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FINAL REPORT

P3_Commissioning of Hamburg Wheel Tracking Device (HWDT)

Project No: 007180

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SUMMARY

As a part of the move to performance-based asphalt specifications, the Queensland Department of Transport and Main Roads has commissioned the Hamburg Wheel Tracking Device (HWTD), a laboratory testing device designed to measure the rutting resistance of an asphalt mix and suitable for measuring susceptibility to moisture-induced damage and rutting resistance.

Moisture-induced damage and stripping have been identified as potential issues with asphalt pavements in Queensland and the HWTD may be a suitable replacement for the modified Lottman method, which is currently used to identify stripping potential in asphalt mixes.

A review of the available literature revealed that the HWTD may prove to be more effective at identifying moisture-sensitive mixes and international experience suggests that the device has been used with success around the world.

Initial laboratory testing proved that the HWTD is capable of identifying the combined impact of moisture sensitivity and the stability of various asphalt mixes. The boundaries of the equipment capabilities were established.

Supplementary testing with a varied water bath temperature and air void content showed that these parameters can have a major effect on the resulting rut depths.

The second year of the project included a discussion with industry that helped in the development of a test method and set of testing conditions for an asphalt mix design. Subsequent testing has shown that this method and conditions are likely to be suitable for future HWTD testing, although further testing would help to establish benchmarks and a correlation between field performance and HWTD results.

A draft test method with accompanying testing conditions has been developed and a series of recommendations are made to establish the HWTD as a valuable tool for asphalt mix design and research.

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1 INTRODUCTION

1.1 Need for the Research Topic and Purpose of the Study

Moisture-induced damage can impact on the functional performance of the entire pavement structure; therefore there is a need to reduce the risk of using inappropriate asphalt mixes. Currently the modified Lottman test is used in Australia for assessing the moisture sensitivity of hot mix asphalt (HMA) and the Hamburg Wheel Tracking Device (HWTD) may be a suitable alternative or supplementary test for moisture sensitivity. Although research organisations have different experiences and views on the applicability of the device, it may be considered as a useful tool to identify potential problems with stripping.

This test method is seen by the Queensland Department of Transport and Main Roads (TMR) as an essential support to their transition towards performance-based asphalt specifications, and to benchmark and prove the performance of heavy duty mixes as part of the *Asphalt Harmonisation* project. The successful transition will result in cost savings and it will also raise expectations regarding expected asphalt performance. Also, it is expected that experiences collected from research studies using the HWTD will provide input for education and training, which will indirectly have a positive impact on the overall performance of asphalt pavements in Queensland and at the national level.

The purpose of this study is to evaluate the suitability of the HWTD as an alternative or supplementary method for assessing the performance of asphalt mixes at the design stage in the laboratory in terms of their ability to reduce moisture-induced damage to pavements.

In the second year of the project, the outcomes have narrowed the focus to be on introducing this test alongside the existing moisture sensitivity tests as a supplementary test method.

1.1.1 Methodology

In year 1, the project comprised the following:

- international scale literature review on the
    - origin, development and applicability of the HWTD in the laboratory
    - test configuration, test methods, repeatability and reproducibility with regard to AASHTO T 324-11
    - experiences of international research organisations which use the HWTD according to AASHTO T 324-11
    - limitations to asphalt types and asphalt applications where the equipment may not be suitable
- development and start of a laboratory test plan for fine-tuning according to the AASHTO test method (operation phase) in order to assess flexibility of the equipment (software and test procedure).

The year 2 outcomes included the following:

- meetings with industry leaders and the ARRB/TMR project team to discuss the application and function of the device, as well as formulating appropriate test parameters
- development of a laboratory test plan (performance assessment phase) in order to compare performance of in-service road pavements by testing real mix designs in the laboratory. It is anticipated that a good correlation could be developed between in-service performance and laboratory testing

- preparing a final technical report and recommended test methods for the HWTD.

1.1.2 Background

The HWTD is a laboratory test device designed to predict the performance of asphalt in the field. While originally developed as a test for evaluating the rut resistance of hot mix asphalt (HMA), the HWTD was found to be a suitable test for evaluating the moisture resistance and overall stability of asphalt mixes.

Asphalt pavements may be susceptible to moisture-induced damage, which normally manifests as stripping, which relates to the de-bonding of adhesion between the binder and aggregate. A degradation in these bonds leads to a reduction in strength and stiffness, and ultimately a reduced ability to withstand stress and strain caused by traffic loading. This failure mode is considered one of the major modes of distress in binder (intermediate) and base courses.

Performance-based asphalt testing, unlike volumetric mix design, is able to better simulate the performance of a pavement in the field. In the case of the HWTD, the test simulates the passage of a wheel over a submerged asphalt sample at elevated temperatures. The deformation caused over the duration of the test can be analysed to determine whether the mix has suitable moisture resistance.

Other tests also exist that are designed to evaluate the stripping resistance of asphalt, such as the modified Lottman method (Austroads 2007). The modified Lottman test historically exhibited a poor correlation with moisture-induced damage, with heavy duty mixes passing the modified Lottman requirements yet showing moisture sensitivity issues in the field. Following the introduction of freeze/thaw conditioning, some mixes are now being identified as non-compliant.

A number of research organisations and road authorities have found that the HWTD may be a suitable addition to the suite of existing moisture-sensitivity tests, as it is thought to better replicate conditions in the field. In the longer term, a performance-based test such as the Hamburg test may be a candidate to form part of a new harmonised asphalt specification.

1.1.3 Structure of the report

Section Section 1 outlines the background behind this project, while Section 2 focuses on the literature review on the HWTD. Section 3 explores the project outcomes, including the development phase as well as the laboratory assessment results and data analysis. Section 4 summarises the findings and presents recommendations for usage of the device going forward.

1.2 Moisture-induced Damage

Moisture damage can have a significant effect on the performance and durability of asphalt mixes. The two main mechanisms by which this occurs are adhesive failure and loss of cohesion.

Adhesive failure involves stripping of the asphalt film from the aggregate surface. As water infiltrates the asphalt, there can be a de-bonding of adhesion between the binder and aggregate. The released binder then migrates through the asphalt mix, which can lead to different failure mechanisms, such as rutting, bleeding or cracking of the pavement.

Adhesion failure also relates to the moisture-induced weakening of the bond between binder and aggregate, which can reduce the strength and stiffness of the mix.

Both mechanisms result in a weaker pavement structure which is more prone to distress and deformation under traffic-induced stress and strain. Over time, stripping can cause the loss of material and a deterioration of the road surface. Additionally, in colder climates aggregate particles can be fractured or degraded by the freeze/thaw cycle.

A large number of factors contribute to the potential for, and extent of, moisture damage in asphalt (summarised in Table 1.1). These include factors relating to the physical mix properties, production and construction processes, as well as external factors such as the traffic load and climate.

If moisture-related distress becomes evident in a pavement, it will often be necessary to replace large sections of the pavement layers at significant cost.

Table 1.1: Factors that can contribute to moisture-related distress

Mix design	▪ Binder and aggregate chemistry ▪ Binder content ▪ Air voids ▪ Additives ▪ Particle size distribution
Production	▪ Percent aggregate coating and quality of passing the No. 200 sieve (Australian Standard 75 µm sieve) ▪ Temperature at plant ▪ Excess aggregate moisture content ▪ Presence of clay
Construction	▪ Compaction – high in-place air voids ▪ Permeability – high values ▪ Mix segregation ▪ Changes from mix design to field production (field variability)
Climate	▪ High rainfall areas ▪ Freeze/thaw cycles ▪ Desert issues (steam stripping)
Other factors	▪ Surface and subsurface drainage ▪ Rehabilitation strategies – chip seals over marginal HMA materials ▪ High truck annual average daily traffic (AADT) volumes

Source: TRB (2003).

1.3 Aim and Scope of the Project

This report aims to evaluate the use of the HWTD as an alternative method of performance-based moisture sensitivity testing for asphalt mixes, and introduce a test method which is able to predict the in situ performance of asphalt pavements under Queensland environmental conditions. According to TMR requirements, there is a specific focus on reviewing the test with regard to the specifications and procedures outlined in AASHTO T 324-11.

This includes an analysis of the test methods employed by various road agencies in the United States, and how these procedures and specifications differ from AASHTO T 324-11. Where available, this will include a summary of the experiences of these practitioners in using the HWTD and associated test methods.

The report is primarily focussed on understanding the sensitivity of moisture-induced damage on dense graded asphalt (DGA) and stone mastic asphalt (SMA) as measured by the HWTD; the assessment of open graded asphalt (OGA) is out of scope at this stage.

2 LITERATURE REVIEW

2.1 History of the HWTD

2.1.1 Original usage of the HWTD

The HWTD was developed in the 1970s by Esso A.G. in Hamburg, Germany. The device was based on a similar British device that used a rubber tyre instead of a steel wheel. The machine was originally known as the Esso Wheel-Tracking Device.

The City of Hamburg designed a test method, including pass/fail criterion, to ensure that mixes had low susceptibility to rutting. The test originally required 9540 wheel passes, in a water bath at 40 or 50 ºC. The required number of wheel passes was later increased to 19 200.

Although the original test method did not specify a target air void content, the air void content of the samples has a substantial impact on the test results. It was of paramount importance that the test samples were compacted to a bulk density which would be achieved in the field after construction. This density had to be equal to the density (and air void content) of the design mix, which is 50 Marshall-blow in Germany. Given that Germany does not follow the Superpave approach, it is not expected that the asphalt mix would experience post-compaction under heavy traffic. As is explained in Section 2.2.2, the US specifications require a different level of air void content and consequently compaction level in the laboratory samples (Drüschner, Harders & Ohmen 1997). For comparison, asphalt mixes for intermediate layers (binder layers) in Germany have a design air void content between 3.5% and 6.5% (Forschungsgesellschaft für Strassen-und Verkehrswesen 2008). The original test method was used for asphalt mixes with a maximum aggregate size of 22 mm (Drüschner 1999).

The machine tests a pair of samples simultaneously, with each sample typically measuring 260 mm wide, 320 mm long and 40 mm thick (although the device can accommodate thicknesses up to 150 mm). The samples subsequently have a mass of approximately 7.5 kg. The device can accommodate temperatures between 25 and 70 ºC. The test method uses a steel wheel that is 47 mm wide, and imparts a fixed load of approximately 700 N. Rubber tire wheels are also available to fit to the device.

2.1.2 Initial use of the water bath

The sample is submerged in water, which is a conditioning and test medium. Originally the test method allowed (and still allows today) the use of a temperature chamber for conditioning the samples in air; however, it was found that the conditioning time was much shorter if a water bath was used.

2.1.3 Initial findings

The early experiences and findings with the HWTD in Germany can be summarised as follows (Drüschner, Harders & Ohmen 1997):

- Some fillers were found to be water sensitive; asphalt samples prepared with quartzite filler showed double rut depth compared to samples with diorite filler.
- Smaller rut depths were experienced under dry conditions (i.e. conditioning and testing in an air chamber).
- Steel wheels had a much greater impact on the deterioration rate compared to the case when rubber-coated wheels were used; under the same test parameters the rut depth was found to be double when the steel wheels were used.

It should be emphasised that the above findings are valid for the sample preparation used in Germany, i.e. the sample density (air void content) is close to the design air void content. It was also well known in the early stages of the equipment development that using water as a temperature conditioning and test medium meant that failure would be related to both the plastic deformation and moisture susceptibility of the asphalt mix (Drüschner 1999).

In this study the term 'stability' is used to describe the combined plastic deformation and moisture susceptibility of the asphalt mix. Before commencing any laboratory and field testing it is suggested that the main symptoms and mechanism of moisture-related failure experienced by TMR should be clarified, in order to assess whether the HWTD would replicate this field-related experience.

2.1.4 Further research

Since 1997, German road authorities have tested the rut resistance of asphalts by following the TP A-StB test method, *Wheel-tracking test – Determining the rut depth in a water bath* (Forschungsgesellschaft für Strassen-und Verkehrswesen 1997). While this test is considered effective, it only allows identification of 'good' and 'bad' mixes and is not able to provide a more detailed evaluation. The test uses a steel wheel in a water bath at 50 ºC. The introduction of the European standards led to the development of EN 12697 *Test method for hot mix asphalt – part 22: wheel tracking* (European Committee for Standardization 2003). This test requires tracking a rubber wheel in air at a specified temperature of 40, 50 or 60 ºC (the selection of the temperature depends on the specifications set by each country).

The development of two different test methods prompted a review of the wheel tracking test in an attempt to determine the ideal test conditions to facilitate a performance-based evaluation of asphalt durability (Bundesministerium fur Verkehr, Bau und Stadtentwicklung 2009). It should be noted that this study was primarily concerned with testing the applicability of various test conditions for rutting, not stability in general.

