

FINAL REPORT

P149: Moisture Susceptibility of Asphalt Mixes (2024–26)

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Summary

Moisture damage in asphalt can lead to premature failures that are often very costly to repair. A key element of the Queensland Department of Transport and Main Roads (TMR) risk mitigation strategy against stripping is the mandatory use of hydrated lime in certain mix types. However, concerns have recently been raised relating to the carbon intensity of hydrated lime production as well as future supply security. This has triggered an investigation of alternative approaches to stripping failure mitigation. In response, Austroads (2024) developed an interim protocol to evaluate the effectiveness of alternative adhesion agents.

This National Asset Centre of Excellence (NACOE) project evaluated the appropriateness of the interim Austroads laboratory assessment protocol using Queensland materials and assessed the performance of different types of locally available binder adhesion agents (BAAs).

A laboratory testing program was undertaken and comprised testing the moisture sensitivity of 4 different South East Queensland aggregates using a C320 binder in combination with hydrated lime, amine-, silane- and bio-oil based adhesion agents.

The laboratory results showed that several locally available liquid anti-stripping agents can provide equivalent or better performance than hydrated lime. However, the effectiveness of the agents is highly dependent on the type of aggregate used in the mix with some demonstrating poorer performance than hydrated lime with certain aggregate types.

The results of the study also indicated there is no single standard laboratory test method available in Australia that can reliably and consistently predict the moisture sensitivity of asphalt mixes with different BAAs. The use of a combination of different binder–aggregate adhesion and asphalt moisture sensitivity tests recommended in the interim Austroads laboratory assessment protocol, therefore, seems to be appropriate until a more robust test method is developed.

The study also identified potential modifications to TMR's current Hamburg Wheel Tracker assessment criteria for asphalt mixes containing BAAs.

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1. Introduction

1.1 Background

Moisture damage (also known as stripping) in asphalt can lead to premature pavement failures that are often very costly to repair. A key element of the Queensland Department of Transport and Main Roads (TMR) risk mitigation strategy against asphalt stripping is the mandatory use of hydrated lime in several of its standard asphalt mix types. However, industry has raised some concerns regarding the future sustainability implications associated with hydrated lime and has suggested that there are alternative additive binder adhesion agents (BAAs) available with a lower carbon footprint, such as liquid adhesion agents (LAAs).

In response to the concerns raised by industry, Austroads engaged the National Transport Research Organisation (NTRO) to investigate the feasibility of using different BAAs as alternatives to hydrated lime in asphalt. Austroads project APT6048 *Feasibility of Using Anti-stripping Additives as an Alternative to Hydrated Lime* developed an interim laboratory assessment protocol to assess the effectiveness of different BAAs in asphalt (Austroads 2024).

The interim Austroads protocol requires the adhesion between the binder and aggregates to be assessed by means of the standard plate stripping test commonly used for sprayed seals in Australia. However, the lack of experience using this test for asphalt applications was identified as a key limitation, and further validation work was required to confirm the suitability of this test method for asphalt. Several alternative binder–aggregate adhesion tests used internationally were also identified, including the rolling bottle and boiling water tests. The Australian asphalt industry recommended that the boiling water test also be considered as a potential test when assessing the adhesion of the binder–aggregate system.

The interim Austroads protocol also recommends that the stripping potential of the compacted asphalt mix be assessed using the standard tensile strength ratio (TSR) test. However, given the concerns with the TSR test to reliably differentiate between the moisture susceptibility of different asphalt mixes in the laboratory, the Hamburg Wheel Tracker (HWT) test was also included in the protocol for higher risk applications.

After the publication of the draft Austroads protocol, TMR developed and published a nonstandard mix design registration procedure for dense graded asphalt (DGA) mixes containing BAAs instead of hydrated lime. This procedure is documented in Technical Note 213 (TN 213) *Registration of Nonstandard Dense Graded Asphalt Mixes Containing Bitumen Adhesion Agents Instead of Hydrated Lime*.

1.2 Purpose and objectives

The primary purpose of this project was to evaluate the appropriateness of the interim Austroads assessment protocol using Queensland materials and to assess the performance of different BAAs. The key objectives of the project were to:

- identify and source 4 asphalt aggregate types commonly used in South East Queensland
- identify and source 4 commercially available BAAs with different chemistries, including hydrated lime
- assess the binder–aggregate adhesion and asphalt moisture sensitivity of the different combinations in the laboratory using the test methods included in the interim Austroads assessment protocol
- evaluate the suitability of the different test methods included in the protocol to rank the effectiveness of the BAAs
- compare the laboratory findings against the known field performance of the different aggregates used in the study
- inform TMR about whether the interim Austroads laboratory assessment protocol is suitable for adoption in its asphalt specifications and mix design registration processes

- inform TMR about any amendments to the interim Austroads laboratory assessment protocol and TN 213 requirements to ensure that asphalt mixes that contain a BAA will provide equivalent or better resistance to moisture, conforming to MRTS30 mix designs that contain hydrated lime
- recommend any Queensland specific modifications to the interim Austroads laboratory assessment protocol
- document the findings in a technical report.

1.3 Report structure

The structure of the technical report is as follows:

- Section 2 provides a background on the moisture susceptibility of asphalt, introduces the evaluation frameworks developed by Austroads (2024) and TMR, and provides a summary of the relevant moisture susceptibility test methods used in the study.
- Section 3 outlines the experimental methodology and presents the test results.
- Section 4 provides a critical review of the laboratory test methods used in the study.
- Section 5 presents the outcomes of the Austroads and TMR evaluation protocols based on the laboratory test results.
- Section 6 summarises the findings of the project and provides recommendations for consideration by TMR.

The detailed laboratory test results are included in Appendix A.

2. Moisture Susceptibility of Asphalt

Asphalt stripping is the failure of the bond between the binder and aggregates (adhesive failure) or within the binder mastic (cohesive failure) (Alam and Aggarwal 2020). Stripping may lead to a decrease in the durability and strength of the asphalt layer and is generally manifested through rutting, shoving, potholes, cracking, ravelling and/or corrugations (Abed et al. 2019; Airey and Choi 2002; Alam and Aggarwal 2020). Figure 2.1 shows examples of asphalt stripping observed on TMR's road network.

Figure 2.1: Asphalt stripping failures



Source: TMR.

Typical moisture-related failure mechanisms include:

- displacement, which is the result of discontinuities in the binder film
- detachment, which is the separation of the binder from the surface of the aggregates in the presence of water
- spontaneous emulsification, which is the result of water diffusing into the binder
- increased pore pressure, caused by the densification of asphalt under traffic loading while moisture is present within the voids
- hydraulic scouring, caused by trafficking wet asphalt (Diab et al. 2017; Shah et al. 2022).

Various factors affect the moisture susceptibility of asphalt, including:

- pavement design and road drainage
- asphalt mix properties
 - the characteristics of the aggregates and binder
 - the presence and type of fillers and additives
 - the asphalt type and mix design
- asphalt manufacturing and construction
- environmental and traffic conditions (Australian Asphalt Pavement Association 2017).

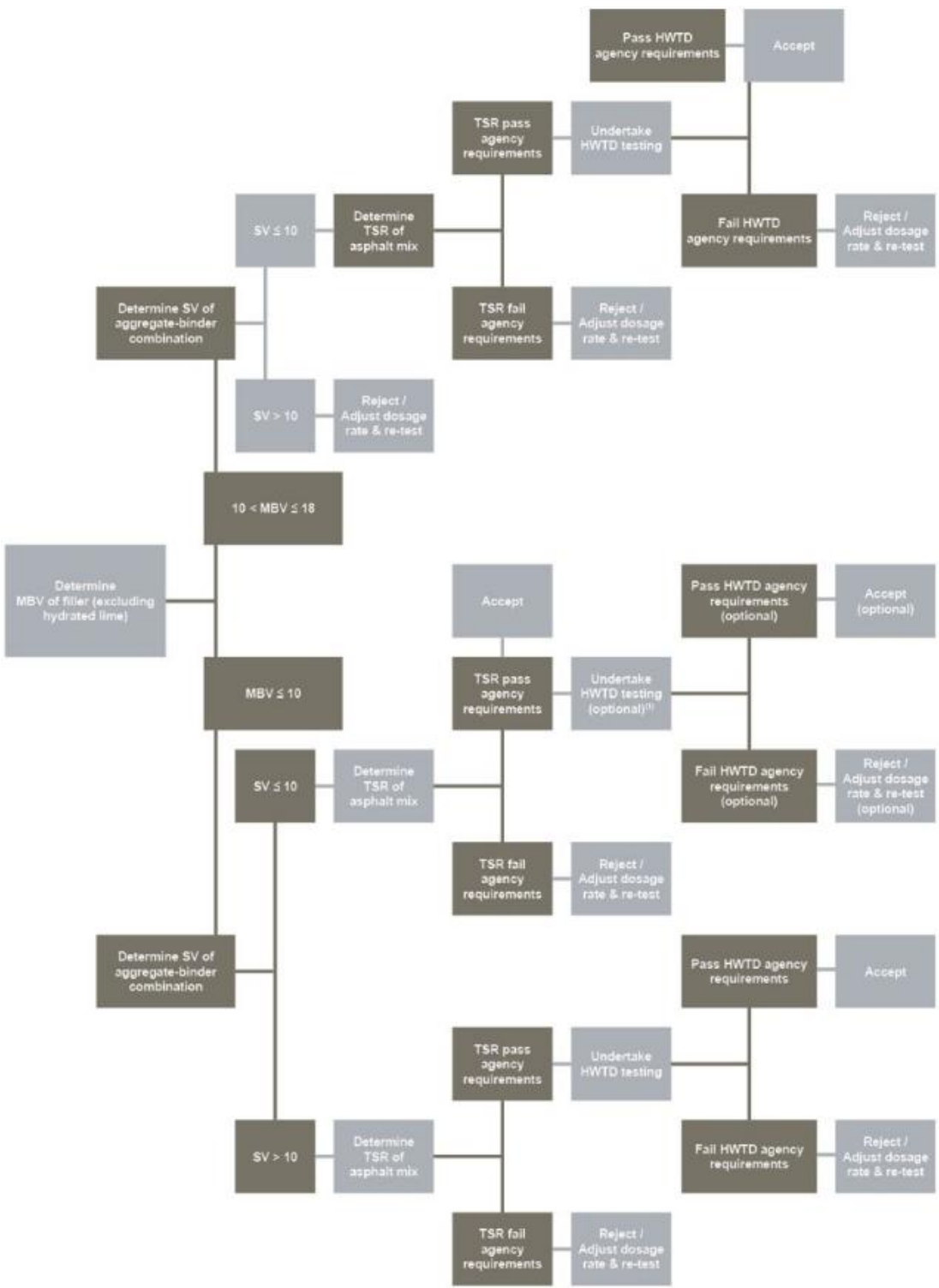
Considering the above, assessing the propensity of asphalt to stripping failure is complex.

2.1 Moisture sensitivity assessment protocols

Austrroads (2024) published an interim laboratory assessment protocol to assess the stripping potential of asphalt, with and without adhesion agents (refer to Figure 2.2). The protocol comprises 2 components:

1. standard material and asphalt mix characterisation testing
2. standard binder adhesion and asphalt performance testing.

Figure 2.2: Austrroads interim laboratory stripping assessment protocol



Source: Austrroads (2024:Figure 6.2), 'Assessment protocol', Austrroads.

Standard material and asphalt mix characterisation testing is recommended to be undertaken when the use of alternative BAAs is considered. The following testing is recommended in the protocol:

- binder testing with and without the BAAs to ensure continued compliance with relevant binder specifications¹
- methylene blue value (MBV) testing of the total combined mineral filler (excluding hydrated lime) in the asphalt mix
- volumetric testing of the asphalt mix with and without the BAA.

Following the development of the Austroads protocol, TMR published TN 213, which provides prequalified asphalt contractors with a pathway to include BAAs (other than hydrated lime) in asphalt mixes through the nonstandard asphalt mix design registration process. TN 213 provides a protocol for assessing the suitability of using BAAs instead of hydrated lime in DGA. The protocol is based on the interim Austroads protocol shown in Figure 2.2 and comprises 4 phases:

1. desktop assessment
2. constituent materials testing
3. binder–aggregate adhesion testing
4. asphalt mix moisture sensitivity testing.

Phase 1 requires:

- the provision of a sample of the BAA proposed for use
- assurance on consistency of the supply
- details of the proposed product
- proposed BAA incorporation methodology
- evidence of proven performance.

Phase 2 generally aligns with the standard material and asphalt mix characterisation testing proposed by Austroads (2024).

