of 1 MPa.

Figure 3.8: Material B UCS values at different cement contents



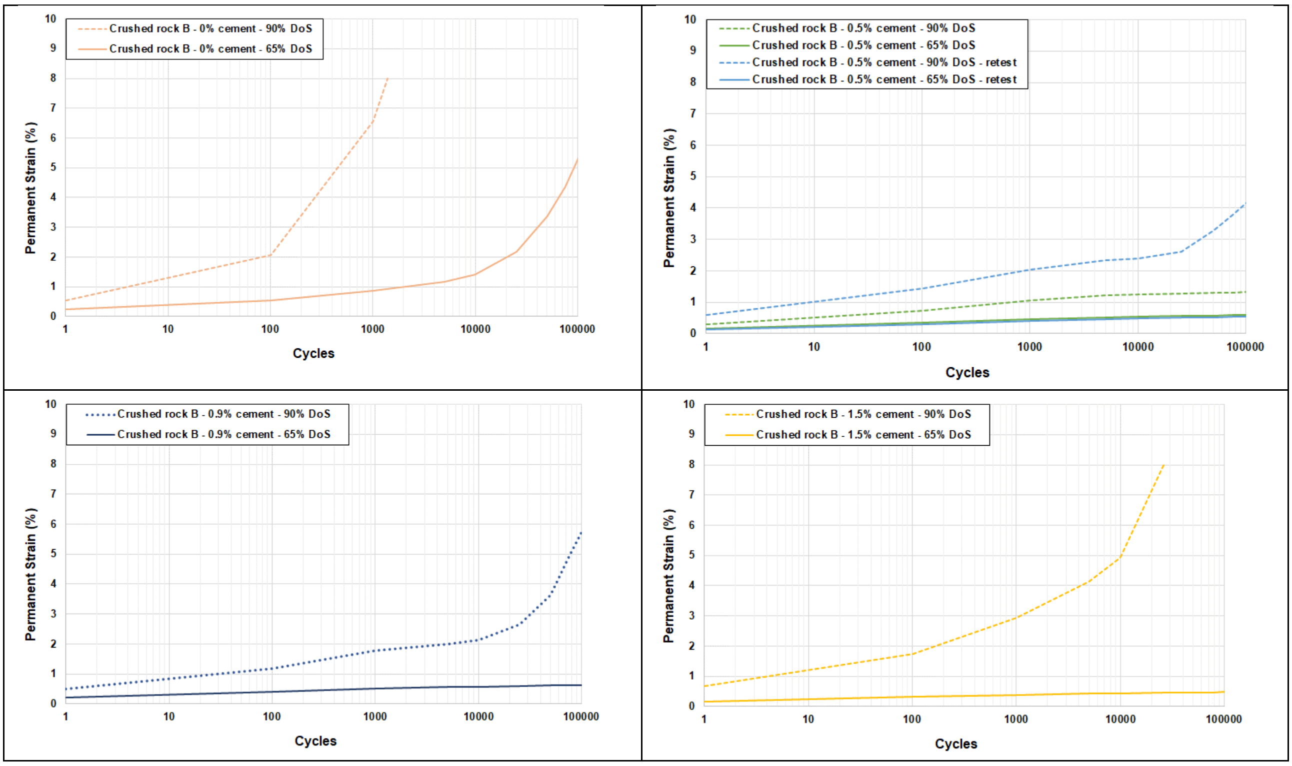
3.4.3 RLT Testing

Three cement contents (i.e. 0.5%, 0.9% and 1.5%) were again selected for the RLT testing to achieve UCS values either side of 1 MPa. An untreated (control) specimen set was also included in the testing program. Each specimen set was prepared and tested at 2 different moisture contents, including:

- at 90% of DoS (7.6% moisture content and 100% of OMC)
- at 65% of DoS (5.5% moisture content and 72% of OMC).

Figure 3.9 shows that the untreated specimens tested at 90% of DoS (i.e. 100% of OMC) failed rapidly and reached a 4% strain level within 300 cycles. However, the untreated specimens prepared at 65% DoS did not reach 4% strain until approximately 60,000 cycles in the RLT test. These results indicate (similar to the ridge gravel and Material A) that the permanent deformation resistance of Material B without any cement is likely to be sensitive to an increase in moisture content.

Figure 3.9: Permanent strain at different moisture and cement contents – Material B



Similar to Material A, the addition of small quantities of cement did improve the deformation resistance of Material B. However, the performance of the material still changed with changes in moisture content at the different cement contents assessed.

