FINAL REPORT

Project Title: P70: Developing Acceptance Criteria for Asphalt with Low Air Voids (Year 1 – 2017/18)

ARRB Project No: PRP17034

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AN INITIATIVE BY:

SUMMARY

This report presents the findings from the first year of a multiyear investigation of *Developing Acceptance Criteria for Asphalt with Low In-situ or Production Air Voids.* The objective of the first year of the study is to:

- review national and international literature regarding the deformation resistance of dense graded asphalt with low air void contents
- recommend interim changes to current TMR practice (MRTS30 *Asphalt Pavements*) based upon outcomes from the literature review
- develop a laboratory testing program to evaluate the deformation resistance of dense graded asphalt with low air voids.

Key findings from the literature review include the following:

- International literature recommended in-situ air voids do not fall below 3.0%, to decrease the risk of flushing, bleeding and premature rutting.
- The Northern Territory Department of Infrastructure, Planning and Logistics (DIPL), TMR and Main Roads Western Australia (MRWA) were the only Australian road agencies reviewed that specified payment reductions for non-conformances below the in-situ characteristic lower limit.

Interim recommendations for updating MRS30 *Asphalt Pavements* and MRTS30 *Asphalt Pavements* include:

- In-situ air void contents should not be less than 3.0% until laboratory testing on local mixes can identify an acceptable lower limit.
- Conduct laboratory testing on typical DGA mixes used by TMR to identify the rejection criteria for insufficient in-situ air void contents for both PMB mixes and conventional binder mixes.

The proposed laboratory testing for year 2 of the study includes:

- Cooper wheel tracker testing of typical TMR DGA mixes:
  - one AC20M and AC20H mix using C600 binder
  - one AC14M and AC14H mix using A15E PMB
  - using at least six percentages of air void contents, 0.0% or refusal, 1.0%, 2.0%, 3.0%, 4.0% and 5.0% to evaluate the deformation resistance at 2.0% above and 3.0% below the minimum characteristic limit currently specified by TMR.
- Hamburg wheel tracking device testing of mixes identified from Cooper wheel tracker testing that may be of significant interest.

Following laboratory investigation in the second year of the study, it is envisaged that results will guide the update to current TMR specification MRS30 *Asphalt*

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Pavements for a reduced payment regime for low, non-conforming air voids. Knowledge transfer of the project findings will be undertaken for both TMR and industry personnel.

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1 INTRODUCTION

1.1 Background

In 2015, the Queensland Department of Transport and Main Roads (TMR) aligned its asphalt specification more closely with New South Wales Roads and Maritime Services (RMS) specification R116 *Heavy Duty Dense Graded Asphalt*. Since this change, there has been a significant increase in the number of 20 mm dense graded asphalt lots that do not comply with specification requirements for in-situ air voids (i.e. Prequalified Asphalt Contractors being unable to consistently comply with RMS requirements which have now been adopted by TMR). The performance implications of these non-conformances are not well understood for TMR registered mixes and has led to contractual disputes on several projects since its implementation.

1.2 Purpose

The purpose of this project was to provide a greater understanding of the performance implications of non-conforming air voids in the production mix, as well as in the compacted asphalt, and improve outcomes for both TMR and industry when these non-conformances arise on projects.

1.3 Objectives

The investigation of *Developing Acceptance Criteria for Asphalt with Low In-situ or Production Air Voids* is a multiyear effort to allow for the evaluation of the performance implications of non-conforming air voids during the production and placements of asphalt mixes. A three-year study has been planned with different objectives set for each year.

In the first year of the study, the aimwas to review literature regarding the current practice of both national and international road agencies. Scope for laboratory investigation will be developed based upon findings of the literature review.

The second year of the study will focus on undertaking laboratory testing on typical dense graded asphalt (DGA) mixes used by TMR, with varying binder and air void contentss. The TMR specifications for asphalt will be updated based upon the results of these experiments and a study of current practice.

The envisaged objective of the final year of the study will be to update current TMR specifications to include a reduced payment regime for low air voids and undertake a knowledge transfer of project outcomes to both TMR and industry personnel.

1.4 Approach

1.4.1 Year 1 – Literature Review

The objective to provide a greater understanding of the performance implications of non-conforming air voids in the production mix as well as in the compacted asphalt was accomplished through:

- a review of national and international literature regarding the deformation resistance of dense graded asphalt with low air voids
- recommending interim changes to current TMR practice based upon outcomes from the literature review
- developing a laboratory testing program to evaluate the deformation resistance of dense graded asphalt with low air voids.

1.4.2 Year 2 – Laboratory Testing and Recommendations

Year 2 of the project will provisionally involve:

- undertaking Cooper wheel tracker testing on typical dense graded asphalt (DGA) mixes used by TMR with varying binder and air void contents to determine the performance implications of low air voids on the deformation resistance of these mixes
- developing recommendations for reduced payment and rejection criteria for asphalt with low air voids
- preparing an update to MRTS30 *Asphalt Pavements* based upon learnings resulting from the literature review and laboratory testing.

1.4.3 Year 3 – Specification Update

Year 3 of the project will include finalisation of the update to current TMR specifications that include a reduced payment regime for low air voids and the preparation of an impact statement for specification publication. Knowledge transfer will be undertaken for dissemination of project outcomes to TMR personnel and the wider industry.

2 LITERATURE REVIEW

2.1 Introduction

Low air voids tested during the production of asphalt mixes and low in-situ air voids of asphalt mixes during construction have a significant influence on the performance of road pavements. Low air void contents may lead to a wide spectrum of asphalt failures, such as permanent deformation, bleeding and/or shoving. Unintended increases in the binder contents or fine components (or both) of asphalt during production are the main reasons for the reduction of air voids during asphalt production. When low air voids are encountered during production or placement of asphalt mixes, the specifying agency must decide whether to require the material that has already been placed to be removed and replaced or whether it can be left in place with a financial penalty to the contractor. This choice involves performance and pecuniary risks for road agencies and contractors (McDaniel & Levenberg 2013).

This section reviews some international studies of the performance implications of low production and in-situ air voids, and then summarises the specification requirements for Australian, New Zealand and selected international road agencies.

2.2 Previous Studies

2.2.1 Study 1

In 2013, McDaniel & Levenberg conducted a study for the Indiana Department of Transportation (INDOT) to develop a decision strategy based on managing risk when accepting or rejecting asphalt layers with low in-situ air void contents. The background, methodology and findings of this study are summarised in the following sections.

Background

Low in-situ air void contents have historically caused several problems for asphalt mixes. During the process of developing the Marshall Mix Design Method, it was discovered that in-place mixes with 2.5% or lower air void contents shoved in hot weather.

Brown and Cross (1989) studied the influence of air void contents on the deformation resistance of in-situ asphalt mixes. The study investigated pavements that had experienced premature permanent deformation and pavements that had no permanent deformation after at least 10 years of service. Results indicated that low in-situ air void contents were a suitable indicator for rutting. Brown and Cross (1992) further investigated the influences of various mix design parameters on rutting, across 42 asphalt pavements in 14 states in the USA. Findings from the study indicated that in-situ asphalt with air voids lower than 3% were subject to rutting (cited in McDaniel & Levenberg 2013).

In contrast to the aforementioned studies, some researches have reported appropriate asphalt performance for low in-situ air void mixes. Davis (1988 cited in McDaniel & Levenberg 2013) stated that large-stone dense graded mixes (with maximum aggregate size of 50 mm or larger) with low in-situ air voids (lower than 3%) demonstrated acutely good performance without experiencing any rutting. However, it is important to note that the mixes investigated utilised very soft bitumen.

In the WesTrack field study (FHWA 1999 cited in McDaniel & Levenberg 2013), a section of asphalt was designed to have a low air void content of 1.7% and achieved an in-situ average of 1.6%. Results found that this section experienced lower rutting/shoving compared to other experimental sections. Furthermore, low air void mixes were recommended for perpetual pavements to develop fatigue resistant mixes, resulting in rich-bottom asphalt base layers. For instance, pavement researchers in California suggested a pavement reconstruction plan which included an asphalt base layer, 50–75 mm thick containing 2% air voids.

Therefore, based on the discussed literature review, it may be concluded that low air voids may be used as an indicator for asphalt mixes with problematic rutting behaviour. However, the actual in-situ behaviour of the pavement may also be influenced by other parameters such as mix design and environmental aspects (McDaniel & Levenberg 2013).

Study plan

INDOT conducted a study into low production and in-situ air voids to develop a decision-support tool for dealing with low air voids based upon the projected rutting performance of the pavement. The study was undertaken in three sections. In the first part, INDOT sponsored two asphalt pavement test sections at the National Center for Asphalt Technology (NCAT) Test Track. The second part involved testing mixes in the Accelerated Pavement Testing (APT) Facility. The third part consisted of using a simulating software named Quality Related Specification Software (QRSS) to study effects of low air voids on flexible pavement performance (McDaniel & Levenberg 2013).

The test sections were comprised of one 12.5 mm nominal DGA surface course mixture, designed in accordance with the Superpave methodology, containing unmodified PG 64-22 binder and compacted at 60 gyrations.

Findings

The significant findings from the investigation were as follows:

- Low in-situ air void contents were achieved by either increasing the fines content or the bitumen content of the mixes (i.e. low air voids in the laboratory compacted samples) and in both situations, significant rutting was observed. Table 2.1 shows the impact the sections using low laboratory and in-situ air voids have on rut depth. If the rutting is from the low void mixes and not the underlying structure, the rut depths of up to approximately 70% for the reconstructed section are significant considering the asphalt lift thicknesses.