Phase 3 is optional and recommends that the stripping value (SV) of the binder–aggregate system be determined and reported in accordance with AS 1141.50 *Methods for Sampling and Testing Aggregates. Resistance to Stripping of Cover Aggregate from Binder*.

Phase 4 comprises:

- the preparation of 3 mix designs with similar gradings and binder contents without any adhesion agent, with hydrated lime, and with the BAA proposed for use
- volumetric testing of the 3 asphalt mixes in accordance with test method Q305 *Stability, Flow and Stiffness of Asphalt – Marshall* or AS/NZS 2891.2.2 *Methods of Sampling and Testing Asphalt. Sample Preparation – Compaction of Asphalt Test Specimens using a Gyratory Compactor*
- TSR testing of the 3 asphalt mixes in accordance with Austroads test method ATM 232 *Stripping Potential of Asphalt – Tensile Strength Ratio*
- HWT testing of the 3 asphalt mixes in accordance with TMR test method Q325 *Stability of Asphalt – Hamburg Wheel Tracker (HWT)*.

The binder-adhesion test results are for reporting purposes only, whereas the HWT test is used to demonstrate equivalent (or better) performance to the same asphalt mix with hydrated lime (i.e. a mix design that conforms with current MRTS30 requirements). The nonstandard mix containing the proposed alternative BAA must also meet the following HWT criteria:

- ≤ 12.5 mm rut depth at 20,000 passes for polymer modified and M1000 multigrade binders
- ≤ 12.5 mm rut depth at 15,000 passes for C600 bitumen
- ≤ 12.5 mm rut depth at 10,000 passes for C320 bitumen.

¹ Only relevant if the adhesion agent is to be blended with the binder before the asphalt mixing process.

2.2 Moisture sensitivity test methods

This section provides a brief description of the relevant moisture susceptibility test methods included in the Austroads and TMR assessment protocols.

The MBV test is described in AS 1141.66 *Methods for Sampling and Testing Aggregates. Methylene Blue Absorption Value of Fine Aggregate and Mineral Fillers*. The method detects the presence of reactive clays on the surface of the fine aggregates used in the asphalt mix. The negatively charged clay minerals undergo an ion exchange with the methylene blue cations. During testing, methylene blue is incrementally added to filler suspended in distilled water until the filler can no longer absorb more of the dye. This is called the endpoint. The MBV of the filler material is defined as the concentration of dye required to reach that endpoint and is an indication of the amount of reactive clays present.

The plate stripping test is commonly used in Australia to assess the adhesion between sprayed sealing aggregates and a bituminous binder to determine the need for adhesion agents. During the plate stripping test, aggregates are embedded into a heated binder on a plate and then conditioned in the oven. Following that, the plate with the binder and aggregates is submerged in a water bath for a standard period of time. After the assembly has been conditioned, the aggregates are pulled out from the binder and the degree of binder coating is visually assessed and expressed as a percentage of stripped aggregates. There are various plate stripping methods available in Australia, including:

- AS 1141.50, *Methods for Sampling and Testing Aggregates. Resistance to Stripping of Cover Aggregates from Binders*
- South Australia TP705, *Determination of Aggregate Stripping by the One Day Plate Stripping Test*
- New South Wales TS 02799.27, *Resistance to Stripping of Aggregates and Binders*
- Queensland Q212B, *Binder Stripping Value – Modified Plate*
- Queensland Q212C, *Binder Stripping Value – Immersion Tray*
- Western Australia WA 720, *Assessment of Liquid Adhesion Agents*.

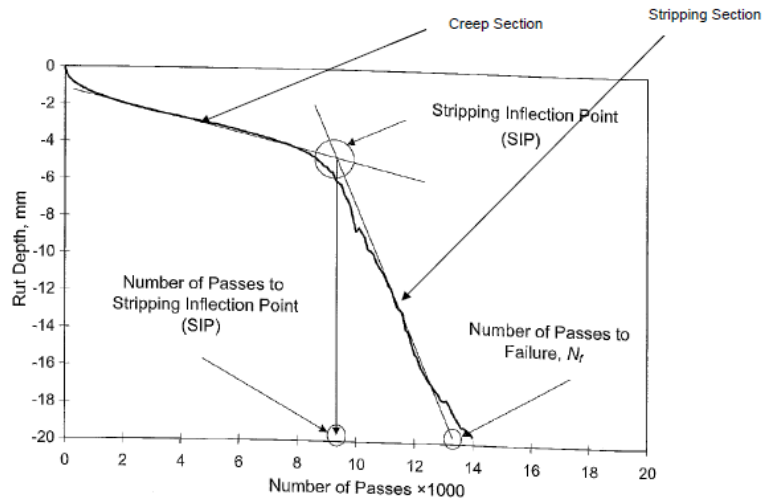
The method referenced in the interim Austroads protocol and TN 213 is AS 1141.50.

In ASTM D3625/D3625M *Standard Practice for Effect of Water on Bituminous-Coated Aggregate Using Boiling Water*, also known as the Texas boiling test, binder-coated aggregates are submerged in boiling water. After 10 minutes, the water is drained and the amount of binder stripped from the surface of the aggregates is visually determined.

Austroads TSR test method (ATM 232) determines the indirect tensile strength (ITS) test of compacted asphalt specimens in dry and saturated conditions. The saturated specimens are also typically subjected to a freeze–thaw conditioning cycle prior to testing. The TSR is calculated as the ratio between the average tensile strength of the saturated and the dry specimens. The fractured surfaces of the asphalt specimens are also visually assessed for any signs of stripping.

TMR test method Q325 uses the HWT device to evaluate the stability (i.e. resistance to rutting and stripping) of asphalt mixes in the laboratory. The test measures the permanent deformation of 2 asphalt specimens submerged in water and subjected to a rolling wheel load. The number of passes to a 12.5 mm rut depth is typically used to assess the deformation resistance of the asphalt mix. The stripping inflection point (SIP) is defined as the number of passes where a distinct change in the slope of the deformation curve as a function of wheel passes occurs and indicates the occurrence of moisture-related damage in the mix (refer to Figure 2.3).

Figure 2.3: Example of asphalt SIP in the HWT test



Source: Reproduced with permission from TMR (2025): Test method Q325, TMR.

It is worth noting that the SIP is visually estimated in the standard test method based on a change in the slope of the deformation curve. This visual estimation may introduce a degree of subjectiveness and is less accurate compared to measured values or analytic methods. Yin et al. (2025) developed software to standardise and automate the calculation of the SIP in the HWT test. The calculation method uses the well-established Francken model (refer to Equation 1) to identify the presence of the onset of stripping by analysing the shape and curvature of the deformation curve. This approach eliminates the need for subjective interpretation of the SIP, as shown in Figure 2.4.

$$RD = A \times N^B + C(e^{D \times N} - 1)$$

1

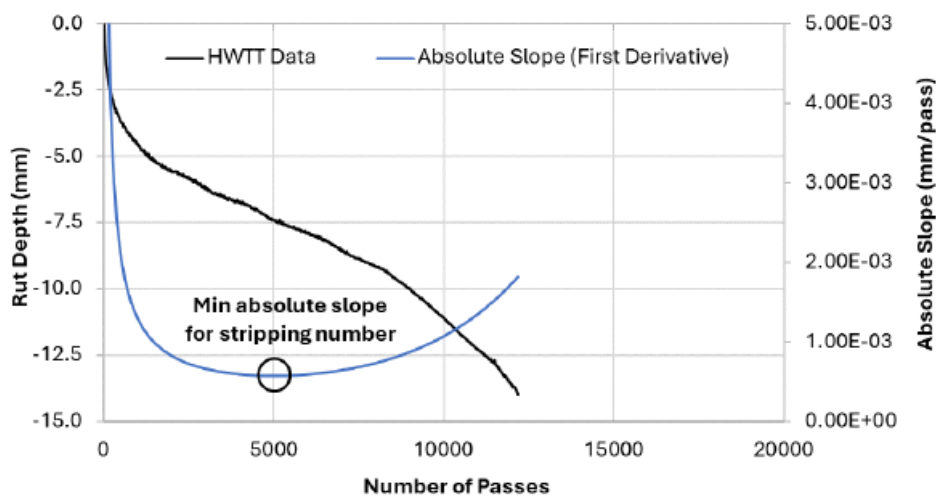
where

RD = HWT rut depth (mm)

N = number of HWT passes

A, B, C & D = model coefficients

Figure 2.4: Example of an SIP calculation using an analytical method



Source: Reproduce with permission from Yin et al. (2025): Figure 17.

3. Laboratory Investigation

3.1 Materials and test methods

The laboratory testing program developed for the project comprised the following:

- binder–aggregate adhesion testing using the:
 - MBV test in accordance with AS 1141.66
 - plate stripping test in accordance with AS 1141.50
 - boiling water test in accordance with ASTM D3625/D3625M
- asphalt mix moisture sensitivity testing using the:
 - TSR test in accordance with ATM 232
 - HWT test in accordance with Q325.

Testing was undertaken on samples prepared using a Class 320 base binder (C320), 4 different South East Queensland aggregates and 4 commercially available BAAs.

The adhesion agents used for the study were:

- hydrated lime
- an amine-based BAA
- a bio-oil based BAA
- a silane-based BAA.

The aggregates sourced for testing were:

- hornfels
- greenstone
- olivine basalt
- metagreywacke.

The hornfels aggregate was included in the testing program as it was known to produce poor plate stripping test results and can be a ‘difficult aggregate’ for binder adhesion. The olivine basalt aggregate was included in the testing program as it was known to contain fines with a methylene blue value typically within the range of 10–18 mg/g. The greenstone and metagreywacke aggregates were included in the testing program as they are the most common rock types used in asphalt mixes in South East Queensland.

The mineralogy and surface chemistry of aggregates are known to have a significant impact on the adhesion with the bituminous binder and, hence, the moisture susceptibility of the asphalt mix (Austroads 2024). The properties of the coarse aggregates used in the study were as follows:

- hornfels: a metamorphic rock with approximately 59% free silica content and 4% clays and moisture-sensitive materials
- greenstone: a metamorphic/sedimentary rock with approximately 8% free silica and 19% clays and moisture-sensitive materials
- olivine basalt: an igneous rock with no free silica and approximately 9% clays and moisture-sensitive materials
- metagreywacke: a metamorphic rock with approximately 35% free silica content and 20% clays and moisture-sensitive materials.

Based on the mineralogy of the aggregates, the hornfels may potentially have poorer affinity to bitumen due to its relatively high free silica content and subsequent negatively charged surface. The olivine basalt contains smectite clays, which are known to be expansive in nature and may negatively impact the moisture susceptibility of asphalt mixes manufactured with this aggregate type.

3.2 Test results

The binder–aggregate adhesion and asphalt stripping test results are presented and discussed below.

3.2.1 Binder–aggregate adhesion

MBV test results

The MBV of the mineral filler from each aggregate source was determined by the TMR laboratory. TMR technical specification MRTS30 *Asphalt Pavements* requires that the MBV of the combined filler component excluding any hydrated lime must not exceed 18 mg/g and that the MBV of the combined filler with hydrated lime must be ≤ 10 mg/g. This requirement is less stringent than some other jurisdictions, such as Transport for New South Wales, which requires that the MBV of the combined filler component excluding any hydrated lime must not exceed 10 mg/g. Table 3.1 provides an indicative correlation between the MBV of fillers and the expected field performance.

Table 3.1: Correlation between MBV and asphalt performance

MBV (mg/g)	Expected field performance
5–6	Excellent
10–12	Marginally acceptable
16–18	Problems or possible failure
20+	Failure

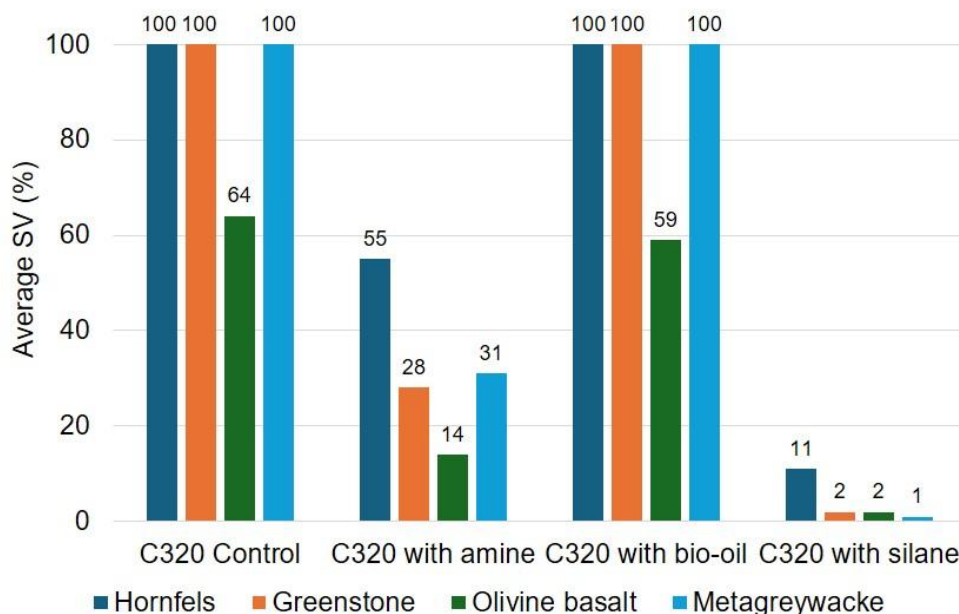
Source: Adapted from Aschenbrener et al. (1994).