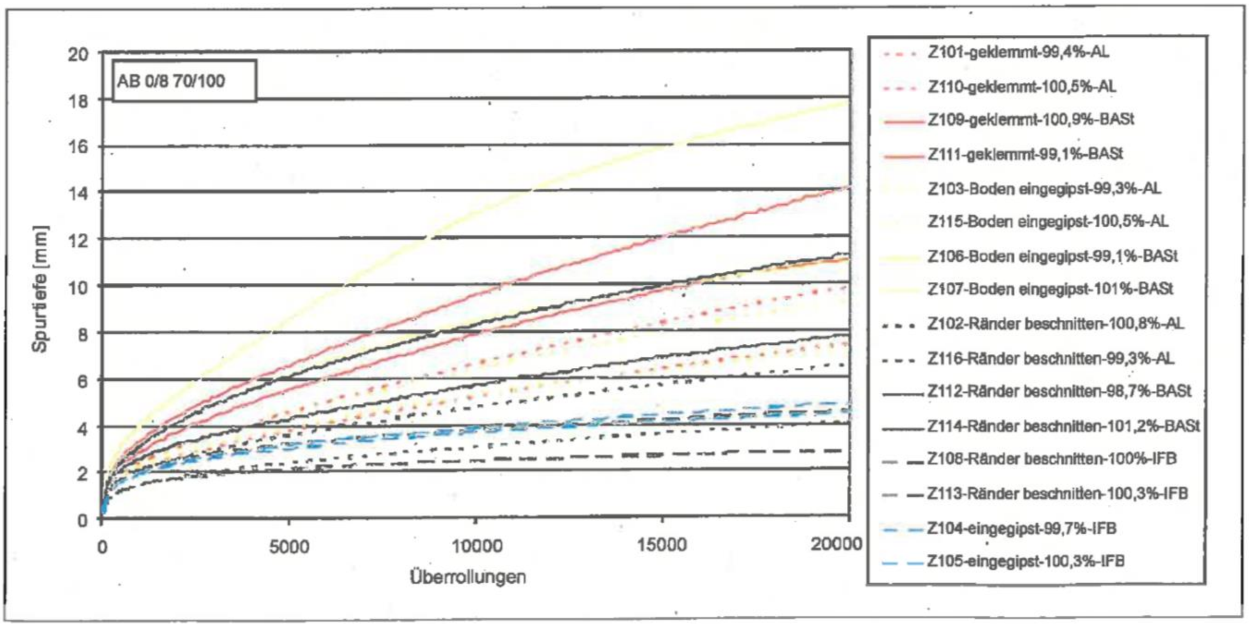
The research involved testing 12 asphalt mixes, in three configurations - steel wheel in 50 ºC water bath, rubber wheel in air at 50 ºC and rubber wheel in air at 60 ºC. The results suggested that the water bath at 50 ºC produced the harshest conditions with greatest rut depths, with the air at 50 ºC producing the shallowest rut depths. Each test condition led to a similar ranking of the asphalt types, although there was some variation (likely due to temperature control or sample preparation).

It was notable that the graphs of rut depth versus passes (Figure 2.1) did not show any inflection point, which is generally considered evidence of stripping in the asphalt according to US specifications (AASHTO 2011) and illustrated in Figure 2.2. The solid yellow, solid red and solid black curves represent the 50 ºC water bath tests, which all exhibited greater rut depths. It was observed that the 'softer' samples had an unusually wide spread of results, which is thought to be caused by the wheel 'grinding' its way through the specimen. This creates an uncontrolled, unpredictable deformation, similar to the effects of stripping in water tests.

The study made several recommendations based on the results, namely:

- The method of fastening the sample is important. It was recommended that rutting tests should be conducted with plates that are embedded in plaster at the bottom and sides.
- For 60 mm thick asphalt binder courses (i.e. intermediate layers), 2 mm was suggested as a maximum rut depth after 20 000 passes.
- The termination conditions should be set so that the test finishes after the rut depth reaches 20% of the slab thickness. Any sample with rutting of greater than 20% slab thickness can no longer be considered durable.

Figure 2.1: Rut depth vs passes for a trial asphalt mix



Source: Bundesministerium fur Verkehr, Bau und Stadtentwicklung (2009).

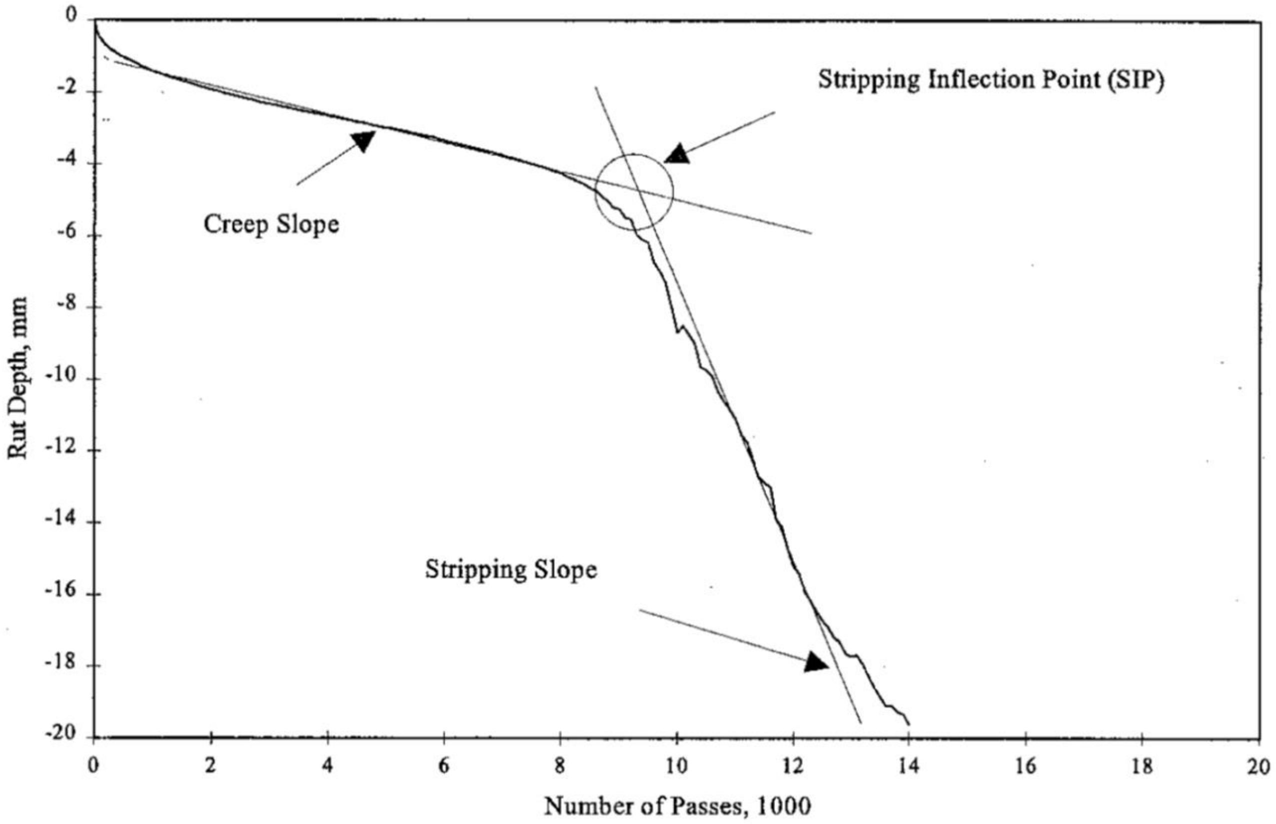
2.1.5 *Adaptation by agencies in the United States*

In 1990, a group of research organisations from the United States participated in an asphalt research tour in six European countries (Aschenbrener 1995). The HWTD was chosen as a performance-based test that was seen as having the potential to improve the quality of hot mix asphalt designs in the United States. The contact stress of 0.73 MPa is approximated as the stress produced by one rear tyre of a double-axle truck. The wheel makes around 50 passes per minute over each sample, and thus a full 20 000 passes (required under AASHTO guidelines) takes around 6.5 hours to complete. The test can also be stopped after a predetermined deformation depth is reached. Road authorities using the device have added specific air void targets, with 7.0 ± 1.0% being the standard requirement for hot mix asphalt in the United States (although this varies between States).

It appears as though the HWTD was not used primarily as a moisture-sensitivity test until it was trialled in the US in the early 1990s. Until that time, it was used as a wheel tracking test in Europe, where the combined effect of moisture and heavy loading was assessed.

The fact that it utilised a water bath meant that the specimens showed moisture-induced damage after roughly 10 000 passes. In the US this was evidenced by an inflection in the plot of rut depth versus wheel passes. After an initial period of linear deformation (creep slope), in the case of poor or not sufficiently performing mixes the rutting accelerated, eventually following a steeper linear deformation trend (stripping slope) (Figure 2.2).

Figure 2.2: Hamburg curve



Source: AASHTO (2011)

A number of agencies in the US decided to build their own modified versions of the HWTD, perhaps due to the high cost of importing a device from Germany or in order to customise the device to better suit their specific needs. This was the case with the University of Arkansas, which built the Evaluator of Rutting and Stripping in Asphalt (ERSA), which was modelled on the German-built HWTD and embraced similar operating specifications (Hall & Williams 1999).

Similarly, Pavement Technology Incorporated developed the Asphalt Pavement Analyzer Junior (APA Jr.) for performance-based testing of asphalt specimens (Collins 2012). APA Jnr can not only run the Hamburg test (AASHTO T 324), but also the wheel tracking test method (AASHTO 2010) in a different configuration. It can accommodate pneumatic tyres or solid rubber wheels in addition to the standard steel wheels, and can hold up to four cylindrical specimens during one test. The tests can be run either wet or dry. APA Jnr can also run across a wider range of temperatures, pressures and frequencies, so it has added flexibility.

2.2 Current Usage of HWTD

2.2.1 Usage around the world

A review of the use of the HWTD in specifications was conducted and it was found that it is not specified as a moisture sensitivity test in Europe where it was developed. It is used as a deformation test (EN 12697-22) alongside the larger French wheel tracking device and the British wheel tracking device, which is the same as that adopted by Austroads.

A combined wheel tracking and moisture sensitivity test is used in specifications in some states in the US where it is used as both a check on deformation resistance and sensitivity to moisture-related damage. In 2007, just two states reported the HWTD in specifications, with that number growing to seven by 2014 (Schram et. al. 2014).

The states that appear to be at the forefront of implementation are Texas, Colorado, California, Utah, Arkansas, Washington and Illinois. As of late 2014, the following states also use or evaluate the HWTD in some capacity: Arizona, Florida, Louisiana, Mississippi, Montana, Nevada, New Hampshire, Oklahoma and Wyoming, giving a total of 16 states at some level of usage of the HWTD (Schram et. al. 2014).

In the case of Arkansas and Utah, modified versions of the HWTD are used, but they operate to the same or very similar specifications as the early German version. Texas has the longest history of use with specification requirements going back to 2004. There are several other states reviewing the HWTD and there were several trials underway.

2.2.2 Scope of materials for use in the HWTD

The majority of applications for the HWTD have been with hot mix asphalt, including dense-graded, stone-mastic and open-graded mixes, and this is acknowledged in each test method. In Illinois, there are special provisions for wheel track testing of warm mix asphalt (WMA) and recycled asphalt pavements (RAP).

There may be the potential to use the wheel tracking test for a wider range of asphalt mixes including WMA and RAP, but this may require further research into the performance of the wheel tracking test with alternative mixes and how it matches with field performance.

2.2.3 Alternatives to the HWTD

TMR currently tests the sensitivity of asphalt to water by measuring the tensile strength ratio, also known as the modified Lottman procedure. This test is detailed in TMR test method Q315 (Department of Transport and Main Roads 2010) and based on the principles contained in Austroads test method AG:PT/T232 (Austroads 2007). The procedure determines the stripping potential of asphalt by comparing the indirect tensile strength of moisture conditioned specimens to dry specimens.

Airey and Choi (2002) documented and summarised a wide range of moisture-damage tests. Most of these tests involve some degree of thermal conditioning (usually in water) followed by a performance test. These methods include the Marshall stability test, the immersion compression test, the Lottman procedure and the modified Lottman procedure. Two wheel tracking tests are documented, including the HWTD and the immersion wheel tracking test.

The immersion wheel tracking test has been used even longer than the HWTD, and operates on similar principles. Three solid wheels pass over a submerged specimen at 25 cycles per minute, subjected to a 20 kg wheel load. The test reaches failure when there is a sudden and significant increase in plastic deformation of the specimen (Airey & Choi 2002).