Table 2.1: Relationship between laboratory air voids, in-situ air voids and rut depth

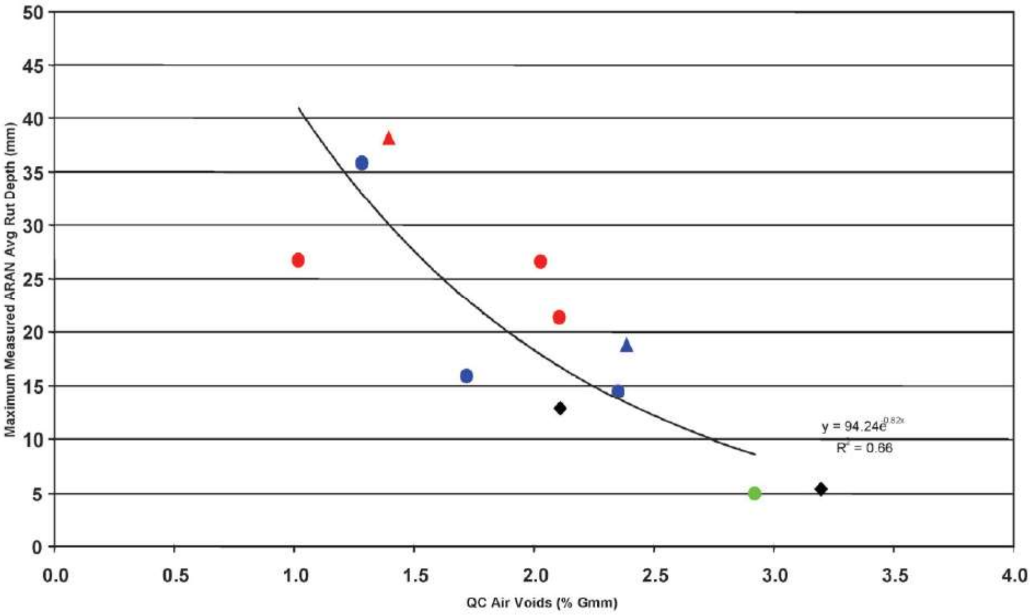
Section	Laboratory air voids (%)	In-situ air voids (%) at construction completion	Rut depth (mm)
Original section (100 mm thickness)			
S7A	1.4	2.2	35
S7B	2.1	3.9	20
S8A	2.0	3.9	22
S8B	1.0	2.3	30
Reconstructed section (50 mm milled and repaved)			
S7A	2.4	–	18
S7B	1.7	–	17
S8A	2.4	–	12
S8B	1.3	–	35

Source: McDaniel & Levenberg (2013).

- Results indicated that mixes with excessive bitumen content developed rutting at a faster rate than mixes with excessive fines; however, both cases developed unacceptable rutting.

- The study recommended that mix removal should be considered for mixes with less than 2.75% in-situ air void contents, but no pay adjustment was necessary for voids above 2.75%. Figure 2.1 summarised the outcomes of the test track project. The figure clearly shows permanent deformation increased significantly for mixes with lower than 2.75% in-situ air voids.

Figure 2.1: Effects of in-situ air void contents on surface layer rutting based on NCAT Test Track



Source: McDaniel & Levenberg (2013).

- In the APT study, permanent deformation took place in the pavement as a result of placing low in-situ air void mixes in the pavement layers (either surface or intermediate course). Similar rutting was obtained in the pavement regardless of placing low air void mixes in the surface or intermediate course, and regardless of low air voids produced by high portion of fine particles or binder contents.
- A mechanistic model was developed to extend the APT study and examine the rutting behaviour when the low in-situ air voids occurred deeper in the pavement structure. The model indicated that similar rutting development would take place, with ruts being wider than if the surface mix rutted.
- QRSS under-predicted the permanent deformation observed at NCAT; however, it was able to predict rutting performance in the APT.

Table 2.2 provides a summary of the outcomes of the NCAT and APT studies where traffic loading is described using equivalent single axle loads (ESALs). The table includes some recommendations, which can be used as a decision-support tool for heavy duty asphalt mixes. It should be noted that the interim criteria provided in Table 2.2 is based upon limited data from two studies. The table should be considered as an indicative tool and does not explicitly account for site-specific conditions, including pavement structure, materials and field conditions (McDaniel & Levenberg 2013).

Table 2.2: Proposed decision-support tool for dealing with mixes with low in-situ air voids

In-situ air void contents (%)	Traffic intensity (20 year) Lower (ESALs 3 000 000)	Traffic intensity (20 year) Higher (ESALs 3 000 000)
3.0	1	1
2.9	1	2
2.8	2	2
2.7	2	2
2.6	2	3
2.5	3	3

Where 1 = accept without monetary reduction,
2 = consider leaving in place with monetary reduction,
3 = consider removing and replacing.

Source: McDaniel & Levenberg (2013).

In summary, the research found that similar permanent deformation performance was obtained in mixes containing low air voids, whether placed in the surface or intermediate courses (at least 50 mm below surface) of the pavement. Additionally, the reason for low air voids in the mix (either excessive binder or fine particles), did not significantly affect the final rutting behaviour of the pavement. Mixes with excessive binder contents had a faster rutting rate, with or without increased fines, but unacceptable rutting still occurred. Mechanistic models indicated that mixes with low air voids can impact surface rutting even if used for lower pavement layers (up to 300 mm below surface) (McDaniel & Levenberg 2013).

2.2.2 Study 2

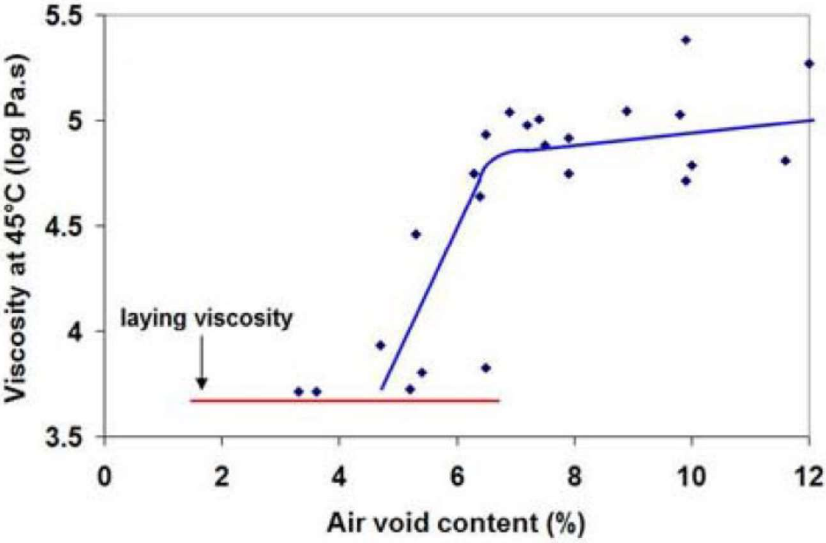
Background

Austroads (2011) published a research report which focused on the influence compaction has on the properties of DGA. The following sections summarise the key findings of that report.

Bitumen hardening

A field study by Oliver (1992) evaluated the performance of a gap-graded trial mix laid 10 years previous for a lightly trafficked residential street. Results from the study indicated that below approximately 5% in-situ air voids, the mix did not show an increased level of hardening of the binder. However, at an in-situ air void content of approximately 6–7%, hardening of the binder was evident in the mix (Figure 2.2). It is important to note that the binder type was not stated in the study.

Figure 2.2: Effect of air void content on the hardening rate of bitumen in an asphalt surfacing



Source: Oliver (1992).

Modulus

One study by Rowe et al. (2009) evaluated the effect of air void contents on the dynamic modulus of a standard Kentucky mix containing unmodified PG 64-22 binder. The mix was designed in accordance with the Superpave design methodology, using a 9.5 mm DGA mix and compacted at 75 gyrations. Results from the study indicated that the mix stiffness increased as voids were decreased over the range 2.3% to 11.3%.

Permeability

Permeability of asphalt mixes is directly affected by the volume of air voids in the mix. Asphalt permeability drops significantly with a decrease in the air void contents of the mix. Table 2.3 provides typical values of the permeability of field and laboratory mixes at various air void contents (Austroads 2011).

Table 2.3: Typical permeability data for dense graded asphalt

14 mm DG – Prepared in laboratory (1)		14 mm DG – Field cores (2)	
Air void content (%)	**Permeability (x10-5 cm/s)**	**Air void content (%)**	**Permeability (x10-5 cm/s)**
3.2	0.0071	5.6	26
4.9	0.30	5.9	130
5.6	0.61	7.7	115
7.7	22	9.1	336

1 Maupin (2001).

2 Hall and Ng (2001).

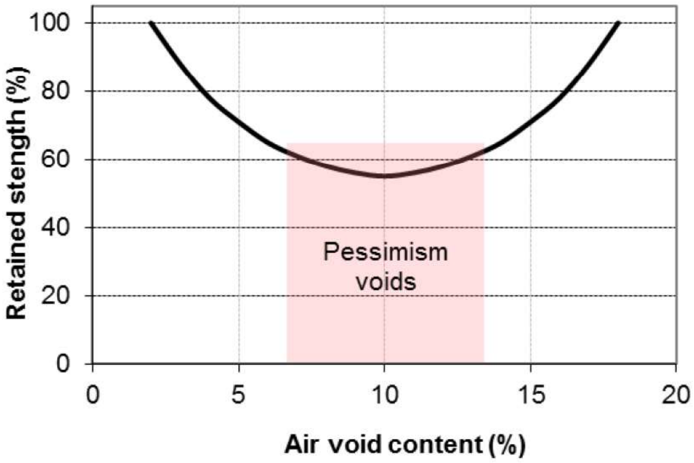
Source: Austroads 2011.

Moisture sensitivity

Information relating asphalt compaction to moisture sensitivity is currently limited as moisture sensitivity testing typically requires sample compaction to fit a relatively narrow air void content range of 6% to 8%. Furthermore, testing outside this range can lead to errors (Austroads 2011).

Moisture sensitivity is typically defined as a strength ratio between the saturated and dry state of an asphalt mix. It is generally believed that asphalt strength may be increased by decreasing the air void contents. Kandhal (1994 cited in Austroads 2011) presented a general model to reflect the impact of air void contents. This model used the term ‘pessimism voids’ for defining a spectrum of air voids which produce the poorest performance for asphalt. This model assumed that asphalt has a higher retained strength either side of the pessimism voids area (Figure 2.3).

Figure 2.3: Model of ‘pessimism voids’ specifying a zone of poorest performance



Source: Kandhal (1994) cited in Austroads (2011).

