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FINAL REPORT

P4_Structural Performance of Unbound Granular Material - Modified 'C' Grading

Project No: 007181

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Client: Queensland Department of Transport and Mains Roads

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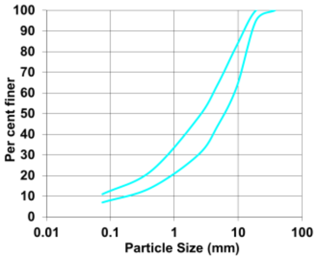
AN INITIATIVE BY:

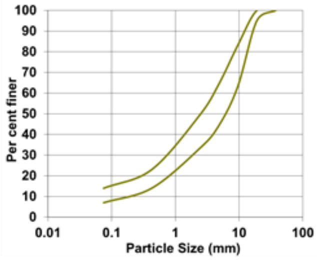
SUMMARY

The Main Roads Technical Specification Part 5 (MRTS05) provides a technical standard which applies to the construction of unbound granular pavements, where it may be used as part of the construction of unbound pavements or as the base and/or sub-base for sprayed seal or asphaltic pavements. Section 7.2.4 of MRTS05 outlines the particle size distribution envelopes that can be specified under construction contract requirements for a given project and location.

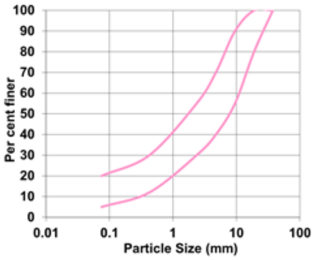
For Type 2 and 3 unbound materials, depending on the project requirements, the grading may be specified as Grading B, C, D or E, with the C grading typically being specified for a high proportion of state roads in regional areas. When compared to equivalent specifications in Victoria and New South Wales, the Queensland grading allows a much wider grading range.



Victoria



New South Wales



Queensland

A modified version of the C grading envelope, as specified in MRTS05, has been introduced after several regions had experienced construction and performance issues with ‘boney’ crushed rock granular pavements.

The modified C grading effectively removes the lower one-third of the existing C grading envelope on the coarse end. The increase in fine material in the modified grading is intended to reduce water infiltration, improve workability on site, and lead to a better surface finish as well as coinciding with improved plasticity values. Anecdotal evidence from regions using the modified grading curve had suggested that some benefits have been realised; however, no control sections had been analysed and the overall effect had not been previously quantified.

This project involved a number of tasks aimed at investigating the overall impact of introducing a modified C grading, either in place of, or alongside an existing C grading, or as an option to specify for use in certain jobs and regions. These tasks included:

- investigating the background to grading envelopes and benchmarking the TMR C grading to other national and international specifications
- site inspections in the Darling Downs, South West and Central West regions which anecdotally showed improved performance of pavements constructed with modified C granular material
- a comprehensive laboratory testing program of three theoretical gradings on the limits of the specification as well as two quarry-sourced modified C samples. This testing provided evidence of:
  - greater impermeability of modified C pavements compared to a coarser C grading

— some improvement to strength characteristics through repeated load triaxial (RLT) and California bearing ratio (CBR) testing.

The final recommended grading requires more fine material to pass the smaller sieve sizes (with at least 8% passing the 75 µm sieve), as well as tightening the allowable percentages passing at the fine limit.

The shift to a modified C grading appears to reduce the likelihood of water infiltration, as well as provide improved workability, constructability and surface finish. The suggested changes to MRTS05 have now been implemented, which means that a modified C grading can now be specified for TMR granular pavement works.

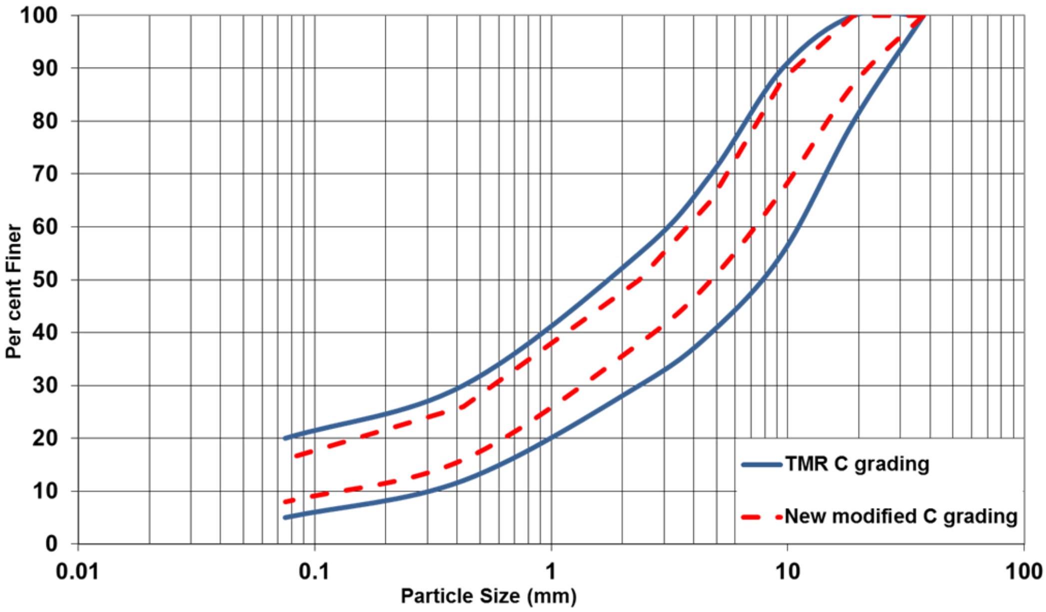
The changes are likely to have the effect of moving typical Queensland material gradings closer to the majority of comparable Type 2 material gradings used across other Australian states.

The new modified C grading is outlined below.

Table S.1: New modified C grading

Size (mm)	Standard 'C'		Modified C specification	
37.5	100	100	100	100
19	80	100	87	100
9.5	55	90	67	88
4.75	40	70	50	65
2.36	30	55	38	50
0.425	12	30	16	26
0.075	5	20	8	16

Figure S.1: New modified C grading



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1 INTRODUCTION

In order to improve the performance of TMR’s Type 2 and Type 3 crushed rock unbound granular pavements, some regions (including Darling Downs, Central Highlands and South West) have adopted a modified C grading in place of the traditional C grading, as specified in the Main Roads Technical Specification Part 05 (MRTS05) for particle size distribution. All other specification limits remain the same, including fines ratio limits. Anecdotal evidence from the field performance of crushed rock unbound granular pavements – where the modified C grading particle size distribution has been used instead of the traditional C grading specified by MRTS05 – has indicated satisfactory performance and resistance to water infiltration. However, no control test is currently available and variability in performance is an ongoing issue.

This project seeks to evaluate the intrinsic properties and structural integrity of the extremities of the C grading to define the magnitude of difference, with a view to adopting the modified C grading (in place of, or in addition to, the current C grading) in MRTS05.

To do this, the first task is to research the background associated with grading curves for granular materials and the properties that have an effect on performance and constructability, as well as summarise the history of the modified C grading in Queensland.

An evaluation program was devised to determine material properties, best practice, current usage and performance of modified C material in Queensland. This included a set of site inspections across three regions who have known modified C material usage over the previous two decades. In the first year of the project, a site inspection was undertaken in the Darling Downs region. A second regional trip was undertaken in the second year of the project, covering a number of known modified C locations across the South West and Central West regions.

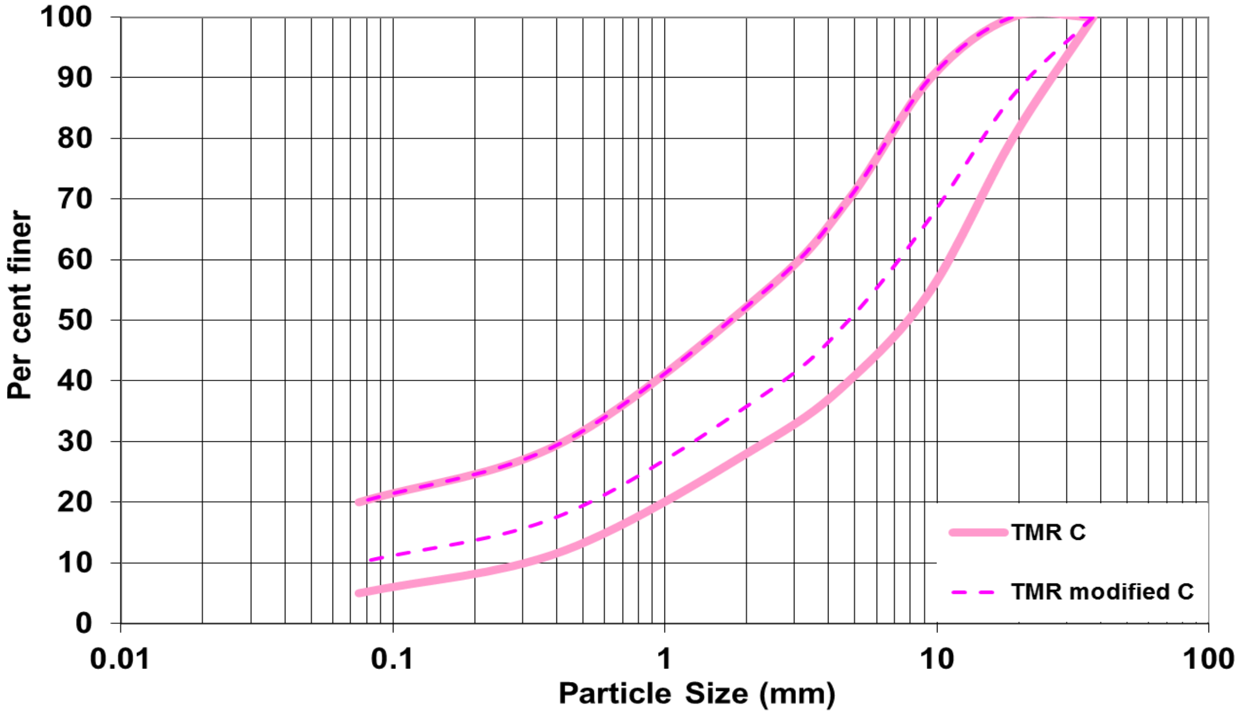
A comprehensive laboratory testing program was undertaken, with analysis of a number of theoretical gradings as well as sampled quarry material from two modified C quarry sources.

This report presents the findings from the project and provides recommendations for a new modified C grading in MRTS05. It should be noted that this recommended grading differs from the modified C grading that has been forwarded to regions in the past, most notably in the fact that the requirement at the 75 µm sieve is recommended to be set at 8% rather than 10%. In this report, some of the graphs will still refer to a 10% limit, as this was in place at the commencement of this project.

2 THE MODIFIED C GRADING

The modified C grading lies within the standard C grading of MRTS05 for Type 2 materials but is confined to the fine side of the envelope. With a higher fines content, it is considered that permeability is reduced and surface texture of a compacted basecourse is not as coarse (i.e. ‘boney’). The envelope is shown in Figure 2.1.

Figure 2.1: Modified C grading and MRTS05 C grading (as of 2013)



A comparison of the TMR C grading with the Class 2 equivalent grading used by other agencies indicates that the traditional C and modified C have allowance for a greater percentage of fine material (passing the 75 µm sieve). In general, most agencies specify 75 µm and finer material to between 5% and 15% passing, as shown in Figure 2.2.

When zoomed in to particle sizes less than 1 mm, we see that the minimum requirements of the current C grading at the 75 µm sieve are among the lowest of all the Australian grading limits; while the maximum allowed levels of fines are far and away the highest in Australia. The move to a modified C grading moves the minimum requirement to well above the minimum requirements in other states, and even exceeds the maximum specification for granular material in VicRoads Section 812 (with Los Angeles Abrasion values of 26 or greater) (VicRoads 2011).

Figure 2.2: TMR C grading comparisons with other agencies

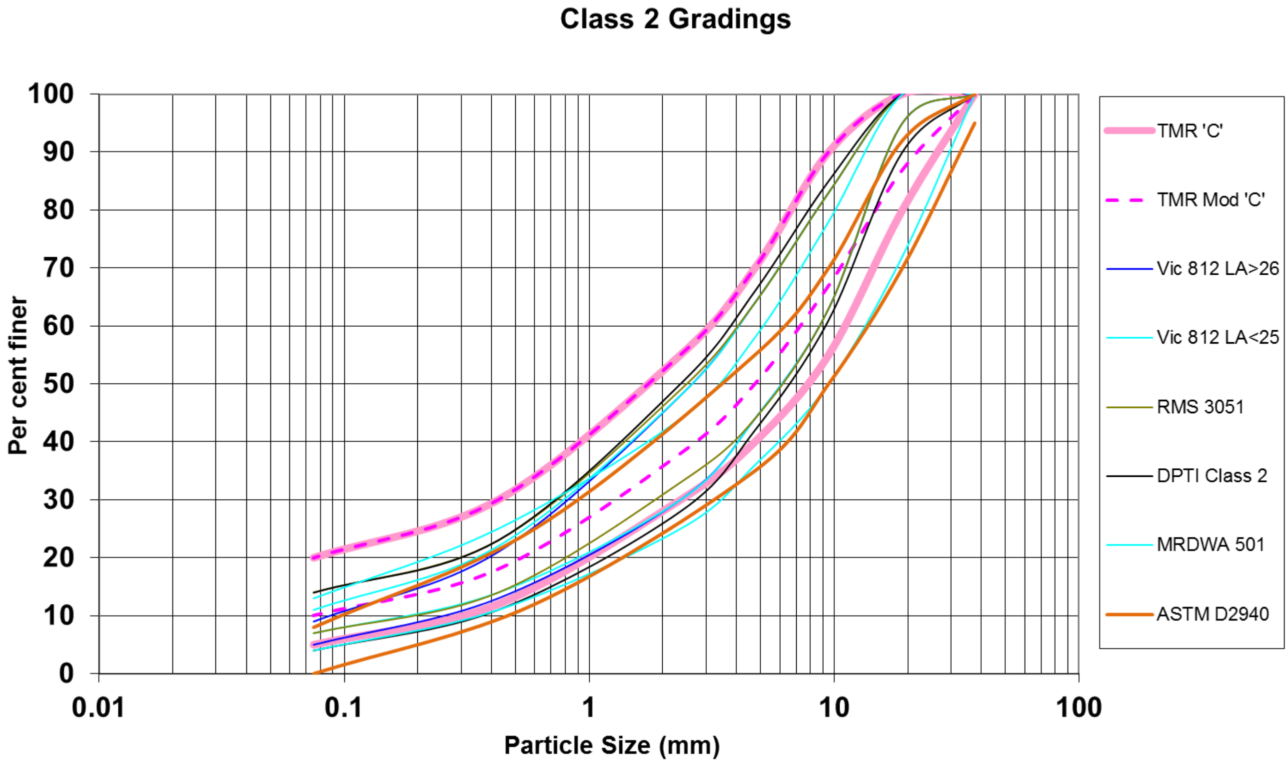
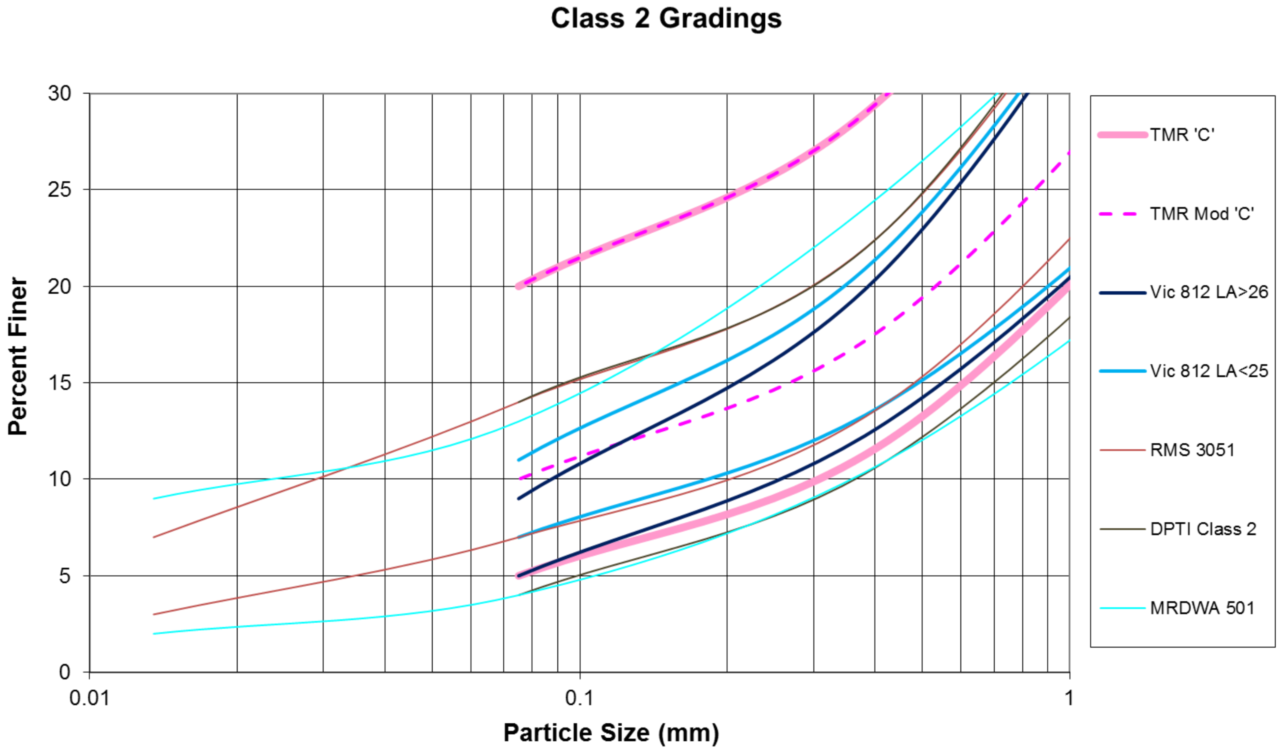


Figure 2.3: TMR C grading comparisons - zoomed in to < 1 mm



An evaluation of the ‘Fuller-Thompson’ (*n*) index had been undertaken by TMR with respect to the maximum density grading relationship: A widely used equation to describe the maximum density gradation developed by Fuller and Thompson (1907) is:

$$\mathrm{P} = \left(\frac{\mathrm{d}}{\mathrm{D}}\right)^{n}$$

where

P = % finer than the sieve

d = aggregate size being considered

D = maximum aggregate size to be used

n = parameter which adjusts curve for fineness or coarseness (for maximum particle density $n \approx 0.5$ according to Fuller and Thompson).