The European Standard for wheel tracking of hot mix asphalt (EN 12697-22) contains specifications and procedures for wheel tracking apparatuses. Although most applications of wheel tracking devices in Europe are in temperature controlled chambers rather than water baths, there are still provisions in place for doing wheel track testing with submerged specimens. There is no mention of testing specifically for moisture sensitivity in this European Standard as it is covered in a different test procedure - EN 12697-12 (European Committee for Standardization 2008).

According to EN 12697-22, small wheel tracking devices, such as the HWTD, can be temperature controlled by any method that can maintain a uniform, specified temperature with ± 1 ^{o}C fluctuation. A water bath is mentioned as one possible method for achieving this. There are also requirements for conditioning. The specimen is to be placed in the water bath at the required test temperature (± 1 ^{o}C) until the specimen reaches equilibrium temperature, and for not less than one hour in total. Wheel tracking is required to run for 10 000 cycles (20 000 passes), or until 20 mm deformation is reached.

It should be noted that EN 12697-22 does not allow the use of steel wheels in the wheel tracking test. Early findings with the HWTD had shown that there is no correlation between tests conducted with rubber-coated wheels and steel wheels and it was also suggested that the praxis-related test method be used, i.e. where the wheels are coated with rubber (Domnick & Beecken 1990).

2.2.4 HWTD as a research tool

Lee and Kim (2014) evaluated three performance-based laboratory tests to determine their moisture sensitivity, and subsequently, their applicability as a moisture sensitivity test. The study used digital imaging analysis to determine the moisture susceptibility of the sample, and compared this to the results of each test. The samples tested were all warm-mix asphalt variants.

The study used the cyclic direct tensile test, the indirect tensile test and the Hamburg wheel tracking test as potential indicators for moisture sensitivity. The other two tests operate quite differently to the Hamburg device, and bring about stripping through detachment or displacement of the binder, rather than the primary modes of stripping seen through Hamburg testing of hydraulic scour and pore pressure.

All three tests use water for conditioning, but only the Hamburg device runs the test under water and utilises a high water temperature. The results suggest that the best indicator for stripping is the fatigue life ratio of wet and dry samples tested using the cycling direct tensile test, with an $R^2 = 0.88$. The second best indicator was the HWTD stripping inflection point, with a calculated R^2 of 0.84, while the HWTD rut depth is not as strong an indicator, with an R^2 of 0.74. The authors note that the Hamburg results may need to be reviewed in some cases to differentiate between the effects of moisture damage and permanent deformation of the sample.

Yin et al. (2014) used the HWTD to study the effect of lime, an anti-stripping liquid and recycled asphalt (RAP) on the rutting resistance and moisture susceptibility of hot-mix and warm-mix asphalt. The results suggest that significant improvements to moisture resistance can be made through the addition of 1% lime or 0.5% of an anti-stripping agent. With the hot-mix asphalt samples, the number of cycles to first evidence of stripping (i.e. cycles to reach the stripping inflection point) increased from less than 6 000 under the control design up to over 9 000 for both lime and the anti-stripping agent. The warm-mix tests showed that the lime had a greater influence on moisture sensitivity than the anti-stripping agent. In both cases, the added RAP lead to reduced resistance to stripping.

When measured against rutting resistance (measured by a projection of the creep slope), the mixes containing RAP were actually found to increase stiffness and rutting resistance, while the lime and anti-stripping agent had no effect (except for the lime in hot-mix asphalt which showed a small increase in rutting resistance). The overall improvement to moisture susceptibility, with little change to rutting resistance, suggests that both lime and anti-stripping agents were suitable for use in warm-mix and hot-mix asphalt, although the lime showed better or equal performance in each test.

2.3 Test Specifications for the HWTD

2.3.1 AASHTO T 324-11

AASHTO T 324-11 is the designated test method for Hamburg wheel track testing of compacted HMA. The test covers methods for testing both rutting and moisture-sensitivity of HMA with the HWTD. The most recent 2011 version is an update on the original version released in 2004.

Essentially, the HWTD has a similar method to other wheel tracking devices, with the major difference being that the test specimen is submerged in a temperature controlled water bath during testing. The test measures rut depth against the number of passes.

Specimen preparation

Two specimens are required for each test. The HWTD can be loaded with a laboratory-compacted specimen (these can be either slab or cylindrical specimens), a saw-cut slab specimen or a core taken from an existing compacted pavement.

The HMA should be produced in line with the specifications relevant to that particular mix, and is then required to be compacted to a specific size and bulk density (air voids). The relevant test methods and standards to follow are referenced in AASHTO T 324-11.

Before testing, the bulk specific gravity, maximum specific gravity and air void content should be measured. The target air voids should be 7.0 ± 1.0%, except in the case of field specimens, which may be tested at the air void content at which they are obtained.

Summary of procedure

The specimen is loaded into a mounting tray, and rigidly fixed into the tray using a plaster of Paris mould. Polyethylene moulds can be used inside the mounting tray when testing cylindrical specimens.

After turning on the testing device, computer and relevant software, a number of testing configurations need to be entered, including project information, the test temperature and allowable rut depth. A start delay of 30 minutes is required to precondition the test specimens, which is in addition to the time taken for the water to reach test temperature. On newer versions of the HWTD, the test runs automatically, although it can still be run manually if required.

After lowering the wheel and aligning the linear variable differential transformer (LVDT), the test can start. The device will shut off after reaching 20 000 passes or when the maximum allowable rut depth has been exceeded. All data is automatically stored on the computer. When the test is complete, the wheel can be raised and the specimen and mould can be removed.

Calculations

The data file can be used to plot the rut depth versus the number of passes (the *Hamburg plot*). From this plot, it is necessary to obtain the slopes and intercepts of the first and second steady-state portions of the curve. An example of this curve is shown in Figure 2.2. The stripping inflection point can be calculated using Equation 1:

$$\text{Stripping inflection point (SIP)} = \frac{\text{Intercept }(second\ portion) - \text{Intercept }(first\ portion)}{\text{Slope }(first\ portion) - \text{Slope }(second\ portion)} \qquad 1$$

The intercept can be found by measuring the point where the slope intercepts with the y-axis (measured in mm) and the slope of the line can be found by dividing the change in rut depth by the change in the number of passes (measured in mm/1000 passes). The stripping inflection point (SIP) can then be multiplied by 1000 to get the total number of passes before the specimen starts to exhibit stripping.

The test method also provides a list of parameters to report, including test specifications and the results of the test.

It should be noted that the test method does not currently have a statement of precision or bias, but mentions that work is underway to develop these statements.

2.3.2 Alternative methods for reporting results

The AASHTO specification requires just the reporting of the stripping inflection point, which requires some subjectivity in determining the relative start and end points of the creep and stripping slopes. This can be problematic for three reasons:

1. The start and end points of the slopes can vary by several hundred cycles in either direction, depending on the individual undertaking the analysis.
2. The influence of a short post-compaction period in the first 1000 cycles can make it hard to distinguish between the slopes, especially with highly moisture-sensitive specimens.
3. The mechanism behind the rutting may need to be determined from visual analysis and experience, as cases of aggregate crushing or dislodged aggregate can lead to erratic rut depth readings.

As a result of these difficulties leading to imprecise measurements, several alternative reporting parameters have been proposed.

A study by Yin et al. (2014) develops three performance parameters based on a curve fitting algorithm of the rut depth vs cycles graph.

2.3.3 Colorado Department of Transportation

The Colorado Department of Transportation uses its own procedure for testing the rutting and moisture sensitivity of asphalt mixes using the HWTD (Colorado Department of Transportation 2013). *Colorado Procedure – Laboratory 5112-14* is the standard test method for HWTD testing of compacted bituminous mixtures. The test method only refers to AASHTO T 324 when providing guidance on compacting Superpave gyratory samples.

While the Colorado procedure follows similar steps and requirements to the AASHTO method, there are a number of notable differences. The Colorado method requires slabs to attain an air void target of 6% ± 2%. The procedure is also more specific regarding temperatures and heating times during specimen preparation. The Colorado method contains a table of the performance graded temperatures, and specifies a test temperature for the water bath based on the asphalt grade (Table 2.1).

Table 2.1: Temperature selection table, Colorado Procedure 5112-14

SHRP high temperature performance graded mix	Test temperature (ºC)
58	45
64	50
70	55
76	55

Source: Colorado Department of Transportation (2013).

The procedure specifies using only 10 000 cycles (20 000 passes), with a rut depth of 4 mm before 10 000 cycles being considered a failure. It was indicated in other test procedures that stripping did not tend to occur (as indicated by the presence of an accelerating rut depth) before 10 000 cycles. It is not clear whether the Colorado method would be any different, and there is no mention of what steps to follow should the stripping inflection point not be reached after 10 000 cycles.

2.3.4 Utah Department of Transportation

The Utah Department of Transportation (2013) has a specification for its use of the HWTD. In Utah, 20 000 passes are required with a maximum LVDT displacement of 20 mm. As with Colorado, the test water temperature is based on the binder grade (Table 2.2).

These values were derived based on testing undertaken on a range of mixes (Romero et. al. 2008). The study found that a critical stripping temperature exists for each mix, at which point the energy is sufficient to reduce the stiffness of the binder, leading to de-bonding and stripping. The study found that this temperature varies by binder grade, and as such, the values of 46ºC, 50ºC and 54ºC were selected for the various binder grades. This indicates that it may be prudent to raise the test temperature for high-performance mixes and when using polymer modified binders. This would allow for a test that can differentiate between various high-performing mixes, rather than having a test temperature that is too low and allows for every sample to pass without evidence of stripping.

Table 2.2: Test temperature selection table, Utah

Contract-required binder grade	Test temperature (ºC)
PG 58-xx	46
PG 64-xx	50
PG 70-xx	54

Source: Utah Department of Transportation (2013).

The test specimens are required to be at a relative compaction of 93% ± 0.5%. The Utah test method instructs practitioners to follow the testing procedure specified by the equipment provider. At the conclusion of the test, the maximum rut depths of the two specimens are compared, and if they differ by more than 6 mm, the test is deemed to be invalid and needs to be re-run.

2.3.5 Texas Department of Transportation

The Texas Department of Transportation (2009) also has a test procedure for the Hamburg wheel tracking test, designated as Tex-242-F. The Texas test method is used to ‘determine the premature failure susceptibility of bituminous mixtures due to weakness in the aggregate structure, inadequate binder stiffness, or moisture damage and other factors including inadequate adhesion between the asphalt binder and aggregate’. This scope is similar to that contained in the AASHTO test method, although rephrased and condensed to one paragraph. The Texas method specifies a relative compaction of 93% ± 1% for the test specimens. The test temperature is required to be 50 ± 1 ºC, and still requires the specimens to be conditioned for 30 minutes at this temperature before testing.

2.3.6 Summary

Table 2.3 details the various test methods in the United States that use the HWTD. Each specification has a required air void content for the specimens, which is generally in the 6–8% range. Air voids of this magnitude are often higher than the design air void content, which requires specimens to undergo less compaction during sample preparation.

Table 2.3: Test methods and the required air voids

Jurisdiction	Test method	Test used for:		Required air voids (%)	Max passes	Failure limit (mm)
		Rutting	Moisture sensitivity			
USA (AASHTO)	AASHTO T 324	Yes	Yes	7.0 ± 1.0	20,000	40
Colorado	CP – L 5112-14	Yes	Yes	6.0 ± 2.0	20,000	20

Jurisdiction	Test method	Test used for:		Required air voids (%)	Max passes	Failure limit (mm)
		Rutting	Moisture sensitivity			
Utah	Section 990	Yes	Unclear	7.0 ± 0.5	20,000	20
Texas	Tex-242-F	Yes	Yes	7.0 ± 1.0	20,000	Not specified
Illinois	IL mod AASHTO T 324	Yes	Unclear	7.0 ± 1.0	5000-20,000*	12.5
Washington	M 46-01.16	Yes	As for AASHTO	7.0 ± 1.0	20,000	40
Arkansas	Hall and Williams (1999)	Yes	Yes	7.0 ± 1.0	20,000	20
California	AASHTO T 324 (modified)	Yes	Yes	7.0 ± 1.0	Up to 25,000*	12.5

* Dependent on the performance grade of the binder.

2.4 Performance/Repeatability/Reproducibility

In late 2014, a report was released by the National Cooperative Highway Research Program presenting the results of a precision estimate study on the Hamburg Wheel Tracking Device (Azari 2014). The study recognised the lack of precision statements in the AASHTO T324 test method and the absence of a statement on the allowable difference between two replicate measurements. The study also seeks to clarify some ambiguities in the test method and analysis of results, to ensure consistency across the various US jurisdictions performing the Hamburg test.

Twenty-eight laboratories across the US contributed to the study, and this led to the development of precision estimates for the various properties and results of Hamburg tests (Table 2.4). The table includes allowable coefficients of variation and acceptable ranges for both single-operator tests and for tests performed across multiple laboratories. As expected, the allowable variation is higher when comparing across multiple laboratories, due to the different equipment and various methodological differences between laboratories.