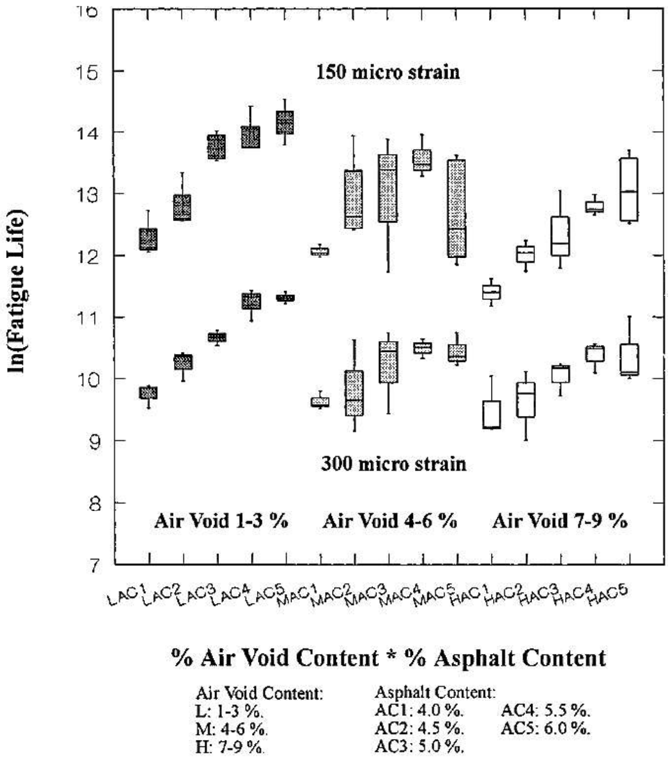
Yapp, Durrani and Finn (1993 cited in Austroads 2011) indicated that moisture sensitivity was reduced when air void contents decreased (for field cores), which may be attributed to the reduction in voids restricting water ingress. Another study by Liu and Kennedy (1991 cited in Austroads 2011) found that pavements with lower voids had a higher tensile strength ratio.

2.2.3 Study 3

Harvey and Tsai (1996) investigated the effect of binder content and laboratory air void content on the fatigue performance and flexural stiffness of a representative Caltrans asphalt mix used for surface overlays. The mix was a 19 mm DGA mix containing AR-4000 unmodified binder, tested at varying binder contents and laboratory air void contents using the flexural bending beam test. Mixes were compacted using a steel-wheel roller.

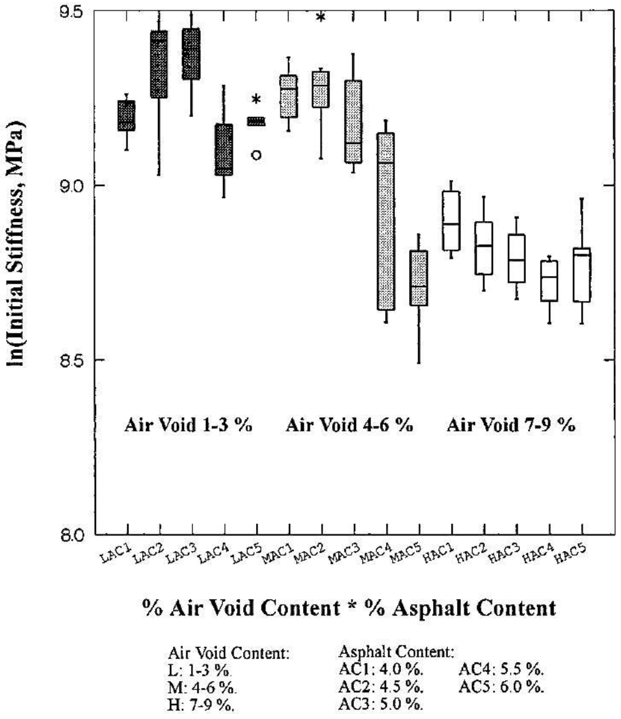
Linear regression between laboratory fatigue life and the natural log of tensile strain, as presented in Figure 2.4 indicates that as the bitumen content increases, and the air voids decrease, the fatigue life of the mix increases. Figure 2.5 presents the relationship between stiffness versus bitumen content and air void content, where it can be observed that lower air void and bitumen contents produces stiffer mixes.

Figure 2.4: Laboratory fatigue life test outcomes vs. air void content, asphalt content, and tensile strain



Source: Harvey & Tsai (1996).

Figure 2.5: Stiffness test outcomes vs. air void content and asphalt content



Source: Harvey and Tsai (1996).

Additionally, an earlier study by Harvey and Monismith (1993) conducted on mixes containing AR-4000 unmodified binder, AC-30 unmodified binder and an AR-4000 modified crumb rubber bitumen, indicated that high air void contents can significantly reduce the fatigue life of asphalt, while low air void contents (between 1% to 3%) can increase the stiffness and extend the fatigue life of asphalt mixes. Lower air void contents establish a homogenous mix with smaller, well distributed voids, and with a reduction of stress concentrations around large voids. Mix compaction was undertaken using three techniques, gyratory, California kneading and rolling wheel.

2.2.4 Other Studies

Previous research has indicated that the air void content in an in-situ asphalt pavement is reduced as a consequence of traffic loading. A field study by Austroads (2011) indicated that the in-situ air void contents changed by an average of 1.3% in less than 1 year. Table 2.4 provides air voids changes in the study conducted by Austroads (2011).

Table 2.4: Average air void contents of dense graded asphalt in service

	Mix 1	Mix 2	Mix 3	Mix 4	Mix 5	Mix 6	Mix 7
Initial average	7.1	8.3	6.8	3.9	7.1	9.5	7.4
Average after 125 days	5.0	7.1	5.7	2.3	6.6	7.0	6.1
Average after 217 days	6.2	7.2	5.1	2.9	6.3	6.7	6.8
Source: Unpublished data by the author.							

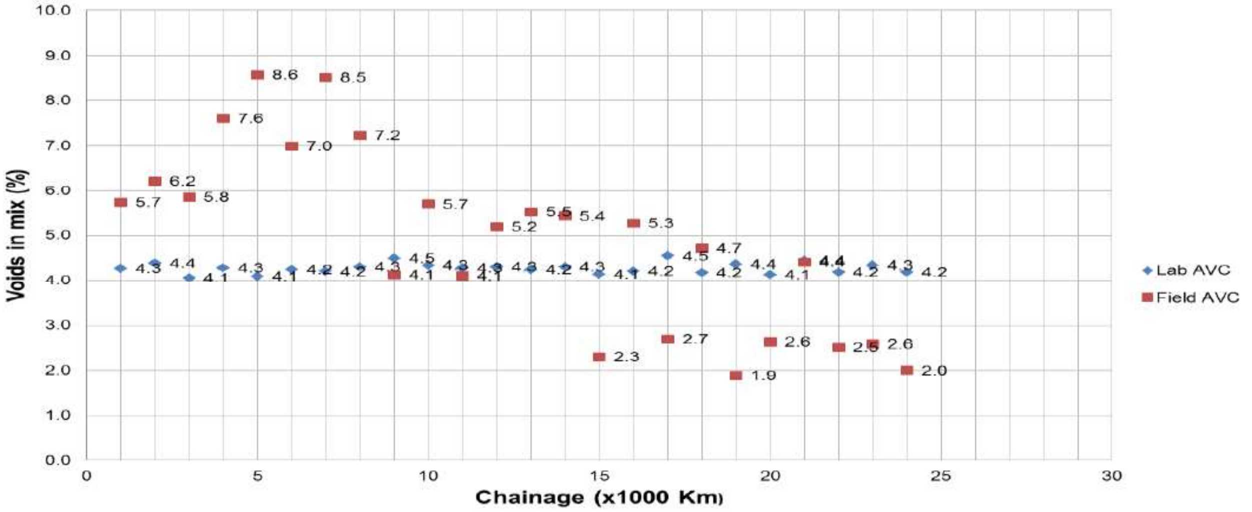
Source: Austroads (2011).

Another study by van Loon and Hood (2007 cited in Austroads 2011) on a DGA-wearing course indicated a reduction of 2% (on average) in air void contents over a period of 2.5 years. Sterling and Zamhari (1997) reported that the air voids in asphalt pavements reduce at a rate of 3% to 4% after loading. Therefore, asphalt mixes designed using the Marshall method to contain between 3% to 4% air voids may have a long-term in-situ air void content of between 0% to 2% as a consequence of traffic loading. This led to the Asphalt Institute (1994 cited in Sterling & Zamhari 1997) recommending compacting asphalt pavements to 8% in-situ air voids to allow for expected consolidation during trafficking, targeting a 'final' air void content of 4%. It is important to note that the asphalt mix types and binder grades were not specified in this research.

Harrigan (2002) investigated the relationship between air void contents and pavement performance using various projects and performance data. The projects investigated included mixes with unmodified and modified binders. However, the research could not establish a link between air void contents and asphalt performance, indicating that the field performance of pavements is not influenced by any single factor such as air voids, but rather by several parameters including traffic, climate and mix design (Austroads 2011).

Kizyalla and Ekolu (2014) compared the laboratory air voids and in-situ air void contentss of an asphalt mix during construction of a pavement in South Africa using Marshall parameters for quality control testing. However, no correlation was found between laboratory and in-situ air void contents as shown in Figure 2.6. It is important to note the binder grade tested was not specified in this report.

Figure 2.6: Laboratory air void versus in-situ air void contents



Source: Kizyalla & Ekolu (2014).

Tran, Turner and Shambley (2016) provided a summary of past research into the effects of air void content on fatigue life of asphalt pavements as presented in Table 2.5. A 1% reduction in air void contents is estimated to improve the fatigue performance of an asphalt pavement by a range of 8.2% to 43.8%, varying with the mix and experiment type.