A brief analysis of the ‘*n*’ values under the various C gradings can be found in Section 3.

3 BACKGROUND TO UNBOUND GRANULAR MATERIALS

The properties of crushed rock pavement material that lead to high load bearing strength are based upon the nature of the source rock in terms of hardness, the shape of aggregate produced by crushing, and the amount of fines and associated plasticity generated.

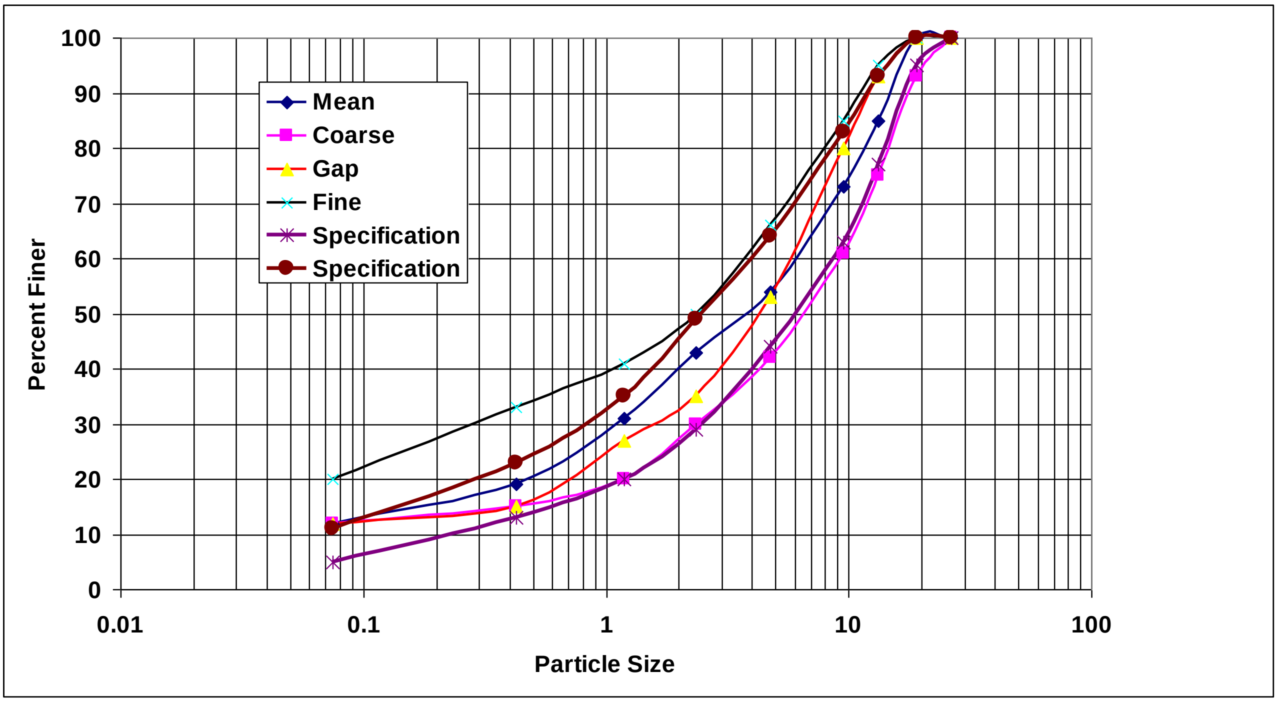
In the context of reviewing the implications of adopting the modified C grading, the basic change is that of introducing a grading envelope with finer overall manufacturing limits. However, the envelope also inherits a consequential higher proportion of fines (i.e. passing the 0.425 mm sieve), which potentially reduces the shear strength due to a loss of particle interlock of aggregate fractions and increased loss of strength due to moisture sensitivity of the fines. The current requirements for aggregate quality in terms of stone hardness, shape and plasticity of fines remain unchanged.

All unbound granular material grading specifications are based upon the Fuller-Thompson maximum density principle as described in Section Section 2. Therefore, the shape of the grading envelope fine and coarse limits reflect an ‘*n*’ value of around 0.45 through the particle sizes.

A study adopting repeated load triaxial testing (Andrews 1999) to determine the relationship between resilient modulus and the rate of permanent deformation development associated with varying particle size distributions is shown in Figure 3.1 .

The research concluded that the very fine grading is relatively insensitive to resilient modulus, in contrast to permanent deformation development (rutting potential) which is at its highest. However, it is not suggested that the changes to MRTS05 would lead to gradings similar to the ‘fine’ grading outlined here. It will be important during the laboratory testing phase to ensure that a move towards a finer grading does not compromise strength and create a risk of high pavement deformation.

Figure 3.1: Fine, coarse, gap and mean gradings for repeated load triaxial testing study



4 INDUSTRY FEEDBACK

In considering a change to the manufacturing requirements of grading C material, it is necessary to gauge commercial industry capacity with regards to the new requirements. A memo has been prepared for TMR to send to all regions, for them to further circulate to all commercial crushed rock suppliers in the regions, as follows (note that the limits and graph suggested here differ somewhat from the eventual recommendations).

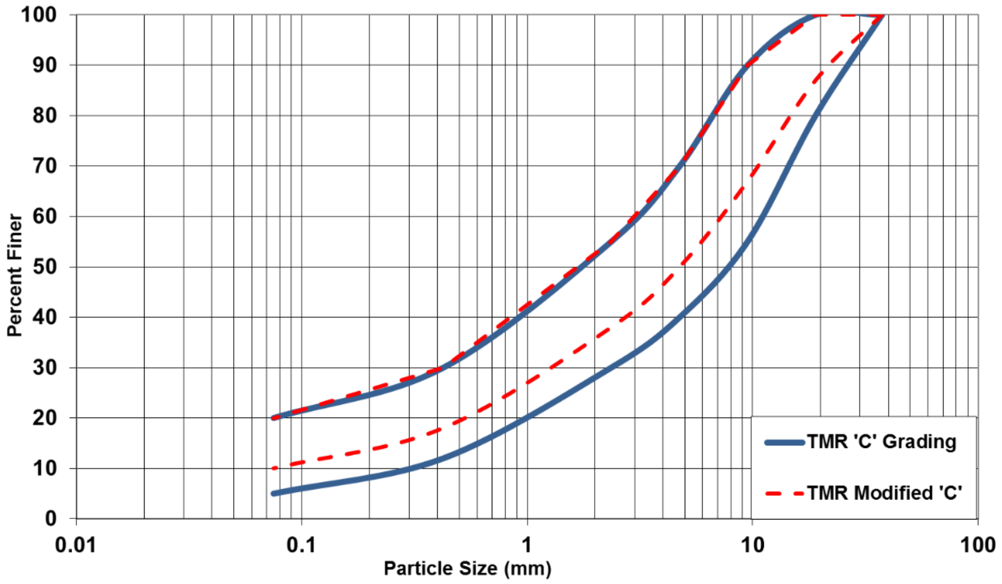
4.1 Memo Sent to TMR Regions

Modified Grading C

Transport and Main Roads are investigating the technical and commercial implications of modifying the current C grading in Specification MRTS05.1. The background to this investigation is to produce a finer grading (remaining within the current C grading) to enhance the finished surface texture of the compacted basecourse surface as well as provide a decrease in pavement permeability.

The proposed grading limits are detailed below:

Size (mm)	Modified C		Standard C	
75	100	100	100	100
53	100	100	100	100
37.5	100	100	100	100
19	87	100	80	100
9.5	67	90	55	90
4.75	50	70	40	70
2.36	38	55	30	55
0.425	18	30	12	30
0.075	10	20	5	20



Concurrent with the technical analysis, the commercial impact on suppliers needs to be determined. Therefore, it is requested that each TMR region obtain feedback from local suppliers in terms of:

(a) ability of current processes to meet the finer grading limits
(b) identifying any need to change process; e.g. adding crusher dust or fines
(c) any cost implications associated with meeting the specification.

4.2 Previous Experience with Modifications to the C Grading

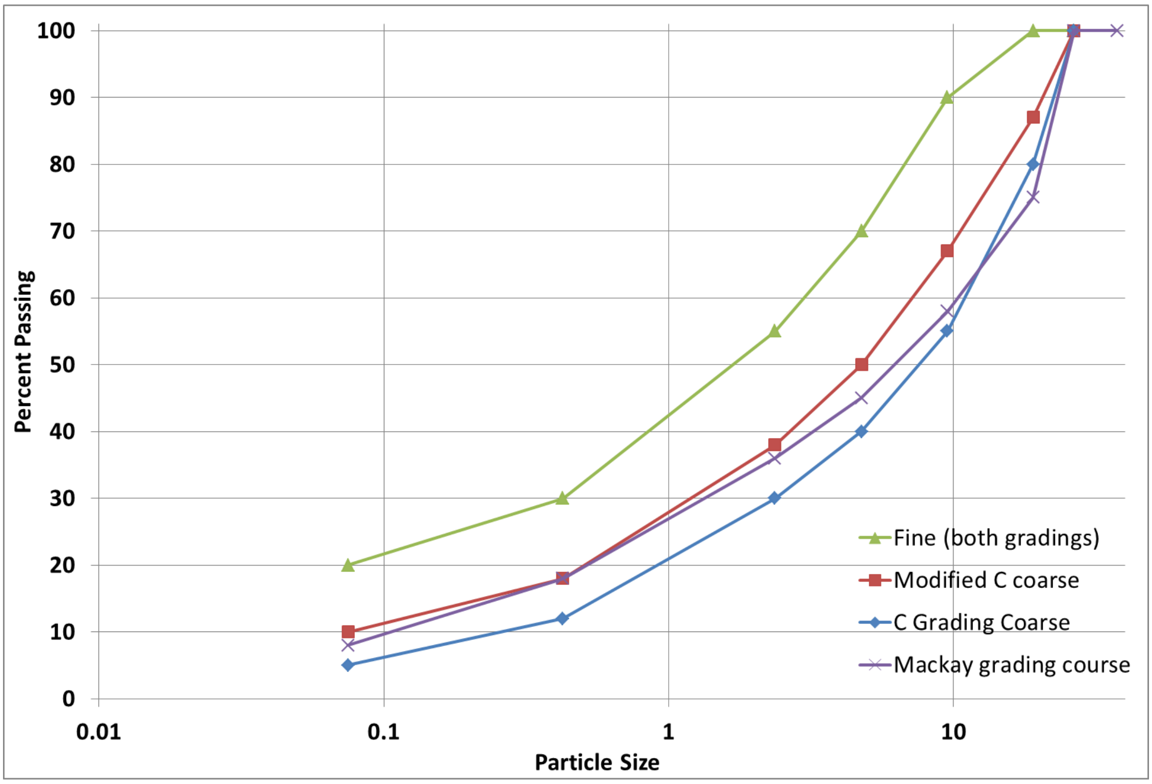
A number of different versions of a modified C grading have been used in the various regions across Queensland over the last two decades.

The common theme among these gradings is that the grading is shifted on the coarse end of the C grading, with the effect of ensuring that gradings contain a certain minimum amount passing the smaller sieve sizes.

A request was sent out in July 2002 by the Central Highlands TMR regional office asking for opinions on the new modified C grading that was being used on a number of projects at the time. Michael O'Sullivan of the Central Highlands district shared his experiences with the modified C grading and the so-called Mackay grading (O'Sullivan 2002). The modified C grading used in 2002 was the same as being proposed currently, although it explicitly mentioned that it had removed the requirement for gradings to not vary from one outer-third to the other outer-third.

The coarse limit of the Mackay grading is similar to the modified C for smaller particle sizes, but closer to the traditional C grading for larger aggregate sizes (Figure 4.1).

Figure 4.1: Three gradings described in letter from Central Highlands district (O'Sullivan 2002)



Of interest in the document was that:

- the standard C grading works well with naturally occurring gravels and crushed rock, with binder used to fill up the bottom end of the grading
- changes to environmental regulations led to quarries using little or no binder and more large stone, leading to a mix closer to the coarse end of the grading
- this change then led to construction problems (material not sealing, unravelling, difficulty priming, and segregation)
- experience with the C grading is that the lower limits of the grading result in a product only just meeting the minimum requirements, with no room for error in grading processes.

Moving to the modified C grading, with the bottom third of the C grading removed meant that:

- it was difficult for operators to produce greater than 10% passing the 75 µm sieve and greater than 67% passing the 9.5 mm sieve.
- this required more work for crushing plants and ultimately higher production costs
- it lead to material with low permeability, cheaper compaction, easier construction and better surface finish
- conversely, due to the higher density, more tonnage of material would be required, there were delays in achieving the required degree of saturation, and the CBR values tended to be somewhat lower.

O’Sullivan (2002) comments that a requirement of 8% passing the 75 µm sieve would be sufficient, but that anything less than this could lead to construction problems.

The Mackay grading is notable for allowing more material to be retained on the 9.5 mm sieve, but still requires at least 8% to pass the 75 µm sieve. This results in a gap graded product with large percentages in the fine and coarse fractions. It was noted that the understanding is that a material on the lower limits of the Mackay grading would not be expected to perform to as high a standard as the modified C grading.

O’Sullivan concludes that for standard road projects in his region, the most suitable grading is one similar to the modified C, with the exception of the final sieve allowing as low as 8% passing.

The document is provided in full in Commentary 1.

5 EVALUATION PROGRAM

In evaluating limiting the C grading to the fine side of the current C grading, it must be recognised that this alone will make little difference to the structural integrity of the material as it is controlled by other parameters which remain unchanged, such as the plasticity, stone hardness and durability, in addition to a minimum CBR. However, it is still required to quantify the structural integrity of the modified C material against the broader C grading. This has been achieved through a series of laboratory tests (Section Table 5.1).

A number of sites are known to have been constructed using modified C material, at least in part. Several of these sites in the Darling Downs region were inspected as a part of this project (Section C.1). Materials from this region have been used in the initial laboratory study. Materials from the South West region were used in subsequent testing during this project to confirm the findings.

5.1 Laboratory Evaluation

It was estimated that 100 kg of material would be required to complete the laboratory evaluation. This figure was increased as the material was found to be lacking in certain fractions, specifically on the very coarse (19 mm) and very fine (75 µm) ends of the grading.

The following tests were performed on the raw material:

Table 5.1: Proposed preliminary tests

Test Method	Test
Q205B	10% fines
Q205C	Wet/dry strength variation
Q208B	Degradation factor
Q201	Flakiness index

This material was split into the following fractions:

- retained on 9.5 mm sieve
- retained on 2.36 mm sieve
- retained on 0.425 mm sieve
- passing 0.425 mm sieve.

These fractions were then used to recombine the material into the three limits of the C grading and modified C grading. When manufacturing the three samples, the gradings should align as closely as possible with the coarse limits of the traditional and modified C gradings, and the fine limit (same for both gradings).

Table 5.2 specifies these target gradings with maximum and minimum values.

Table 5.2: Test sample gradings to be manufactured

Percentage passing sieve size (mm)	Sample 1		Sample 2			Sample 3	
	C grading coarse		Modified C coarse			Fine limit	
	Target (min)	Max	Min	Target	Max	Min	Target (max)
75	100	100	100	100	100	100	100
53	100	100	100	100	100	100	100
37.5	100	100	100	100	100	100	100
19	80	82	86	87	88	100	100
9.5	55	57	66	67	68	88	90
4.75	40	42	49	50	51	68	70
2.36	30	32	37	38	39	53	55
0.425	12	14	17	18	19	28	30
0.075	5	7	9	10	11	18	20

After recombining the samples as specified, the following tests were undertaken (Table 5.3):

Table 5.3: Recommended tests for laboratory evaluation

Test Method	Test	Conditions
Q103A	Particle size distribution	
Q104A/5/6	Atterberg limits tests	
Q113A	California bearing ratio (CBR)	Soaked
Q142A	Moisture density relationship (MDR)	
AS1289.6.7.1	Permeability	Maximum dry density (100% compaction)
Q109	Apparent Particle Density (APD)	
Q137	Repeated load triaxial (RLT)	At 60% and 70% degree of saturation

Full results of the laboratory evaluation are contained in Section 6.1.