Table 2.4: Precision estimates for AASHTO T324

	Single-operator		Multi-laboratory	
Properties	COV (%)	Acceptable range of two test results (per cent of mean)	COV (%)	Acceptable range of two test results (per cent of mean)
Deformation (mm)	14.2	40.2	26.0	73.6
Number of passes to threshold rut depth	16.6	47.0	24.2	68.5
Number of passes to inflection point	23.9	67.6	32.1	90.9
Creep slope (mm/cycle)	16.6	47.0	28.3	80.1
Strip slope (mm/pass)	17.7	50.0	20.8	58.8

Source: Azari (2014).

The report also recommends a range of changes to the AASHTO T324 test method, including specifying wheel alignment and starting placement, requiring more consistent specimen sizing and better mould fit and recommending routine maintenance checks and periodic calibration with reference specimens.

Several other studies have evaluated the performance, repeatability and reproducibility of laboratory-based moisture sensitivity tests.

Two studies in particular assessed the repeatability and reproducibility of the HWTD (Table 2.5). These studies indicate that the HWTD does not have exceptionally strong repeatability and reproducibility, but there appears to be less variability than with other performance-based moisture-sensitivity tests. As discussed earlier, the method of sample preparation has a large effect on the test results and it is envisaged that these findings relate to specimens compacted to 7 ± 1% air void content, which may explain the large variability in the test results. It is suggested that this question is investigated in the laboratory study phase.

Table 2.5: HWTD test accuracy, reported by field studies

Study/reference	Test method	Repeatability	Reproducibility
Izzo & Tahmoressi (1999a)	HWTD deformation depth	16% to 37%	Not reported
Izzo & Tahmoressi (1999b)	HWTD stripping inflection point	15.1%	Not reported
Cox et al. (2013)	HWTD deformation depth	24%	67%

Two studies have assessed the performance of laboratory-based moisture-sensitivity tests against actual field results, with a reasonably strong correlation between field and laboratory mix performance (Table 2.6).

Table 2.6: HWTD test performance

Study/reference	Test method	Performance
Aschenbrener et al. (1994)	HWTD stripping inflection point	5 of 7 good mixes identified 10 of 11 poor mixes identified
Solaimanian et al. (2007)	Stripping inflection point and deformation depth	5 of 8 mixes identified correctly

A research project in Germany (Bundesministerium fur Verkehr, Bau und Stadtentwicklung 2009) looked into determining the appropriate test conditions, precision and accuracy of the wheel tracking test, as outlined in Section 2.1.4. Overall, there were a number of restrictions and inconsistencies that meant that the study did not come to any statistically significant conclusions regarding the accuracy of the wheel tracking test methods. However, the researchers were able to develop preliminary performance measures for the wheel tracking test. The accuracy of rubber wheel tests at 60 ºC in air can be assumed to be:

- repeatability – 30% of the mean value of two individual test specimens
- comparability – 60% of the mean value of two individual test specimens.

2.5 Limitations of AASHTO T 324-11

The AASHTO test method sets a testing procedure for the HWTD in relation to susceptibility of the pavement to rutting and moisture-induced damage. Agencies that have adopted the HWTD in their performance-testing program have generally either adopted the AASHTO test method or adapted it to conditions in their particular state. Examples of these specifications were reviewed in Section 2.2.2.

The AASHTO method has received some criticism from highway agencies, and these reasons have contributed to the overall lack of acceptance of the HWTD in performance testing (Cox et al. 2013):

- Some have cited a lack of standardisation in the preparation of specimens for testing.
- No statement of precision or bias is mentioned. This has not changed since the 2004 version of the test method. At some point, this may be rectified based on the work by Azari (2014) and the National Cooperative Highway Research Program.

- The test method does not recommend repeat testing in terms of reproducing or rejecting results based on the two specimens producing vastly different rut depths or reaching failure at a different number of passes.
- Preconditioning requirements are not strict; some other test methods prescribe a conditioning period with a small margin either side, which is considered acceptable (for example ‘add water at required temperature and leave to condition for 30 ± 2 minutes before starting the test’).

3 PROJECT OUTCOMES

3.1 Delivery and Project Planning

The HWTD (Figure 3.1) was delivered to TMR during the first week of October 2013; as part of the project TMR also commissioned a slab compactor (Figure 3.2). Both pieces of equipment were supplied by *Controls*, an Italian manufacturer. Based on discussions, the schedule outlined in Table 3.1 was developed.

Figure 3.1: HWTD

Figure 3.2: Slab compactor

TMR and ARRB personnel met on 9 October 2013 to discuss:

- the general progress of the project
- questions arising from the preliminary literature review
- schedule and plans for the laboratory phase (which is summarised in Table 3.1).

Table 3.1: Proposed schedule of activities

Item	Comment	Who/when
Commission the equipment, including OH&S	N/A	TMR/30 November 2013
Develop draft test method	It will be used for initial testing; the draft procedure would be refined during the laboratory testing phase	ARRB/30 November 2013
Conduct training (provided by the supplier)	TMR invited ARRB to participate in this process	TMR, including ARRB/30 November 2013
Items for laboratory testing (with sequence)		
Limit testing to DG14 and DG20 samples, independent of their functionality (i.e. wearing, basecourse, etc.); limit maximum aggregate size to 20 mm	N/A	N/A

Item	Comment	Who/when
Validate test parameters: conditioning time, test temperatures, number of cycles, sample air void content (if manufactured), sample fixing (plastic clamps or plaster), sample 'curing' time after manufacturing, sample thickness (aggregate size dependent), and allowable difference between duplicates Investigate equipment capability/operation if one of the samples reaches termination point, what happens to the second specimen	Plan and conduct initial testing to be able to set appropriate test parameters	TMR + ARRB/February 2014
Conduct sensitivity analysis at different compaction levels (air voids) and finalise initial suggestions for air void content of test specimens	Number of test series would be worked out based on budget limitations	Not defined, based on previous outcomes
Obtain mix designs with proven in situ performance and replicate mix and test in the laboratory in the HWTD; repeat this series with poor-performing mixes		Not defined, based on previous outcomes

It was agreed that the results of the HWTD should not be compared to other test methods (such as the Lottman test) as they are completely different and test different properties. The HWTD tests overall stability (not only moisture sensitivity).

A number of questions regarding the device remained that should be investigated during the laboratory testing phase:

- What should be done when the graph does not show a clear inflection point? Is the inflection point critical at all from the performance point of view?
- The original German approach indicated that mixes with a stripping inflection point had particularly poor performance. What happens if the mix does not reach the inflection point before 20 000 passes but still produces a large rut depth?
- Are the laboratory test results comparable with field samples? Are the results really 'performance based'? This can be investigated through testing core samples or production mix from projects with known performance over a reasonable period of time.
- What is the representative symptom of stripping failure in Queensland?
- Is stripping considered as a result of incorrect material selection or incorrect in situ air void content (compaction)?
- What is the sample preparation procedure for samples obtained from the road pavement? It is envisaged that there will only be cores sampled, not slabs removed from in situ pavements.
- How does a failure look after testing? Photos should be taken of each slab, before and after testing, as well as after cutting the slab along the wheel path.
- With a high air void content in the laboratory samples, is it possible to clearly delineate post-compaction and moisture-induced damage?
- Conditioning time is set at 30 minutes in the AASHTO standard. It is envisaged that a specimen of this weight would require a conditioning time of 2 hours, also allowing some infiltration of water. A short laboratory study should be conducted to validate the required conditioning time.
- Test temperatures: it was discussed that mixes with proven superior rut resistance (tested in the wheel tracking device, 60 °C, air) would be reproduced and retested in the HWTD at 60 °C, under water. If these mixes were to pass the HWTD test, there would be no doubt that test parameters of 60 °C combined with underwater testing would be appropriate. It is not suggested that the test temperature should be altered as per the Colorado or Utah approaches.

- The cut-off point during initial testing will be set to 20 mm, which is equivalent to between 26–40% proportional (relative) rut depth of the overall slab thickness.
- How would the rut depth be determined (one point or 25 points along the test track)? The output files give a number of options for calculating this value.
- Would the end result be measured as absolute rut depth (mm) or relative rut depth (%)? Maybe the latter would be more useful in the comparison of different aggregate size and sample thicknesses.
- Determine the method of density testing:
  - saturated surface dry (SSD) method, including water absorption check – move to silicone if absorption is greater than 2% for DGA mixes
  - silicone sealing on cores extracted from the field.
- Does an allowable difference between the pair of test specimens need to be determined? Should the difference be too large, would another set of slabs need to be tested?

The initial questions collected at the beginning of the program were partly or in whole addressed during the testing program.

3.2 Laboratory Test Results - Operational Testing Phase

Initially, five materials were selected for testing, representing a range of estimated performance (Table 3.2). Each material was to have two slabs tested, ideally at the same time in the dual tracker. This was not attempted for the first few trial runs, and then a malfunction was encountered with one of the transducers which meant that one side of the tracker was not usable for a period of time. Due to time limitations, EME2 samples were not tested in the initial program, but were included in the program for the second year of testing (see Section 3.3).

Table 3.2: Selection of materials

Material	Mix type	Binder type	Design air voids (%)	Estimated performance
SM 14	Stone mastic asphalt (14 mm)	A5S	2.5 – 4.0	Very good
DG20 HM	Dense graded (20 mm) heavy duty	Class 600	4.1 – 5.1	Fairly good
DG14	Dense graded (14 mm)	Class 320	4.3 – 5.3	Poor
BCC Type 1	Type 1 footpath mix	Class 170	4.9 – 5.9	Poor
EME2	Enrobés à Module Elevé 2	Pen 15/25	3	Very good

The selected mixes were chosen as they cover a range of expected performance, with some materials expected to pass the test easily and others expected to fail before the programmed number of cycles was reached.

The tests were run under the following configuration and conditions:

- slab manufactured to within design air void range
- for maximum aggregate size less than 19 mm use 50 mm deep slab, above 19 mm use 75 mm deep slab
- no aging required, but in practice slabs stored for 7–8 days in the laboratory before commencing test
- water bath set to 60 °C
- slab conditioned in water bath for 120 minutes before commencement of test
- five conditioning cycles (to smooth out the surface and reach tracking speed)

- tracking rate of 26 ± 1 cycles/minute (equivalent to 52 ± 2 passes/minute)
- wheel load of 705 N ± 4.5 N
- wheel width of 47 mm ± 1 mm
- a total of 10 000 cycles before termination (equivalent to 20 000 passes)
- maximum rut depth of 20 mm before termination.

The output files from the HWTD provide transducer offsets at 1 inch (2.54 cm) increments, which represent the rut depth along the tracked path. Recordings are made after each cycle up to the 10th cycle, then every 10 cycles up to the 100th cycle and every 100 cycles up to the 10 000th cycle. Errors with the transducer meant that many of the early .csv output files had missing data along much of the tracked path. As a result, it was decided to use the data for the central rut depth, which measures the rut depth at the mid-point of the tracked path (115 mm from the start). The central rut depth over time for each slab was merged into a single spreadsheet to generate a graph of all the results (Figure 3.3). Results for each material are presented in Table 3.3.

Appendix A contains photos of each slab after completing the test.