Table 2.5: Relationship between air voids on fatigue performance

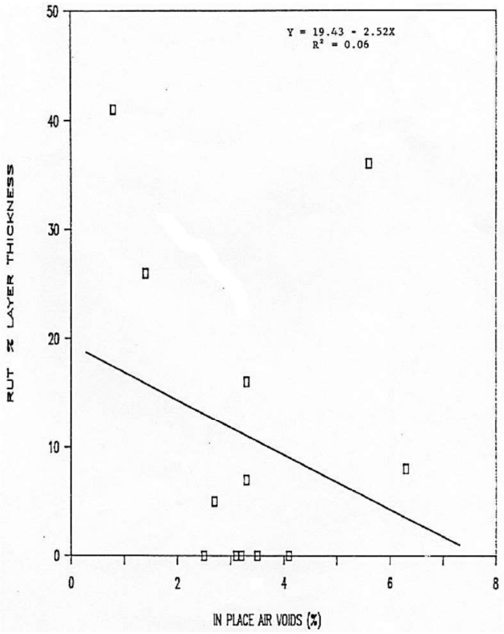
Study	Lab/field experiment	Mix type	Air voids evaluated	Increase in fatigue life for 1% decrease in air voids
Epps & Monismish (1969)	Lab	British Standard	4–14%	20.6%[1]
		California fine	5–8%	43.8%[1]
		California coarse	2.5–7%	33.8%[1]
Harvey & Tsai (1996)	Lab	California dense graded	1–3% 4–6% 7–9%	15.1%[1]
Epps et al. (2002)	Lab	Fine	4, 8, 12%	13.5%[1]
		Fine-plus	4, 8, 12%	13.3%[1]
		Coarse	4, 8, 12%	9.0%[1]
	Field	Fine/fine-plus	4, 8, 12%	21.3%[1]
		Coarse	4, 8, 12%	8.2%[1]
Fisher et al. (2010)	Lab	9.5 mm dense graded	4–11.5%	9.2%

1 Seeds et al. (2002).

Source: Tran, Turner and Shambley (2016).

Brown and Cross (1989) indicated that asphalt layers near the surface of flexible pavements containing low air void contents may cause critical rutting problems. According to literature reviews cited in this study, rutting initiates when the voids content of the mix is below 3%. This study provided a connection between rutting and air voids, where significant rutting develops as the air void content is reduced for DGA mixes used for both surfacing and intermediate coarse asphalt layers, as presented in Figure 2.7. Another study in 1991 by Brown and Cross found that low air void contents (lower than 3%) significantly increase the rutting potential in asphalt pavements.

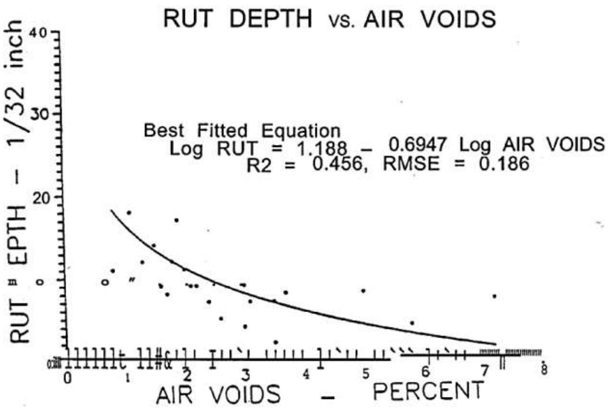
Figure 2.7: In-situ air voids versus layer rutting



Source: Brown and Cross (1989).

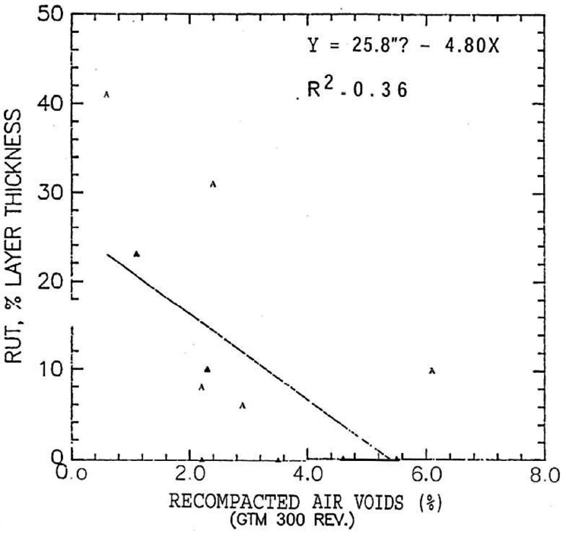
Brown (1990) reviewed several studies concerning low air voids in asphalt. The literature reviewed indicated that low air voids (below 3%) are one of the main precursors for rutting. Additionally, it indicated that asphalt should be produced and placed to have at least 2.5% air voids, as observed in Figure 2.8. Brown concluded that the minimum final in-situ air voids should be at least 3%, otherwise excessive rutting can occur (Figure 2.9). The study did not specify mix types or binder grades.

Figure 2.8: Air void contents versus rut depth



Source: Brown (1990).

Figure 2.9: Air void contents versus rut depth



Source: Brown (1990).

McLeod (1987) indicated that a minimum of 3% air void is required for preventing flushing and bleeding and recommended that DGA is designed to contain air void contents in the range 3% to 5% using Marshall compaction.

2.3 Australian Practice

This section provides a comprehensive review of available documents and specifications used by Australian state road agencies (SRAs) regarding production and in-situ air voids of DGA mixes.

2.3.1 TMR

TMR in-situ air voids

TMR's approach to specifying the required in-situ compaction of asphalt layers has undergone a relatively recent change in practice.

Prior to 2009, TMR only specified a maximum requirement for in-situ air voids at the time of construction (i.e. there was no minimum requirement for in-situ air voids). The in-situ air voids requirements included in the 2009 version of the specification are presented in Table 2.6.

Table 2.6: In-situ air voids limits for dense graded asphalt (MRTS30, July 2009)

Asphalt mix nominal size (mm)	Surfacing, binder and base layers		Corrector layers	Joints
	Characteristic value (%)		Average value (%)	Average value (%)
	Minimum	Maximum	Maximum	Maximum
DG7	3.0	10.0	10.0	–
DG10	3.0	10.0	10.0	12.0
DG14	3.0	8.0 (9.0*)	8.0 (9.0*)	10.0
DG20	2.0	7.0	7.0	10.0
DG28	2.0	7.0	7.0	10.0

* For target compacted layer thickness < 50 mm.

Source: TMR (2009).

Since 2009, TMR's specification MRTS30 *Asphalt Pavements* (2017b) was revised to align with current RMS specifications for asphalt mixes. The 2017 version of MRTS30 *Asphalt Pavements* states that asphalt pavement layers thicker than 30 mm must meet the characteristics values for in-situ air voids as summarised in Table 2.7. The characteristic values of the in-situ air voids of the asphalt are determined in accordance with test method Q311 (TMR 2016), or AS/NZS 2891.8 and Q020 (TMR 2016).

Table 2.7: In-situ air voids limits for dense graded asphalt (MRTS30, October 2017)

Location	Layer	Limits of characteristic value of the in-situ air voids (%)	
		Specified layer thickness > 30 mm and < 50 mm	Specified layer thickness ≥ 50 mm
Mat	Surfacing layer and layer below surfacing	$V_L = 3.0$ and $V_U = 8.0$	$V_L = 3.0$ and $V_U = 7.0$
	Layer covered by two layers of asphalt	$V_L = 2.5$ and $V_U = 8.0$	$V_L = 2.5$ and $V_U = 7.0$
	Layer covered by three or more layers of asphalt	$V_L = 2.0$ and $V_U = 8.0$	$V_L = 2.0$ and $V_U = 7.0$
Joints(1)	All	$V_U = 11.0$	$V_U = 10.0$

1 Only asphalt constructed as part of the Works shall be tested (including asphalt abutting existing pavement or other infrastructure).

Note: V_L is the lower limit for characteristic value of in-situ air voids and V_U is the upper limit for characteristic value of in-situ air voids.

Source: TMR (2017b).

It is important to note that in accordance with the 2017 version of MRTS30 *Asphalt Pavements*, the allowable in-situ air voids at the pavement joints are higher than the maximum characteristic value allowed for within the mat. Deductions are applied to non-conformances below the lower limit and in excess of the upper limit of the characteristic air voids value in accordance with Table 2.8 and Table 2.9 respectively (TMR 2017a).

Table 2.8: TMR deductions for non-conforming in-situ air voids below the lower limit specified

In-situ air voids below minimum specified limit V_L by	Deduction (% of lot or sub-lot value) *
0.1%	5
0.2%	10
0.3%	15
0.4%	20
0.5%	25

* Deductions do not apply to surfacing layers.

Source: TMR (2017a).

Table 2.9: TMR deductions for non-conforming in-situ air voids above the upper limit specified

In-situ air voids out of specified limit V_u by	Deduction (% of lot value)	
	AC7M, AC7H, AC10M, AC10H, AC14M, AC14H	AC20M and AC20H
≤ 0.5%	2.5	5
0.6–1.0%	7.5	15
1.1–1.5%	15	30
1.6–2.0%	30	50
> 2.0%	Reject	Reject

Source: TMR (2017a).

TMR mix design air voids

Prior to 2009, TMR registered mixes were required to comply with the requirements listed in Table 2.10 using 50 blows per face Marshall compaction. Compliance was checked using the tolerances mixes (i.e. fine grading, high binder content and coarse grading, low binder content) for each mix design. MRTS30 was undated in 2009 to include an air voids requirement for the 'design mix'. In 2009, a production mix air voids test was included in the specification for characterisation purposes (and not for compliance).

Table 2.10: TMR DGA requirements for air voids in laboratory compacted specimens (MRTS30 (1993 to April 2015))

Property	Unit	Limit	Value				
			Asphalt nominal size (mm)				
			DG7	DG10	DG14	DG20	DG28
Voids in mineral aggregate (VMA)	%	Minimum Maximum	15.0 19.0	14.0 18.0	13.0 17.0	12.5 16.5	12.0 16.0
Voids filled with binder (VFB)	%	Minimum Maximum	58 78	58 78	58 78	58 78	58 78
Air voids in the compacted mix (design mix)	%	Minimum Minimum	4.9 5.9	4.6 5.6	4.3 5.3	4.1 5.1	4.0 5.0

Source: TMR (2009; 2011); Queensland Transport (1993a; 1993b).

The current TMR requirements for air voids in laboratory compacted specimens are presented in Table 2.11. It is important to note that TMR allows the use of either Marshall or gyratory compaction methods for DGA mixes, but the method used must be specified on the asphalt mix design certificate.

Whilst the requirements in Table 2.11 explicitly refer to the air voids in laboratory compacted specimens (Marshall or gyratory) and not the in-situ air void content, this may provide an indication of how prone a mix may be to over-compaction in the field.