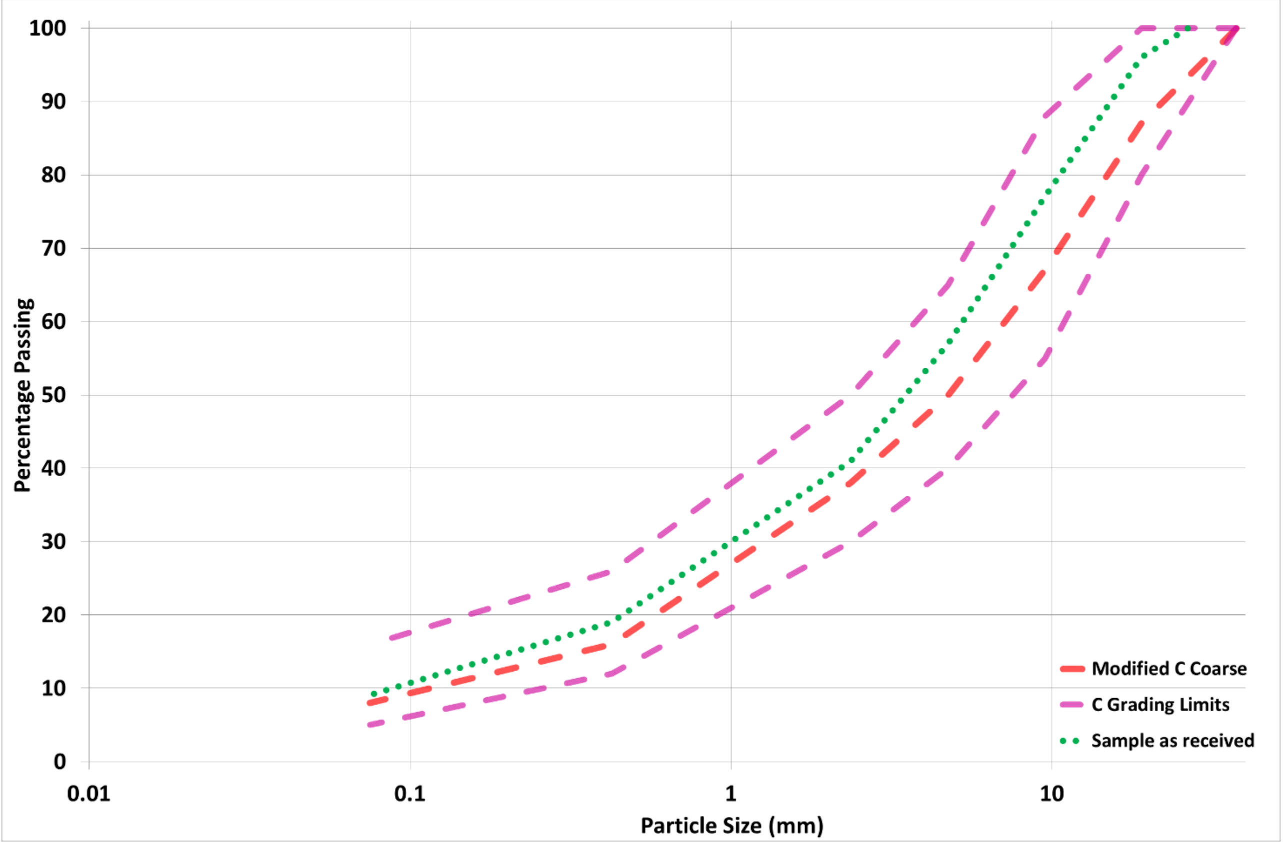
6 RESULTS

6.1 Laboratory Testing Results

The laboratory testing program as outlined in Section 5.1 took place between February and June 2014. There was a delay of several weeks due to a lack of material passing the 75 µm sieve. This fine material was subsequently sourced from other quarries in the area; however, the same mix of fines material was used across all samples. All testing took place in the TMR laboratories at Herston. A full summary table of the results is provided in Appendix A, with the original test reports also available separately.

The total sample was initially tested 'as received' from a quarry in the Darling Downs region. The material from this quarry is a basic igneous basalt. The grading sits towards the finer end of the C grading curve for larger aggregate sizes, but contains a large proportion of material in between 0.425 mm and 4.75 mm in size (Figure 6.1). This results in a relatively low percentage of 9.6% passing the 75 µm sieve. This would not pass the requirements under the previous modified C grading specification at the 75 µm sieve, although it would pass when considering a proposed 8% minimum at the 75 µm sieve. Extra material was delivered in August to enable further testing on the material 'as received'.

Figure 6.1: Total sample grading compared to C grading specification limits



The sample 'as received' was tested to determine the flakiness index (Q201) and degradation factor (Q208A/B) of the material (Table 6.1). These parameters comply with the specified limits as stated in MRTS05 for Type 2.1 materials.

Table 6.1: Testing on material ‘as received’

	Specification Limit (Type 2.1)	Result – Total sample
Flakiness Index	35 max	23
Degradation Factor (coarse aggregate)	40-50 min	60

The three samples were then broken down into several component gradings and recombined into three target gradings representing the coarse end of each grading, as well as the fine end of the envelope. The gradings produced were very close to the target numbers (Table 6.2 and Figure 6.2). This will enable testing to take place at the extreme ends of the C grading envelopes, replicating materials that should only narrowly pass the specification requirements.

It is important to note that these three target gradings are very much theoretical and do not represent grading curves likely to be manufactured in practice. These curves were selected to explore the properties of blends designed at the extremes of the grading, to ascertain parts of the specification which have variable results under the various extremes of the grading envelope.

Figure 6.2: Three recombined gradings compared to target gradings

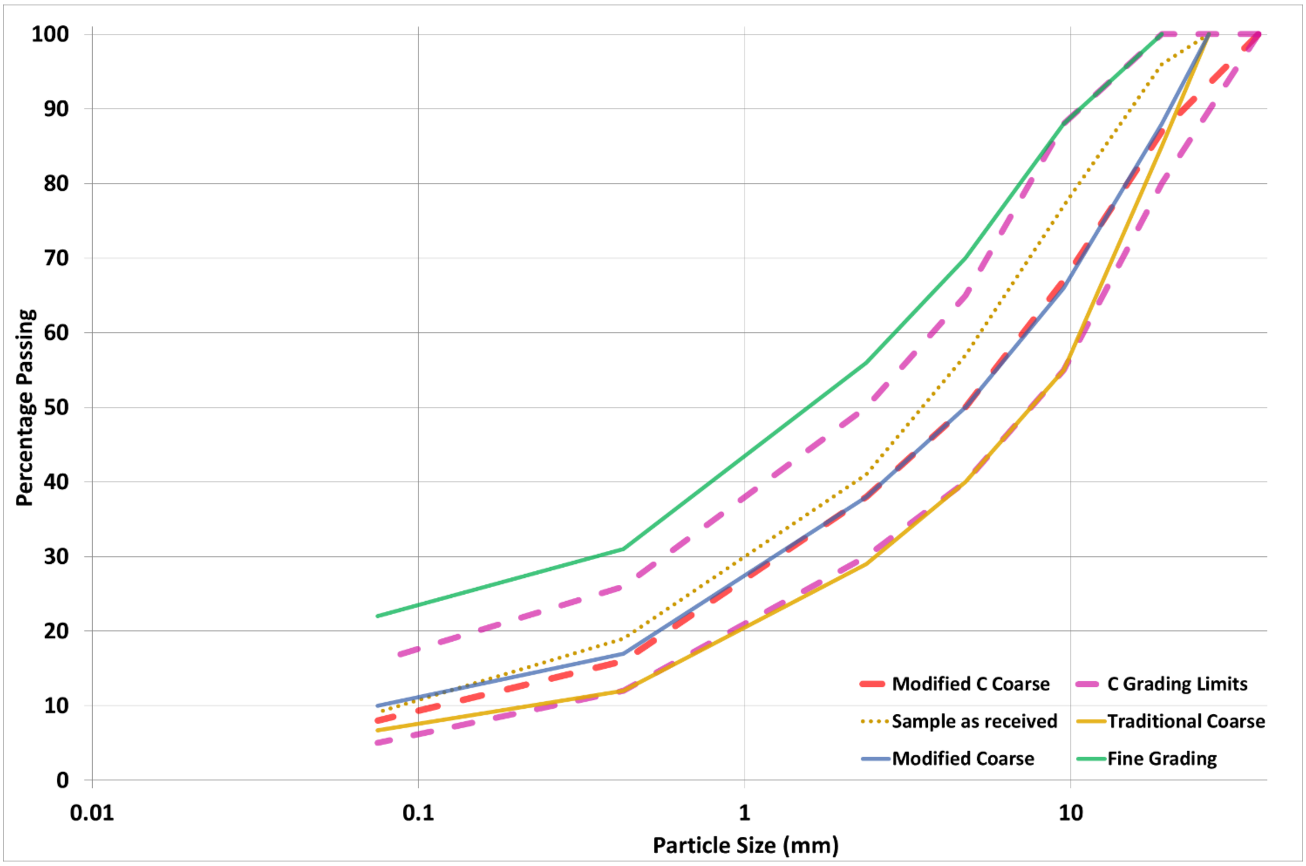


Table 6.2: Recombined gradings

Percentage passing sieve size (mm)	Total sample (second batch)	Sample 1		Sample 2		Sample 3	
		C grading coarse		Modified C coarse		Fine limit	
	Actual	Target	Actual	Target	Actual	Target	Actual
75	-	100	-	100	-	100	-
53	-	100	-	100	-	100	-
37.5	100	100	100	100	100	100	-
19	96	80	85	87	88	100	100
9.5	77	55	55	67	66	90	88
4.75	57	40	40	50	50	70	70
2.36	41	30	29	38	38	55	56
0.425	19	12	12	18	17	30	31
0.075	9.1	5	6.7	10	10	20	22

The three gradings were then subjected to Atterberg limits tests (Table 6.3), cutting the C grading envelope by around one-third on the coarse end results in a material with increased plasticity and increased linear shrinkage (LS). The increased linear shrinkage of 3.2% is on the high end of the allowable scale, while the traditional C grading (2.2%) and the total sample (2.0%) had values well below the MRTS maximum. Additionally, the linear shrinkage and weighted linear shrinkage measurements for the fine grading exceeded the specification limits. All sampled materials conformed to MRTS05 plasticity index (PI) requirements (PI < 6) for TMR Type 2.1 materials.

Both the fine grading and the modified C coarse grading had proportionally too much of the fine portion (material passing the 0.425 sieve) passing the 75 µm sieve.

Table 6.3: Atterberg limits test results

	Specification (Type 2.1)	Total Sample		Traditional Coarse	Modified Coarse	Fine
		21/2/2014	27/8/2014			
Liquid Limit (%)	25 max	20.8	22.0	20.4	22.4	23.2
Plasticity Index (%)	6 max	2.6	2.2	2.4	3.6	3.6
Linear Shrinkage (%)	3.5 max	2.0	2.4	2.2	3.2	3.6
Weighted PI	150 max	49	41	29	60	112
Weighted LS	85 max	38	45	27	54	112
Ratio 0.075 to 0.425	0.30 - 0.55	0.51	0.48	0.55	0.62	0.72

Figures outside of specification limits are highlighted.

The three gradings were tested for their apparent particle density and moisture density relationships (Table 6.4). There is no significant difference between the density values for the two coarse gradings, and even the fine grading has a comparable apparent particle density. This indicates that the compaction properties do not differ significantly across the different sized material fractions.

There was a large difference in in optimum moisture content (OMC) across the four samples, with the fine and ‘as received’ samples requiring a higher level of moisture in order to achieve optimal compaction. This may have a flow-on effect to construction practices and the required dry-back time.

Table 6.4: Density testing results

	Traditional Coarse	Modified Coarse	Fine	Sample ‘as received’
Apparent particle density (Fine) (t/m^3)	2.876	2.879	2.862	2.877
Apparent particle density (Coarse) (t/m^3)	2.937	2.935	2.937	2.945
Apparent particle density (t/m^3)	2.922	2.913	2.895	2.918
Optimum moisture content (%)	6.1	6.5	7.6	7.8
Maximum dry density (t/m^3)	2.355	2.352	2.304	2.325

The California bearing ratio was tested at the optimum moisture content for each grading (Table 6.5). The testing indicates that the shift away from the coarse third of the C grading envelope has a major effect on the bearing capacity of the material. The coarse end of the C grading and the sample ‘as received’ were the only samples to pass the MRTS soaked CBR specification of 80. The modified coarse grading saw the bearing capacity decrease by nearly two-thirds. This brings the CBR significantly below the requirement, and considering that many rural roads principally require the Type 2.1 basecourse to directly support traffic loads, a low CBR value and low shear strength may lead to deformation failures such as rutting and shoving. Even when used as a Type 2.3 material, the modified C grading would not reach the MRTS strength requirement.

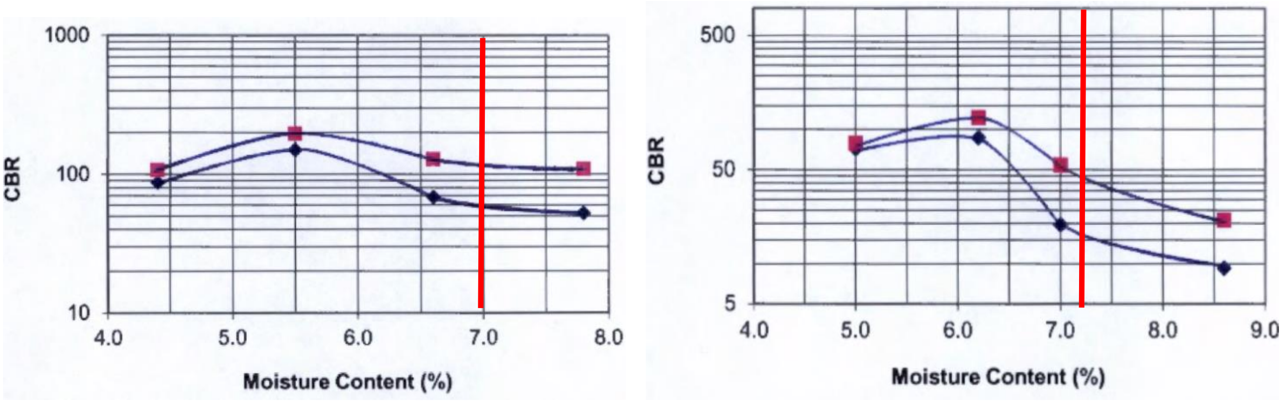
Table 6.5: California bearing ratio results

	MRTS Specification			Traditional Coarse	Modified Coarse	Fine	Sample ‘as received’ (27/8/2014)
	Type 2.1	Type 2.2	Type 2.3				
Soaked CBR Value	80 min	60 min	45 min	120 at OMC	42 at OMC	22 at OMC	125 at OMC

Not only is the CBR higher for the coarse grading, but it retains this strength with increasing moisture content (Figure 6.3). This is not the case with the two finer gradings, which lose significant percentages of their strength with increasing moisture content. The modified C coarse grading drops from a CBR of 122 at 6.2% initial moisture, down to a CBR of 21 at 8.6% initial moisture. This moisture content was well above the optimal conditions, so a large decrease in CBR at these levels is not unexpected. The large drop off with increasing moisture content for the fine and modified C gradings indicates a higher degree of sensitivity to moisture content.

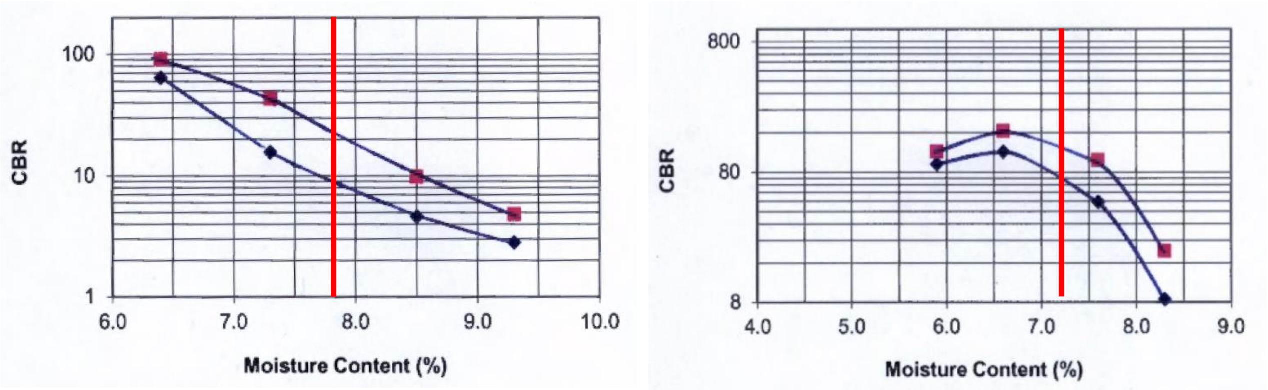
The total sample ‘as received’ performed much better, with a CBR of 125, although this was at 92% of the optimum moisture content, so may be expected to be high. The test is defined as a four-day soaked CBR, and the results under unsoaked conditions would likely show much higher CBR values.