The testing undertaken on the specimens prepared with 0.5% cement returned results that did not seem to align with the test results at higher cement contents and the testing at 0.5% cement was therefore repeated. The same moisture sensitive behaviour was observed for the specimens prepared at the different cement contents compared to the untreated specimens. For cement contents correlating to UCS values just either side of 1 MPa, the specimens prepared at OMC exceeded the 1.5% permanent strain level within 1,000 cycles, whereas the specimens prepared at 0.5% and 0.9% cement contents did not reach the 4% permanent strain threshold until after 50,000 cycles. At a 65% DoS level, the corresponding specimens showed a significant improvement in performance (even at the lowest cement content) and completed the 100,000 cycles below 1% strain. The RLT results, therefore, indicate that the addition of cement did improve the permanent deformation resistance at higher moisture contents, but the performance of Material B treated with small quantities of cement may still change with changes in moisture content.

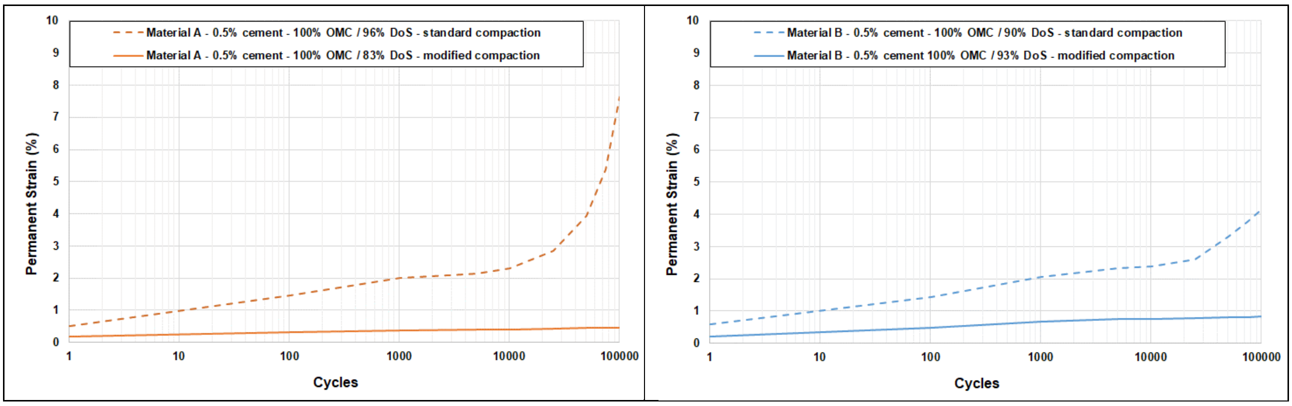
Similar to Material A, the specimen treated with 1.5% cement and tested at OMC exhibited a higher rate of permanent deformation in the triaxial test compared to the specimens treated with lower quantities of cement contents. Again, the reason for this behaviour was not further investigated.

3.5 RLT Testing at Different Levels of Compaction

TMR is considering adopting modified compaction for the density control of pavement layers, with the increase in laboratory compaction energy expected to better reflect current construction practices. Limited RLT testing was undertaken on specimens prepared with the 2 crushed rock materials (i.e. Material A and Material B) at a 0.5% cement content. The cement treated specimens were compacted at 100% of OMC using both 100% modified standard compaction effort.

The RLT results shown in Figure 3.10 indicate that the compaction energy does have an influence on the permanent strain measured in the RLT test for the 2 materials included in the study. Both Material A and Material B (with 0.5% cement added) performed significantly better in the RLT test compared to standard compaction when the specimens were compacted using a higher compaction energy (i.e. modified compaction). It is worth noting that the higher compactive effort is expected to result in a higher density, lower OMC and higher UCS for the same material.

Figure 3.10: Permanent strain at different levels of compaction



3.6 Summary of Findings

The capillary rise test results indicate that the addition of small percentages of cement significantly reduced the amount of time for moisture to penetrate the full height of the specimens, irrespective of the material type. However, as the cement content increased, the time for moisture to penetrate the full height of the specimens did improve slightly, albeit still less than for the unbound granular specimens.

The UCS of the 3 materials tested increased linearly with an increase in cement content consistent with expectations. However, a significantly higher cement content was required to achieve a UCS value of 1 MPa (the lower limit for lightly bound materials) for the lower quality ridge gravel (i.e. 1.4%) compared to the crushed rock materials (i.e. 0.7%).

The RLT testing undertaken indicates that all 3 materials are moisture sensitive without any cement added. Interestingly, the ridge gravel prepared at 65% of DoS had a very high permanent strain value after 1,000 RLT cycles, but the rate of strain accumulation slowed down significantly after 5,000 cycles, resulting in a similar permanent strain of approximately 5.5% after 50,000 cycles when compared to Material A that was composed of crushed rock. Both the crushed rock materials (i.e. Material A and Material B) had similar initial strain values (i.e. approximately 1%) after 1,000 cycles; however, Material B had the lowest strain after 50,000 cycles (i.e. 3.5%) compared to the other materials.