Table 2.11: TMR laboratory compacted specimen requirements for DGA

Asphalt type	Laboratory compaction method(1)	Air voids in laboratory compacted specimens(2) (%)	Applicable test methods/standards
Medium duty dense graded asphalt	Marshall compaction (50 blows per face) or gyratory compaction (120 cycles)	3.0–6.0	AS/NZS 2891.2.2, RMS T662 or Q305[4] AS/NZS 2891.7.1 or Q307A[4] AS/NZS 2891.8 or Q311[4] AS/NZS 2891.9.2 or Q306B[4]
Heavy duty dense graded asphalt	Marshall compaction (50 blows per face) or Marshall compaction (75 blows per face)	3.0–6.0 3.0–6.0	
	Gyratory compaction (120 cycles) and (350 cycles)	3.0–6.0 ≥ 2.0(3)	

1 The laboratory compaction method to be used for a particular mix design must be stated on the asphalt mix design certificate.
2 Compliance shall be assessed using the average of results from duplicate test specimens.
3 Lot average.
4 Source: (TMR 2016).

Source: TMR (2017b).

2.3.2 *Department of Infrastructure, Planning and Logistics (DIPL)*

DIPL in-situ air voids

The Northern Territory Department of Infrastructure, Planning and Logistics (DIPL) applies payment reduction levels to the asphalt compaction (i.e. in-situ air voids). The limits for the characteristic value of in-situ air voids for newly constructed mixes with a thickness of at least 30 mm are summarised in Table 2.12 (DIPL 2017a). However, for asphalt mixes used for road repair and maintenance with a thickness of at least 30 mm, the characteristic value of in-situ air void contents should comply with Table 2.13.

Table 2.12: DIPL conformance and reduction levels of characteristic air voids value for new pavements

Reduction level (payment reduction %)	Light traffic	Medium traffic	Heavy traffic
Conformance (0%)	3.0–8.0	3.0–8.0	3.0–7.0
Reduction level 1 (5%)	8.1–9.0	8.1–9.0	7.1–8.0
Reduction level 2 (10%)	9.1–10.0	9.1–10.0	8.1–9.0
Reduction level 3 (20%)	> 10.1 and < 3.0	> 10.1 and < 3.0	> 9.1 and < 3.0

Source: DIPL (2017a).

Table 2.13: DIPL characteristic value of air voids conformance limits for road maintenance

	Light traffic	Medium traffic	Heavy traffic
Conformance	3.0–9.0	3.0–9.0	3.0–8.0

Source: DIPL (2017b).

Conformance testing is conducted by taking core samples of lots in accordance with the DIPL *Standard Specification for Road Maintenance* (2017b) and the in-situ density is determined in accordance with test method NTCP 102.1 (DIPL 2013) and AS 1289.5.8.1.

DIPL mix design air voids

DIPL specifies the requirements for design air voids in DGA mixes based upon the nominal size of mix, the level of traffic and the binder type. DIPL also allows the use of either Marshall or gyratory compaction methods for DGA mixes, where the current requirements are presented in Table 2.14. It is important to note that the with the exception of deep lift (≥ 80 mm thickness) design, the mix design voids are not specified as an acceptable range.

Table 2.14: DIPL design air voids for DGA mixes

Mix type	**1[1]**	**2[1,2]**	**3[3]**	**4[4]**	**5[5]**	**6[3]**
Mix size (mm)	7	10	14	20	14	10
Marshall design air voids	4.0	5.0	5.0	5.0	5.0	4.0
Compaction cycles	Design air voids in laboratory compacted mix (%)					
50	4.0	N/A	N/A	N/A	N/A	N/A
80	N/A	4.0	N/A	N/A	N/A	4.0
120 (deep lift[6])	N/A	4.0	4.0	4.0 (3.0–6.0)	4.0 (3.0–6.0)	4.0
250 (deep lift[6])	N/A	> 2.5	> 2.5	> 2.0 (≥ 2.0)	> 2.5 (≥ 2.0)	N/A

1 Light traffic, cycle paths and pedestrian traffic.
2 Medium traffic, car parking with no heavy vehicles, low volume traffic.
3 Medium traffic, car parking with heavy vehicles, buses.
4 Heavy traffic, structural layers.
5 Heavy traffic, all urban roads and intersections and industrial estates.
6 Pavement installation ≥ 80 mm in thickness.

Source: DIPL (2018).

2.3.3 Department of Planning, Transport and Infrastructure (DPTI)

DPTI in-situ air voids

The conformance criteria for the characteristic in-situ air voids is presented in DPTI Specification R28 *Construction of Asphalt Pavements* (2016) and is summarised in Table 2.15 for projects estimated to contain less than 50 000 tonnes of asphalt, whereas the requirements for major projects (> 50 000 tonnes of asphalt) are summarised in Table 2.16. The characteristic air void content is determined using the bulk density, expressed as a percentage of the mean maximum density. Bulk density is determined in accordance with AS 2891.9.2 for DGA, where the maximum density is determined in accordance with AS 2891.7.1.

Table 2.15: DPTI compaction criteria (projects < 50 000 tonnes of asphalt)

Pavement layers	**Asphalt mixes**	**Characteristic air voids (%) – min**	**Characteristic air voids (%) – max**
Wearing & levelling layers	AC10	4.0	8.0
Levelling, intermediate & base layers	AC14	2.5	7.0
Intermediate & base layers	AC20	2.5	7.0
High binder base layer	AC14 high binder	1.0	5.0
Wearing course	FineAC7	2.0	6.0
Wearing course	FineAC10	2.5	7.0

Source: DPTI (2016).

Table 2.16: DPTI compaction criteria for major projects (> 50 000 tonnes of asphalt)

Pavement layers	Asphalt mixes	In-situ voids target (%)	Characteristic air voids (%) – min	Characteristic air voids (%) – max
Wearing course	Dense graded mix	6.5	4.0	8.0
Levelling course	Dense graded mix	6.0	4.0	8.0
Intermediate courses	Dense graded mix	5.0	2.5	7.0
Base course	Dense graded mix	4.0	2.5	7.0
High binder base course	Dense graded mix	2.5	1.0	5.0
Wearing course	FineAC7	4.0	2.0	5.0
Wearing course	FineAC10	4.5	2.5	6.0

Source: DPTI (2016).

DPTI mix design air voids

Air void characteristics for mix design and production control of coarse and fine DGA (excluding RAP) must comply with Table 2.17 and Table 2.18 respectively. In addition to these tables, DPTI Specification R27 *Supply of Asphalt* (2017) requires compliance with the mix production tolerances for air voids, specified in Table 11 of AS 2150.

Table 2.17: DPTI mix properties for coarse DGA

Characteristic		Gyratory cycle no.	AC10	AC14	AC20	AC14HB
Nominal mix sieve size (mm)			9.5	13.2	19	13.2
Design & production air voids target (%)	Medium duty (MD)	80	4.0	4.0	4.0	2.5
	Heavy duty (HD)	120	4.0	4.0	–	–
Production air voids tolerance (%)			Target ± 1.5	Target ± 1.5	Target ± 1.5	Target ± 1.5

Source: DPTI (2017).

Table 2.18: DPTI mix properties for fine DGA

Characteristic	FineAC7	FineAC10
Nominal mix sieve size (mm)	6.7	9.5
Light duty design (gyratory cycles)	50	50
Design & production air voids target (%)	4.0	4.0
Production air voids tolerance (%)	Target ± 1.5	Target ± 1.5
Target in-situ voids (%) (refer to Spec R28)	2.0–5.0	2.5–6.0

Source: DPTI (2017).

The design and production air voids target and tolerance are 4.0% and ±1.5% respectively, for both coarse and fine DGA mixes, apart from the AC14HB (high bitumen) mix where the target air void content is 2.5%.

2.3.4 Main Roads Western Australia (MRWA)

MRWA in-situ air voids

The characteristic in-situ air void content requirements for intermediate asphalt courses is presented in Table 2.19. However, it is important to note that the maximum characteristic in-situ air void content for an intermediate mix is currently 7.0% to allow asphalt suppliers to implement new asphalt mix designs (MRWA 2017a).

Table 2.19: MRWA intermediate course in-situ air void requirements

Mix type	Characteristic value (%)	
	Minimum	Maximum
All layers of 14 mm and 20 mm asphalt	3.0	6.0(1)

1 The aim is for asphalt suppliers to be able to consistently achieve a characteristic in-situ air void content of 3–6%. To allow for asphalt suppliers to implement new asphalt mix designs and construction practices to achieve this outcome, and until a transition is fulfilled, the maximum characteristic value for in-situ air voids is 7.0%.

Source: MRWA (2017a).

In accordance with MRWA Specification 504 *Asphalt Wearing Course* (MRWA 2017b), in-situ conformance is based upon the characteristic Marshall density of each lot, as summarised in Table 2.20.

Table 2.20: MRWA wearing course density conformance pay factors

Characteristic percent Marshall density, Rc (%)	Quality level	Pay factor
≥ 93.0	Conformance	1.0
≥ 91.0 and < 93.0	Conditional conformance	0.15 * Rc – 12.95
< 91.0	Non-conformance	N/A

Source: MRWA (2017b).

MRWA mix design air voids

Similar to the in-situ air void requirements, MRWA mix design air void limits vary for wearing course and intermediate course asphalt. The wearing course production voids requirement also varies based on the compaction method used. The voids in Gyratory compacted specimens must not be less than 2.5% voids after 350 cycles. The Marshall compaction limits for various constituent materials used by MRWA are summarised in Table 2.21 (MRWA 2017b).

Table 2.21: MRWA Marshall method (75 blows) wearing course DGA mix assessment values

Parameter	Minimum (%)	Maximum (%)
Nominal 10 mm Laterite	3.0	6.0
Nominal 10 mm – Perth and Southern areas of the state	4.0	6.0
Nominal 10 mm – Northern and Eastern areas of the state	4.0	7.0
Nominal 5 mm	3.0	5.0
Nominal 14 mm (Intersection Mix)	4.0	7.0

Source: MRWA (2017b).

The design air void content requirements for 14 mm or 20 mm DGA, in accordance with MRWA Specification 510, *Asphalt Intermediate Course* (2017a) are summarised in Table 2.22.

Table 2.22: MRWA intermediate course mix properties

Air void content	Test method	Minimum (%)	Maximum (%)
Design target PSD	WA 733.1	4.2	4.8
Production range		3.5	5.5
After 350 cycles gyratory compaction*		2.0	–

* Applicable for design target only.