Figure 6.3: CBR values by moisture content



Traditional C coarse grading

Modified C coarse grading



Fine grading

Sample ‘as received’

Permeability testing on the materials shows a large difference between the permeability of the coarse ends of the traditional and modified C gradings (Table 6.6). The fine grading has a relatively impermeable coefficient of permeability of 8.2 * 10^{-7} m/sec, with the coarse end of the modified C grading almost identical at 8.1 * 10^{-7} m/sec. The sample ‘as received’ performed similarly in terms of permeability, indicating that the typical grading for modified C materials in the field has a mix of aggregate sizes that leads to a relatively impermeable pavement layer.

The hydraulic gradient was higher for the fine grading, indicating that a greater head of pressure was required to produce the same permeability as for the modified coarse sample, which in turn required a greater head of pressure than the sample ‘as received’.

The coarse end of the traditional C grading is considerably more permeable at 6.1 * 10^{-5} m/sec. This is despite having just 5% less of the material passing the 0.425 mm sieve and 3.3% less passing the 75 µm sieve. It appears as though the small shift towards a finer grading has resulted in a large change in permeability.

Optimal permeability essentially depends on the function of the material within the pavement structure in question. When considering a common application as a basecourse under a spray seal, a lower permeability would reduce the movement of water through the layer. Based on these findings, moving to a modified C material may be beneficial where permeability of the basecourse is a major consideration.

Table 6.6: Permeability testing results

	Traditional Coarse	Modified Coarse	Fine	Sample 'as received'
Coefficient of permeability (m/sec)	$6.1 * 10^{-5}$	$8.1 * 10^{-7}$	$8.2 * 10^{-7}$	$8.4 * 10^{-7}$
Permeability level (TMR Materials Testing Manual Q707A)	C (Permeable)	A2 (Low permeability)	A2 (Low permeability)	A2 (Low permeability)
Hydraulic gradient	0.10	0.85	1.52	0.51
Placement moisture ratio (%)	98.4	100.0	97.4	96.2
Placement dry density ratio (%)	100.1	100.0	100.2	100.2
Placement dry density (t/m^3)	2.357	2.351	2.308	2.330
Material retained on 19 mm sieve	15	12	0	4

Repeated load triaxial (RLT) testing was also undertaken on the three samples. This was done at two degrees of saturation (DoS), a relatively high level of 70%, and a drier sample of 60% (Table 6.7). Of the results recorded, the most important values to note are the permanent strain levels.

An indicator used by TMR for heavy duty unbound materials under RLT testing is to determine the maximum degree of saturation for the granular layer, which is to be the lesser of:

(a) 70%
(b) the maximum value required to achieve a permanent strain of less than 1.5% at 1000 cycles
(c) the maximum value required to achieve a permanent strain of less than 4.0% at 50 000 cycles.

Under MRTS05, the requirement is that the maximum degree of saturation should be 65%, but the values described in (b) and (c) above can also be applied to this modified C material for general guidance.

The high DoS (70%) modified coarse and traditional coarse materials both exceeded the strain levels in (b) and (c), as did the fine sample at a high DoS, but only by a small margin at 1000 and 50 000 cycles. Both the traditional and modified coarse gradings had relatively high values of OMC for both samples.

To ensure satisfactory long-term performance, it is recommended that after 50 000 loading cycles, the permanent strain should not exceed 4%. Two of the three 'dry' samples passed the requirement of less than 4% permanent deformation, with the coarse end of the modified grading hitting 5.55% after 50 000 cycles (Figure 6.4). This would suggest that significant deformation may be encountered with the coarse end of the modified grading at any DoS over 60%, leading to likely difficulties during construction and early trafficking.

All of the wet samples failed this requirement, although the fine limit sample performed comparatively well, only narrowly exceeding 4% permanent strain after 50 000 cycles. Both the coarse limit of the modified and traditional gradings failed the test very rapidly, hitting 8%

permanent deformation after 2970 and 3269 cycles, respectively. It should be noted that this ‘ranking’ of materials is the opposite as that for CBR, where the fine material exhibited the lowest strength characteristics.

Additional RLT testing on the sample ‘as received’ showed that the level of permanent strain was again much higher with the sample closer to OMC, reaching the 8% threshold after 37 013 cycles, which was a large improvement over the coarse limits of both C gradings. The low DoS sample passed the requirement at 1000 cycles (1.4% strain) and at 50 000 cycles (3.27%).The testing confirms TMR’s 65% DoS limit as a reasonable approach.

When analysing the graph for the higher DoS samples, it can be seen that there is an improvement in performance from what are listed as the coarse and medium samples, which failed this test, towards the finer samples. This trend indicates that a shift towards gradings with a greater percentage of fine material will lead to improved resistance to strain, particularly in regards to samples with higher moisture content.

Figure 6.4: Permanent strain levels for the eight RLT tests

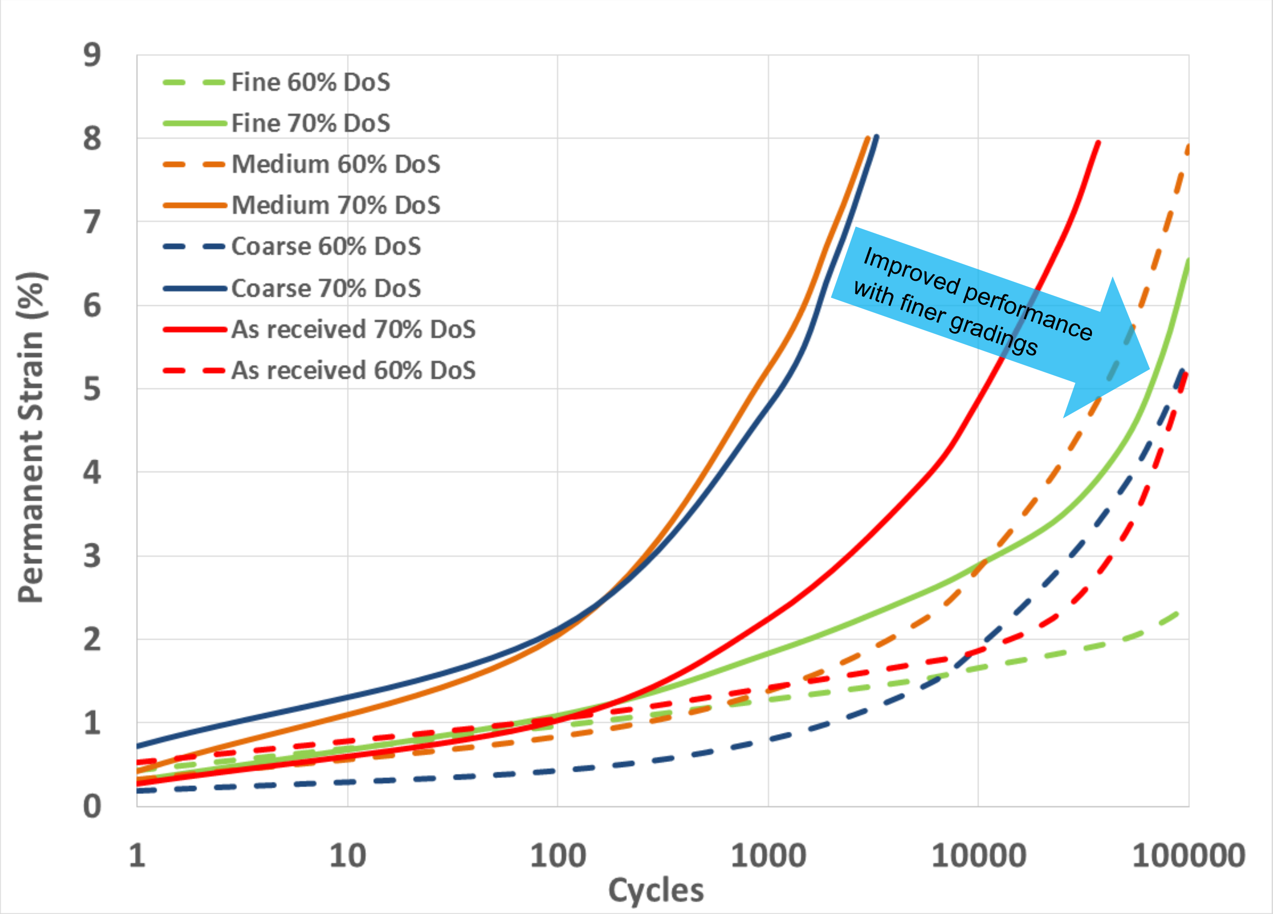


Table 6.7: RLT testing results

		Limit (max)	Sample as received	Traditional Coarse	Modified Coarse	Fine
Low DoS (60%)	DoS achieved (%)		61	61	61	61
	Achieved percentage of OMC (%)	-	69	82	76	71
	Permanent strain (%) after 1000 cycles at low DOS	1.5%	1.42	0.80	1.39	1.28
	Permanent strain (%) after 50 000 cycles at low DOS	4%	3.27	3.86	5.55	2.01
High DoS (70%)	DoS achieved (%)		71	68	69	69
	Achieved percentage of OMC (%)	-	79	92	87	80
	Permanent strain (%) after 1000 cycles at high DOS	1.5%	2.25	4.79	5.24	1.84
	Permanent strain (%) after 50 000 cycles at high DOS	4%	7.95 after 37,013 cycles	8.02 after 3269 cycles	8.00 after 2970 cycles	4.39

* Highlighted cells indicate failure to meet criteria.

This data is visualised differently in Figure 6.5 and Figure 6.6. Here it is quite clear to see the ranking of materials. The fine grading and the sample 'as received' both performed well, with the fine grading performing particularly well after 50 000 cycles. The traditional and modified coarse gradings both showed susceptibility to increased moisture.

Figure 6.5: Permanent strain after 1000 cycles with four gradings

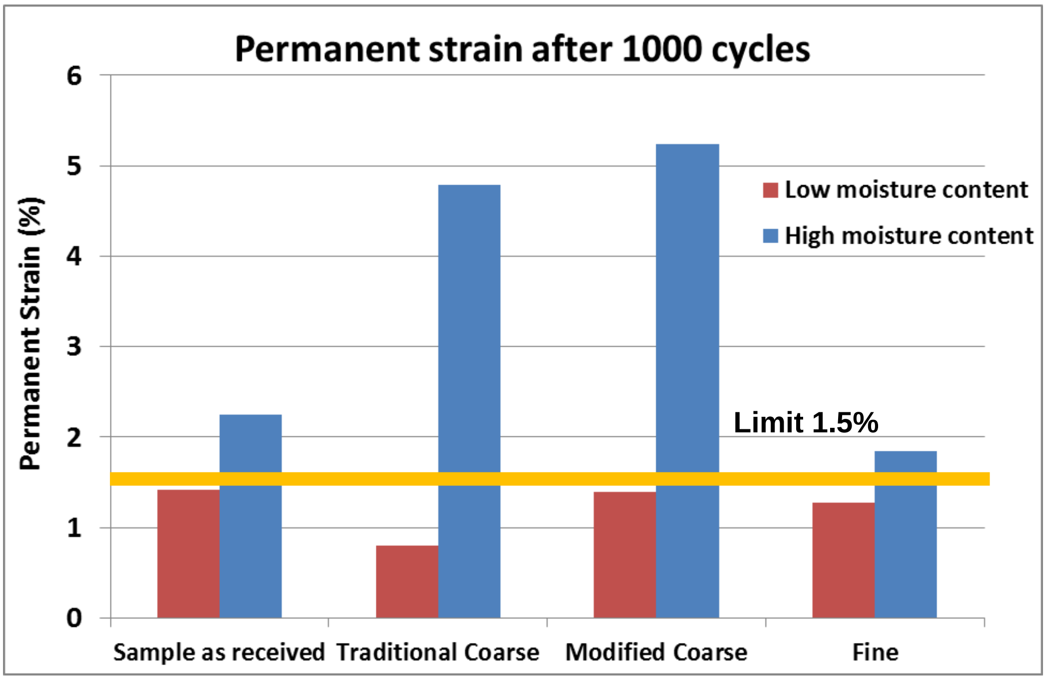
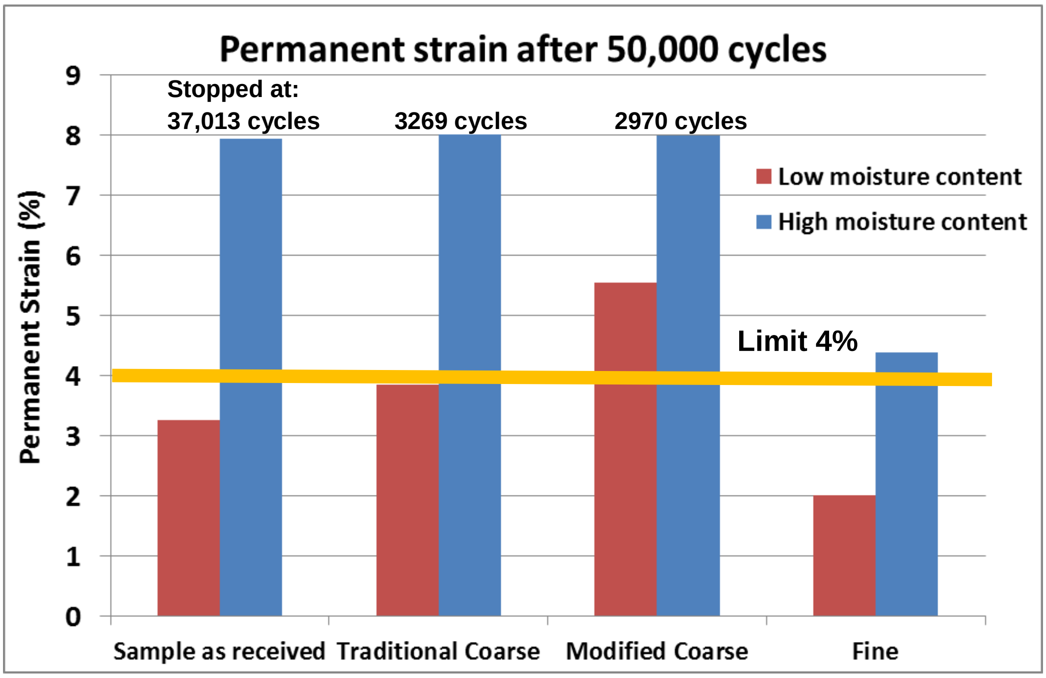


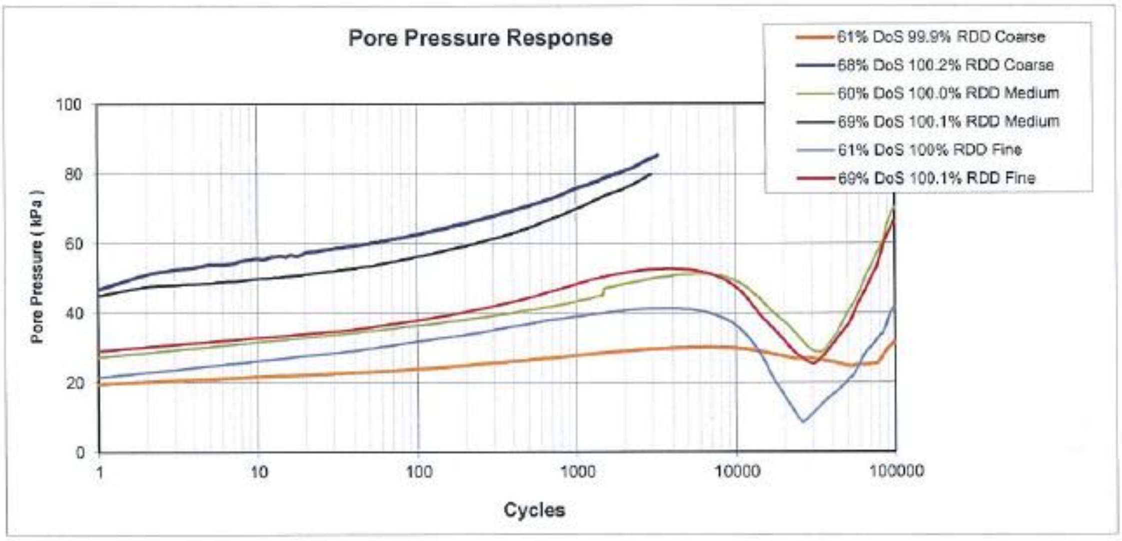
Figure 6.6: Permanent strain after 50 000 cycles with four gradings



The graph of pore pressure responses during the RLT test shows sharp drop-offs for three of the tests (Figure 6.7), with two more of the tests failing before reaching this point. The fine blends are able to re-align and find a more stable configuration, while the coarse blends cannot. The increased pore pressure and reduced effective stress on the materials leads to failure in shear. This allows the pore pressure to quickly dissipate and fall to very low levels. Both of the RLT tests for the 'sample as received' also showed this trend after around 4000 cycles.

The RLT test reveals that the material is relatively sensitive to moisture levels, which was also shown with the rapid drop in CBR values when the moisture content rose.