The metagreywacke- and greenstone-derived fillers had relatively low MBVs of 6 and 4.7 mg/g, respectively, suggesting these fillers are expected to perform well in-service. The filler derived from the hornfels aggregate was found to be marginally acceptable with a MBV of 10 mg/g, whereas the olivine basalt-derived filler had a very high MBV result of 22.5 mg/g, indicating potentially very poor field performance without the use of any hydrated lime.

Plate stripping test results

The SV of the coarse aggregates used in the study was determined using the plate stripping test. The interim Austroads protocol does not provide any specific sample preparation details for the test, and it was decided that, for this study, the aggregates were to be tested in the as-received condition to represent a potential worst-case scenario (i.e. dusty aggregates). This test was not undertaken for the hydrated lime combinations as it would not necessarily be representative of the typical asphalt manufacturing process in Queensland. The results of the plate stripping tests are shown in Figure 3.1 and tabulated in Appendix A.1.

Figure 3.1: Plate stripping test results



The metagreywacke, greenstone and hornfels aggregates performed very poorly in the plate stripping test without any BAAs.

Of the BAAs investigated, the silane agent was found to be most effective for all aggregate sources in the plate stripping test. The amine agent also had a significant effect on the SV of the different aggregates tested, but the effectiveness varied based on aggregate type. The bio-oil did not have any meaningful effect on the SV of the aggregates included in the study.

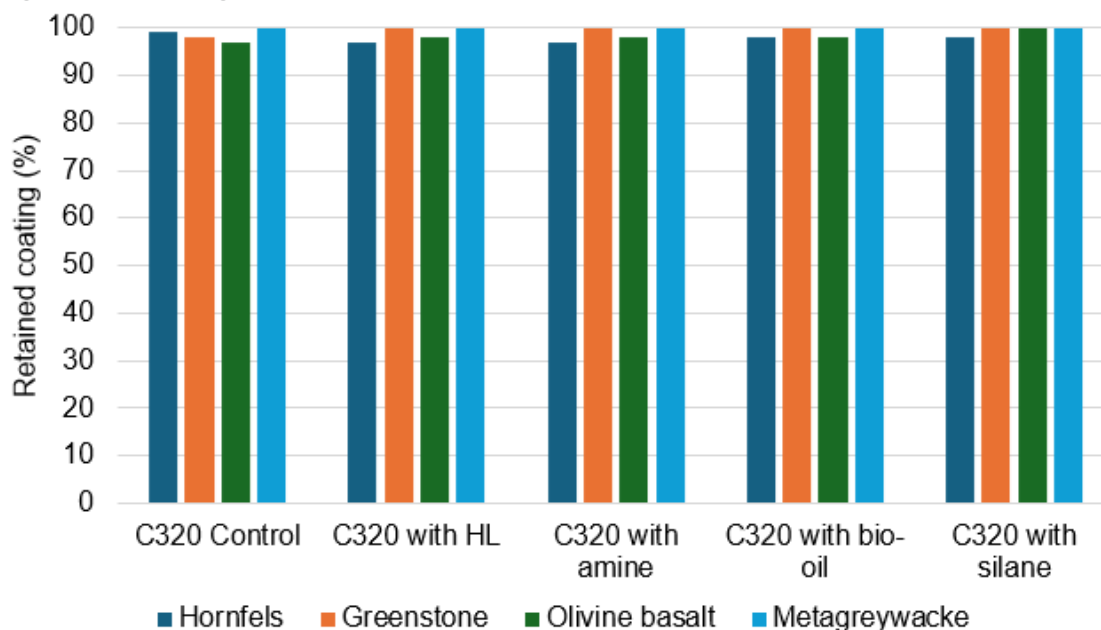
The interim Austroads protocol in Figure 2.2 sets an SV of 10% as a decision point, where a result above 10% would subject the asphalt mix to a more extensive testing regime. This value was originally selected based on the maximum SV typically specified for sprayed sealing aggregate, and it is unclear how applicable this upper limit is for asphalt applications. Nevertheless, only the silane agent achieved an SV below or near the 10% limit.

Notably, the SV results for the control binder and different aggregate sources did not necessarily correlate well with the MBV results. Having the lowest SV of 64%, the olivine basalt aggregate demonstrated the best performance with the C320 control binder without any BAA. This is contrary to the MBV results, whereby the high MBV determined for this aggregate suggested poor adhesion with the binder without any BAA.

Boiling water test results

There is currently no Australian standard asphalt boiling water test method available. Testing was therefore undertaken in accordance with ASTM D3625/D3625M. The results of the boiling water tests undertaken by the TMR laboratory are shown in Figure 3.2 and included in Appendix A.2.

Figure 3.2: Boiling water test results



The boiling water test results ranged between 97 and 100% and were essentially indistinguishable. It appears that the test is not sensitive enough to determine the stripping potential of the different aggregate–BAA combinations used in the study. As a result, the boiling water test results were not included in any subsequent analysis undertaken for this study.

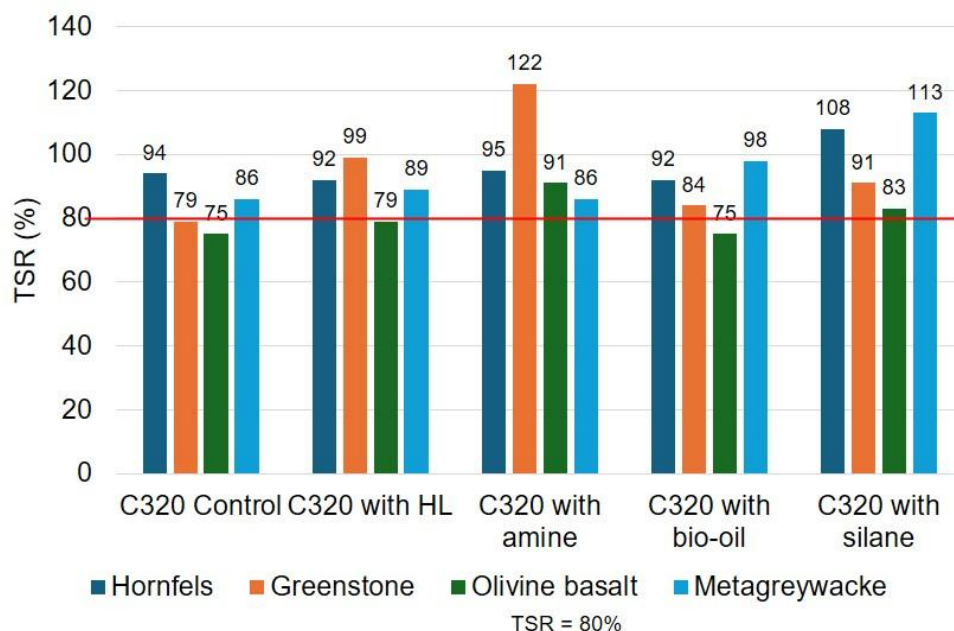
3.2.2 Asphalt moisture sensitivity

TSR test results

The TSR test was undertaken on specimens manufactured using the different aggregate–BAA combinations and specimens without any adhesion agent. The testing included a freeze–thaw conditioning cycle in accordance with ATM 232. ATM 232 requires the moisture-conditioned specimens to have a degree of saturation between 55% and 80%, which is larger than the range specified in AASHTO T283 *Standard Method of Test for Resistance of Compacted Asphalt Mixtures to Moisture-Induced Damage* (i.e. 70–80%). Austroads (2024) raised concerns regarding the reproducibility of ATM 232 given such a large saturation range. Higher specimen saturation levels are also expected to be better representations of field conditions where asphalt stripping is expected to occur (Kandhal and Rickards 2001). A degree of saturation between 70 and 80% was therefore targeted for the TSR testing in this study. The results of the TSR tests are shown in Figure 3.3 and included in Appendix A.3.

MRTS30 requires a TSR of $\geq 80\%$ for an asphalt mix to be considered as having adequate resistance to moisture damage. The control specimens manufactured with the hornfels and metagreywacke aggregates had a TSR of 94% and 86%, respectively, which exceed the minimum limit. The control specimens manufactured with the greenstone aggregates had a TSR of 79%, which is only marginally below 80%. The olivine basalt aggregates without a BAA had a nonconforming TSR of 75%. The low TSR results for the specimens containing the olivine basalt aggregates may be, in part, due to the high MBV for the fines.

Figure 3.3: TSR results



The addition of hydrated lime had a variable effect on the different aggregate types in the TSR test. The lime significantly increased the TSR of the specimens manufactured with the greenstone aggregates, whereas the TSR of the hornfels and metagreywacke samples remained essentially unchanged. The lime also had a minor effect on the TSR of the specimens manufactured with the olivine basalt.

Similar to the hydrated lime, the amine agent significantly increased the TSR of the greenstone specimens and had no meaningful effect on the hornfels and metagreywacke aggregates. However, unlike the lime, the amine agent also significantly increased the TSR of the specimens manufactured with the olivine basalt aggregates.

The bio-oil increased the TSR of the specimens manufactured with the metagreywacke aggregate, slightly increased the TSR of the specimens manufactured with the greenstone aggregate, and had no effect on the hornfels and olivine basalt aggregates.

Notably, adding the silane agent significantly increased the TSR of all the aggregate types included in the study.

The TSR results highlighted the dependency of stripping performance on the compatibility of the aggregate surface and binder-adhesion agent chemistry.

The TSR of the specimens manufactured with the control binder without any BAA did not necessarily correlate well with the MBV results for all the aggregates tested. The filler derived from the hornfels aggregates had a marginal MBV of 10 mg/g but exhibited good performance in the TSR test. Conversely, the filler derived from greenstone aggregates had a low MBV but performed marginally in the TSR test. The MBV test was, however, able to identify the poor moisture sensitivity of the olivine basalt aggregate consistent with the low TSR determined for this material.

Notably, the TSR values of the specimens manufactured with the control binder without any BAA also did not correlate well with the SV results. The specimens manufactured with the hornfels and metagreywacke aggregates performed well in the TSR test but had very high SVs. Conversely, the olivine basalt performed the best in the plate stripping test but had the lowest TSR compared to the other aggregate combinations.

There appears to be a reasonable correlation between the TSR and SV results for some of the aggregate and BAA combinations. For example, both the plate stripping and TSR test were generally able to demonstrate the effectiveness of the amine and silane agents with the greenstone, basalt and

metagreywacke aggregates. However, a poor correlation was observed between the SV and TSR results for the different BAAs used with the hornfels aggregates.

HWT test results

TMR does not have any specification criteria for asphalt mixes tested in the HWT device. However, TN 213 requires DGA mixes containing BAAs to have a rut depth of:

- ≤ 12.5 mm at 20,000 passes for polymer modified and M1000 multigrade binders
- ≤ 12.5 mm at 15,000 passes for C600 bitumen
- ≤ 12.5 mm at 10,000 passes for C320 bitumen.

Table 3.2 provides a summary of the specification criteria used by several states in the USA where the HWT test is used. The C320 bitumen used in this study is expected to be similar to a PG64 binder in the USA.