Source: MRWA (2017a).

2.3.5 Roads and Maritime Services

RMS in-situ air voids

RMS typically utilises two types of DGA, light duty asphalt for design traffic less than 10 million equivalent standard axles (ESAs) or heavy duty asphalt for design traffic greater than 10 million ESAs or other high stress locations. However, the characteristic in-situ air void requirements are the same for both types of asphalt, as summarised in Table 2.23. It is important to note that asphalt layers less than or equal to 30 mm thickness do not require in-situ air void testing (RMS 2013a; 2013b; 2013c).

Table 2.23: RMS in-situ air voids standard

Limits for characteristic values of in-situ air voids	
Specified layer thickness > 30 mm and < 50 mm	Specified layer thickness ≥ 50 mm
V_L = 3.0% and V_U = 8.0%	V_L = 3.0% and V_U = 7.0%

Note: V_L is the lower limit of characteristic value of in-situ air voids and V_U is the upper limit of characteristic value of in-situ air voids.

Source: RMS (2013a; 2013b; 2013c).

RMS only applies payment deductions to lots where the air void content is higher than the upper limit specified, as summarised in Table 2.24. It is worth noting that RMS does not include payment deductions for lots where the air void content is lower than the lower limit specified.

Table 2.24: RMS deductions for non-conforming in-situ air voids

In-situ air voids out of specified limit V_u by	Deduction (% of value of lot)	
	Light duty	Heavy duty
< 0.5%	2.5%	5%
0.5–1.0%	15%	30%
1.1–1.5%	30%	50%
1.6–2.0%	50%	Reject*
> 2.0%	Reject	Reject*

* In-situ air voids outside of V_u by > 1.5% are rejected.

Source: RMS (2013a; 2013c).

RMS mix design air voids

The required air void limits for laboratory compacted DGA mixes are summarised in Table 2.25. RMS uses the gyratory compaction method for DGA mixes but varies the required number of compaction cycles with the type of asphalt. However, except for heavy duty DGA compacted under 350 cycles of gyratory compaction, the air voids requirements for light duty and heavy duty DGA are within the same range (3.0–6.0%).

Table 2.25: RMS laboratory compacted specimen requirements for DGA

Asphalt type	Laboratory compaction method	Air voids in laboratory compacted specimens (%)	Applicable test methods/standards
Light duty dense graded asphalt	Gyratory compaction (80 cycles)	3.0–6.0	AS/NZS 2891.2.2, RMS T662 AS/NZS 2891.7.1 or AS 2891.7.3 AS/NZS 2891.8 AS/NZS 2891.9.2
Heavy duty dense graded asphalt	Gyratory compaction (120 cycles)	3.0–6.0	
	Gyratory compaction (350 cycles)	≥ 2.0*	

* Does not apply to 5 mm nominal size asphalt.

Source: RMS (2013a; 2013b; 2013c).

2.3.6 Transport Canberra and City Services (TCCS)

TCCS in-situ air voids

TCCS specifies both an upper and lower limit for in-situ air voids, as presented in Table 2.26. Asphalt layers with a thickness less than 30 mm are not tested for in-situ air voids (TCCS 2010). For layers greater than 60 mm thick, a nuclear gauge may be used to measure in-situ voids.

Table 2.26: TCCS limits for in-situ air void contentss for dense graded and fine gap graded asphalt

Limits for characteristic values of in-situ air voids for DGA	
Heavy duty application excluding courses of specified thickness less than 50 mm.	All other asphalt including heavy duty application courses of specified thickness less than 50 mm.
$V_L = 3\%$ and $V_U = 7\%$	$V_L = 3\%$ and $V_U = 8\%$

Note: Layer less then 30 mm shall not be tested for in-situ air voids.

Source: TCCS (2010).

TCCS mix design air voids

The mix design requirements for TCCS asphalt pavements utilisation of DGA varies depending on the intended purpose, where moderate duty DGA is typically used on collector and arterial roads while heavy duty DGA is typically used on roads subject to heavier loads such as highways (TCCS 2010). The mix production air void requirements for moderate and heavy duty DGA used by the TCCS are summarised in Table 2.27.

Table 2.27: TCCS laboratory compacted specimen requirements for DGA

Asphalt type	Laboratory compaction method	Air voids in laboratory compacted specimens (%)	Applicable test methods/standards
Moderate duty dense graded asphalt	Gyratory compaction (80 cycles)	3.0–6.0	AS/NZS 2891.2.2 AS 2891.7.3 AS/NZS 2891.8 AS/NZS 2891.9.2
Heavy duty dense graded asphalt	Gyratory compaction (120 cycles)	3.0–6.0	
	Gyratory compaction (350 cycles)	≥ 2.5	

Source: TCCS (2010).

2.3.7 VicRoads

VicRoads in-situ air voids

The VicRoads specification for asphalt, Section 407 *Hot Mix Asphalt* (VicRoads 2017), does not specify limits for in-situ air voids, but rather, conformance is based upon the characteristic density ratio (field bulk density to approved laboratory bulk density) of each lot, in accordance with

Table 2.28. Instead, the in-situ characteristic air voids are calculated using Equation 1 and are only required to be reported and any reductions in payment are based upon the density ratios.

Table 2.28: VicRoads limits for characteristic density ratio

For layers < 50 mm thickness		For layers ≥ 50 mm thickness	
Characteristic value of the density ratio (Rc)	Assessment	Characteristic value of the density ratio (Rc)	Assessment
≥ 94.0%	Accept lot	≥ 96.0%	Accept lot
91.0% to 93.9%	Lot may be accepted at a reduced rate, calculated by P = 10 * Rc – 840	91.0% to 95.9%	Lot may be accepted at a reduced rate, calculated by P = 6 * Rc – 476

Source: VicRoads (2017).

$$In - situ\ air\ voids = \frac{Maximum\ density - field\ bulk\ density}{Maximum\ density} * 100 \qquad 1$$

VicRoads mix design air voids

The volumetric properties of DGA types used by VicRoads is generally divided into mixes intended for wearing course applications and mixes intended for structural (intermediate and base course) asphalt layers. The VicRoads air void requirements for asphalt mix design are summarised in Table 2.29. It is important to note that for selected mixes VicRoads allows the use of both the gyratory and Marshall compaction methods.

Table 2.29: VicRoads laboratory compacted mix requirements for DGA

Course	Asphalt type	Laboratory compaction method	Air voids in laboratory compacted specimens (%)	Minimum air voids at 250 gyratory cycles (%)
Wearing course	Light duty (L)	Gyratory compaction (50 cycles) Marshall method (50 blows)	4.0 3.8–4.2	N/A
	Medium duty (N)	Gyratory compaction (80 cycles) Marshall method (50 blows)	4.0 4.9–5.3	2.0
	Heavy duty (H, HG)	Gyratory compaction (120 cycles) Marshall method (50 blows)	4.0 4.9–5.3	2.5
	High performance and/or flexibility (HP)	Gyratory compaction (120 cycles) Marshall method (50 blows)	3.0 –	2.0
Structural course	Heavy duty intermediate (SG, SI, SS)	Gyratory compaction (120 cycles) Marshall method (50 blows)	4.0 4.9–5.3	2.5
	High performance intermediate (SP)	Gyratory compaction (120 cycles) Marshall method (50 blows)	3.0 –	1.2
	Base (SF)	Gyratory compaction (80 cycles) Marshall method (50 blows)	2.0 –	N/A

Source: VicRoads (2016).

2.4 International Practice

2.4.1 New Zealand

New Zealand Transport Authority (NZTA) in-situ air voids

Acceptance criteria for asphalt constructed in accordance with the NZTA *Specification for Dense Graded and Stone Mastic Asphalt* (2014b) are based upon the air voids of the approved mix design. The density of a lot is deemed acceptable if the characteristic air voids are in accordance with the upper and lower offset values presented in Table 2.30.

Therefore, based on the limits for characteristic values of in-situ air voids (Table 2.30) and laboratory compaction requirements (Table 2.31) the indicative minimum in-situ air voids limit may be as low as 1.0% for high fatigue base courses.

Table 2.30: NZTA limits for characteristic values of in-situ air voids based on approved mix design

Asphalt type and thickness (mm)	Maximum characteristic offset value (%)	Minimum characteristic offset value (%)
Asphalt layers greater than 150 mm from a joint	+3	–2
Asphalt layers within 150 mm of a joint	+5	–2

Source: NZTA (2014b).

In-situ air void contents are typically determined using a nuclear gauge or testing core specimens (NZTA 2014a). However, testing using core specimens are not performed on layers less than 30 mm thick and hot mix asphalt (HMA) layers with a nominal thickness less than three times the nominal aggregate size.

NZTA mix design air voids

The approval of a design mix with respect to air void content requires the mean value of three samples' air voids in a plant-produced mix to fall in the range of between +1.1% and –0.8% compared with the design air voids, as presented in Table 2.31, for typical NZTA DGA mixes. Mixes that do not meet these criteria require adjustment to either the production and/or mix design (NZTA 2014b). For assessing the effects of long-term heavy traffic loads and low air void contents in-situ, a minimum 2% air voids under 250 gyratory cycles is introduced as an appropriate indicator.

Table 2.31: NZTA laboratory compacted mix requirements for DGA

Mix type		Laboratory compaction method	Air voids in laboratory compacted specimens (%)	Minimum air voids at 250 gyratory cycles (%)
Traffic category	Application			
Light	Wearing and base	Gyratory compaction (80 cycles) Marshall method (50 blows)	4.0 4.0	N/A
Medium	Wearing and base	Gyratory compaction (80/120 cycles) Marshall method (50/75 blows)	4.0 4.0	Report
	High fatigue base	Gyratory compaction (80/120 cycles) Marshall method (50/75 blows)	3.0 3.0	N/A
Heavy	Wearing and base	Gyratory compaction (120 cycles) Marshall method (75 blows)	4.0 4.0	Report
	High fatigue base	Gyratory compaction (80/120 cycles) Marshall method (50/75 blows)	3.0 3.0	N/A

Mix type		Laboratory compaction method	Air voids in laboratory compacted specimens (%)	Minimum air voids at 250 gyratory cycles (%)
Traffic category	Application			
Very heavy	Wearing and base	Gyratory compaction (120 cycles)	5.0	2.0
		Marshall method (75 blows)	5.0	
	High fatigue base	Gyratory compaction (80/120 cycles)	3.0	N/A
		Marshall method (50/75 blows)	3.0	

Source: NZTA (2014b).