Figure 6.7: Pore pressure responses of samples during RLT test



When considering the overall effects of the move towards a modified C grading envelope, a finer grading did appear to exhibit benefits in terms of reduced susceptibility to water infiltration. Very fine gradings did introduce the possibility of deformation and shear failures. When applied as a basecourse under a spray seal, the material would be expected to bear a large portion of traffic loading and therefore a material that fails MRTS strength requirements may be unsuitable. Therefore, it may be beneficial to limit the level of very fine material.

A coarser grading has the effect of relying on the quality of material for overall performance. The finer modified grading allows interlock properties to carry much of the load rather than relying on aggregate quality, but this must be balanced against the possibility of an overly fine mix introducing other failure mechanisms.

Overall, the ‘sample as received’, which is typical of what quarries can produce, performed very well. Both the CBR results and RLT results suggest that this grading is capable of fulfilling the strength requirements under the specification, while the permeability numbers are relatively low. The grading was slightly outside the limit at the 75 µm sieve; however, at 9.1% it was within the tolerable margins.

Using a material near the fine limit across all sieves is highly unlikely to result in adequate performance. This situation appears unlikely, however, as the analysis of quarry gradings in the Toowoomba region shows that every grading lies towards the coarse fraction of the curve. Compared to other states and countries, the very high allowable level of fines is unique to Queensland. This issue should be investigated and addressed (see Section 7).

It should be noted that the testing was only performed on one material and the trends identified here may not apply to other materials. Testing on additional materials may be required to confirm these results. In addition, duplicate testing was not undertaken during this program, so variability in performance due to fluctuations in natural material properties and testing variation are not able to be quantified.

6.1.1 Laboratory Testing of Amby Quarry Material

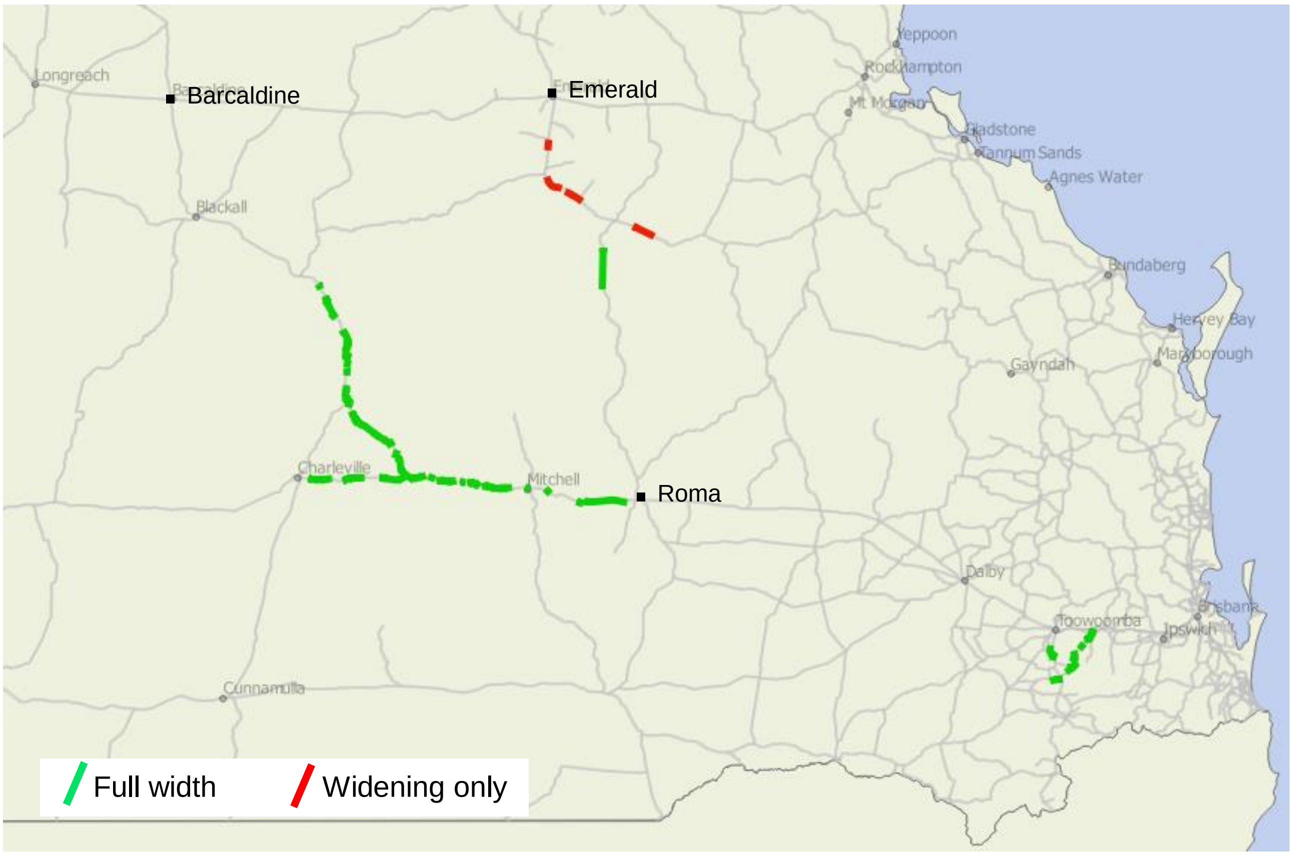
A small sample of material from an Amby quarry stockpile was collected and tested, with the results documented in Section 6.3.2.

6.2 Performance of Existing Sections

A number of sources have provided a database of various projects known to be constructed with modified C material. This will be an important outcome of this project, as it is difficult to make specific conclusions about the performance of modified C gradings after (in many cases) just a few years of pavement life. This list of projects should be monitored over the coming years to ensure that the performance is satisfactory. An indication of the location of these projects can be seen in Figure 6.8. Several projects constructed with a traditional C grading have also been provided, which will be useful for a direct comparison of performance.

A full table of these sections is provided in Appendix C.2 .

Figure 6.8: Map of known modified C sections across southern Queensland



South West

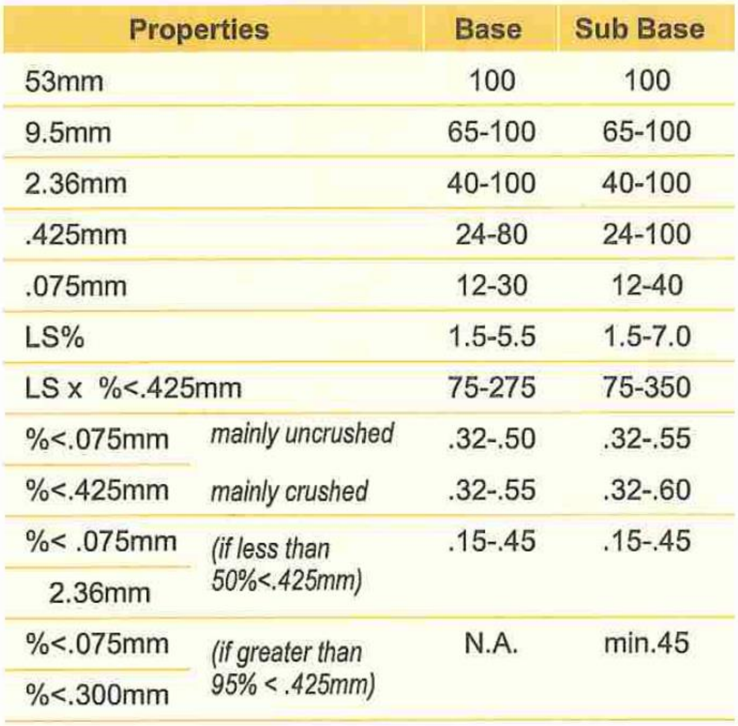
Much of the Transport Network Reconstruction Program (TNRP) works completed across the South West district were constructed by cement stabilising the existing base layer and applying an unbound granular layer on top. Much of this material forming the top layer was specified to be modified C. A summary of roughly 450 km of the TNRP was obtained, which suggests that 75–80% of total kilometres treated specified modified C material, with the notable exception being works on 24D and 24E north of Roma.

The fact that almost all the roads in this region used modified C material also makes it difficult to assess performance against control sections (for example, TNRP sections using standard C material).

Central West

A list of projects completed in the Barcaldine district during the TNRP reveals that little or no pavement designs specified modified C materials. Local materials are incorporated wherever possible, and some of these fit the WQ35 grading (Transport and Main Roads 2014) (see Figure 6.9 and Figure 6.12). The WQ35 grading is a very wide grading envelope that suits the soils found in parts of Western Queensland. Soils in this region have naturally high fines content.

Figure 6.9: WQ35 material requirements



Properties		Base	Sub Base
53mm		100	100
9.5mm		65-100	65-100
2.36mm		40-100	40-100
.425mm		24-80	24-100
.075mm		12-30	12-40
LS%		1.5-5.5	1.5-7.0
LS x %<.425mm		75-275	75-350
%<.075mm	*mainly uncrushed*	.32-.50	.32-.55
%<.425mm	*mainly crushed*	.32-.55	.32-.60
%< .075mm 2.36mm	*(if less than 50%<.425mm)*	.15-.45	.15-.45
%<.075mm %<.300mm	*(if greater than 95% < .425mm)*	N.A.	min.45

Source: Transport and Main Roads (2014)

In Emerald, however, the region used the modified C grading extensively from 1999–2005 (see Commentary 1). Material was typically Type 2.3 with a modified C grading, in response to poor performance in the region with material that typically only had 6–7% passing the 75 µm sieve. A number of these projects were widening jobs on low/moderate traffic rural links, with relatively shallow depth and only had a calculated design life of 2–5 years.

Performance of these sections varies, with some surviving to today and others failing early or during the major weather events in 2010–2012.

6.2.1 Pavement Maintenance Spend

One method of assessing the performance of known modified C sections over time is to look at the annual pavement maintenance spending on each section. The pavement maintenance spend is based on the '100 series' pavement maintenance costs in TMR's ARMIS database. The relatively small length of road analysed makes it difficult to draw any major conclusions, however, it may give some indication of high or poor performance. Table 6.8 compares the before and after maintenance spend on sections reconstructed/rehabilitated with modified C material compared to all sections on that road link.

Table 6.8: Yearly maintenance spending comparison

Region	Road Number	Count of km		Avg. yearly km maintenance before ($)		Avg. yearly km maintenance after ($)		Comments
		Mod C	Other	Mod C	Other	Mod C	Other	
Darling Downs	22A	9	124	$768	$1182	$115	$301	Lower maintenance before and after (only 1 year after)
Darling Downs	22B	2	74	$7819	$5643	$5255	$3964	Higher maintenance before and after (only 2 km of Mod C and only 1 year)
South West	18E	35	54	$2638	$2429	$3097	$2355	Higher maintenance before and after
South West	18F	36	57	$811	$858	$706	$439	Similar maintenance spend before, increased after treatment (only 1 year)
Central West	24E	36	138	Not available (pre-2000)		$803	$710	Slightly higher on Mod C sections
Central West	27A	5	61	Not available (pre-2000)		$445	$1206	Significantly lower on Mod C sections but only 5 km treated
Central West	46C	17	153	Not available (pre-2000)		$733	$993	Lower on Mod C sections
Central West	46D	21	50	Not available (pre-2000)		$381	$634	Lower on Mod C sections

The data suggests that of the sections treated during the TNRP, there is no indication of changes to maintenance spending as yet, but the 2013 (‘after’) data is likely inclusive of some pre-treatment maintenance. Several more years of data would be necessary to draw conclusions from performance on 22A, 22B, 18E and 18F.

When looking at the older modified C sections, three of the four have lower maintenance spending on the modified C treated sections, while one is slightly higher. On these four roads, the average yearly maintenance spend per km was $653/km on sections with modified C material compared to $883/km on other sections.

6.3 Modified C Quarry Data

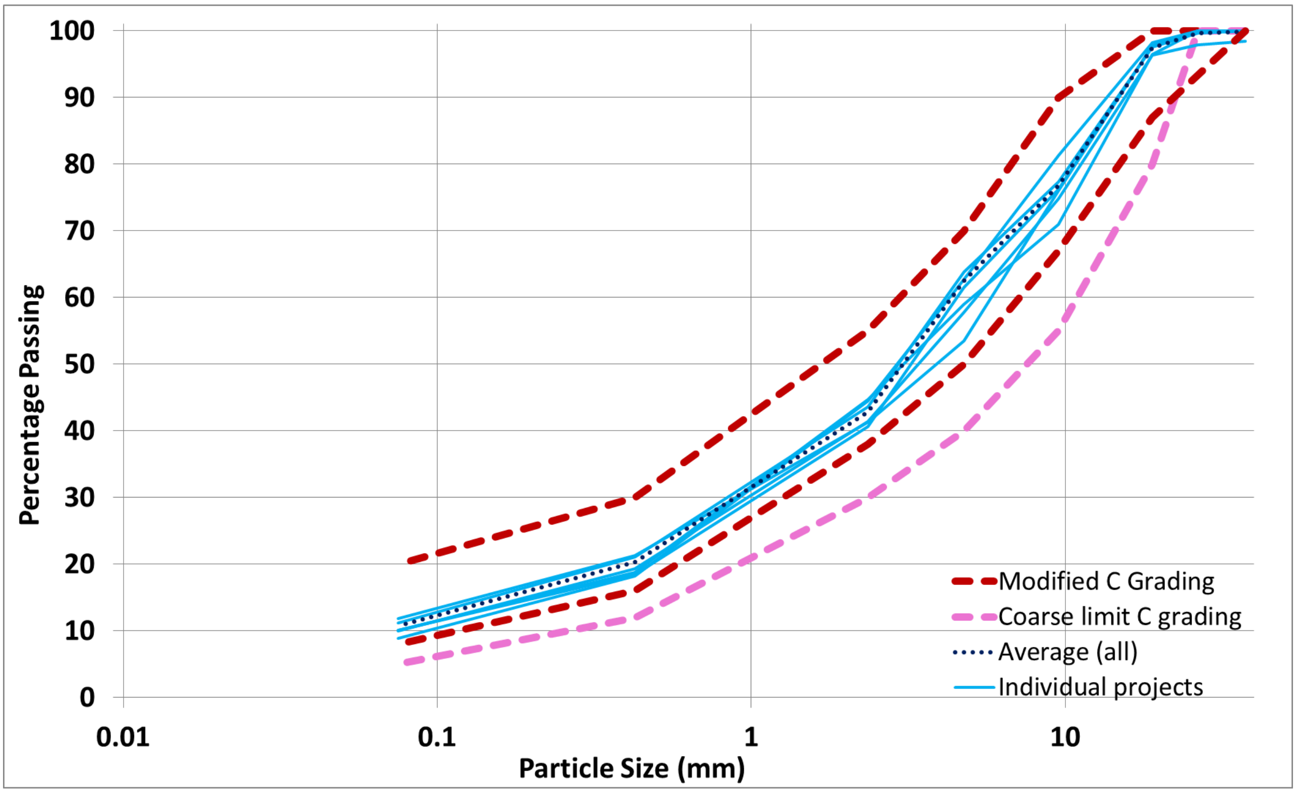
The following section presents and analyses the data provided by quarries and district laboratories across three regions.

6.3.1 Toowoomba (Darling Downs Region)

Data has been acquired from the TMR laboratory in Toowoomba which documents the gradings and other test parameters from jobs that used modified C material. One qualifier with this data is that there is likely to be some non-modified C material contained within this data set where a mix of modified C grading and traditional C grading is used for the project.

The data reveals that quarries are producing modified C products very close to the coarse end of the specification (Figure 6.10). Two projects actually fell outside the specification limit for the 75 µm sieve, and many projects contained sample results outside the specification limits for one or more sieves. In total, around 30% of samples fell outside the limits on the 75 µm sieve, 14.6% outside the specification on the 0.425 mm sieve, and 9.3% over the coarse limit on the 2.36 mm sieve. As previously mentioned, some of these samples were likely manufactured to a traditional C grading.

Figure 6.10: Data from quarries compared to modified C limits



All of the discrepancies were on the coarse end of the specification; that is, quarries are not crushing enough material down to the smaller fractions, or adding sufficient fine material. Fines are not only added to adhere to grading curves, extra fine material is often required to meet linear shrinkage and plasticity index requirements. This is partly a cost cutting exercise, as crushing rock is one of the most expensive and time consuming parts of the process. Indeed, before the modified C grading was introduced, anecdotal evidence suggests that quarries operated much the same, only crushing rock as fines when absolutely necessary under the specification. Under a broader grading envelope, this meant even coarser overall gradings. The modified C appears to have at least pushed quarries to produce an overall grading near the middle of the traditional C grading rather than towards the coarse end.

When matched against the Mackay grading described in Section 4.1, every project met the grading and only 4.9% of individual samples had insufficient material passing the 75 µm sieve. Every sample also adhered to the grading as suggested by O’Sullivan (2002; Appendix B).