Table 3.3: Full results

Material	Slab no.	Date manufactured	Date tracked	Age in days	Compacted density (t/m^3)	Air voids (%)	Final rut depth (mm)	Cycles tracked
DG20HM	1	26/02/14	05/03/14	8	2.392	4.9	6.67	10 000
	2	17/03/14	25/03/14	8	2.386	5.2	19.40	7983
	3	06/03/14	13/03/14	7	2.389	5.0	5.86	9248
DG14	1	11/03/14	19/03/14	8	2.354	5.5	12.86	10 000
	2	12/03/14	20/03/14	8	2.366	5.0	19.87	5474
	3	13/03/14	21/03/14	8	2.368	4.9	19.61	4944
SM 14	1	06/05/14	21/05/14	15	2.421	3.5	4.12	10 000
	2	07/05/14	22/05/14	15	2.418	3.5	5.95	10 000
Type 1	1	05/05/14	20/05/14	15	2.331	4.9	17.86	1816
	2	06/05/14	23/05/14	17	2.332	4.9	20.10	2231

Figure 3.3: Graph of all HWTD results

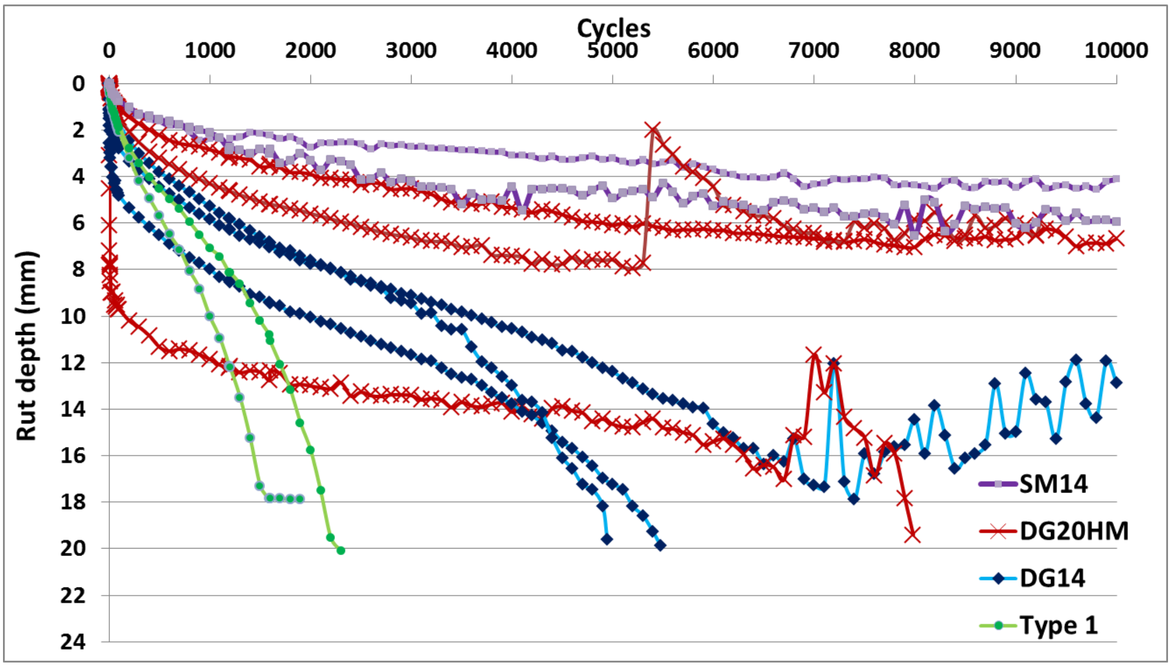
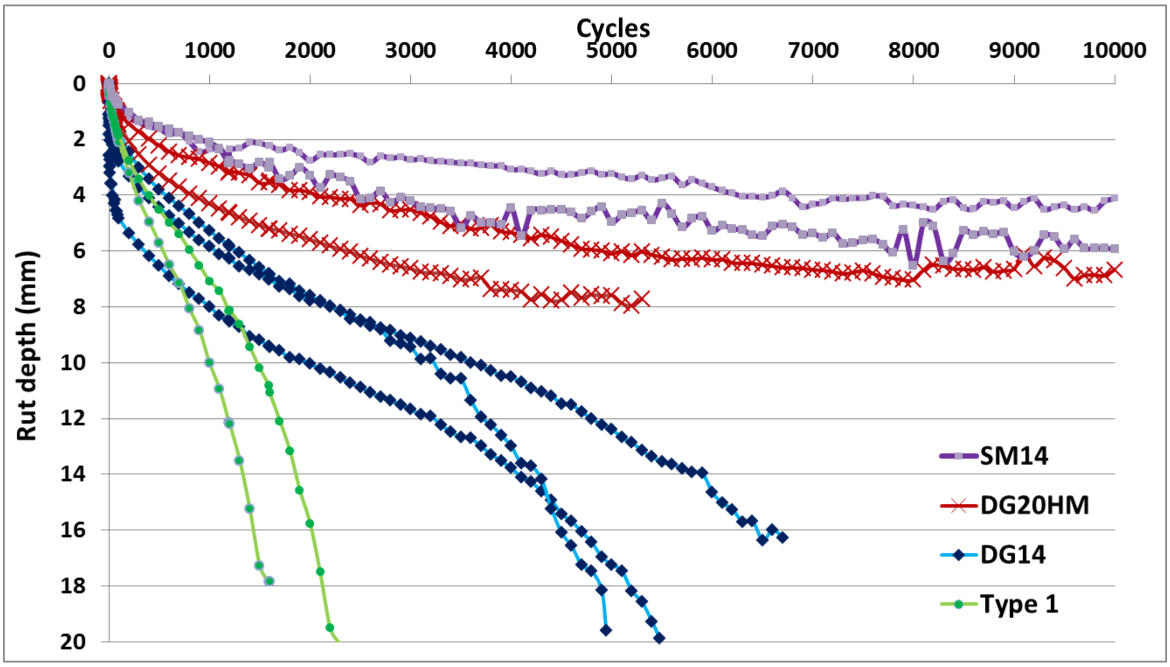


Figure 3.3 shows that there are some irregular rut depths at higher loading cycles in the tests, and some highly variable rutting in the early stages of one DG20HM test. The erratic rut depths are likely due to dislodged aggregate particles or transducer errors. In order to better visualise the data, the irregular results have been removed, leaving a clearer representation of the relative performance of the four mixes (Figure 3.4).

Figure 3.4: Graph of all results with irregular readings removed



Cooper wheel tracking was performed on the SM14 mix to cross-reference the results. The two samples at 2.5% and 2.8% air voids only rutted to 1.14 mm and 1.25 mm respectively after the full 5000 cycles. This confirms that the SM14 is indeed a high-performing mix.

3.2.1 *Varying test temperature*

It was decided to explore two particular issues in more depth – the temperature of the water bath and the impact of varying the sample density. The temperature of the water bath for the test is required to be 40 ºC or 50 ºC in other test specifications, including the United States. Even states with relatively high average pavement temperatures use a value of 50 ºC for much of their testing.

A poor performing mix, the Type 1 asphalt, was tested again at 50 ºC and 55 ºC. Conditioning in the device would be the same as for the 60 ºC test framework, although the age of the compacted specimens differed somewhat. It would be expected that the slabs rut at a slower rate than previously, but it is unclear how sensitive the material will be to the lower water temperatures of the bath.

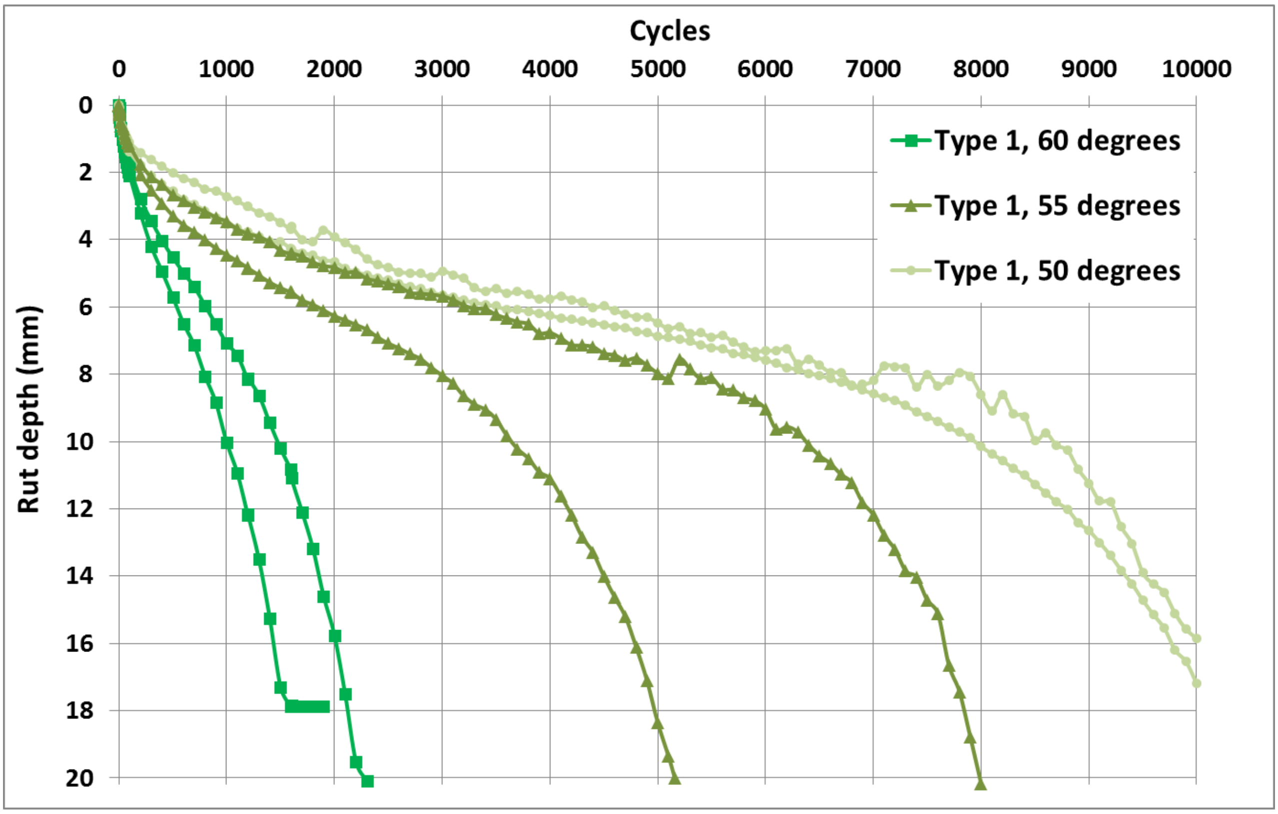
Slabs 3 and 4, tested at 50 ºC, had similar compacted densities as slabs 1 and 2 of the Type 1 material, while slabs 5 and 6 had slightly lower density and therefore higher air voids (Table 3.4). The 50 ºC slabs reached the full 10 000 cycles without reaching the maximum rut depth of 20 mm, while slabs 5 and 6 at 55 ºC did hit the maximum rut depth, but after 5159 and 8000 cycles respectively. This is a significant improvement in performance for samples with very similar densities, and is a strong indication of the influence that temperature has on results.

Table 3.4: Results for Type 1 slabs at 60 ºC, 55 ºC and 50 ºC

Slab no.	Date manufactured	Date tracked	Age in days	Compacted density (t/m^3)	Air voids (%)	Water temperature (ºC)	Final rut depth (mm)	Cycles tracked
1	05/05/14	20/05/14	15	2.331	4.9	60	17.86	1816
2	06/05/14	23/05/14	17	2.332	4.9	60	20.10	2231
5	21/07/14	22/07/14	1	2.313	5.7	55	20.01	5159
6	21/07/14	22/07/14	1	2.322	5.3	55	20.16	8000
3	28/05/14	04/06/14	7	2.327	5.1	50	17.19	10 000
4	29/05/14	05/06/14	7	2.329	5.0	50	15.86	10 000

There was some evidence of stripping with the two slabs tested at 60 ºC, with an increasing rate of rutting between 1000 and 2000 cycles (Figure 3.5). The slabs at 55 ºC showed accelerated rutting after around 3000–4000 cycles. The slabs tracked at 50 ºC began to show accelerated rutting after 5000–6000 cycles. It appears as though the reduced temperature slowed the rutting (and stripping) process, but the material still showed a strong indication of stripping in the second half of the cycles (as indicated in Figure 2.2).