The refusal air void content for DGA used in wearing course applications is 2%, as summarised in Table 2.32 (Transit New Zealand (TNZ) 2005).

Table 2.32: TNZ asphalt performance criteria for DGA wearing course

Test/reference	Method	Test value (%)	Comments
Refusal air voids (%)	ASTM D2726 & ASTM D3203	2 min unless otherwise agreed by Engineer	Heavy/very heavy traffic

Source: TNZ (2005).

2.4.2 United States of America

Asphalt design in the USA is similar to Australia in that each state jurisdiction has adopted design practice relevant to local conditions, based upon a national guide. In the USA the national guide is the American Association of State Highway and Transportation Officials (AASHTO) *Guide for Design of Pavement Structures* (1993).

The AASHTO design guide principally describes the asphalt design practice used in the USA and as such, does not specify acceptance criteria, allowing each jurisdiction to develop their own limits. The jurisdictional requirements reviewed as part of this study are summarised below.

California

The California Department of Transportation (Caltrans) *Standard Specifications* (Caltrans 2015) states compliance of HMA is based upon the in-situ density and theoretical maximum density determined in accordance with California Test 216 (Caltrans 2006), where the allowable maximum density is in the range of 91.0–97.0%. Caltrans allows HMA to remain in place for a maximum density ±2.0% from the specified range with a payment reduction factored in accordance with Table 2.33.

Table 2.33: Caltrans reduced payment factors for per cent of maximum theoretical density

HMA percent of max theoretical density	Reduced payment factor	HMA percent of max theoretical density	Reduced payment factor
91.0	0.0000	97.0	0.0000
90.9	0.0125	97.1	0.0125
90.8	0.0250	97.2	0.0250
90.7	0.0375	97.3	0.0375
90.6	0.0500	97.4	0.0500
90.5	0.0625	97.5	0.0625
90.4	0.0750	97.6	0.0750
90.3	0.0875	97.7	0.0875

HMA percent of max theoretical density	Reduced payment factor	HMA percent of max theoretical density	Reduced payment factor
90.2	0.1000	97.8	0.1000
90.1	0.1125	97.9	0.1125
90.0	0.1250	98.0	0.1250
89.9	0.1375	98.1	0.1375
89.8	0.1500	98.2	0.1500
89.7	0.1625	98.3	0.1625
89.6	0.1750	98.4	0.1750
89.5	0.1875	98.5	0.1875
89.4	0.2000	98.6	0.2000
89.3	0.2125	98.7	0.2125
89.2	0.2250	98.8	0.2250
89.1	0.2375	98.9	0.2375
89.0	0.2500	99.0	0.2500
< 89.0	Remove and replace	> 99.0	Remove and replace

Source: Caltrans (2015).

Texas

The Texas Department of Transportation (TxDOT) *Standard Specifications for Construction and Maintenance of Highways, Streets and Bridges* (TxDOT 2015) utilises pay adjustment factors based on in-situ air voids, as presented in Table 2.34. The asphalt may remain in place where the in-situ air voids are within the range of 2.7–9.9%. However, in-situ voids lower than 3.75% and higher than 8.50% will result in a reduced payment. Notably, air voids between 3.80% and 8.40% will result in an increased payment to the contractor.

Table 2.34: TxDOT pay adjustment factors for DGA in-situ air voids

In-situ air voids	Placement pay adjustment factor	In-situ air voids	Placement pay adjustment factor
< 2.7	Remove and replace	6.4	1.042
2.7	0.71	6.5	1.04
2.8	0.74	6.6	1.038
2.9	0.77	6.7	1.036
3	0.8	6.8	1.034
3.1	0.83	6.9	1.032
3.2	0.86	7	1.03
3.3	0.89	7.1	1.028
3.4	0.92	7.2	1.026
3.5	0.95	7.3	1.024
3.6	0.98	7.4	1.022
3.7	0.998	7.5	1.02
3.8	1.002	7.6	1.018
3.9	1.006	7.7	1.016
4	1.01	7.8	1.014

In-situ air voids	Placement pay adjustment factor	In-situ air voids	Placement pay adjustment factor
4.1	1.014	7.9	1.012
4.2	1.018	8	1.01
4.3	1.022	8.1	1.008
4.4	1.026	8.2	1.006
4.5	1.03	8.3	1.004
4.6	1.034	8.4	1.002
4.7	1.038	8.5	1
4.8	1.042	8.6	0.998
4.9	1.046	8.7	0.996
5	1.05	8.8	0.994
5.1	1.05	8.9	0.992
5.2	1.05	9	0.99
5.3	1.05	9.1	0.96
5.4	1.05	9.2	0.93
5.5	1.05	9.3	0.9
5.6	1.05	9.4	0.87
5.7	1.05	9.5	0.84
5.8	1.05	9.6	0.81
5.9	1.05	9.7	0.78
6	1.05	9.8	0.75
6.1	1.048	9.9	0.72
6.2	1.046	> 9.9	Remove and replace
6.3	1.044		

Source: TxDOT (2015).

2.4.3 South Africa

Asphalt design in South Africa is based on the Southern African Bitumen Association (Sabita) Manual 35 / TRH 8: *Design and use of Asphalt in Road Pavements* (2018). This design manual supersedes the 2001 *Interim Guidelines for the Design of Hot-Mix Asphalt*, which started the move towards performance-related specifications for the design of asphalt pavement materials. The design approach is centred around the selection of a binder content to provide a specified void content of 4% design air voids (Sabita 2018).

Design air voids could be determined using Marshall compaction (SANS 3001-AS1) or Superpave gyratory compaction (AASHTO 2015). Volumetric data is generated and the voids in mineral aggregate (VMA) and voids filled with binder (VFB) are compared at the design binder content to ensure the criteria presented in Table 2.35 and Table 2.36 are met.

Table 2.35: Minimum percent VMA

Nominal maximum particle size (NMPS) (mm)	Minimum VMA(1) for design voids		
	3%	4%	5%
28	11	12	13
20	12	13	14

Nominal maximum particle size (NMPS) (mm)	Minimum VMA[(1)] for design voids		
	3%	4%	5%
14	13	14	15
10	14	15	16

1 Only values for continuously graded mixes are available and presented in this table.

Source: Sabita (2018).

Table 2.36: Percent VFB

Minimum	Maximum
65	75

Source: Sabita (2018).

The *Standard Specifications for Road and Bridge Works for State Road Authorities* (Committee of Land Transport Officials (Colto) 1998) refers to limits specified in the applicable statistical judgement scheme during construction. These limits can be altered in the contract document. For continuously graded mixes, minimum density specifications are generally set at 93% of maximum theoretical relative density (MTRD). Maximum density specifications are often set at 96% of MTRD (Verhaeghe, Myburgh & Denneman 2007). The statistical judgement scheme allows for partial payments generally up to 70% reduction based on lot size and statistical parameters.

For conditional acceptance, the payment reduction factor for a lower limit can be calculated using Equation 2 while the payment reduction factor at an upper limit may be calculated using Equation 3.

$$f_r = 0.67 + 0.3 * (\frac{\bar{x}_n - L_r}{L_a - L_r}) \tag{2}$$

where

f_r = payment reduction factor

$\bar{x}_n$ = arithmetic mean

L_r = rejection limit for sample mean

L_a = acceptance limit for sample mean

$$f_r = 0.67 + 0.3 * (\frac{L_r - \bar{x}_n}{L_r - L_a}) \tag{3}$$

where

f_r = payment reduction factor

$\bar{x}_n$ = arithmetic mean

L_r = rejection limit for sample mean

L_a = acceptance limit for sample mean

2.5 Comparison of Current Practice

A summary of the air voids acceptance criteria and payment reductions for non-conformance in DGA pavement layers used by the NZTA, Caltrans and each of the Australian SRAs is presented in Table 2.37.

Table 2.37: Comparison of road agency air void acceptance criteria for DGA

Road agency	Air voids acceptance criteria	Payment reductions for in-situ non-conformance
TMR	In-situ layer thickness > 30 mm and < 50 mm: Mat, layers covering: 0–1 3.0% and 8.0% 2 2.5% and 8.0% ≥ 3 2.0% and 8.0% Joint: 11.0% max In-situ layer thickness ≥ 50 mm: Mat, layers covering: 0–1 3.0% and 7.0% 2 2.5% and 7.0% ≥ 3 2.0% and 7.0% Joint: 10.0% max Production: Medium/heavy duty: ≥ 3.0%(1, 2) Heavy duty (350 cycles): ≥ 2.0%(2)	Nom. mix size 7/14 mm: Upper limit ≤ 0.5%: 2.5% 0.5–1.0%: 7.5% 1.1–1.5%: 15% 1.6–2.0%: 30% > 2.0%: Reject Nom. mix size 20 mm: Upper limit < 0.5%: 5% 0.5–1.0%: 15% 1.1–1.5%: 30% 1.6–2.0% 50% > 2.0%: Reject Lower limit (in-situ and laboratory compacted) 0.1%: 5% 0.2%: 10% 0.3%: 15% 0.4%: 20% 0.5%: 25%
DIPL	In-situ air voids: Light traffic: 3.0% and 8.0% Medium traffic: 3.0% and 8.0% Heavy traffic: 3.0% and 7.0% Mix design: Light traffic: 4.0%(1, 2) Medium traffic: 4.0%(1) and 5.0%(2) Heavy traffic: 5.0%(1) and 3.0–6.0%(2)	Upper limit: 0.1–1.0%: 5% 1.1–2.0%: 10% > 2.1%: 20% Lower limit: < lower limit: 20%
DPTI	In-situ air voids: Wearing course: 4.0% and 8.0% Levelling course: 4.0% and 8.0% Intermediate course: 2.5% and 7.0% Base course: 2.5% and 7.0% High binder base course: 1.0% and 5.0% Wearing course AC7: 2.0% and 5.0% Wearing course AC10: 2.5% and 6.0% Mix design: Medium/heavy duty: 4.0% ± 1.5%[2]	Not specified.
MRWA	In-situ air voids: Wearing course: Based on characteristic Marshall density DGA 14/20: 3.0% and 6.0%	Not specified for intermediate course. Wearing course payment reductions based upon characteristic Marshall density.