6.3.2 South West Region

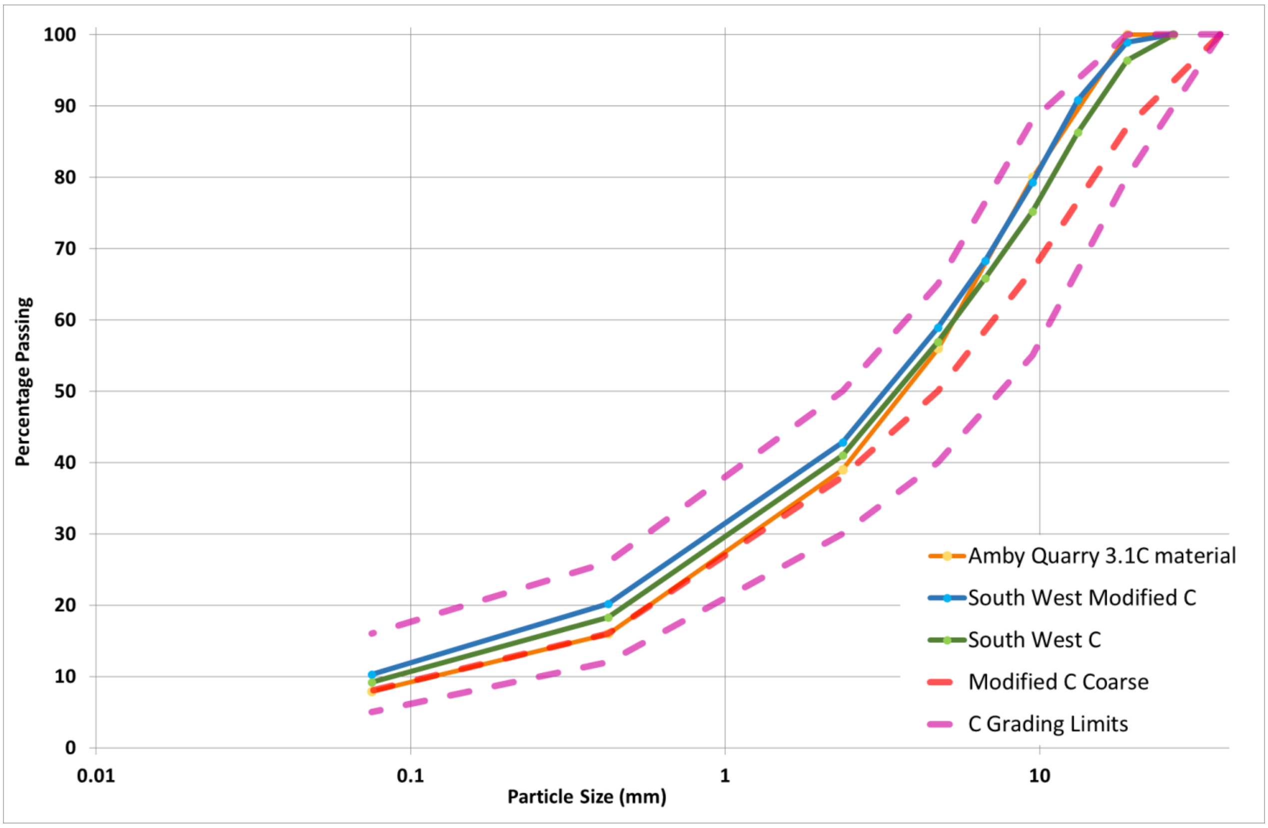
Information has been sourced from a quarry in the South West region that has a significant amount of data from testing taken between 2005 and 2014, with much of that during the 2011–2014 TNRP disaster recovery program of works.

Roughly three-quarters of the test results from this sample are specified as modified C, with the remaining quarter listed as standard C grading material. When these two sets are compared, it is clear that there is a small but consistent shift towards the finer end of the grading with the modified C results (Figure 6.11).

Five buckets of 3.1C material from the Amby quarry, just outside Mitchell, was brought back for testing at the TMR laboratory. The same suite of characterisation tests was undertaken, as well as a permeability test. RLT strength tests are forthcoming. The results, and how they compare to the data obtained from the Amby quarry, are documented in Table 6.9.

The material sampled from the quarry fits a similar grading curve at the 2.36 mm sieve and above, but sits just below the modified C specification at the fine sieve sizes. It is possible that the stockpile this material was sourced from would need some fines added before this material would be supplied as Type 3.1 modified C. In terms of material properties, the Amby material has low permeability but the liquid limit was above the MRTS specification limit for Type 3.1 material. The material would however fit inside the relaxed maximum liquid limit as specified for many TNRP jobs (Table 6.10).

Figure 6.11: South West region quarry data – grading comparison



Permeability results from this sample indicate that the material is impermeable, with similar properties to the quarry sampled Darling Downs material. Under Test Method Q707A, this material would be classified as a category A1 (very low permeability).

Upon investigation of various projects using modified C material, it was found that the South West region has been specifying a slightly different version of the modified C grading. The requirement is that a minimum of 8% material passes the 75 µm sieve, rather than the minimum 10% required under the 'official' modified C grading.

The MRTS05.1 Annexure for projects in this region often included a requirement that the materials fit a number of additional requirements that differ from the standard requirements of a Type 3.1 material under MRTS05 (Table 6.10). These projects specified Type 3.1 material for base layers, but the Annexure relaxes the requirement on the Liquid Limit and Linear Shrinkage to somewhere between the Type 3.1 and Type 3.3 limits. The Plasticity Index requirements are tightened to be between 3% and 5.5%.

Table 6.9: Results from South West quarry data, including performance data

Percentage passing sieve size (mm)	Specification (Type 3.1)	Modified C grading	C grading	Amby Quarry material sample – 22/04/15
26.5		100.0	100.0	
19		98.9	96.4	100
13.2		90.9	86.3	
9.5		79.3	75.2	80
6.7		68.3	65.9	
4.75		58.9	56.9	56
2.36		42.8	41.1	39
0.425		20.2	18.3	16
0.075		10.3	9.2	7.9
Liquid Limit (%)	25 max	28.2	27.4	30.2
Plasticity Index (%)	6 max	3.1	3.5	2.0
Linear Shrinkage (%)	3.5 max	1.3	1.5	2.6
Ratio 0.075 to 0.425	0.30–0.55	0.51	0.50	0.49
Coefficient of Permeability (m/sec)				$8 * 10^{-8}$

Table 6.10: Fines component properties under MRTS05 compared to project-specific requirements in South West

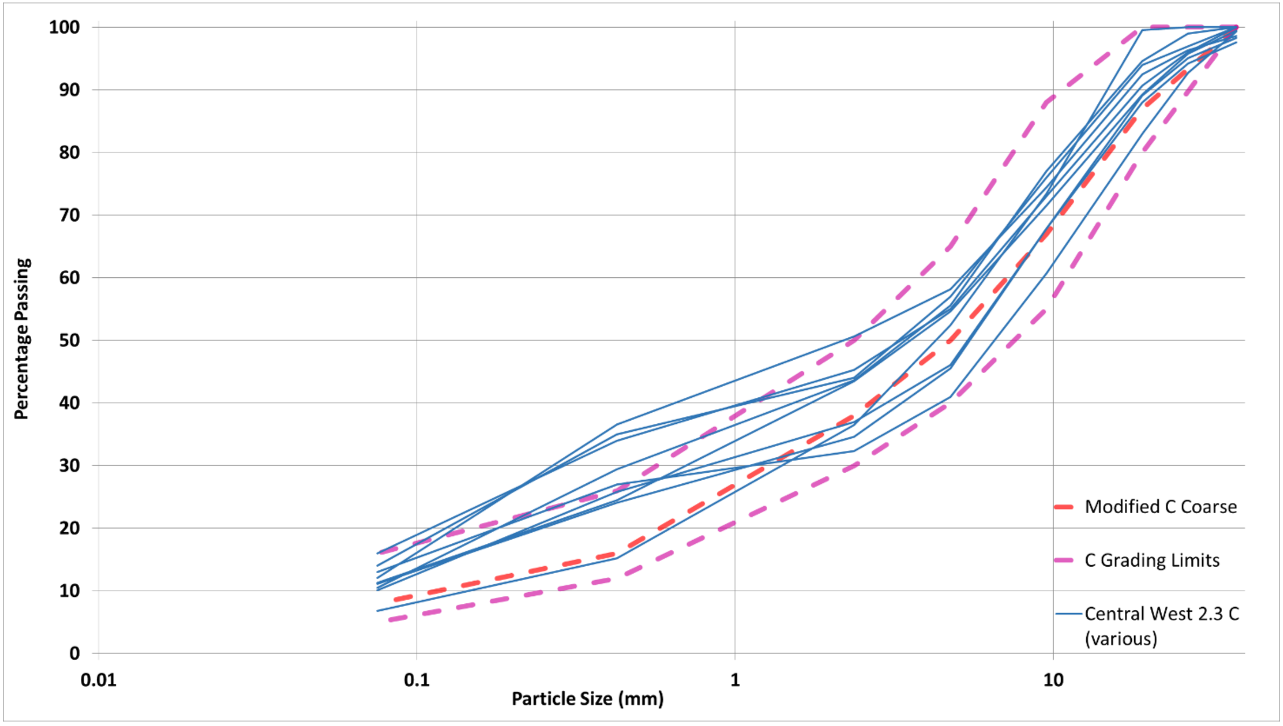
	MRTS05 Type 3.1	South West requirement under TNRP project works	MRTS05 Type 3.3
Liquid Limit (%)	25 max	30.5 max	35 max
Plasticity Index (%)	6 max	3.0 min to 5.5 max	12 max
Linear Shrinkage (%)	3.5 max	0.5, 1.0 or 1.5 min to 4.5 max	6.5 max
Plastic Limit (%)		27.5 max	
Ratio 0.075 to 0.425	0.30–0.55	0.30–0.54	0.30–0.65

6.3.3 Central West Region

The WQ35 grading is used widely in Western Queensland, and a number of pavements rehabilitated and reconstructed during the TNRP have the 200–300 mm existing base layer modified with a small percentage of cement, with 150–200 mm of imported WQ35 material overlaid.

Projects constructed with Type 2.3 material in the Central West region sit across a wide range of gradings. The materials generally fulfil the requirement for 10–20% passing the 75 µm sieve, with the notable exception being the material sourced from Alpha Quarry for part of the TNRP reconstruction works on the Landsborough Highway (13E). This section has performed well to date, despite having a very low percentage of fines. The shape of the grading curve from Alpha is more consistent with a typical C grading, which cannot be said for several of the other material sources which lack material in the intermediate fractions and demonstrate a natural ridge-gravel ‘armchair’ grading. The Alpha Quarry material also had better CBR results than most other Central West materials.

Figure 6.12: The range of 2.3 C material used in the Central West region during TNRP



6.3.4 *Summary*

Overall, the data suggests that most of the material being used on ‘C grading’ projects fits within a relatively narrow envelope of particle sizes at each sieve, even across the different regions. A large version of the typical gradings in each region is contained in Appendix B. The two lines for each region represent the 90% percentile (coarse) and 10% percentile gradings (fine) in the data provided.

It can be seen that the Central West region produces a much coarser set of materials, although much of this was not specified as modified C. The South West and Darling Downs data align closely with each other. The vast majority of material analysed in these two regions would fit a modified C grading with a minimum 8% passing the 75 µm sieve.

The overall good level of performance on roads with this material suggests that future guidance and specifications around modified C material could use a curve similar to these as a benchmark.

In terms of other data in the laboratory results, there are some significant differences across the various Atterberg tests and strength measurements (Table 6.11). The values in this table are averages from the quarry and laboratory data supplied, and testing results from the sampled material is also added. Linear shrinkage was low for much of the Amby quarry data, although the material sampled produced results more in line with typical values for the Darling Downs region. In terms of the plasticity index, almost all individual results were below the 6% limit. CBR results were generally well above the Type 3.1 requirement of 80.

Table 6.11: Additional laboratory and testing results summary

	Limit (MRTS05 Type 3.1)	Amby C Grading	Amby modified C grading	Amby material sampled	Darling Downs laboratory data	Darling Downs material sampled
Flakiness Index	35 max	17.8	14.7	-	-	23
Linear Shrinkage (%)	3.5 max	1.5	1.3	2.6	2.5	2.2
Liquid Limit (%)	25 max	27.4	28.2	30.2	21.4	21.4
Plasticity Index (%)	6 max	3.5	3.0	2.0	4.5	2.4
CBR (2.5 mm)	N/A	81	80	-	-	70
CBR (5 mm)	80 min (unsoaked)	128	127	-	-	125

7 RECOMMMENDATIONS AND NEXT STEPS

The modified C material has the potential to improve unbound pavement permeability characteristics, whilst also improving the surface finish and workability. Initial laboratory results suggest that this should be carefully balanced against the loss of strength that may occur when shifting to a finer grading. The risks associated with strength loss can be mitigated by bringing the fine limit of the grading into line with the requirements in other jurisdictions (i.e. not allowing as high as 20% passing the 75 µm sieve). The overall effect is a tightening of the grading envelope.

Other evidence for the inclusion of the modified C grading includes:

- Laboratory data through this project that suggests a modified C grading may lead to better moisture resistance (reduced permeability) while maintaining satisfactory strength.
- Anecdotal evidence from contractors and the regions that modified C material improves the constructability, workability, and surface finish of projects. This is based on various projects between 2 and 15 years old.
- Requiring a higher proportion of fines allows for some loss of fines during construction (during transit or laying) without significantly compromising performance.
- Early success of the TNRP projects using modified C material (important to monitor these over time).
- The improved ability of quarries to hit specific grading numbers at each sieve size owing to the widespread use of modern crushing equipment and the technical resources available.
- Evidence from quarries and regions that the extra cost in producing modified C material ranges from negligible to very low.
- The relative benefits provided by moving from the traditional C grading envelope to a modified grading are likely to outweigh the small extra costs in production.

The decision to shift from a minimum 10% passing the 75 µm sieve down to a minimum 8% passing the 75 µm sieve was made with reference to the fact that performance issues have been occurring with 5–7% passing the smallest sieve, and that many projects are already specifying 8% with good results. Data from quarry sources suggests that good performance has been achieved with gradings that sit just below the minimum 10% passing the 75 µm sieve.

Consideration should also be given based on the local material properties as to the minimum allowable percentage passing the 75 µm sieve. The MRTS05 Annexure 1 provides an option for regions to specify a higher minimum at the 75 µm sieve, such as 10%. This will help to ensure that quarry operators are aware of the importance of a certain minimum requirement for fine material.

It has also been recommended to bring the fine side of the grading more into line with the requirements in other jurisdictions. No other state allows more than 14% passing the 75 µm sieve, while Queensland has set the limit at 20%. Testing has shown that a material comprising 20% very fine material suffers from low strength and a high propensity for shear failure. Despite the fact that the data suggests that no quarries produce material near this limit, it should still be taken into account for specifications. It is suggested that the limits are brought in at the 4.75 mm sieve and smaller.

It may be worth considering removing the requirement to not vary from one outer-third of the grading at one sieve to the opposite outer-third of the grading for the next lower sieve. The tightening of the envelope for the modified C grading renders this requirement less critical; however, it should still be noted that grading curves are required to be relatively smooth.

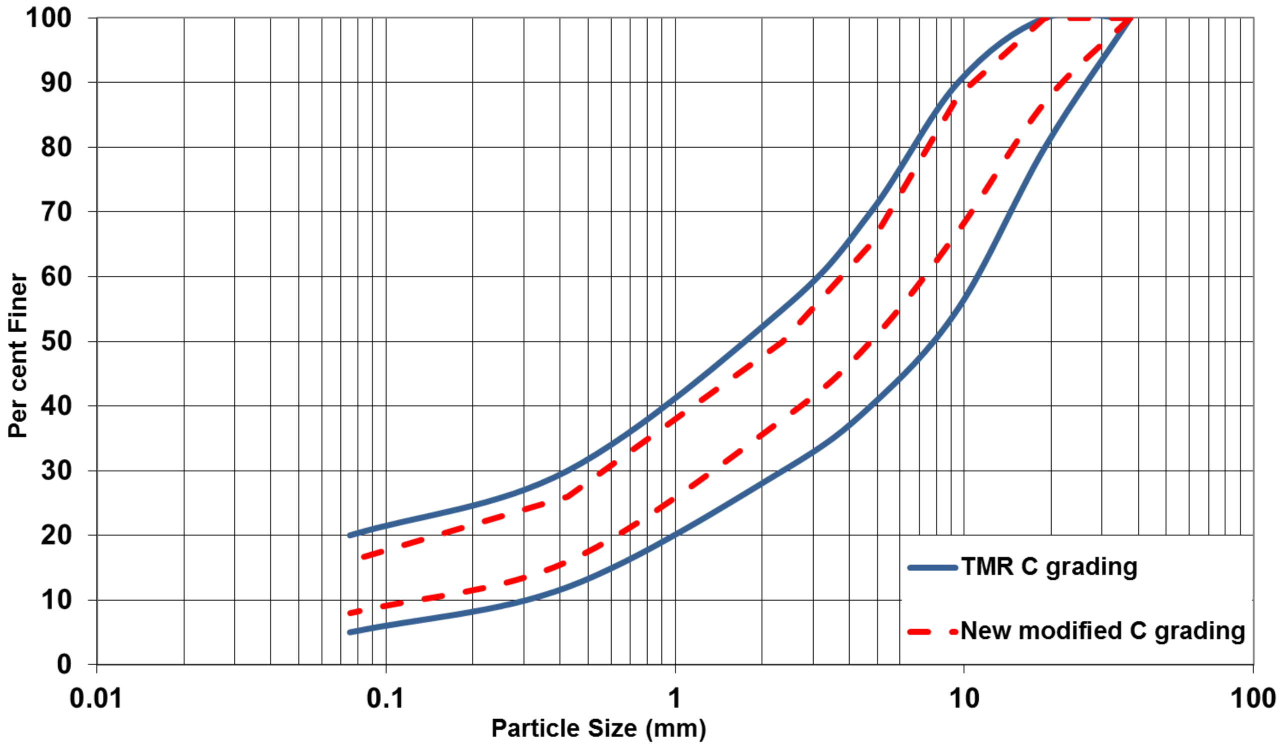
It is not recommended to add any other clauses with regards to plasticity, CBR, etc., as these can be addressed through the project Annexure, as is already the case.