Table 3.2: USA HWT specification limits

Jurisdiction	Rut depth	SIP
California ⁽¹⁾	• Min. 10,000 passes to a 12.5 mm rut depth (PG58 binder) – Type A mixes • Min. 15,000 passes to a 12.5 mm rut depth (PG64 binder) • Min. 20,000 passes to a 12.5 mm rut depth (PG70 binder) • Min. 25,000 passes to a 12.5 mm rut depth (PG76 or higher binder) – Type A mixes • Test temperature depends on binder grade: – 45 °C for PG58 binder – 50 °C for PG64 binder – 55 °C for PG70 and above binders	Report only
Georgia ⁽²⁾	• Min. 15,000 passes to a 12.5 mm rut depth at 50 °C (4.75 and 9.5 mm SP Type 1 mixes P64 or PG67 binders) • Min. 15,000 passes to a 12.5 mm rut depth at 50 °C (9.5 mm SP Type 2 mixes with P64 or PG67 binders) • Min. 20,000 passes to a 12.5 mm rut depth at 50 °C (12.5, 19 and 25 mm SP mixes with PG64 or PG67 binders) • Min. 20,000 passes to a 12.5 mm rut depth at 50 °C (All mix types with PG76 binder)	• Min. 10,000 passes with no SIP at 50 °C (4.75 and 9.5 mm SP Type 1 mixes PG64 or PG67 binders) • Min. 15,000 passes with no SIP at 50 °C (9.5 mm SP Type 2 mixes with PG64 or PG67 binders) • Min. 20,000 passes with no SIP at 50 °C (12.5, 19 and 25 mm SP mixes with PG64 or PG67 binders) • Min. 20,000 passes with no SIP at 50 °C (All mix types with PG76 binder)
Illinois ⁽³⁾	• Min. 5,000 passes to 12.5 mm rut depth at 50 °C (PG58 or lower binder) • Min. 7,500 passes to 12.5 mm rut depth at 50 °C (PG64 binder) • Min. 15,000 passes to 12.5 mm rut depth at 50 °C (PG70 binder) • Min. 20,000 passes to 12 mm rut depth at 50 °C (PG76 or higher binder)	No requirement
Idaho ⁽⁴⁾	• Max. 10 mm rut depth after 12,500 passes (design ESALs < 1 million) • Max. 10 mm rut depth after 15,000 passes (design ESALs ≥ 10 million) • Test temperature not specifically stated	• Min. 12,500 passes with no SIP (design ESALs < 1 million) • Min. 15,000 passes with no SIP (design ESALs ≥ 10 million) • Test temperature not specifically stated
Massachusetts ⁽⁵⁾	• Max. 12.5 mm rut depth after 10,000 passes (design ESALs < 0.3 million, not required for basecourses) • Maximum 12.5 mm rut depth after 15,000 passes (design ESALs > 0.3 million, not required for basecourses) • Test temperature not specifically stated	• Min. 10,000 passes to SIP (design ESALs < 0.3 million, not required for basecourses) • Min. 15,000 passes to SIP (design ESALs > 0.3 million, not required for basecourses) • Test temperature not specifically stated

Jurisdiction	Rut depth	SIP
Maine ⁽⁶⁾	• Max. 12.5 mm rut depth after 20,000 passes • Test temperature depends on binder grade: – 45 °C for PG64 binder – 48 °C for PG64E binder – 50 °C for PG70E and crumb rubber binder in gap graded asphalt	• Min. 15,000 passes with no SIP • Test temperature depends on binder grade: – 44 °C for PG64 binder – 48 °C for PG64E binder – 50 °C for PG70E and crumb rubber binder in gap graded asphalt
Montana ⁽⁷⁾	• Min. 15,000 passes to 13 mm rut depth at test temperature • Test temperature depends on binder grade: – 44 °C for PG58 binder – 50 °C for PG64 binder – 56 °C for PG70 binder	No requirement
Oklahoma ⁽⁸⁾	• Min. 10,000 passes to 12.5 mm rut depth at 50 °C (PG64 binder) • Min. 15,000 passes to 12.5 mm rut depth at 50 °C (PG70 binder) • Min. 20,000 passes to 12.5 mm rut depth at 50 °C (PG76 binder)	No requirement
Texas ⁽⁹⁾	• Min. 10,000 passes to 12.5 mm rut depth at 50 °C (PG64 or lower binder). May be decreased to at least 5,000 passes when shown on the plans • Min. 15,000 passes to 12.5 mm rut depth at 50 °C (PG70 binder). May be decreased to at least 10,000 passes when shown on the plans • Min. 20,000 passes to 12.5 mm rut depth at 50 °C (PG76 or higher binder) • A minimum rut depth of 2.5 mm is also required at the different allowable passes	No requirement
Utah ⁽¹⁰⁾	• Max. 10 mm rut depth at 20,000 passes ($\geq$ 75 gyratory cycle and stone mastic asphalt mixes) • Max. 10 mm rut depth at 10,000 passes ($<$ 75 gyratory cycle mixes) • Test temperature depends on binder grade: – 46 °C for PG58 binder – 50 °C for PG64 binder – 54 °C for PG70 binder	No requirement
Washington ⁽¹¹⁾	• Min. 10,000 passes to 10 mm rut depth at 50 °C ($<$ 0.3 million design ESALs) • Min. 12,500 passes to 10 mm rut depth at 50 °C (0.3–3 million design ESALs) • Min. 15,000 passes to 10 mm rut depth at 50 °C ($\geq$ 3 million design ESALs)	• Min. 10,000 passes with no SIP at 50 °C ($<$ 0.3 million design ESALs) • Min. 12,500 passes with no SIP at 50 °C (0.3–3 million design ESALs) • Min. 15,000 passes with no SIP at 50 °C ($\geq$ 3 million design ESALs)

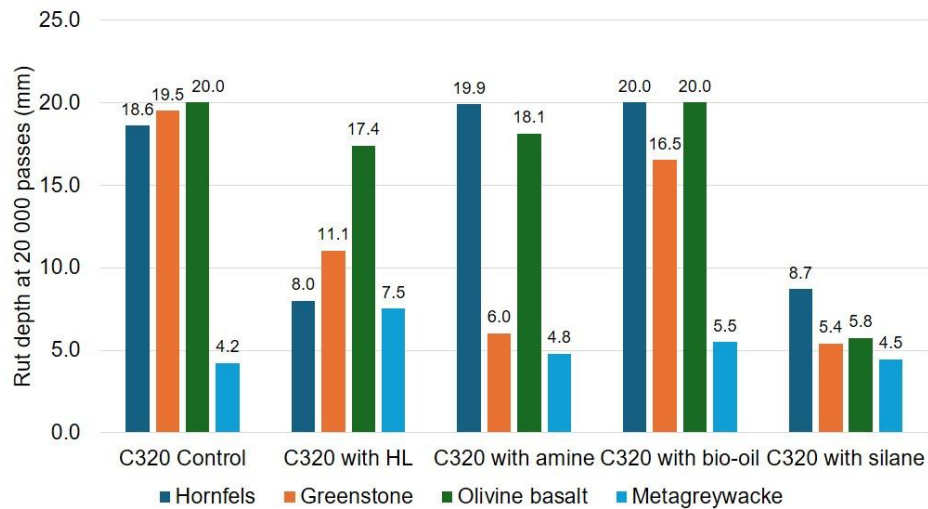
1. California Department of Transportation (2018).
2. Georgia Department of Transportation (2018).
3. Illinois Department of Transportation (2021; 2022).
4. Idaho Department of Transportation (2023).
5. Massachusetts Department of Transportation (2026).
6. Hajj et al. (2021) and Maine Department of Transportation (2021).
7. Montana Department of Transportation (2025).
8. Oklahoma Department of Transportation (2019).
9. Texas Department of Transportation (2024).
10. Utah Department of Transportation (2015; 2026)
11. Washington State Department of Transportation (2024; 2026).

HWT testing was undertaken on specimens manufactured using the different aggregate–BAA combinations (as well as the control binder) in accordance with Q325. The HWT test results are shown in Figure 3.4 and included in Appendix A.4.

The average rut depth at 20,000 passes for the binder–aggregate combinations investigated is presented in Figure 3.4. Without any adhesion agent, all the aggregates, except for the metagreywacke, had a high rut depth (i.e. $>$ 12.5 mm) at 20,000 passes.

The inclusion of hydrated lime significantly reduced the total rut depth of the specimens manufactured with the hornfels and greenstone but had no meaningful impact on the total rut depth measured for the olivine basalt and metagreywacke aggregates. The amine agent also significantly reduced the total rut depth of the specimens manufactured with the greenstone aggregates but had no meaningful effect on the total rut depth for the other aggregates. Notably, the bio-oil did not have any meaningful effect on the total rut depth in the HWT test, irrespective of the aggregate type. The silane agent significantly decreased the total rut depth of the hornfels, greenstone and olivine basalt aggregates.

Figure 3.4: Average HWT rut depth at 20,000 passes



As shown in Figure 3.5, during some HWT tests the rut depth results became unstable towards the end of the test.

Figure 3.5: HWT deformation curve – hornfels with control binder

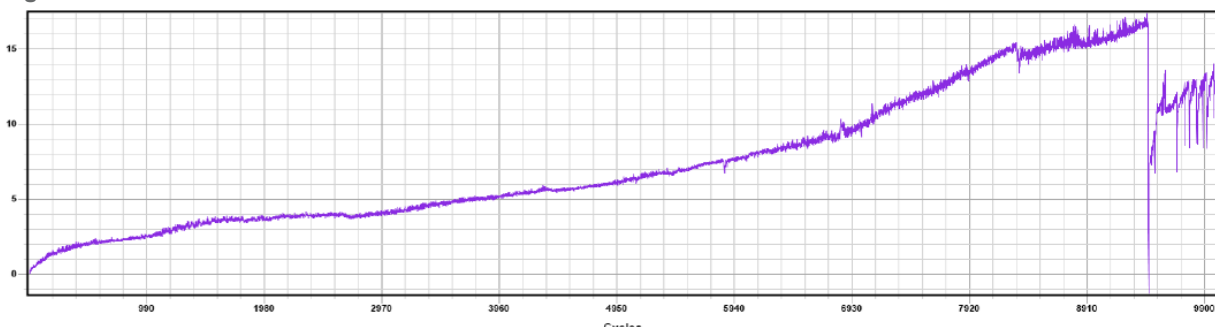
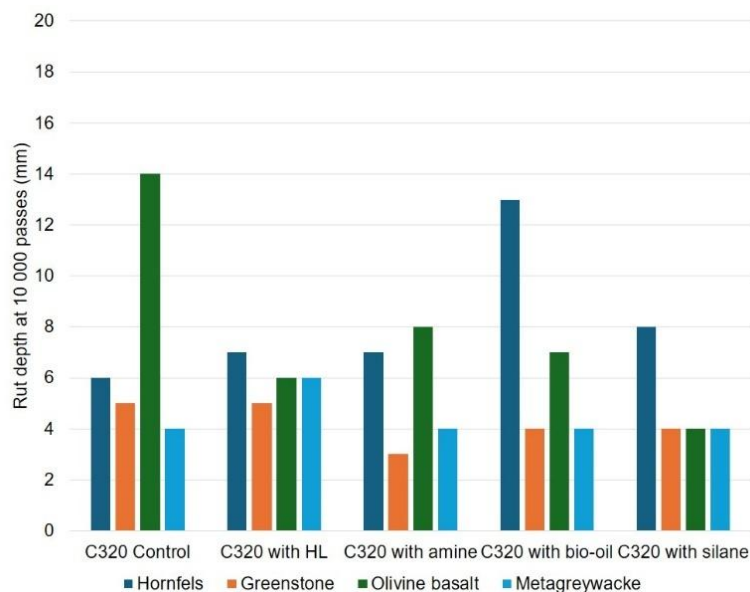
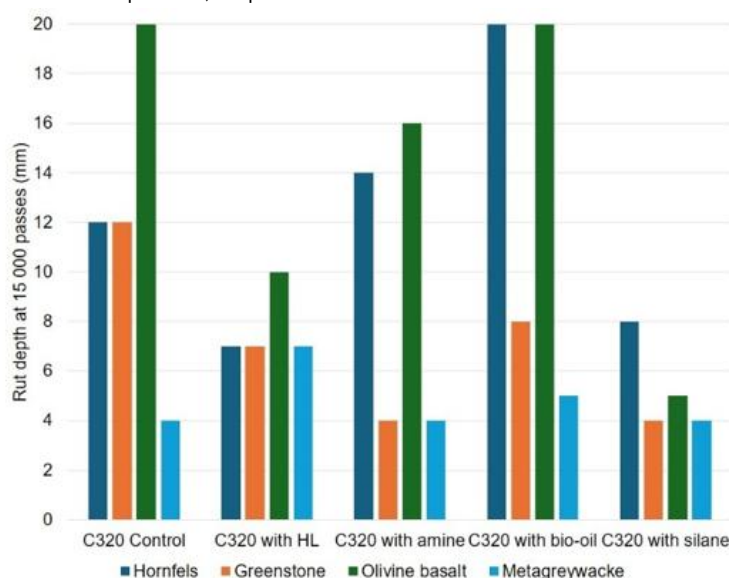


Figure 3.6 shows the HWT rut depth at 10,000 and 15,000 passes. The HWT test was unable to reliably distinguish between the performance for several of the different aggregate-adhesion agent combinations at 10,000 passes. For example, there were no meaningful differences between the rut depth at 10,000 passes for the hornfels and olivine basalt specimens containing hydrated lime and the amine agent, whereas the rut depths at 15,000 passes were significantly higher for these aggregates with the amine agent. The rut depth at 15,000 passes criterion, therefore, appears to be more discriminative than the rut depth at 10,000 passes criterion.