Figure 3.5: Type 1 asphalt mixes at variable temperature

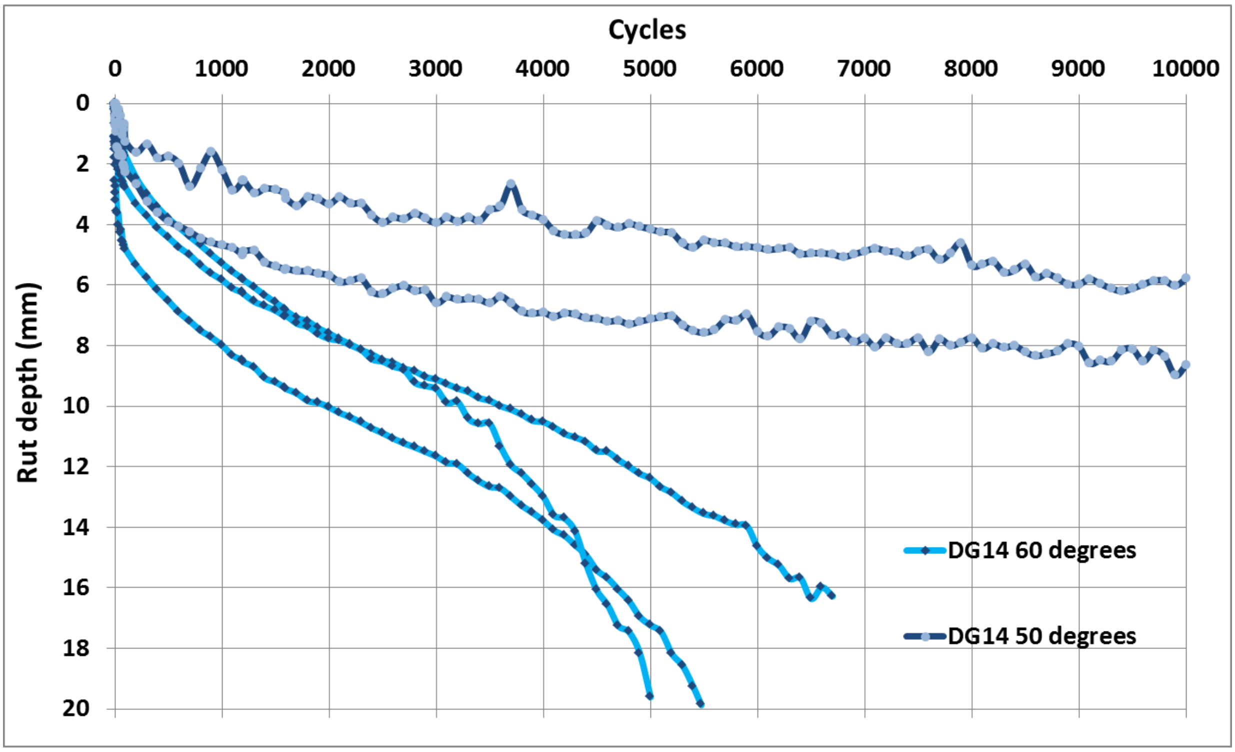


To confirm the high sensitivity to changes in water temperature, two slabs of DG14 were also tested at 50 ºC. As with the Type 1 mixes, the DG14 slabs rutted much slower at 50 ºC than at 60 ºC (Table 3.5 and Figure 3.6). However, with the DG14 mix, there was no longer any sign of stripping behaviour based on the progressive rut depth. There were also very few fine aggregate particles on the top of the slab after tracking, as opposed to the first three slabs tested at 60 ºC (see Appendix B for photos).

Table 3.5: Results for DG14 slabs at 60 ºC and 50 ºC

Slab no.	Date manufactured	Date tracked	Age in days	Compacted density (t/m^3)	Air voids (%)	Water temperature (ºC)	Final rut depth (mm)	Cycles tracked
1	11/03/14	19/03/14	8	2.354	5.5	60	12.86	10 000
2	12/03/14	20/03/14	8	2.366	5.0	60	19.87	5474
3	13/03/14	21/03/14	8	2.368	4.9	60	19.61	4944
4	17/06/14	24/06/14	7	2.372	4.8	50	8.64	10 000
5	18/06/14	25/06/14	7	2.368	4.9	50	5.78	10 000

Figure 3.6: DG14 slabs at variable temperature



3.2.2 *Varying sample density*

It was noted that under AASHTO specifications, specimens are to be tested at 7 ± 1% air voids. This is consistent with requirements of other road authorities in the United States. It was decided that the initial stages of testing would focus on testing slabs within the design air void range, which will generally be in the 3–5% range for the chosen mixes. This is intended to represent very well compacted mixes in the field that represent good construction practices and are anticipated to have reduced secondary compaction from traffic. Thus, the key element that requires testing is the ability of a mix to withstand moisture ingress and stripping when it is properly constructed and compacted to within the design air void range.

In addition to testing at a standard density, the HWTD provides an opportunity to assess the sensitivity to changes in compacted density for an otherwise high-performing mix. The SM14 was chosen as both slabs performed well in initial testing. Two further slabs were compacted to air void contents of 4.4% and 7.0% respectively, and run through the HWTD under the same test conditions as previously. The rut depths, as expected, increased for the slabs with higher air voids (Figure 3.7 and Table 3.6)

Based on these results it could be suggested that higher air voids mean that there is more potential for post-compaction in the slab, as the force from the wheel causes the mix to compress. However, this is not a complete explanation of the behaviour in this case, as mechanical interlock properties will also influence the level of rutting as air voids increase. The slab with 7.0% air voids appears to continue rutting at a constant rate from around 2000 to 10 000 cycles, while the three slabs with higher densities did not rut significantly after around 2000 cycles, indicating a strong aggregate bond at low air voids content which is characteristic for stone mastic asphalt.

Figure 3.7: SM14 slabs at various air voids

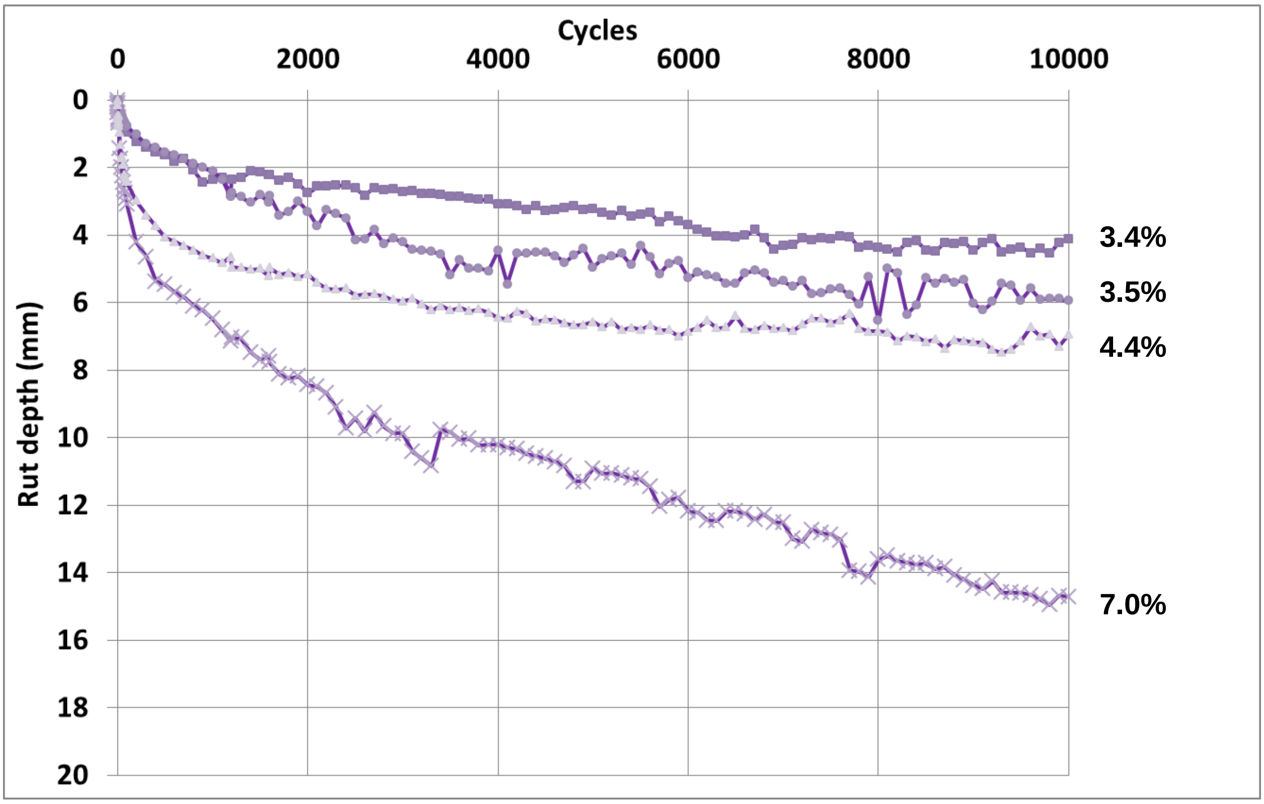


Table 3.6: Results for SM14 slabs at various air voids

Slab no.	Date manufactured	Date tracked	Age in days	Compacted density (t/m^3)	Air voids (%)	Final rut depth (mm)	Cycles tracked
1	06/05/14	21/05/14	15	2.421	3.4	4.12	10 000
2	07/05/14	22/05/14	15	2.418	3.5	5.95	10 000
3	27/05/14	10/06/14	14	2.395	4.4	6.95	10 000
4	29/05/14	06/06/14	8	2.331	7.0	14.72	10 000

The final results, with irregular readings removed, are summarised in Appendix A.

3.3 Year 2 Supplementary Testing

The Enrobés à Module Elevé 2 (EME2) testing that was originally scheduled for year 1 was delayed until year 2. EME2 is a high-modulus, high binder content mix originally from France, which is being trialled in Australia. Material from the EME2 trial in Eagle Farm, Brisbane was sourced to run through HWTD testing. Material from the adjoining DG20HM section was also collected for comparison. A number of field cores were also collected. A number of the test runs at this stage were compromised by a faulty transducer connection, which meant that the output from the device were unreliable or failed completely.

Two pairs of EME2 cores and one pair of DG20HM cores, as well as two DG20HM slabs completed the full cycles with the results shown in Figure 3.8 and Table 3.7. The average density of the EME2 was higher than that of the DG20HM.

The average of the rut depths for the EME2 and DG20HM cores are very close, although the EME2 slabs did generate significantly greater rut depths. Unfortunately, the EME2 slabs produced did not return usable results, however the minimal rut depths after testing can be seen in pictures taken after testing (Appendix B).

Several of these tests were continued past the standard 10 000 cycles to as high as 30 000 cycles to test the limits of high-performing mixes. It was found that at a point, the steel wheel begins to crush the aggregate particles into dust. It is not recommended that this length test is carried out routinely, as it becomes difficult to isolate the course of rut depth progression.

Figure 3.8: EME2 and DG20HM comparison

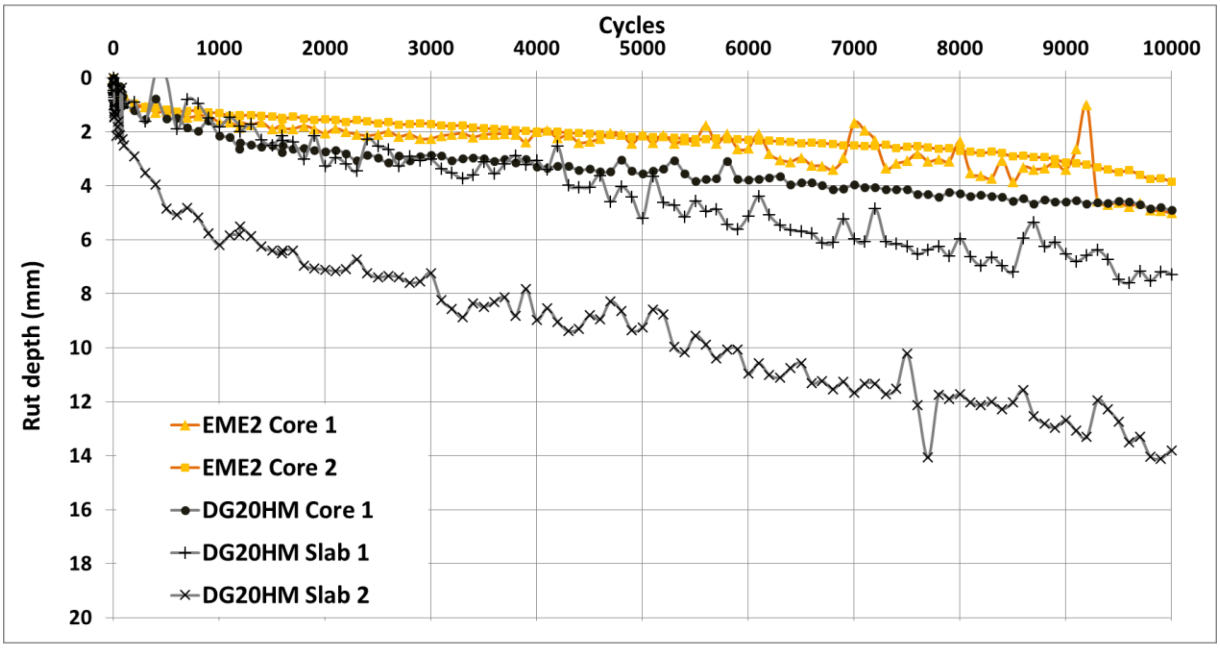


Table 3.7: Summary of results from EME2 and DG20HM testing

	Test No.	Core no.	Date tracked	Age in days	Final rut depth (mm)	Cycles tracked
EME2	Core 1	3	9/10/14	n/a	5.01	10 000
		4		n/a		
	Core 2	5	9/10/14	n/a	3.84	10 000
		6		n/a		
DG20HM	Core 1	2	15/10/14	n/a	4.90	10 000
		7		n/a		
	Slab 1		17/12/14	n/a	7.29	10 000
	Slab 2		18/12/14	n/a	13.80	10 000

3.4 Industry Consultation Meeting

In December 2014, a meeting between industry and the project team was organised in order to clarify the purpose and future applications for the HWTD. Some key outcomes from this meeting include:

- There was general agreement that the test is specified as a *moisture sensitivity and stripping* test, rather than have any focus on rutting susceptibility.
- The group did not have major concerns about the moisture sensitivity of high-performance mixes, and concluded that the focus should be on developing a test for standard basecourse mixes that have traditionally been the most vulnerable to stripping.
- In terms of specifying an air void range to test at, it was decided that there were merits in testing at the design voids as well as at a higher void content (97–98% of design voids), as this is commonly seen in the finished product and therefore should be tested for vulnerability to stripping.
- Cylindrical samples (laboratory compacted cylindrical specimens or field cores) were considered the most appropriate style of test, rather than slabs, as they are easier to sample in the field and produce in the lab. Focussing on testing cylindrical samples is also the general approach in the US, which will aid with comparison of results.
- The test temperature was debated, with 60°C considered too high and 40°C likely to be too low. The approach taken in the US to have different temperatures for different performance grade of binder may also be appropriate for Queensland with the initial thoughts being to use 50°C for standard mixes and 55°C for high-grade or polymer-modified binders.
- The discussion with industry experts suggested that the device would be very useful at the mix design stage and that it would be a valuable tool for industry.