Road agency	Air voids acceptance criteria	Payment reductions for in-situ non-conformance
	Mix design: Wearing course: 3.0–4.0% min$^{(1)}$, 5.0–7.0% max$^{(1)}$ Int. course DGA 14/20: 3.5% and 5.5%$^{(2)}$	
RMS	In-situ layer thickness > 30 mm and < 50 mm: Mat: 3.0% and 8.0% In-situ layer thickness ≥ 50 mm: Mat: 3.0% and 7.0% Mix design: Light/heavy duty: ≥ 3.0% and 6.0%$^{(2)}$ Heavy duty (350 cycles): ≥ 2.0%$^{(2)}$	Light duty upper limit < 0.5%: 2.5% 0.5–1.0%: 15% 1.1–1.5%: 30% 1.6–2.0%: 50% > 2.0%: Reject Heavy duty upper limit: < 0.5%: 5% 0.5–1.0%: 30% 1.1–1.5%: 50% > 1.5%: Reject
TCCS	In-situ layer thickness < 50 mm: Mat: 3.0% and 8.0% In-situ heavy duty layers ≥ 50 mm: Mat: 3.0% and 7.0% Mix design: Moderate/heavy duty: ≥ 3.0% and 6.0%$^{(2)}$ Heavy duty (350 cycles): ≥ 2.5%$^{(2)}$	Not specified.
VicRoads	Not specified. Acceptance criteria based upon field/lab bulk density.	Not specified. Payment reductions based upon field/lab bulk density.
NZTA	Asphalt layers > 150 mm from a joint: Mix design voids offset: +3.0% and –2.0% Asphalt layers ≤ 150 mm from a joint: Mix design voids offset: +5.0% and –2.0% Wearing course voids ≤ 2.0%: Reject Mix design: Wearing/base course: 4.0%$^{(1, 2)}$ High fatigue base: 3.0%$^{(1, 2)}$	Not specified.
Caltrans	In-situ air voids: Asphalt layers: 3.0% and 9.0%	Upper limit 0.1–2.0% 1.25–25% > 2.0%: Reject Lower limit 0.1–2.0% 1.25–25% > 2.0%: Reject
TxDOT	In-situ air voids: DGA layers: 3.75% and 8.50%	Upper limit 0.1–1.4% 2.0–28% > 1.4%: Reject Lower limit 0.1–1.0% 2.0–29% > 1.0%: Reject

Road agency	Air voids acceptance criteria		Payment reductions for in-situ non-conformance
Sabita	In-situ air voids: DGA layers: Mix design: DGA layers:	 4.0% and 7.0% 3.0% and 5.0%	Payment reductions based upon statistical judgement scheme, generally up to 70% reduction based on lot size and statistical parameters.

1 Marshall compaction.
2 Gyratory compaction.

The road agencies reviewed generally adopt different approaches to air voids acceptance criteria, typically based upon the types of asphalt that are commonly used in their jurisdiction and their intended application. However, a lower characteristic limit of 3.0% in-situ air voids is adopted for most of the mixes specified by the road agencies, apart from DPTI, VicRoads and NZTA. Similarly, the lower mix design air void limit of 3.0% is adopted for most of the mixes specified by the SRAs.

Furthermore, payment reductions for in-situ air void non-conformances were only specified by three SRAs and of the three, only two specified payment reductions for lower limit non-conformances.

In 2015, TMR harmonised its asphalt specification, MRTS30 *Asphalt Pavements* with RMS specification R116 (RMS 2013a). As a result, the air voids acceptance limits and payment reductions for non-conformances are similar for these two SRAs. However, TMR has included different limits for pavement joints and the acceptance criteria vary depending on the number of asphalt layers in the mat.

The approach taken by DIPL for payment reductions for non-conformances is similar to TMR in that lower limit non-conformances are penalised. Any lot with a characteristic air void content of less than 3.0% will be subject to a 20% reduction in payment, equivalent to exceeding the upper limit by more than 2.1% air voids thus indicating DIPL regards the lower characteristic limit as more critical to the pavement performance.

DPTI varies the characteristic air void acceptance limits based upon the intended function of the asphalt layer (wearing/structural course), resulting in a range of upper and lower air void limits. The lower limits range from 1.0% for high binder content base course layers to 4.0% for wearing and levelling courses, whereas the upper limits range from 5.0% for high binder content base courses and a 7 mm nominal wearing course to 8.0% in wearing and levelling courses.

MRWA specifies in-situ acceptance limits for intermediate and wearing course DGA layers based upon the nominal size of the mix. Payment reductions for non-conformances are only specified for the wearing course and are based upon characteristic Marshall density. The lower limit of 3.0% is in general agreement with practice of the other road agencies, although, the upper limit of 6.0% is lower than equivalent layers elsewhere. However, it is important to note that MRWA currently allows asphalt producers to comply with an upper limit of 7.0% (1.0% above the specified upper limit) to allow asphalt suppliers to implement new asphalt mix designs.

The VicRoads specifications were silent on the characteristic in-situ air void acceptance limits, preferring to use the characteristic density ratio (field bulk density to approved laboratory bulk density) for lot acceptance.

The compaction acceptance criteria for NZTA asphalt mixes is based upon the approved mix design, where the allowable voids content for the mat is +3.0% and –2.0% from the design air voids. The lowest design air voids used by the NZTA is 3.0% for high fatigue base courses, thus indicating that a minimum of 1.0% in-situ characteristic air voids is allowed in some base courses. However, wearing course layers with a characteristic air void contents less than 2.0% is rejected.

The Caltrans specification, similar to VicRoads, bases acceptance upon the comparison between in-situ and theoretical maximum density. Payment reductions range from 1.25% for non-conformances of 0.1% to 25% for non-conformances of 2.0% for both the maximum and minimum allowable limits.

The acceptance criteria for TxDOT was comparatively unique to the other road agencies reviewed in that the contractor is incentivised by increased payments to provide conforming mixes. The pay adjustment factors result in lower pay for in-situ air voids lower than 3.75% and higher than 8.50% whereas air voids between 3.80% and 8.40% will result in an increased payment to the contractor.

Sabita's statistical judgement scheme bases conformance and payment reduction upon the relative density. The statistical judgement scheme allows for partial payments generally up to 70% reduction based on lot size and statistical parameters.

3 PROPOSED LABORATORY INVESTIGATION

Based on the findings from the literature review and limited information available regarding the impact of low air voids on local asphalt mixes, it is recommended that laboratory testing be undertaken on TMR registered mixes to determine the performance implications of low air voids on deformation resistance using the Cooper wheel tracker. The proposed scope for further investigation is as follows:

- Cooper wheel tracker testing (AGPT/T231) of typical DGA mixes used by TMR:
  - one AC20M and AC20H mix using C600 binder
  - one AC14M and AC14H mix using A15E PMB
  - using at least six percentages of air void contents, 0.0% or refusal, 1.0%, 2.0%, 3.0%, 4.0% and 5.0% to evaluate the deformation resistance at 2.0% above and 3.0% below the minimum characteristic limit currently specified by TMR. The mix design will be varied based upon the Marshall method to achieve the different percentages of air voids in the laboratory, using 50 blow compaction effort.
- Hamburg wheel tracking device (Test Method Q325) of mixes identified from Cooper wheel tracker testing that may be of significant interest.

The results of the laboratory investigation will inform any future changes to the acceptance criteria for low in-situ and production voids in MRTS30 *Asphalt Pavements.*

4 CONCLUSIONS AND RECOMMENDATIONS

A review of national and international current practice relating to the performance implications and acceptance criteria for non-conforming air voids in the production mix, as well as in compacted asphalt was conducted. Significant findings resulting from the review include:

- The international literature reviewed suggests that the in-situ air voids of asphalt layers do not fall below 3.0%, as the risk of flushing, bleeding and premature rutting is increased. However, asphalt layers with in-situ air voids of less than 3.0% can remain in place when a reduced level of service (with associated payment deductions) are acceptable.
- For pavements subject to heavy traffic, the international literature suggests that asphalt layers with in-situ air voids less than 2.6% should be removed.
- In one US-based study, similar permanent deformation performance was obtained in mixes containing low air voids, whether placed in the surface or intermediate courses (at least 50 mm below surface) of the pavement. Furthermore, mechanistic models indicated that pavement layers with low voids up to 300 mm impacted surface rutting.
- Asphalt specimens containing in-situ air voids of between 3.0% and 14.0% were found to have an improved fatigue performance of between 8.2% and 43.8% for every 1.0% reduction in air void content.
- DIPL, TMR and MRWA were the only Australian road agencies reviewed that specified payment reductions for in-situ air void contents below the lower limit specified.
- DPTI varies the characteristic air void acceptance limits based upon the intended function of the asphalt layer (wearing/structural course) and the mix design, resulting in a range of upper and lower in-situ air void limits with a minimum of 1.0% for high bitumen base course layers.
- RMS practice in specifying air voids is similar to the practice adopted by TMR and TCCS.
- The acceptance limits and payment reduction factors in VicRoads are based upon the characteristic density ratio rather than in-situ air void contents.
- Compaction acceptance criteria for NZTA pavements is based upon the approved mix design, where the allowable in-situ air void contents ranges from 1.0% to 3.0% varying with the application.
- The acceptance criteria and payment reduction factors for Caltrans HMA are based upon the relative compaction.
- TxDOT pay adjustment factors for HMA are based upon in-situ air voids and allow for both increased and decreased payments.
- Sabita payment reduction factors are based upon the statistical judgement scheme, allowing for partial payments that may be up to a 70% reduction based on lot size and statistical parameters.

Considering the findings of the literature review and the limited information available on the impact of low air voids on local asphalt mixes, it is recommended that TMR undertakes laboratory testing on typical DGA mixes used by TMR to identify the rejection criteria for insufficient in-situ air void contents for both PMB mixes and conventional binder mixes. At a minimum, the in-situ air void contents should not be less than 3.0% until laboratory testing on local mixes can identify an acceptable lower limit.

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