Figure 3.6: Average HWT rut depth at 10,000 and 15,000 passes



a. Rut depth at 10,000 passes



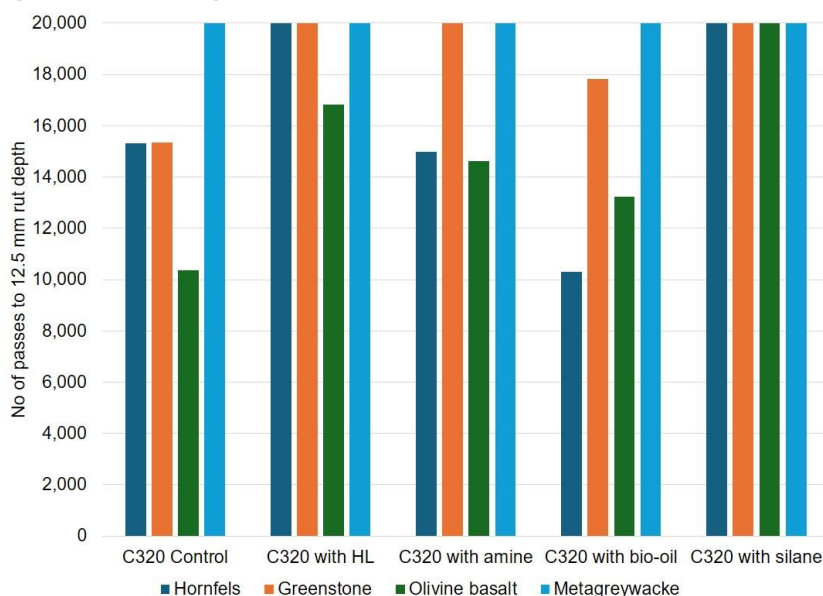
b. Rut depth at 15,000 passes

The number of passes to achieve a maximum rut depth of 12.5 mm is more commonly used in international specifications to assess the moisture sensitivity of an asphalt mix in the HWT test. In Queensland, TN 213 also stipulates the minimum number of passes required to achieve a 12.5 mm rut depth depends on the class of binder used in the mix. For the C320 binder used in this study, a minimum of 10,000 passes to a 12.5 mm rut depth would apply.

Figure 3.7 shows that, without any adhesion agent and with hydrated lime, the hornfels, greenstone and metagreywacke exceeded the 10,000 passes to a 12.5 mm rut depth criterion. However, without any adhesion agent, the olivine basalt only marginally exceeded 10,000 passes, and the result may very well be within the precision of the test method. Notably, the hydrated lime significantly increased the number of passes to a 12 mm rut depth for the specimens manufactured with the olivine basalt.

Similar to the hydrated lime, all the aggregate–BAA combinations tested met 10,000 passes to a 12.5 mm rut depth criterion. However, the number of passes to a 12.5 mm rut depth were only marginally higher than 10,000 for the hornfels aggregate with the bio-oil, which again may be within the precision of the test method.

Figure 3.7: Average number of HWT passes to 12.5 mm rut depth



Note: Values shown as 20,000 passes in the figure represents $\geq 20,000$ passes in the HWT test.

Given that some of the aggregates performed poorly in the TSR and plate stripping tests, the 10,000 passes criterion may not be sufficiently conservative. Several states in the USA (refer to Table 3.2) have more stringent criteria for mixes containing binders equivalent to C320 bitumen, whereby the minimum number of passes required to achieve a 12.5 mm (and even a 10 mm) rut depth varies between 15,000 and 20,000 passes, depending on the binder used. If a more stringent criterion of 15,000 passes to a 12.5 mm rut depth was adopted, the following combinations would have failed the HWT test:

- no adhesion agent with the olivine basalt aggregate
- bio-oil with the hornfels and olivine basalt aggregates.

Also, the following combinations only demonstrated marginal performance against the 15,000 passes to a 12.5 mm criterion:

- no adhesion agent with the hornfels and greenstone aggregates
- amine agent with the hornfels and olivine basalt aggregates.

The more stringent 12.5 mm HWT criterion correlated reasonably well with the MBV results for the aggregates with the control binder. The olivine basalt performed the worst in both tests, whereas the hornfels aggregates also exhibited marginal performance based on the MBV and HWT results. However, the greenstone aggregates had a low MBV but performed marginally in the HWT test based on the stricter criterion.

The 12.5 mm rut depth results correlate well with the TSR results for the greenstone, olivine basalt and metagreywacke aggregates without any BAA. However, the hornfels aggregates performed very well in the TSR test but only marginally in the HWT test based on the stricter 12.5 mm rut depth criterion.

The correlation between the TSR and 12.5 mm rut depth for the different aggregate–BAA combinations is not necessarily always consistent. For example:

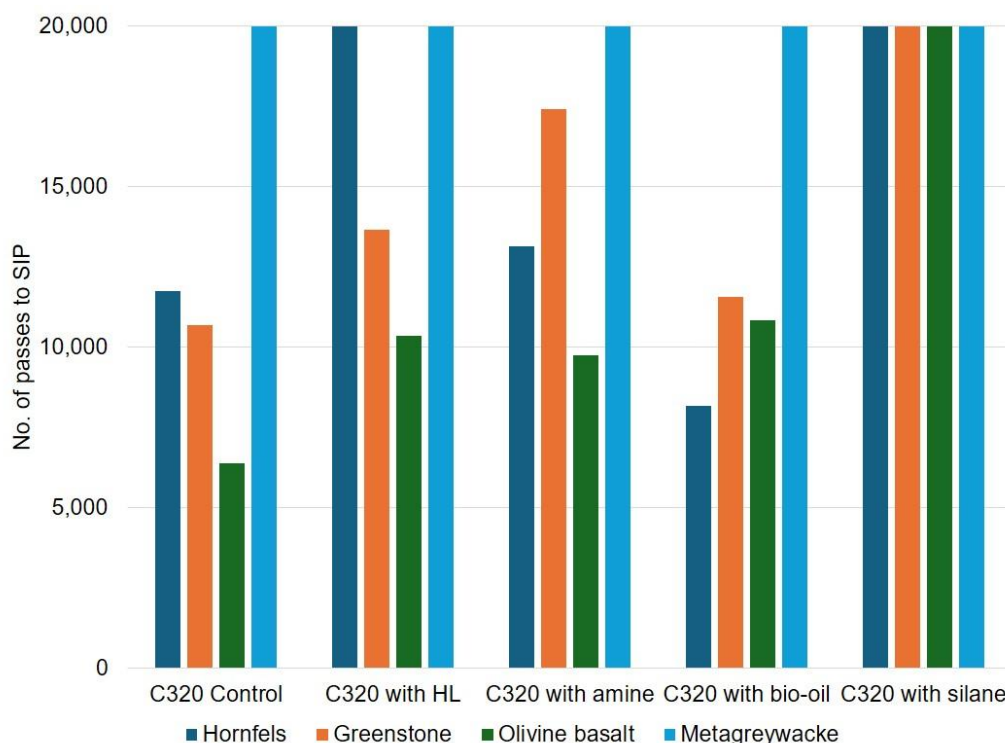
- Olivine basalt with hydrated lime performed marginally in both the TSR and HWT (depending on the criterion used) tests.
- Olivine basalt with amine agent performed well in the TSR test and marginally in the HWT test.
- Hornfels with the amine agent performed well in the TSR test and marginally in the HWT test.
- Hornfels with the bio-oil performed well in the TSR test and poorly in the HWT test.

Figure 3.8 shows the average number of passes to the SIP (visually estimated) for the different aggregate–BAA combinations (including the control binder) tested. According to the HWT test, the asphalt specimens with a high degree of moisture resistance (i.e. no SIP observed during the test) were those prepared using the metagreywacke aggregates (with and without any adhesion agent) and all the specimens prepared with silane agent irrespective of aggregate type.

Consistent with the findings from the MBV, TSR and number of HWT passes to a 12.5 mm rut depth, the olivine basalt aggregates without any adhesion agent showed a propensity for stripping based on the SIP criterion. The number of passes to the SIP for the olivine basalt did, however, increase when adhesion agents were added.

Both the hornfels and greenstone aggregates without a BAA also showed a propensity for stripping based on the SIP criterion. The addition of hydrated lime significantly reduced this propensity for stripping with the hornfels aggregate, but only marginally for the greenstone aggregates. Unlike the lime, the amine agent only marginally improved the moisture resistance of the hornfels and olivine basalt aggregates but had a greater effect on the greenstone aggregates. The bio-oil reduced the number of cycles to the SIP for the hornfels aggregate and only marginally improved the moisture resistance of the greenstone and olivine basalt aggregates based on the SIP criterion. For the olivine basalt aggregate, a similar improvement in moisture resistance was seen with the hydrated lime, amine and the bio-oil additives based on the SIP criterion.

Figure 3.8: Average number of HWT passes to SIP



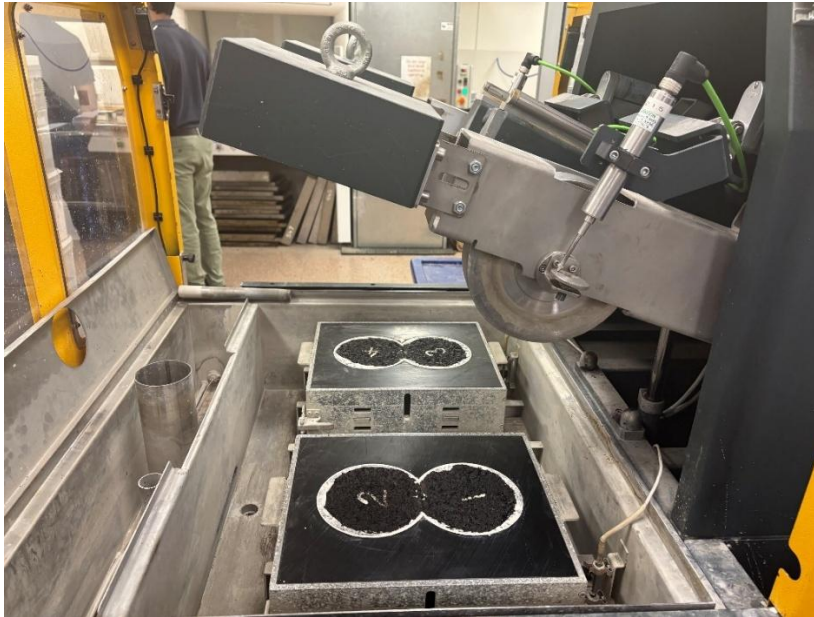
Note: Specimens with the silane-based agent and those prepared with the metagreywacke aggregate did not present an SIP and are shown as 20,000 passes in the figure for illustration purposes only.

Table 3.2 shows that Idaho, Iowa, Massachusetts and Maine specify a minimum SIP of between 10,000 and 15,000 passes based on traffic level. Georgia, Louisiana and Washington have a more stringent criteria of no SIP during the test (i.e. within 20,000 passes). If a minimum SIP of 15,000 passes was adopted, only the following combinations would have passed the HWT test:

- metagreywacke aggregates, with and without any of the adhesion agents
- hornfels aggregates with hydrated lime and the silane agent
- greenstone aggregates with the amine and silane agents
- olivine basalt aggregates with the silane agent.

The laboratory investigation identified some repeatable concerns with the HWT test method. The current test method (Q325) requires that 2 asphalt specimens (comprising 2 pats per specimen) be tested in the HWT device, as shown in Figure 3.9.

Figure 3.9: HWT test specimen arrangement



The deformation versus number of load passes is reported separately for each specimen. Large variability was observed for some of the aggregate and BAA combinations between the deformation results of the 2 sets in the same test (refer to Table 3.3). The reason for this variability was not further investigated as part of this study. However, consideration should be given to include a requirement in the test method that if the results between the 2 specimens in a single test vary significantly, the test may have to be repeated. Based on a review of the test data, an upper limit of 30% difference between the total rut depth measured for the 2 sets of specimens appears to be reasonable.