The RLT results also suggest that the behaviour of all 3 materials treated with relatively small quantities of cement may still change with changes in moisture content. The relative deformation resistance of the 3 materials tested at different moisture contents was, however, not consistent. The 2 crushed rock materials performed well at a 65% DoS level irrespective of the cement content. However, the performance of the same materials changed at a higher moisture content and DoS level even when the 7-day UCS exceeded 1 MPa. Conversely, the ridge gravel failed rapidly at a high moisture content without any cement or at very low cement contents. However, the performance of the same material improved significantly when treated with enough cement to achieve a UCS value of greater than 1 MPa.

The limited comparative RLT testing undertaken on the 2 crushed rock samples (treated with 0.5% cement and prepared at 100% of OMC) using both modified and standard compaction indicated that the permanent deformation resistance of the materials increased significantly (particularly during the first 1,000 cycles) when the specimens were compacted using a higher compaction energy (i.e. modified compaction). However, additional testing of different materials treated with varying quantities of cement would be required to confirm the effect of increasing the compaction energy for modified or lightly bound materials.

4 Conclusions and Recommendations

4.1 Conclusions

There have been instances on TMR projects where granular materials were treated with small quantities of a cementitious binder without an accompanying mix design to marginally improve the material's properties and to avoid the DoS requirements prior to sealing the road. It is believed that in some cases these practices may have resulted in premature moisture-related pavement failures. Considering the concerns raised by TMR staff, this study investigated the moisture sensitivity of granular materials treated with small percentages of a cementitious binder (i.e. modified materials).

TMR has detailed mix design and construction requirements for lightly bound materials; however, the Department currently does not have any specification requirements for modified materials. The literature review found that in other jurisdictions, modified materials are constructed similar to unbound granular materials, including requirements for controlling the moisture content of the material prior to sealing the pavement.

A series of laboratory tests composed of material characterisation, capillary rise, UCS and RLT testing was undertaken to assess the moisture sensitivity of 3 different granular materials treated with varying quantities of cement. The materials included a ridge gravel meeting the requirements for a Type 2.3 material and two Type 2.1 crushed rocks obtained from different sources.

The capillary rise test results indicated that the addition of small quantities of cement significantly reduced the amount of time required for moisture to penetrate the full height of the specimens, irrespective of the material type. The testing also found that the ridge gravel required double the amount of cement compared to the crushed rock materials in order to achieve a 7-day UCS of 1 MPa in the laboratory.

The RLT testing showed that the performance of all 3 materials treated with relatively small quantities of cement may still change with changes in moisture content. The relative deformation resistance of the 3 materials tested at different moisture contents was, however, not consistent. The 2 crushed rock materials performed well at a 65% DoS level irrespective of the cement content. However, the performance of these materials still changed at a higher moisture content and DoS level even when the 7-day UCS exceeded 1 MPa. Conversely, the moisture sensitivity of the ridge gravel reduced significantly when treated with enough cement to achieve a UCS value of greater than 1 MPa.

The limited comparative RLT testing undertaken on the 2 crushed rock samples (treated with 0.5% cement and prepared at 100% of OMC) using both modified and standard compaction indicated that the permanent deformation resistance of the materials increased significantly (particularly during the first 1,000 cycles) when the specimens were compacted using a higher compaction energy (i.e. modified compaction).

4.2 Recommendations

Based on the findings from this study, it is recommended that the moisture content (i.e. DoS) of granular materials modified with small quantities of cementitious binders be controlled during construction, similar to the requirements for unbound pavement layers in MRTS05. It is also recommended that where the DoS requirements are proposed to be relaxed during construction due to the addition of small quantities of cement to modify the properties of the granular material, additional laboratory testing be undertaken to assess the moisture sensitivity of the modified material.

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TMR Test Methods

Q102A *Standard moisture content of soil – oven drying.*

Q103A *Particle size distribution of soil – wet sieving.*

Q104A *Liquid limit of soil.*

Q105 *Plastic limit and plasticity index of soil.*

Q106 *Linear shrinkage of soil.*

Q109 *Apparent particle density of soil.*

Q115 *Unconfined compressive strength of stabilised materials.*

Q125D *Capillary rise of stabilised materials.*

Q137 *Permanent deformation and resilient modulus of granular unbound material.*

Q142A *Dry density-moisture relationship of soils and crushed rock – standard.*

Q146 *Degree of saturation of soils and crushed rock.*