Thus, the following interim specification is recommended based on this study (Table 7.1 and Figure 7.1).

Table 7.1: New modified C grading

Size (mm)	Standard C		Previously used modified C		New modified C specification	
75	100	100	100	100	100	100
53	100	100	100	100	100	100
37.5	100	100	100	100	100	100
19	80	100	87	100	87	100
9.5	55	90	67	90	67	88
4.75	40	70	50	70	50	65
2.36	30	55	38	55	38	50
0.425	12	30	18	30	16	26
0.075	5	20	10	20	8	16

Figure 7.1: New modified C grading



The study to date has shown that there appears to be no issues associated with the changes to the grading envelopes, and there are no other related changes to the specification. Despite this, it is recommended that modified C sections continue to be monitored against a control set of sections with a coarser typical grading. Likewise, any new projects specifying modified C should be added to this list to monitor over coming years.

In order to improve the understanding of the requirements of the new grading envelope in the regions, a draft Technical Note is to be prepared. This Technical Note should be released as soon as possible after publishing the updated MRTS05 specification, and should be referenced in the specification. This will ensure that regions, quarries and contractors have the required knowledge on the background, benefits and methodology behind the modified C grading.

REFERENCES

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Transport and Main Roads 2014, Western Queensland Best Practice Guidelines: WQ35 Paving Materials and Type Cross Sections for Roads on Expansive Soils in Western Queensland, September 2014.

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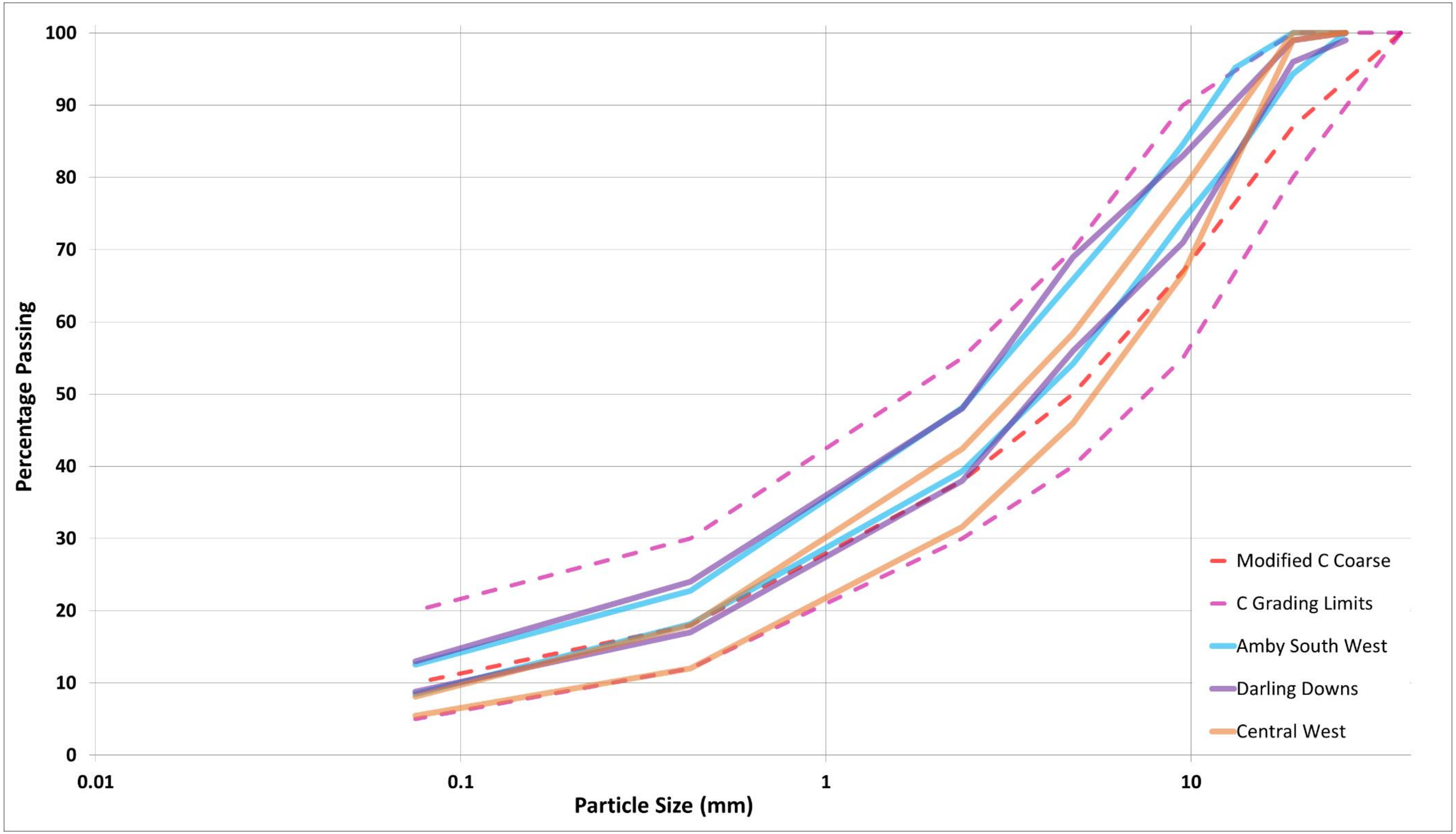
APPENDIX A FULL SUMMARY OF RESULTS

	Sieve Size	Specs (2.1)	Total Sample (21/2/14)	Total Sample (27/8/14)	Traditional Coarse	Modified Coarse	Fine
Grading	**26.5**	100	100	100	100	100	-
	19.0	80–100	97	96	85	88	100
	9.50	55–90	80	77	55	66	88
	4.75	40–70	63	57	40	50	70
	2.36	30–55	44	41	29	38	56
	0.425	12–30	19	19	12	17	31
	0.075	5–20	9.6	9.1	6.7	10	22
Atterberg	**Liquid Limit (%)**	25 max	20.8	22	20.4	22.4	23.2
	Plasticity Index (%)	6 max	2.6	2.2	2.4	3.6	3.6
	Linear Shrinkage (%)	3.5 max	2.0	2.4	2.2	3.2	3.6
	Weighted PI	150 max	49	41	29	60	112
	Weighted LS	85 max	38	45	27	54	112
	Ratio 0.075 to 0.425	0.30–0.55	0.51	0.48	0.55	0.62	0.72
	Flakiness Index (%)	35 max	23	N/A			
	Degradation Factor	45 min	60				
Apparent Particle Density	**APD (Fine Fraction) (t/m^3)**		N/A	2.877	2.876	2.879	2.862
	APD (Coarse Fraction) (t/m^3)			2.945	2.937	2.935	2.937
	Overall APD (t/m^3)			2.918	2.922	2.913	2.895
MDR	**OMC (%)**			7.8	6.1	6.5	7.6
	MDD (t/m^3)			2.325	2.355	2.352	2.304
Permeability	**Coefficient of Permeability (m/s)**			8.4E-07	6.1E-05	8.1E-07	8.2E-07
	Hydraulic Gradient			0.51	0.10	0.85	1.52
	Placement Moisture Ratio (%)			96.2	98.4	100.0	97.4
	Placement Dry Density Ratio (%)			100.2	100.1	100.0	100.2
	Placement Dry Density (t/m^3)			2.330	2.357	2.351	2.308
	Material Retained on 19 mm Sieve			4	15	12	0
CBR	**CBR at OMC**	80 min		125 at 7.2%	120 at 7.0%	42 at 7.2%	22 at 7.8%
RLT	**Permanent strain (%) after 1000 cycles at 60% DOS**	1.5% max		1.42	0.80	1.39	1.28
	Permanent strain (%) after 50000 cycles at 60% DOS	4% max		3.27	3.86	5.55	2.01
	Permanent strain (%) after 1000 cycles at 70% DOS	1.5% max		2.25	4.79	5.24	1.84
	Permanent strain (%) after 50 000 cycles at 70% DOS	4% max		7.95 after 37 013 cycles	8.02 after 3269 cycles	8.00 after 2970 cycles	4.39

APPENDIX B GRAPH OF QUARRY DATA

Figure B 1: General boundaries of material gradings (exclude top and bottom 10%)



APPENDIX C SITE INSPECTIONS

C.1 Darling Downs Site Inspection

There was not an opportunity to conduct any field trials or assessments during the first year of the project; however, a small site inspection was undertaken in March 2014. This involved visiting four sites in the Darling Downs region known to have been constructed with modified C material (at least in part).

Site 1: New England Highway 265/22A/2 – Chainages 92.4–94.8 and 84.3–86.8

The first sites, on the New England Highway between Toowoomba and Yarraman, were mostly small widening and rehabilitation works completed between 2010 and 2013.

According to design cross-sections, between chainage 92.4 and 94.8, modified C material has been used as a base material across the widened section of the road to a depth of 160 mm. Part of this widening only incorporates shoulders but the new northbound traffic lane is modified C material. This section was mostly in good condition, with some minor flushing in the wheel paths being the only noticeable pavement deformity (Figure C 2).

The section between chainages 84.3 and 86.8 appears to be a relatively new section, and it is less clear how much of this section was constructed using the modified C material. This section is through a small township with a reduced speed limit. There was noticeable surface deterioration in the outer wheel path along several hundred metres of this section (Figure C 2). It is difficult to determine the impact of the base granular material on this damage.

Figure C 2: Minor flushing in wheel paths and some surface deterioration in outer wheel path

Traffic levels in this area were quite high, with 5497 AADT and 6.9% heavy vehicles over the last three years.

Site 2: New England Highway 40/22A/48 – Chainage 77.6–79.6

Further towards Yarraman on the New England Highway, a section of the highway has undergone re-alignment and widening works between 2008 and 2009. Design drawings indicate that the works comprised a 140 mm base layer of Type 3.1 material (likely to be modified C based on laboratory data) on the shoulders in the widened sections and across the whole road width in the sections with a new alignment.

This section is in very good condition overall, with few deformities for a road that is now over five years old. There was some minor flushing in the wheel paths and the beginnings of edge line distortion and shoving around the outer wheel path (Figure C 3). The level of rutting appeared to be very minor and not excessive for a road of that type after several years of traffic.

Figure C 3: Some edge line distortion and minor flushing in wheel paths

This section of road has had an AADT of 2642 over the last three years, with around 9% heavy vehicles. This is a lower overall level of traffic compared to Site 1.

Site 3: New England Highway 265/22B/801 – Chainage 14.7–16.8 (Toowoomba–Warwick)

Site 3 was located south of Toowoomba, again on the New England Highway. The road was rehabilitated in 2010, seemingly with a combination of materials forming the base granular layers. There is some doubt over the extent of modified C usage along this section, as the TMR ChartView data suggests that there is a section with a cement stabilised base located along this part of road. There is a relatively high level of traffic in the area, with 6393 AADT and 11.1% heavy vehicles over the last three years.

Some quite significant shoving and edge line distortion was visible in parts, as well as minor flushing in the wheel paths (Figure C 4).

This site was initially thought to be a good candidate for FWD testing, but due to concerns over the exact composition of the base layers, it was decided to find another section with more detailed construction data.

Figure C 4: Shoving causing edge line distortion and some flushing in the wheel paths

Site 4: Gatton–Clifton Road 114/313/17 – Chainage 19.4–20.5

This section of road between Gatton and Clifton was constructed in 2010 as a re-alignment due to a bridge upgrade. The old alignment was still visible to the west. This road has much lighter traffic than the previous sites, at just 776 AADT and 15.9% heavy vehicles over the last three years.

Design drawings do not shed much light on the composition of the base layers, but it appears as though modified C material has been used based on the Toowoomba laboratory data.

The road was in very good condition throughout, with only minor flushing in the wheel paths (Figure C 5). With a pavement less than four years old and under 800 AADT, there should not be any major defects in this section.

Figure C 5: Minor flushing in the wheel paths

C.2 Discussions with Regional Offices and Quarries

A more comprehensive site visit was planned for early 2015. An ARRB/TMR project team, made up of Andrew Beecroft and Dr Jeffrey Lee of ARRB Group, Jothi (Rama) Ramanujam, Budi Soetanto and Damian Volker of TMR, and Phil Hunt of Road Engineering Services, visited the South West and Central West regions from April 13–16. This included visits to regional offices in Roma, Barcaldine and Emerald and to the Amby Quarry between Roma and Mitchell.

The main goals of this trip were to:

1. document the experiences of TMR regional office staff using modified C material in projects over the last several years, including during the 2011–2014 flood repair works
2. visit quarries in the region to learn about the process required to produce modified C material and to gather any further data on projects and material testing
3. drive along several roads known to be constructed with modified C material and report any signs of good performance or distress.

C.2.1 Roma TMR Regional Office

On April 13, a meeting was held at the TMR Roma regional office with District Director Chris Lunson, Dylan Hesselberg and Roger Hacquoil. Experiences with the modified C grading and works during the TNRP were discussed, with the main findings being:

- Inconsistencies were reported with the process of blending multiple materials from various Maranoa Council gravel pits.
- Materials were generally selected based on location (as in, distance to the job) as well as considerations regarding the existing base and subgrade materials.
- It was reported that there were some failures, but that it was not believed that the material quality and grading were responsible.

C.2.2 Boral Amby Quarry

A 60 km long lava flow of pure basalt runs just to the west of the town of Amby, around 65 km west of Roma. This is the only hard rock supply for several hundred kilometres in any direction, so it supplies high quality material to a very large portion of south-west and western Queensland. Most major road projects require these higher quality gravels, and the Amby quarries were used extensively during the TNRP works. Amby also supplies much of the region with sealing aggregates. Discussions with Phillip Krueger at the quarry site gave the project team insight into the process behind manufacturing modified C material. Findings included:

- Amby quarry produced significant quantities of modified C material during the TNRP and have large quantities on stock at the moment. They have not supplied road base material since mid-2014.
- In order to meet the finer grading required for modified C, Amby would typically add dust that was available in large quantities on site (from crushing operations, etc.).
- Addition of overburden material may be suitable to achieve minimum shrinkage requirements.
- Overall, major changes to production (time and money) are not required to produce modified C as compared to traditional C grading material (may not be the case at every quarry).
- No additional tests are undertaken when switching to a modified C grading.
- A large quantity of test results and material summaries have been provided and will be analysed for the project report (see Section 6.3).
- Five buckets of material were provided to run through a range of tests (see Section 6.3.2).

C.2.3 Barcaldine TMR Regional Office

A meeting was held on April 14 at the Barcaldine offices with District Director Eric Denham and Eric Peterson. This meeting was framed around the experiences throughout the TNRP in the region, and a discussion around the use of modified C material, with the main findings being:

- Materials in this region were generally designed according to a WQ35 grading (or a modified version of WQ35). This would likely be in line with the modified C grading requirements, although may not reach all performance requirements. This may make it difficult to directly compare performance with known modified C projects in other regions.
- Materials high in sand or with too little fines created constructability and performance issues. When fines were too low, any subgrade movement meant that the highly interlocked upper layer had no chance to move and subsequently cracked.
- Some local materials have very high levels of fines (up to 16% passing 75 µm sieve), but perform relatively well.
- A material more in line with the modified C grading would allow some forgiveness with reactive subgrades, and this has been taken into account when specifying materials (as a ‘modified’ WQ35 material).

C.2.4 Emerald TMR Regional Office

Although the Emerald office has been significantly scaled back and many duties for the region are now carried out from Rockhampton, a meeting was arranged with Principal Engineer Alicia Ruhl of TMR and Michael O’Sullivan who had previously worked with TMR and has extensive experience in the quarry industry. Michael was a vocal proponent of the Modified C grading in the early years of its adoption (see Commentary 1).

Discussions around modified C focussed on the following:

- Emerald had used a lot of modified C material between 1999 and 2005, but very little since. Material now typically sits around 7–9 % passing the 75 µm sieve, which leaves little room for error. Fines below 8 or 9 % can lead to problems (as documented).
- Construction practices mean that it can be easy to lose 1% fines in transport, which can make a big difference. Thus, there needs to be a focus on construction practices, not just specifications.
- Some modified C was used on widening jobs, partly with a view to stop water getting in and out of the pavement (lower permeability).
- Emphasised the importance of the *[Linear Shrinkage] x [% passing 0.425 mm]* relationship; this can have a big impact on CBR if outside specification.
- Some modified C material was manufactured by adding fines to an in-situ base material.
- The test results provided by quarries and contractors should be audited and checked carefully, especially when 1–2 % change in fines can be critical.
- Most quarries in the Emerald region cannot naturally produce modified C, so need to add fines. This will come at some additional cost but these days most quarries have the required equipment to do this. The region just needs to specify the material requirements.
- During TNRP, the region had little input with regards to materials used, so there may be large sections of road with a more traditional C grading (less fines). This would be interesting to monitor over coming years.
- Quarries will aim for the highest profit from their production runs, which would often mean running a fairly coarse grading to reduce the amount of crushing required.