Table 3.3: Repeatability of the HWT test

Aggregate and BAA combination	Test	Final rut depth at 20,000 passes (mm)		
		Specimen set #1	Specimen set #2	Percentage difference
Hornfels – no additive	Original	> 20.0	17.2	> 15.1
Hornfels–lime	Original	7.5	8.5	12.5
Hornfels–amine	Original	20.0	20.0	–
Hornfels–bio-oil	Original	20.0	> 20.0	–
Hornfels–silane	Original	9.6	14.0	37.3
	Re-test	9.4	8.0	16.1
Greenstone – no additive	Original	20.0	19.0	5.1
Greenstone–lime	Original	10.5	4.7	76.3
	Re-test	13.9	8.3	50.5
Greenstone–amine	Original	> 20.0	4.9	> 121
	Re-test	5.0	7.1	34.7
Greenstone–bio-oil	Original	17.7	15.3	14.5
Greenstone–silane	Original	4.7	6.1	25.9
Basalt – control	Original	> 20.0	5.9	> 109
	Re-test	> 20.0	> 20.0	–
Basalt–lime	Original	19.4	15.4	23.0

Aggregate and BAA combination	Test	Final rut depth at 20,000 passes (mm)		
		Specimen set #1	Specimen set #2	Percentage difference
Basalt–amine	Original	20.0	9.2	74.0
	Re-test #1	6.0	15.0	85.7
	Re-test #2	> 20.0	16.2	21.0
Basalt–bio-oil	Original	> 20.0	> 20	–
Basalt–silane	Original	18.1	6.7	91.9
	Re-test	5.4	6.1	12.2
Metagreywacke – control	Original	4.7	3.8	21.2
Metagreywacke–lime	Original	8.6	6.8	23.4
Metagreywacke–amine	Original	5.5	4.2	26.8
Metagreywacke–bio-oil	Original	6.1	4.9	21.8
Metagreywacke–silane	Original	4.6	4.4	4.4

3.2.3 Effectiveness of hydrated lime and liquid BAAs

The effectiveness of the different BAAs included in the study is briefly discussed below.

Hydrated lime

As noted in Section 3.2.1, the plate stripping test was not undertaken on any hydrated lime samples.

The hydrated lime did not have any meaningful effect on the TSR results for the specimens manufactured with the hornfels, olivine basalt and metagreywacke aggregates. It did, however, significantly improve the TSR of the specimens manufactured with the greenstone aggregates.

The hydrated lime demonstrated improved performance in the HWT test for the hornfels, greenstone and olivine aggregates based on the rut depth at 15,000 passes. Similarly, the hydrated lime increased the average number of passes to a 12.5 mm rut depth for these aggregates. A similar trend was observed based on the SIP criterion. However, the addition of hydrated lime did not improve the HWT performance of the specimens manufactured with the metagreywacke aggregate.

Amine agent

The specimens containing the amine agent generally exhibited similar or better performance in the TSR test compared to hydrated lime for the hornfels, greenstone, olivine basalt and metagreywacke aggregates.

Notably, the amine agent consistently performed poorer than the hydrated lime in the HWT test for the specimens manufactured with the hornfels aggregate based on the rut depth at 15,000 passes, average number of passes to 12.5 mm rut depth and SIP criteria. Conversely, the amine agent performed similarly to hydrated lime with the olivine basalt aggregate in the HWT test. It is, however, worth noting that the HWT results for the amine agent with the olivine basalt were highly variable, and the test had to be repeated twice due to the large differences observed between the rut depth of the duplicate asphalt specimens used in the test.

Bio-oil

The effectiveness of the bio-oil agent was variable and appears to be highly dependent on the aggregate type and test method used.

The TSR test indicated similar or better performance of the bio-oil compared to the hydrated lime for the hornfels and metagreywacke aggregates. However, the hornfels aggregate consistently exhibited poorer performance compared to the specimens containing hydrated lime in the HWT test.

The bio-oil and greenstone combination exhibited poorer performance compared to the hydrated lime in the TSR test and marginally poorer performance in the HWT test (depending on the test parameter used).

The TSR test indicated similar performance compared to the hydrated lime for the olivine basalt specimens containing the bio-oil. However, the bio-oil with the olivine basalt aggregate performed poorer in the HWT test based on the rut depth at 15,000 passes and passes to 12.5 mm rut depth criteria. Conversely, the bio-oil performed similar to the hydrated lime with the basalt aggregate in the HWT test based on the SIP criterion.

Silane agent

The specimens containing the silane-based agent consistently exhibited similar or better performance compared to hydrated lime, except for the TSR of the specimens manufactured with the greenstone aggregates. For this combination, the use of the silane-based agent resulted in an 8% reduction in the TSR. It is, however, important to note that the specimens with the silane-based agent still achieved a TSR of 91%, which is significantly higher than the minimum 80% specified by TMR. Notably, no SIP was observed in the HWT for any of the aggregate–silane combinations, which indicates very good moisture resistance.

4. Critical Review of Laboratory Tests

The laboratory investigation in Section 3 and studies undertaken by others (e.g. Austroads 2024) found that there is not necessarily a single standard test method currently available in Australia that can reliably and consistently predict the moisture sensitivity of asphalt mixes with different BAAs in the laboratory. This section provides a critical review of the test methods recommended in the interim Austroads laboratory assessment protocol.

4.1 Correlation between laboratory results and known field performance

TMR provided insights on the known moisture susceptibility of the aggregates used in this study based on historic field performance. Metagreywacke aggregates are typically the best performing aggregates in the field, whereas the olivine basalt, hornfels and greenstone aggregates may present some occasional stripping issues in mixes without any hydrated lime.

The pass/fail criteria in the framework shown in Figure 2.2 were also compared to the known field performance of the aggregates. This analysis used the results from the control and specimens containing hydrated lime, given that these were the only combinations where a known field performance estimate could be ascribed based on TMR experience. All the specimens containing hydrated lime were assigned a 'good' field performance designation and so were all the specimens manufactured with the metagreywacke aggregates. For the remaining 3 mixes, which were characterised as having occasionally poor performance, a 33% failure rate (1 in 3) was assumed. This means that 1 of the 3 control mixes (with hornfels, greenstone or olivine basalt) was assigned a failure designation randomly. For example, if the mix with hornfels aggregate failed the laboratory test and the olivine basalt and greenstone passed the test, then hornfels was assigned a true failure designation. If both greenstone and hornfels failed the laboratory test, then one aggregate was assigned a true pass designation and the other aggregate a true failure designation. Table 4.1 presents the confusion matrix used for the analysis.

Table 4.1: Confusion matrix

Laboratory test result criteria	Field Pass (good)	Field Fail (poor)
MBV $\geq$ 18 mg/g	0	1
MBV < 18 mg/g	3	0
SV $\geq$ 10%	0	0
SV < 10%	3	1
TSR $\geq$ 80%	5	0
TSR < 80%	2	1
No of passes to 12.5 mm > 10,000	7	1
No of passes to 12.5 mm $\leq$ 10,000	0	0
SIP $\geq$ 15,000 passes	3	0
SIP < 15,000 passes	4	1

Note: SV and MBV results were accounted only for the aggregates with the control bitumen as the test was not undertaken with hydrated lime.

Equations 2 to 7 were used to evaluate the error of the tests compared to their known field performance and how effective each test method was for capturing true fails and true passes and positively predicting a good field performance.

$$FPR = \frac{FP}{FP+TN} \quad 2$$

$$FRR = \frac{FN}{FN+TP} \quad 3$$

$$E_r = \frac{FP+FN}{TP+FP+FN+TN} \quad 4$$

$$S = \frac{TN}{FP+TN} \quad 5$$

$$S_p = \frac{TP}{TP+FN} \quad 6$$

$$PPV = \frac{TP}{TP+FP} \quad 7$$

where

FPR = false acceptance rate (risk factor)

FP = false pass

TN = true fail

FRR = false rejection rate (cost factor)

FN = false fail

TP = true pass

Er = misclassification rate

S = sensitivity (true fail capture)

S_p = specificity (true pass retention)

PPV = positive predictive value

Table 4.2 presents the calculations from Equations 2 to 7 for all tests. The identification of false passes represents a risk as mixes that pass the test may fail in the field. False rejection, on the other hand, suggests conservatism, which may have a potential cost impact.

Table 4.2: Evaluation results

Factor	MBV	SV	TSR	HWT test (no of passes to 12.5 mm)	HWT test (no of passes to SIP)
FPR	0.00	0.00	0.00	1.00	0.00
FFR	0.00	1.00	0.29	0.00	0.57
Er	0.00	0.75	0.25	0.12	0.50
S	1.00	1.00	1.00	0.00	1.00
S _p	1.00	0.00	0.71	1.00	0.43
PPV	1.00	Zero division	1.00	0.87	1.00

The SV, MBV, TSR and HWT based on the number of passes to SIP tests did not identify any false passes, whereas one false pass was given by the HWT test based on the number of passes to 12.5 mm rut depth. However, it should be noted that the field performance was assumed to have a 33% failure rate for the hornfels, greenstone and olivine basalt aggregates without any adhesion agent, and a direct correlation across the mixes could not be established. Regardless, the olivine basalt achieved a marginal pass result (10,374 passes to 12.5 mm rut depth). Recognising that the pass/fail criterion for the HWT test results was adopted from the Texas Department of Transportation (2024), it may be reasonable to suggest that the limit needs to be adjusted to better represent the Queensland experience. A different output from the HWT device test may also be found to be more suitable for this purpose. For example, the Texas Department of Transportation (2024) uses number of passes to 12.5 mm, but perhaps the SIP may be considered more appropriate.

The SV was found to be most conservative, with 3 false fails identified out of the 4 results analysed. The next most conservative criterion was that of more than 15,000 passes required to achieve an SIP measured by the HWT test, which identified 4 false fails out of the 8 results analysed. The TSR introduced a moderate level of conservatism, whereby 2 of the mixes that were assigned a pass in the field failed the TSR criterion. However, it is understood that no TSR nonconformances have been reported for these mixes in practice. The HWT test results for the number of passes to 12.5 mm were found to have the lowest overall error, despite the fact that the Texas failure criterion was used to assess the pass/fail behaviour.

The MBV results were found to represent TMR's experience the best, with a PPV of 1.00. It is, however, once again highlighted that the failure rate across the 3 aggregates (i.e. hornfels, greenstone and olivine basalt) was assumed to a 33% distribution, which is in line with the 1 out of 3 aggregates having failed the test.

4.2 Correlation between binder adhesion and asphalt stripping tests

To evaluate the effectiveness of the binder adhesion tests for use as a screening tool, their pass/fail agreement with the TSR and HWT tests was evaluated. The same pass/fail criteria as those used for the analysis in Section 4.1 were also used in this analysis for consistency.

Equation 8 was used to calculate the overall agreement between tests.

$$P_o = \frac{a+d}{n} \quad 8$$

where

- P_o = overall agreement
- a = both pass
- d = both fail
- n = total

Sections 3.2.1 and 3.2.2 showed that SV has a predominantly fail outcome while all samples tested passed the number of passes to 12.5 mm rut depth criterion from the HWT test. Therefore, Cohen's Kappa (chance-corrected agreement index) was used to adjust for the chance agreement due to that fact using Equations 9 and 10.

$$P_e = \frac{(a+b)(a+c) + (c+d)(b+d)}{n^2} \quad 9$$

$$\kappa = \frac{P_o - P_e}{1 - P_e} \quad 10$$

where

- P_e = expected agreement
- b = asphalt test passes/binder adhesion test fails
- c = asphalt test fails/binder adhesion test fails
- κ = kappa
- κ = 0: agreement no better than chance
0.4–0.6: moderate
0.6–0.8: substantial
> 0.8: excellent

Table 4.3 to Table 4.8 present the agreement matrices between the binder adhesion tests and the asphalt performance tests.