As a result of this meeting, it was possible to develop a test method for the performance assessment phase.

3.5 Laboratory Test Results - Performance Assessment Phase

The primary aim of the performance assessment phase was to trial a standard procedure for a mix design and develop benchmarks to evaluate future mixes. It was envisaged that a correlation could be developed between in-service performance and laboratory testing, although this development will be ongoing. Upon completion of this phase, a laboratory testing procedure can be developed.

The initial aim was to source two current production mixes and run a suite of tests at a specific set of conditions. Due to a series of equipment malfunctions, including a pump failure, a worn transducer lead and a faulty transducer sensor, the device was non-operational for approximately three months in early 2015. This ultimately meant that there was only time to complete one mix, and a discussion on what this means is included in Section 4.

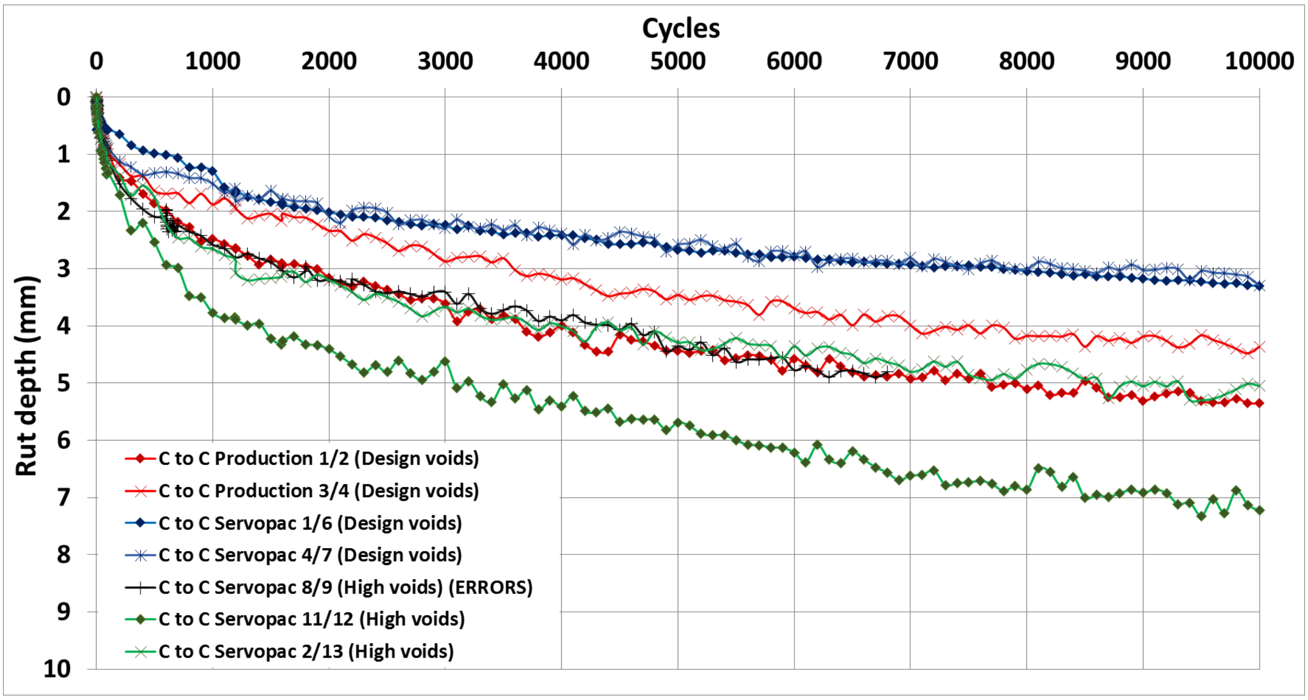
In late 2014, the Bruce Highway upgrade from Cooroy to Curra was beginning asphalt works. This allowed for sampling of the DG20HM (with a C600 binder) used on this section. Around 300 kg of loose production mix was supplied, as well as four field-sampled production cores. A copy of the testing plan for the Cooroy to Curra material is contained in Appendix C. The conditions for this testing were:

- 50°C test temperature – in line with the general consensus across the industry meeting
- production cores at the design voids
- laboratory produced cylindrical specimens (using the Servopac device) at two densities;
  - design air voids (± 1%)
  - air voids corresponding to 97% of the compacted density of the design mix (± 1%)
- 10 000 cycles and termination conditions set to 20 mm maximum rut depth
- all other conditions as for previous tests.

The results are detailed below in Figure 3.9 and Table 3.8.

As for the operational phase testing, the results appear to hold consistent for the pairs of samples, indicating good repeatability of results. The production cores had higher rut depths at the design voids than the laboratory produced samples, however it should be noted that the average density of the laboratory produced samples was slightly lower. The shape of the slopes is similar for all tests.

Figure 3.9: Cooroy to Curra (C to C) DG20HM – Production cores and Servopac samples



When looking at the higher void laboratory samples, the rut depths are higher. The Servopac samples 2/13 did have average voids roughly 0.5% lower than the Servopac samples 11/12. This may account for some of the 2 mm difference in rut depth between this pair of tests. The Servopac 8/9 sample that was halted prematurely was tracking towards similar results to Servopac11/12.

Figure 3.10 plots the air voids against the final rut depth for each pair of samples. Although the total number of data points is still low, a trend can be identified that indicates the relationship between increased air voids and rut depths. There may be some point where the increase in rut depth is proportionately greater than the increase in air void content (which would result in a trend line curving upwards at high air void contents). Once a mix has undergone Hamburg testing on a range of air voids as shown here, it may also be possible to predict the propensity for rutting based on any compacted density measured in the field.

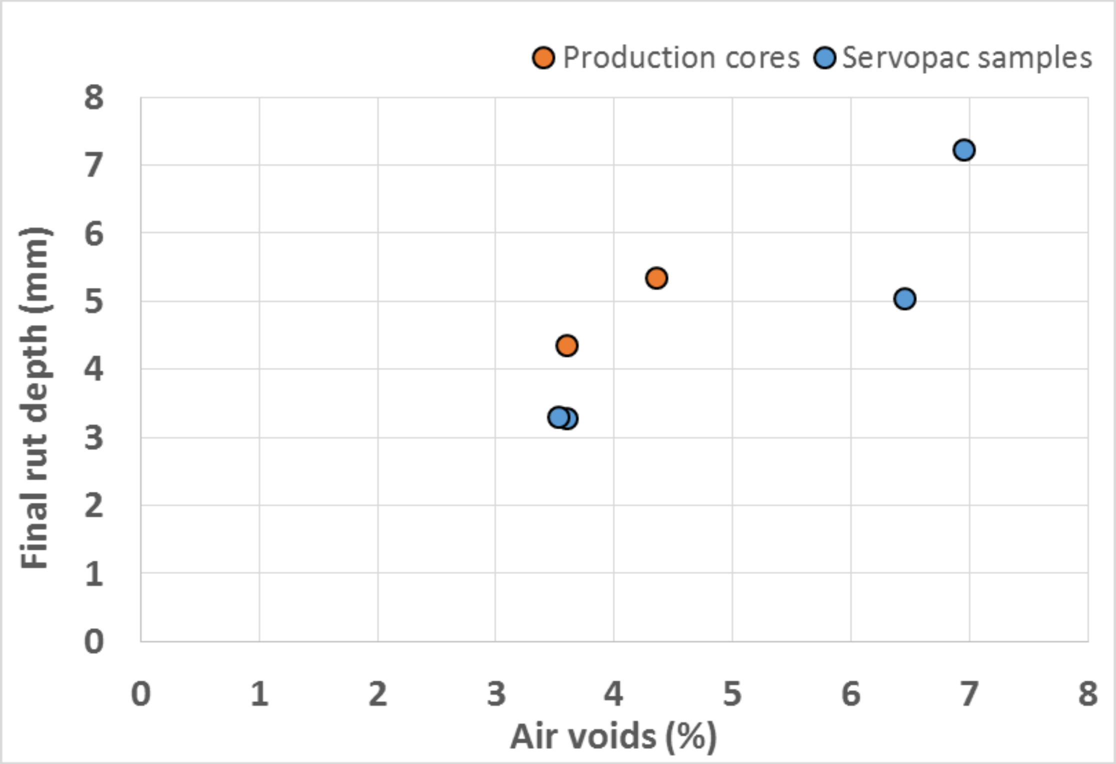
Table 3.8: Results for Cooroy to Curra – Production cores and Servopac samples

	Test No.	Core no.	Date manufactured	Date tracked	Age in days	Compacted density (t/m^3)	Air voids (%)	Final rut depth (mm)	Cycles tracked
Production cores	Design voids Test 1	1		18/02/2015		2.358	3.8	5.35	10 000
		2		18/02/2015		2.331	4.9		
	Design voids Test 2	3		18/02/2015		2.357	3.9	4.36	10 000
		4		18/02/2015		2.370	3.3		

	Test No.	Core no.	Date manufactured	Date tracked	Age in days	Compacted density (t/m^3)	Air voids (%)	Final rut depth (mm)	Cycles tracked
Servopac samples	Design voids Test 1	1		26/02/2015		2.370	3.3	3.30	10 000
		6		26/02/2015		2.358	3.8		
	Design voids Test 2	4		26/02/2015		2.367	3.5	3.30	10 000
		7		26/02/2015		2.364	3.6		
	Higher voids Test 1A*	8		2/03/2015				4.81	6800
		9		2/03/2015					
	Higher voids Test 2	11	11/02/2015	20/05/2015	98	2.293	6.5	7.23	10 000
		12	11/02/2015	20/05/2015	98	2.271	7.4		
	Higher voids Test 1B	2	11/02/2015	20/05/2015	98	2.304	6.0	5.05	10 000
		13	11/02/2015	20/05/2015	98	2.282	6.9		

* The first set of cores at the higher voids reached 6800 cycles before the test cut out due to a device malfunction. An additional pair of cores was tested (Test 1B).

Figure 3.10: Air voids vs final rut depth - Cooroy to Curra mix



4 SUMMARY OF FINDINGS AND RECOMMENDATIONS

A comprehensive study of the use of the Hamburg Wheel Tracking Device around the world has found that the device is gaining acceptance as a valuable tool as a moisture sensitivity and rutting resistance check on a range of asphalt mixes.

Laboratory testing has proved that the HWTD is capable of identifying the combined impact of moisture sensitivity and plastic deformation of various asphalt mixes. The testing has also revealed that changes to the temperature of the water bath and the air voids of the samples can have a considerable effect on the resulting rut depths during testing.

The consultation process with industry helped to clarify the future use of the device and enabled the finalisation of a set of conditions for the performance assessment phase.

A proposed test method, in the style of existing TMR laboratory test methods and developed based on the method contained in AASHTO T324, is under development in consultation with TMR laboratory staff who have experience with the device. This is expected to be finalised in July 2015.

It is recommended that the following steps are taken to ensure the best application of the HWTD going forward:

1. Any asphalt material testing over the coming months should include a request for additional material to test in the HWTD. The funding of this testing can be discussed with contractors, but running a series of tests on several mixes will be greatly beneficial and should be encouraged. ARRB will be available to monitor and analyse results should this be required.
2. The attached test method should be reviewed and incorporated into the TMR Laboratory Testing Manual to ensure consistency of testing. This will be especially important should another HWTD be purchased by an Australian contractor or laboratory, and will enable TMR to facilitate a consistent and reliable testing process.
3. The proposed test conditions should also be reviewed and developed into a set list of conditions to ensure consistency across mixes, including:
   (a) A table designating water bath temperature depending on the binder and/or mix properties, such as:

Mix type	Test temperature (ºC)
Standard	50
High-performance mixes & polymer modified binders (PMB)	55

   A definition may be required for what defines a ‘high-performing mix’.