- Modified C in Emerald looks to be of most benefit on roads where a relatively shallow pavement depth is designed. Not as critical on 400 mm+ depth pavements with stabilisation.

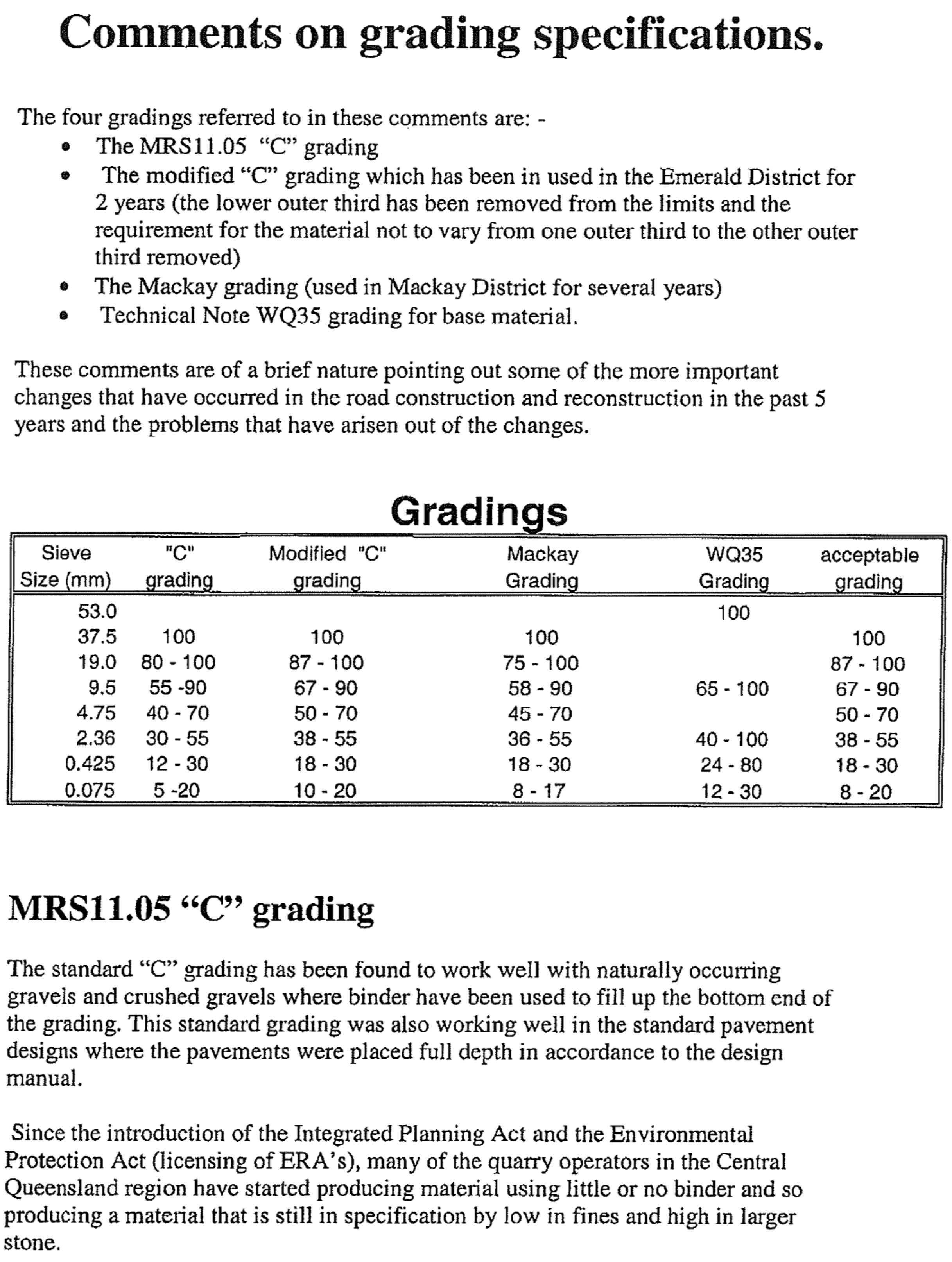
In summary, the trip to south-west and central-west Queensland was important in validating and clarifying several of the important findings of Year 1 of the research, and allowed for greater confidence in framing the recommended limits for changes to the specification. It will be important to continue to gather feedback from the regions and industry over the coming years if a modified C grading is to be introduced more widely.

APPENDIX D KNOWN MODIFIED C PAVEMENTS FOR ONGOING MONITORING

Table D 1: Jobs identified as being constructed using Modified C material

Material	Job Name/Number	Project Number	Road	Chainage Start	Chainage End	Distance	Additional Requirements
Mod C 3.1 and 3.3	SWTD-888	259/18E/6, 259/18E/656, 259/18E/7 & 259/18E/657	18E	40.5	63.44	22.94	Additional requirements for LL, PI, PL, LS, Dust Ratio
Mod C 3.1 and 3.3	SWTD-888	259/18E/11 & 259/18E/658	18E	69.5	76.96	7.46	Additional requirements for LL, PI, PL, LS, Dust Ratio
Mod C 3.1 and 3.3	SWTD-888	259/18F/1 & 259/18F/652	18F	0.2	3.75	3.55	Additional requirements for LL, PI, PL, LS, Dust Ratio
Mod C 3.1 and 3.3	SWTD-1002	259/18E/13	18E	9.81	10.81	1	Additional requirements for LL, PI, PL, LS, Dust Ratio
Mod C 3.1 and 3.3	SWTD-1002	259/18E/655, 259/18E/802	18E	18.265	31.44	13.175	Additional requirements for LL, PI, PL, LS, Dust Ratio
Mod C 3.1	SWTD-981	259/18E/653	18E	10.675	18.12	7.445	Additional requirements for LL, PI, PL, LS, Dust Ratio
Mod C 3.1 and 3.4	SWTD-744	259/18E/650	18E	5.84	9.845	4.005	Additional requirements for LL, PI, PL, LS, Dust Ratio
Mod C 2.2	SWTD-848	247/13B/650	13B	45.4	53.3	7.9	
Mod C 2.2	SWTD-835	247/13B/650	13B	53.3	57.09	3.79	
Mod C 3.1	SWTD-864	247/13B/650	13B	0.03	45.4	45.37	Linear Shrinkage = 1.5 min
Mod C 3.1	SWTD-859	247/13A/651	13A	0	88.88	88.88*	Linear Shrinkage = 1.5 min
Mod C 3.1	SWTD-947	247/18G/650	18G	0	79.73	79.73*	Linear Shrinkage = 1.5 min
Mod C 3.1	STHD-1489	247/18G/652	18G	0.12	5.8	5.68	Linear Shrinkage = 1.5 min
Mod C 3.1	STHD-1489	247/23C/650	23C	15.48	19.2	3.72	Linear Shrinkage = 1.5 min
Mod C 3.1	STHD-1489	247/23C/650	23C	19.6	77.3	57.7*	Linear Shrinkage = 1.5 min
Mod C 3.1	SWTD-973	259/18F/651	18F	3.75	85.6	81.85	Linear Shrinkage = 1.0 min
Mod C	Pre-TNRP work in Darling Downs region	265/22A/2	22A	92.4	94.8	2.4	
				84.3	86.8	2.5	
Mod C		40/22A/48	22A	77.6	79.6	2	
Mod C		265/22B/801	22B	14.7	16.8	2.1	
Mod C		114/313/17	313	19.4	20.5	1.1	
Mod C	Work in late 1990s in Emerald region	12/46C/301	46C	137.5	153.5	16	
Mod C		50/27A/302	27A	23.15	27.83	4.68	
Mod C		12/96B/31	96B	130.2	147.6	17.4	
Mod C		12/96B/32	96B	111.7	130.2	18.5	
Mod C		12/46D/304	46D	54	65	11	
Mod C		12/46D/310	46D	34	44	10	

COMMENTARY 1



Comments on grading specifications.

The four gradings referred to in these comments are: -

- The MRS11.05 "C" grading
- The modified "C" grading which has been in used in the Emerald District for 2 years (the lower outer third has been removed from the limits and the requirement for the material not to vary from one outer third to the other outer third removed)
- The Mackay grading (used in Mackay District for several years)
- Technical Note WQ35 grading for base material.

These comments are of a brief nature pointing out some of the more important changes that have occurred in the road construction and reconstruction in the past 5 years and the problems that have arisen out of the changes.

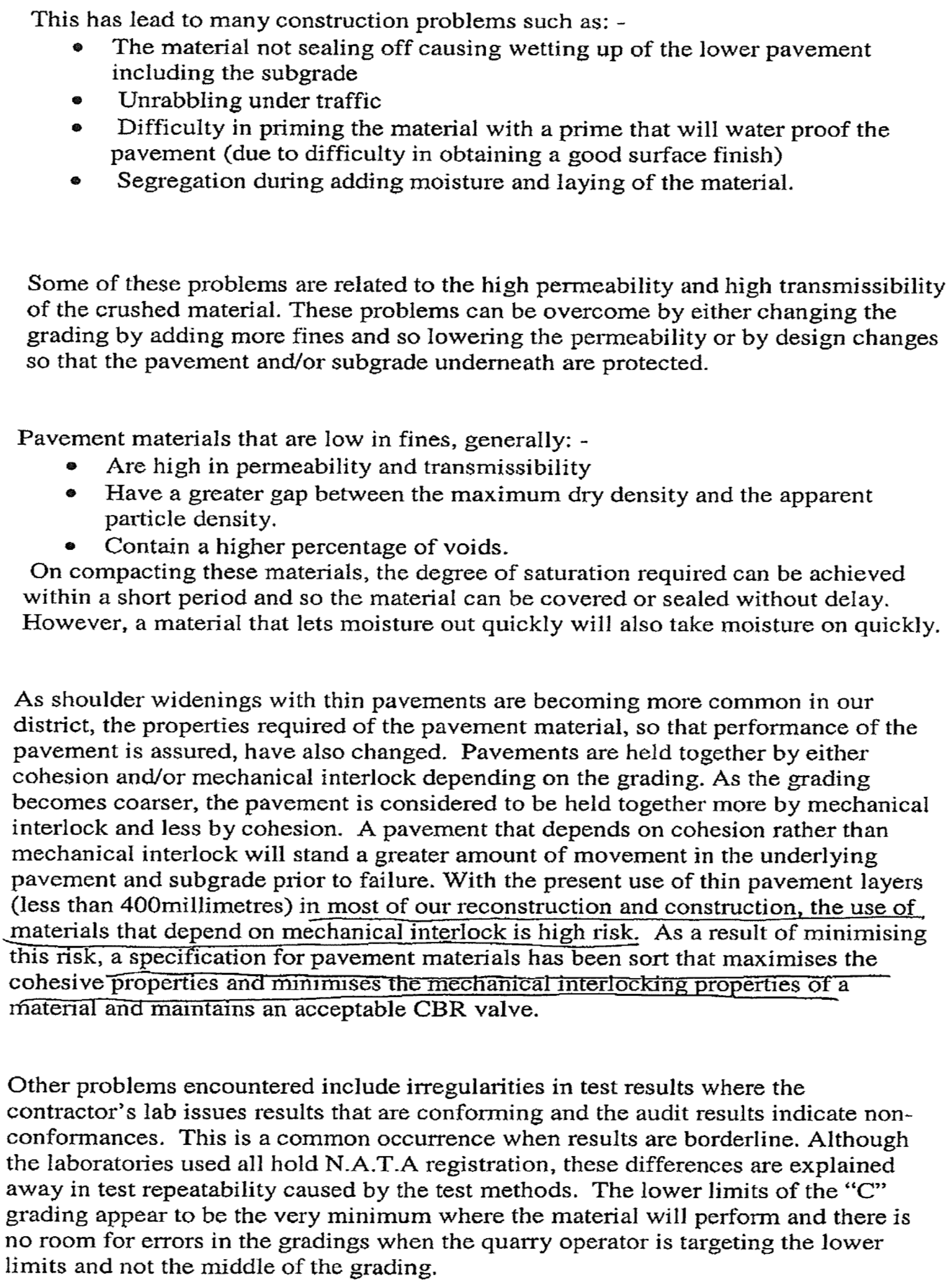
Gradings

Sieve Size (mm)	"C" grading	Modified "C" grading	Mackay Grading	WQ35 Grading	acceptable grading
53.0				100	
37.5	100	100	100		100
19.0	80 - 100	87 - 100	75 - 100		87 - 100
9.5	55 -90	67 - 90	58 - 90	65 - 100	67 - 90
4.75	40 - 70	50 - 70	45 - 70		50 - 70
2.36	30 - 55	38 - 55	36 - 55	40 - 100	38 - 55
0.425	12 - 30	18 - 30	18 - 30	24 - 80	18 - 30
0.075	5 -20	10 - 20	8 - 17	12 - 30	8 - 20

MRS11.05 "C" grading

The standard "C" grading has been found to work well with naturally occurring gravels and crushed gravels where binder have been used to fill up the bottom end of the grading. This standard grading was also working well in the standard pavement designs where the pavements were placed full depth in accordance to the design manual.

Since the introduction of the Integrated Planning Act and the Environmental Protection Act (licensing of ERA's), many of the quarry operators in the Central Queensland region have started producing material using little or no binder and so producing a material that is still in specification by low in fines and high in larger stone.



This has lead to many construction problems such as: -

- The material not sealing off causing wetting up of the lower pavement including the subgrade
- Unrabbling under traffic
- Difficulty in priming the material with a prime that will water proof the pavement (due to difficulty in obtaining a good surface finish)
- Segregation during adding moisture and laying of the material.

Some of these problems are related to the high permeability and high transmissibility of the crushed material. These problems can be overcome by either changing the grading by adding more fines and so lowering the permeability or by design changes so that the pavement and/or subgrade underneath are protected.

Pavement materials that are low in fines, generally: -

- Are high in permeability and transmissibility
- Have a greater gap between the maximum dry density and the apparent particle density.
- Contain a higher percentage of voids.

On compacting these materials, the degree of saturation required can be achieved within a short period and so the material can be covered or sealed without delay. However, a material that lets moisture out quickly will also take moisture on quickly.

As shoulder widenings with thin pavements are becoming more common in our district, the properties required of the pavement material, so that performance of the pavement is assured, have also changed. Pavements are held together by either cohesion and/or mechanical interlock depending on the grading. As the grading becomes coarser, the pavement is considered to be held together more by mechanical interlock and less by cohesion. A pavement that depends on cohesion rather than mechanical interlock will stand a greater amount of movement in the underlying pavement and subgrade prior to failure. With the present use of thin pavement layers (less than 400millimetres) in most of our reconstruction and construction, the use of materials that depend on mechanical interlock is high risk. As a result of minimising this risk, a specification for pavement materials has been sort that maximises the cohesive properties and minimises the mechanical interlocking properties of a material and maintains an acceptable CBR valve.

Other problems encountered include irregularities in test results where the contractor's lab issues results that are conforming and the audit results indicate non-conformances. This is a common occurrence when results are borderline. Although the laboratories used all hold N.A.T.A registration, these differences are explained away in test repeatability caused by the test methods. The lower limits of the "C" grading appear to be the very minimum where the material will perform and there is no room for errors in the gradings when the quarry operator is targeting the lower limits and not the middle of the grading.

Modified "C" grading (Emerald)

After considering several possible solutions to solving these problems, it was decided to trial deleting the bottom third off the "C" grading. The construction problems were considerably reduced however the quarry operators experienced problems in producing material that had a greater than 10% passing the 0.075millimetre sieve and greater than 67% passing the 9.5 millimetre sieve and maintaining a C B R valve of 80. Effectively, this change means that the material has to be finer with more stone in the middle of the grading. As the stone needs to be smaller, the production rates of the crushing plants are lower and so the cost of production higher.

The advantages in using this specification are: -

- The material has a low permeability and so when placed protects the layer under neath.
- The material will compact with the placement moisture and does not require flooding from the top to gain compaction (cheaper to compact).
- The material is less prone to unrabble under traffic and so less watering is required prior to priming or covering.
- Better chance of obtaining a waterproof prime on the pavement due to a better surface finish.
- The material will withstand some subgrade movement, prior to failure. The resulting failure is usually not a seal failure and so although failed the seal still offers some protection to the pavement.

The disadvantages in using this specification are: -

- The material has a higher density in the pavement and so more tonnes of material (if purchasing material over a weighbridge) are required to complete the project.
- The required degree of saturation will take longer to achieve in the pavement (delays of 1 or 2 days in covering the layer or priming the layer).
- As production rates are lower, the cost of the material may be higher.
- The CBR values gained from this material are lower however they still meet the minimum requirements.

My comment with this grading is that 8% passing the 0.075 millimetre sieve from the auditing lab is sufficient. If the 0.075 millimetre sieve specification was lowered to 8% and the auditing lab obtains a result of 6 or 7% than the construction problems of the past will resurface.

The changing of the minimum required on the 0.075 millimetre sieve may also affect the maximum allowed in the standard specification for L.S * %< 0.425 mm which may require relaxing to 95 for Type 2.2 and 120 for Type 2.3.