Table 4.3: MBV and TSR agreement matrix

	MBV < 18 mg/g	MBV ≥ 18 mg/g	Row total
TSR ≥ 80%	a = 2	b = 0	2
TSR < 80%	c = 1	d = 1	1
Column total	2	1	n = 3

Table 4.4: SV and TSR agreement matrix

	SV < 10%	SV ≥ 10%	Row total
TSR ≥ 80%	a = 3	b = 10	13
TSR < 80%	c = 0	d = 3	3
Column total	3	13	n = 16

Table 4.5: MBV and number of passes to 12.5 mm agreement matrix

	MBV < 18 mg/g	MBV ≥ 18 mg/g	Row total
No of passes to 12.5 mm >10,000	a = 3	b = 1	4
No of passes to 12.5 mm ≤10,000	c = 0	d = 0	0
Column total	3	1	n = 4

Table 4.6: SV and number of passes to 12.5 mm agreement matrix

	SV < 10%	SV ≥ 10%	Row total
No of passes to 12.5 mm >10,000	a = 3	b = 13	16
No of passes to 12.5 mm ≤10,000	c = 0	d = 0	0
Column total	3	13	n = 16

Table 4.7: MBV and number of passes to SIP agreement matrix

	MBV < 18 mg/g	MBV ≥ 18 mg/g	Row total
No of passes to SIP ≥ 15,000	a = 1	b = 0	1
No of passes to SIP < 15,000	c = 2	d = 1	3
Column total	3	1	n = 4

Table 4.8: SV and number of passes to SIP agreement matrix

	SV < 10%	SV ≥ 10%	Row total
No of passes to SIP ≥ 15,000	a = 3	b = 3	6
No of passes to SIP < 15,000	c = 0	d = 10	10
Column total	3	13	n = 16

The Matthews Correlation Coefficient (MCC), which is preferred for binary classifications, was also calculated according to Equation 11. This was a useful metric to compare the test pairs in Table 4.3 to Table 4.8.

$$MCC = \frac{ad-bc}{\sqrt{(a+b)(a+c)(d+b)(d+c)}}$$

11

Equation 11 returns a number between -1 and 1, where -1 shows perfect disagreement, 0 shows no association, and 1 perfect agreement. The results of this analysis are shown in Table 4.9.

Table 4.9: Agreement analysis results

	MBV and TSR	SV and TSR	MBV and HWT (No of passes to 12.5 mm)	SV and HWT (No of passes to 12.5 mm)	MBV and HWT (No of passes to SIP)	SV and HWT (No of passes to SIP)
P _o	0.75	0.37	0.75	0.19	0.50	0.81
P _e	0.50	0.30	0.75	0.19	0.37	0.58
κ	0.5	0.10	0.00	0.00	0.20	0.55
MCC	0.58	0.23	Zero division	Zero division	0.33	0.62

The MBV and TSR results showed moderate correlation with MCC equivalent to 0.58. The HWT results based on number of passes to 12.5 mm showed no association with MBV or SV with a Cohen's Kappa of 0.00. The correlation between SV and TSR was also found to be poor, with both Cohen's Kappa and MCC being close to zero (0.10 and 0.23, respectively). HWT results based on the number of passes to the SIP were also found to correlate poorly with MBV, with Cohen's Kappa and MCC being close to zero (0.20 and 0.33, respectively). A moderate correlation between the HWT results based on the number of passes to the SIP and SV was, however, identified.

4.3 Correlation between TSR and HWT tests

The correlation between the 2 asphalt stripping tests was also assessed following the method described in Section 4.2. Both HWT test criteria used internationally, namely the number of passes to 12.5 mm rut depth and number of passes to SIP, were evaluated. The agreement matrices are presented in Table 4.10 and Table 4.11.

Table 4.10: TSR and number of passes to 12.5 mm rut depth agreement matrix

	TSR $\geq 80\%$	TSR $< 80\%$	Row total
No of passes to 12.5 mm $> 10,000$	a = 16	b = 4	20
No of passes to 12.5 mm $\leq 10,000$	c = 0	d = 0	0
Column total	16	4	n = 20

Table 4.11: TSR and number of passes to SIP agreement matrix

	TSR $\geq 80\%$	TSR $< 80\%$	Row total
No of passes to SIP $\geq 15,000$	a = 10	b = 0	10
No of passes to SIP $< 15,000$	c = 6	d = 4	10
Column total	16	4	n = 20

The results of the analysis are shown in Table 4.12.

Table 4.12: Agreement analysis results

	TSR and HWT (no of passes to 12.5 mm)	TSR and HWT (no of passes to SIP)
P _o	0.80	0.70
P _e	0.80	0.50
κ	0.00	0.40
MCC	Zero division	0.50

The TSR results showed no meaningful correlation with the HWT test results for number of passes to 12.5 mm with a Cohen's Kappa of 0.00. However, the TSR results were found to have a moderate correlation with the number of passes to the SIP output from the HWT test.

4.4 Ranking of BAAs based on type of test

The test results presented in Appendix A were used to rank the performance of the aggregates and adhesion agent combinations using the various test methods included in the study. The results were ranked from 1 to 20, where 1 was best performing and 20 was the worst performing aggregate and BAA combination. Where the results were the same, the same ranking was assigned. These outputs were used to assess whether the binder adhesion plate stripping test would apply the same ranking across the various mixes as the asphalt performance tests. A Pearson's correlation above 0.70 was considered 'good' for this analysis.

Figure 4.1 shows the ranking correlation between the SV and TSR results. The Pearson's correlation between the SV and TSR results was poor at 0.37. Considering a pass/fail criterion of 80% for TSR and 10% for SV, their correlation remains poor.

Only the greenstone, olivine basalt and metagreywacke aggregates with the silane agent were found to pass the $\leq 10\%$ criterion of SV, whereas the hornfels aggregates had an SV of 11%, which is only marginally above the current limit. These combinations were also found to pass the 80% criterion for TSR. However, more aggregate and BAA combinations were found to pass the TSR criterion as shown in Figure 3.3.

Figure 4.1: Correlation between SV and TSR

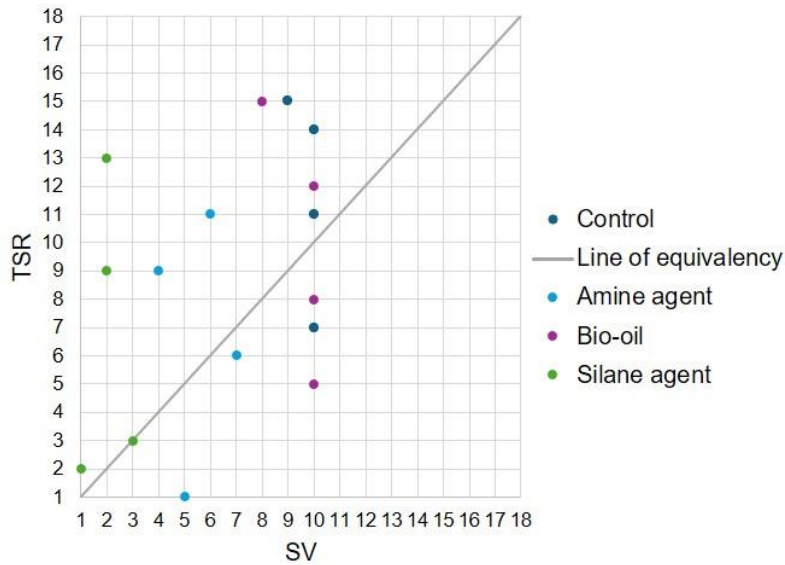


Figure 4.2 shows the ranking correlation between the SV and the number of cycles to 12.5 mm rut depth as measured in the HWT test. The Pearson's correlation between these tests was moderate at 0.4.

Figure 4.2: Correlation between SV and number of passes to 12.5 mm rut depth

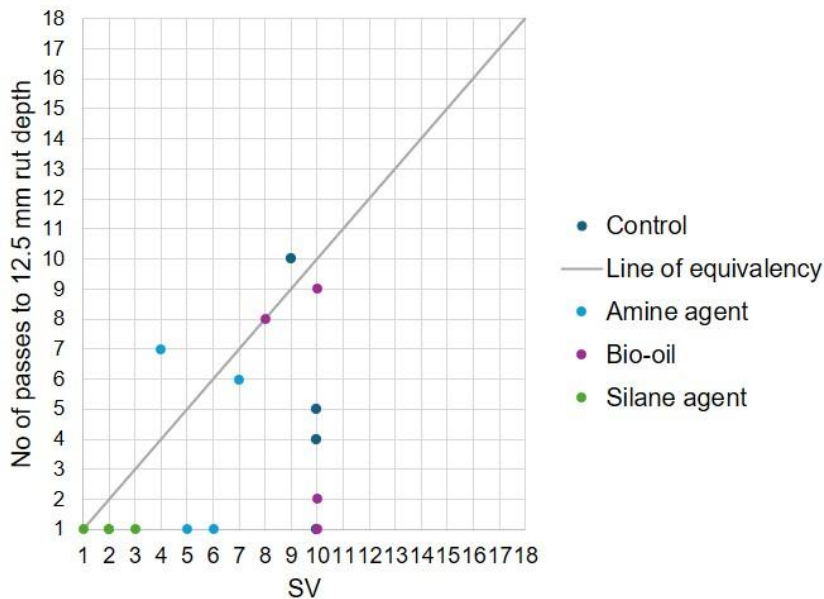
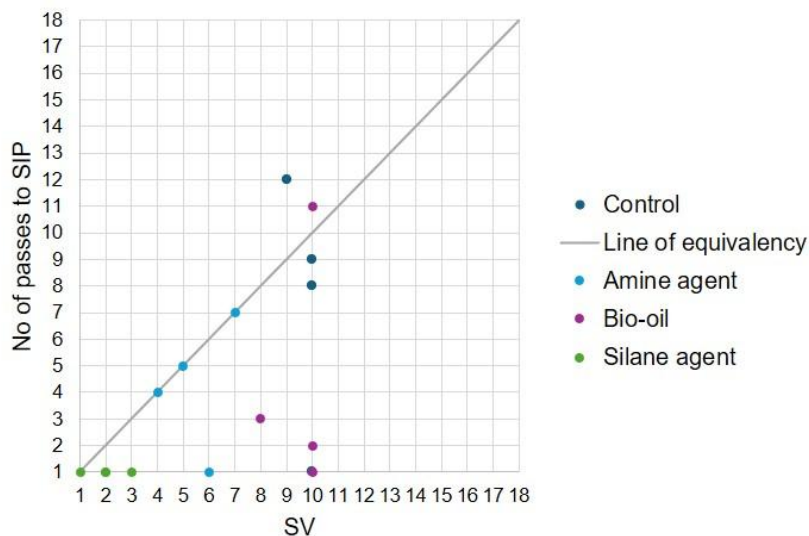


Figure 4.3 shows the ranking correlation between the SV and the number of cycles to the SIP as measured using the HWT device. An SIP was not identified for all aggregate–adhesion agent combinations and a ranking of 1 was assigned where no SIP occurred during the test. The Pearson's correlation between the SV and SIP results was moderate at 0.51.

Figure 4.3: Correlation between SV and number of passes to SIP



Overall, the binder adhesion test results were not found to consistently rank the performance of the different aggregate–adhesion agent combinations in line with the TSR and HWT tests. The $\leq 10\%$ pass limit for SV may be too low if used as an independent screening tool. On the other hand, the boiling water test results returned retained coating percentages above 97%. However, the HWT device test (number of passes to 12.5 mm rut depth) was found to have an $S = 0.00$ in Section 4.1, suggesting a poor sensitivity when compared to known field performance.

Figure 4.4 shows the ranking outputs using the SV. Hydrated lime was not tested in this method, so the markers were concentrated at 0. The silane agent was found to be the most effective adhesion agent for all aggregates, followed by the amine agent. Some differentiation was possible through this method; however, as shown in Figure 4.1 to Figure 4.3, this ranking showed a moderate correlation to the asphalt performance tests at best.

Figure 4.4: Ranking of efficiency of BAAs for each aggregate according to their SV

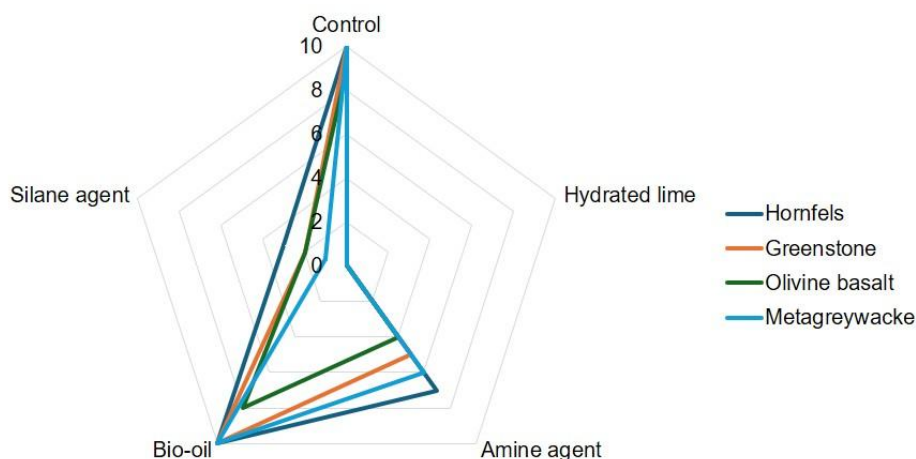


Figure 4.5 shows the ranking of adhesion agents and aggregate combinations according to the TSR results. The ranking of the various aggregate and BAA combinations was easily distinguished using this test. Interestingly, however, the metagreywacke aggregate was not ranked the best with the control C320 binder. The hornfels aggregate, which had a greater MBV value, was ranked higher instead. It can also be seen that amine agent had a notable impact on the TSR ranking of greenstone aggregates. The amine agent also

improved the ranking of olivine basalt aggregates, which were found to be largely unaffected by any of the other adhesion agents, including hydrated lime.