   (b) A requirement for testing at two air void contents, one at design air voids and one at a lower compacted density consistent with what is typically achieved in the field.

   An example of a set of test conditions is documented in Appendix C.

4. The equipment malfunctions encountered thus far during testing have hampered the development of the HWTD in Queensland. Continual, repeated problems with the device will prohibit its use as a design tool for industry and/or a screening tool for TMR. Every effort must be made to rectify these problems. Should further problems be encountered, concerns may need to be communicated to the equipment manufacturers stressing the need for permanent solutions, as it may be jeopardising the future of the device in Australia.

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APPENDIX A FULL TABLE OF RESULTS

Material	Sample no.	Compacted density (t/m³)	Air voids (%)	Water temperature (ºC)	Final rut depth (mm)	Cycles tracked
DG20HM	Slab 1	2.392	4.9	60	6.67	10 000
	Slab 2	2.386	5.2	60	19.40	7983
	Slab 3	2.389	5.0	60	5.86	9248
DG14	Slab 1	2.354	5.5	60	12.86	10 000
	Slab 2	2.366	5.0	60	19.87	5474
	Slab 3	2.368	4.9	60	19.61	4944
	Slab 4	2.372	4.8	50	8.64	10 000
	Slab 5	2.368	4.9	50	5.78	10 000
SM 14	Slab 1	2.421	3.5	60	4.12	10 000
	Slab 2	2.418	3.5	60	5.95	10 000
	Slab 3	2.395	4.4	60	6.95	10 000
	Slab 4	2.331	7.0	60	14.72	10 000
Type 1	Slab 1	2.331	4.9	60	17.86	1816
	Slab 2	2.332	4.9	60	20.10	2231
	Slab 5	2.313	5.7	55	20.01	5159
	Slab 6	2.322	5.3	55	20.16	8000
	Slab 3	2.327	5.1	50	17.19	10 000
	Slab 4	2.329	5.0	50	15.86	10 000
EME2	Core 3/4	Average air voids across all samples of 1.0% with standard deviation of 2.8%		60	5.01	10 000
	Core 5/6			60	3.84	10 000
DG20HM (from EME trial)	Core 2/7	Average air voids across all samples of 4.7% with standard deviation of 0.8%		60	4.90	10 000
	Slab 1	-	4.8	60	7.29	10 000
	Slab 2	-	5.3	60	13.80	10 000
Cooroy to Curra	Core 1	2.358	3.8	55	5.35	10 000
	Core 2	2.331	4.9	55		
	Core 3	2.357	3.9	55	4.36	10 000
	Core 4	2.370	3.3	55		
	Servopac 1	2.370	3.3	55	3.30	10 000
	Servopac 6	2.358	3.8	55		
	Servopac 4	2.367	3.5	55	3.30	10 000
	Servopac 7	2.364	3.6	55		
	Servopac 11	2.293	6.5	55	7.23	10 000
	Servopac 12	2.271	7.4	55		
	Servopac 2	2.304	6.0	55	5.05	10 000
	Servopac 13	2.282	6.9	55		

APPENDIX B PHOTOS OF TRACKED SAMPLES

The following photos give an indication of what the slabs look like after wheel tracking. Slabs were cut to assess the damage within the slab and to get a better view of the extent of rutting. It should be noted that these are all high performing and regularly used mixes and the test results and visual performance only indicate performance under a given set of test conditions.

B.1 DG20HM

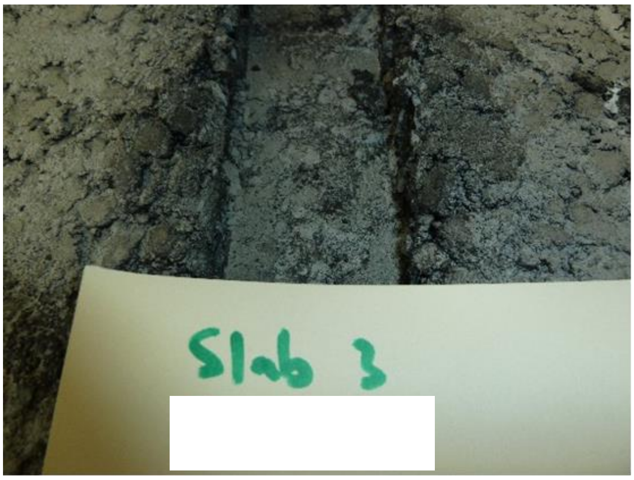
B.2 DG14


[redacted] DG14(320)
Slab 1
SAS14-031


DG14(320)
Slab 2
SAS14-031


[redacted] DG14(320)
Slab 2
SAS14-031


DG14(320)
Slab 3
SAS14-031
[redacted]


Slab 3
[redacted]


[redacted]


[redacted]


[redacted]

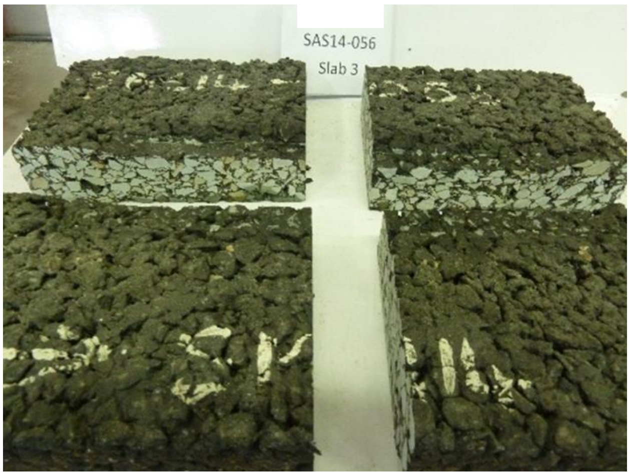

[redacted]

B.3 SM14


[redacted]
SAS14/056
Slab 1


[redacted]
SAS14/056
Slab 1


SAS14-056
Slab 3

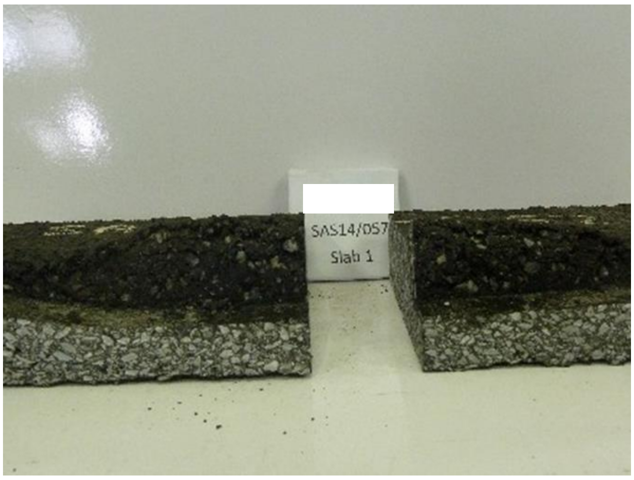

SAS14-056
Slab 3


[redacted]
SAS14-056
Slab 4

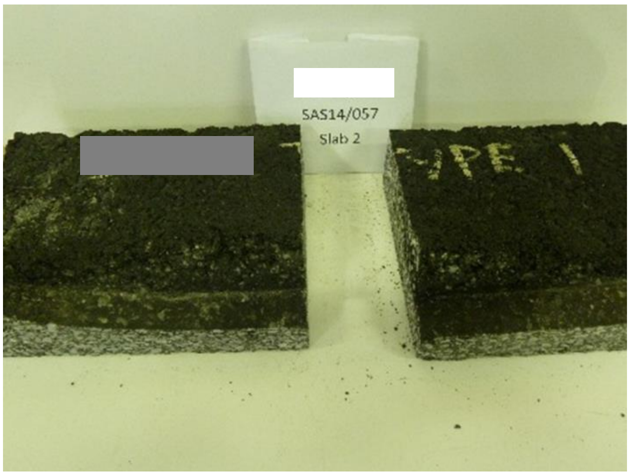

[redacted]
SAS14-056
Slab 4

B.4 Type 1


SAS14-057
SAS14/057
Slab 1


[redacted]
SAS14/057
Slab 1


[redacted]
TYPE 1
[redacted]
SAS14/057
Slab 2
057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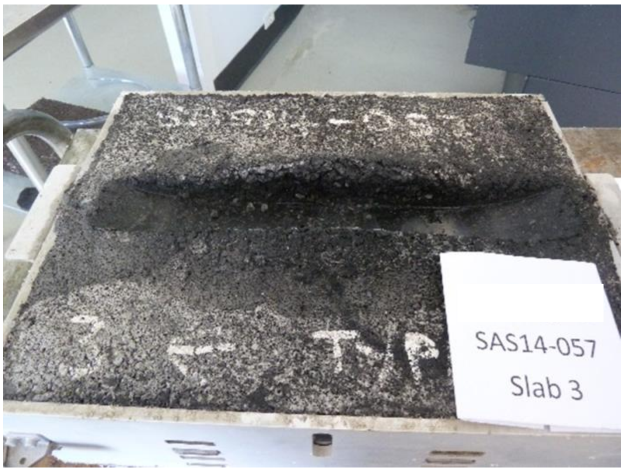
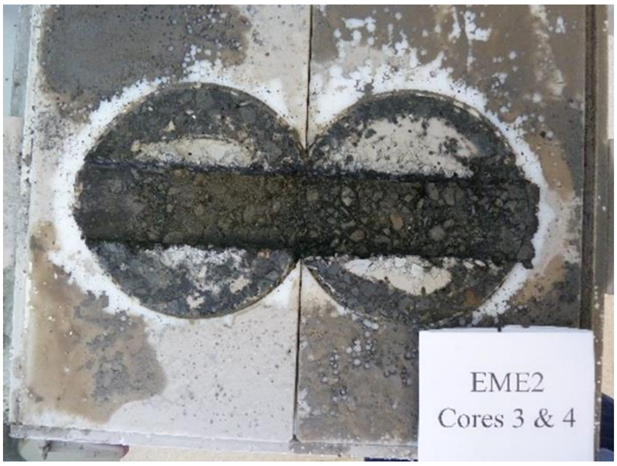
SAS14/057
Slab 2
TYPE 1


SAS14-057
3 ← TYP
[redacted]
SAS14-057
Slab 3


[redacted]
[redacted]
SAS14-057
Slab 4

B.5 EME2 and DG20HM testing



B.6 DG20HM – Cooroy to Curra

APPENDIX C TESTING PLAN – PHASE 2

Performance Assessment Phase: Laboratory Testing Plan for 2014/15: Cooroy to Curra mix

The testing will be done with cores, with one ‘sample’ being comprised of two 150 mm diameter cores with a straight edge cut on one side such that they fit snugly in the customised mould.

Each sample will be run with a duplicate (preferably at the same time), and testing will take place at two different void contents.

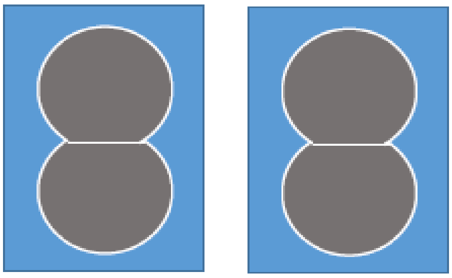
Thus, the total amount of testing is eight cores making up four samples.

The tests are to be run under the following conditions:

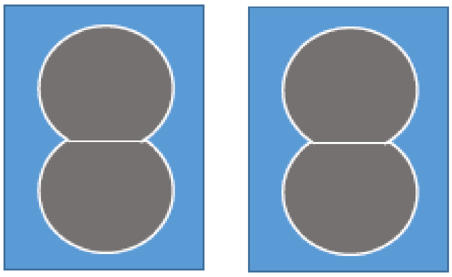
- Air voids to be set at two different values:
    - At the design air voids, with a tolerance of ± 1%
    - at air voids corresponding to 97% of the compacted density of the design mix, with a tolerance of ± 1%
- Cores are to be produced using the Servopac according to AS2891.2.2.
- No ageing required for the samples, but should be consistent between samples
- Test temperature to be set at 50°C with a conditioning time of 120 minutes taken from the time the sample reaches test temperature
- Passes per minute of 52 ± 2 – this is equivalent to **26 ± 1 cycles** (pass is defined as one single load)
- Load: **705 N ± 4.5 N**
- Wheel width: **47 mm ± 1 mm**
- Number of cycles: **10 000** (one pass is one movement; ‘back and forth movement=2 passes=1 cycle)
- Termination conditions set to 20 mm maximum rut depth.

As with the slabs tested in the first phase of testing, we would require:

- pictures of the slabs before and after tracking (cross-section and from above)
- cutting the samples in half along the longitudinal axis then across (cut in 4 pieces) and take photos of these pieces.



Tested at design air voids ± 1%



At air voids corresponding to 97% of the compacted density of the design mix ± 1%