Figure 4.5: Ranking of efficiency of BAAs for each aggregate according to their TSR

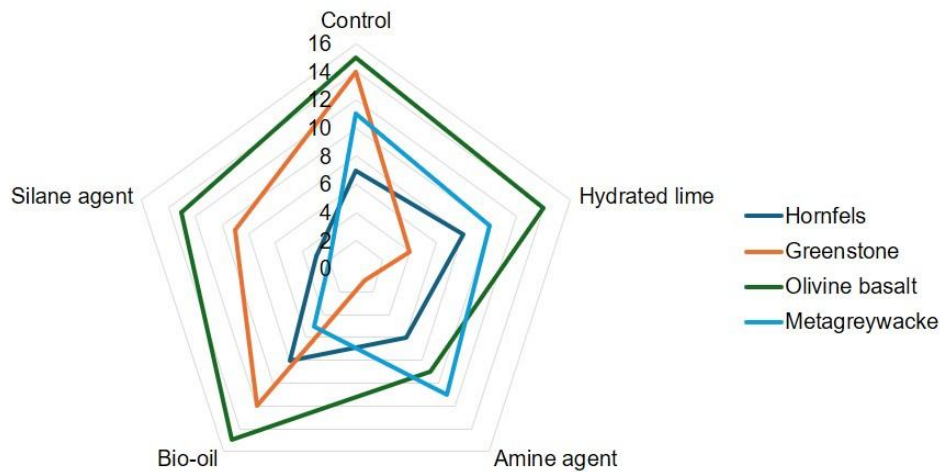


Figure 4.6 shows the ranking of the BAA and aggregate combinations according to the minimum number of passes to a 12.5 mm rut depth in the HWT test. Distinct ranking across the various aggregate–BAA combinations could also be achieved using this criterion. Notably, the olivine basalt without any adhesion agents ranked the worst when compared with the other aggregates without the incorporation of any adhesion agents. This is in line with the expectations set by the MBV results. The overall ranking also correlates well with the MBV results.

Figure 4.6: Ranking of efficiency of BAAs for each aggregate according to their number of passes to a 12.5 mm rut depth using the HWT device

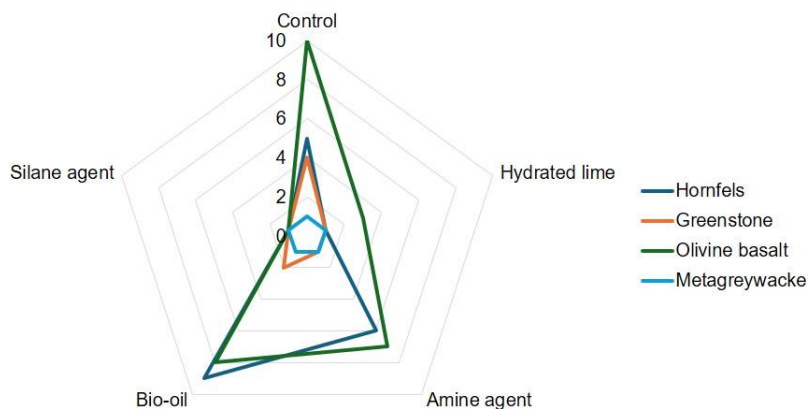
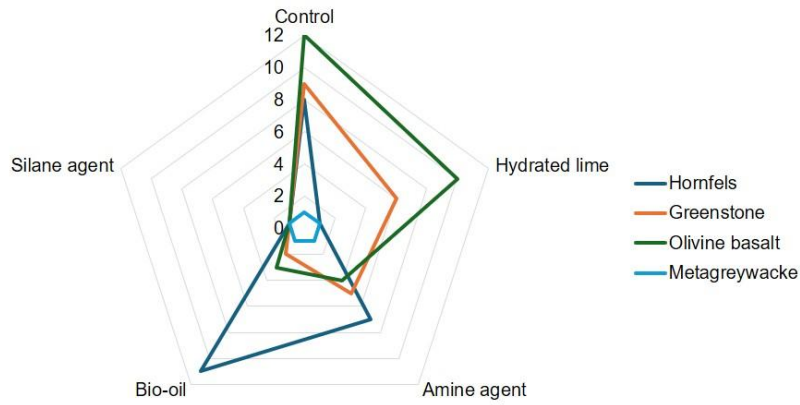


Figure 4.7 shows the ranking of adhesion agent and aggregate combinations according to the number of passes to an SIP in the HWT test. It is noted that no SIP was identified for samples with metagreywacke aggregate irrespective of the adhesion agent and for all aggregates with the silane agent. The hornfels aggregates with hydrated lime did not present a distinct SIP either. Hence, these specimens were assigned a ranking of 1.

Figure 4.7: Ranking of efficiency of BAAs for each aggregate according to their number of passes to SIP using the HWT device



Notably, the 2 different HWT test outputs in Figure 4.6 and Figure 4.7 did not rank the different aggregate–BAA combinations the same. For example, the ranking between the olivine basalt, hornfels and greenstone aggregates is not consistent between the 12.5 mm and SIP criteria.

The analysis also shows that the TSR and HWT tests do not always rank the different combinations consistently.

5. Austroads and TMR Assessment Protocols

The laboratory investigation results indicated, similar to the findings in Austroads (2024), that there is not a single local laboratory test available that reliably and consistently predicts the moisture susceptibility of different aggregate–adhesion agent combinations. This also supports the current approach adopted by the interim Austroads and TMR assessment protocols to use a combination of methods to assess the performance of adhesion agents in asphalt.

The interim Austroads and TMR protocols were used to assess the effectiveness of the different aggregate–BAA combinations tested in this study.

5.1 Interim Austroads assessment protocol

The laboratory test results were evaluated using the interim Austroads protocol in Figure 2.2 to assess the effectiveness of the different aggregate–adhesion agent combinations included in the study. Where the pass/fail criteria are not explicitly stated in the protocol, the following criteria were used for the initial assessment:

- minimum TSR of 80% based on the standard requirement adopted by most transport agencies in Australia (including TMR)
- minimum 10,000 HWT passes to achieve a 12.5 mm rut depth (10,000 based on the requirement in TN 213)
- minimum 15,000 HWT passes to an SIP based on the standard requirement adopted by several states in the USA.

The path of each aggregate–BAA combination through the Austroads protocol is visually presented in Figure 5.1 through to Figure 5.5. The aggregate-adhesion agent combination labels used in these figures are summarised in Table 5.1.

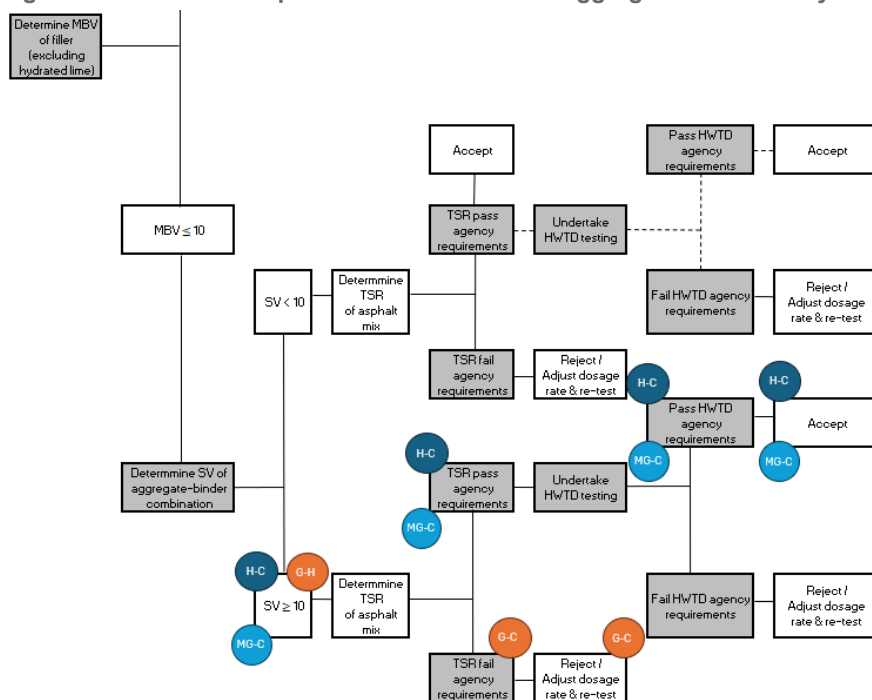
Table 5.1: Label convention

Binder	Aggregate type			
	Hornfels	Greenstone	Olivine basalt	Metagreywacke
C320 control without BAA	H-C	G-C	OB-C	MG-C
C320 with hydrated lime	H-H	G-H	OB-H	MG-H
C320 with amine agent	H-A	G-A	OB-A	MG-A
C320 with bio-oil	H-B	G-B	OB-B	MG-B
C320 with silane agent	H-S	H-S	H-S	H-S

The interim Austroads protocol considers mixes that contain fillers with a MBV ≤ 18 mg/g (excluding any hydrated lime) only. Aggregates with a high SV (i.e. $> 10\%$) in combination with a high MBV (i.e. between 10–18 mg/g) are considered to have a high risk of stripping and is not suitable for use based on the Austroads protocol. All the other aggregates contained natural fillers with a MBV ≤ 10 mg/g and were, therefore, assessed through the downward pathway of the protocol.

Figure 5.1 shows that the hornfels and metagreywacke aggregates without any BAA were expected to have acceptable moisture susceptibility based on the criteria included in the interim Austroads protocol. Both the hornfels and metagreywacke would have also been accepted if the HWT criterion was stricter (i.e. requiring 15,000 passes to a 12.5 mm rut depth). However, if a no SIP within 15,000 passes criterion was adopted instead, the hornfels aggregates without the incorporation of any adhesion agents would have been rejected, which is consistent with TMR's experience with this aggregate source. The greenstone aggregates would also, consistent with TMR's experience, require an adhesion agent based on the assessment protocol. The olivine basalt without any BAA would have been rejected based on the MBV, SV, TSR and HWT criteria.

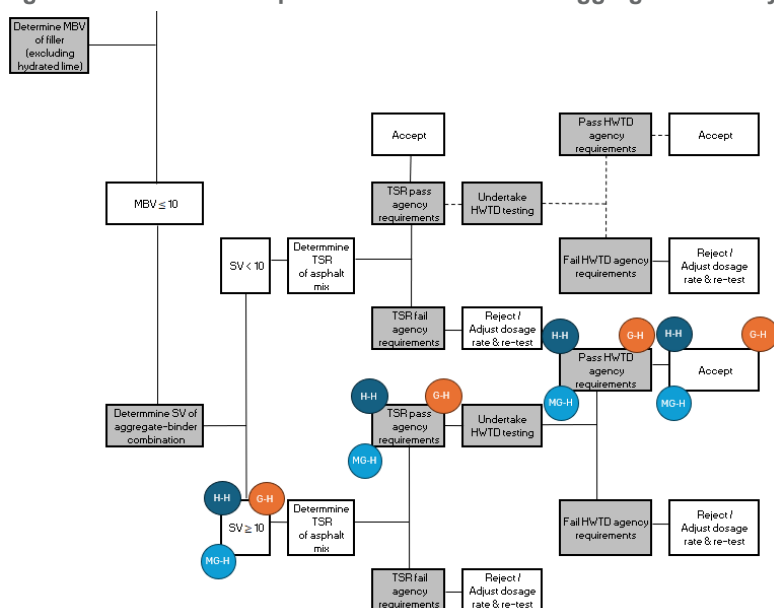
Figure 5.1: Austroads protocol assessment for aggregates without any adhesion agent



Source: Adapted from Source:Austrroads (2024:Figure 6.2), 'Assessment protocol', Austrroads.

Figure 5.2 shows that the hornfels, greenstone and metagreywacke aggregates with hydrated lime were expected to have an acceptable resistance to moisture damage. However, the greenstone aggregates with hydrated lime would have been rejected if the minimum 15,000 passes to an SIP criterion was applied. As noted above, the olivine basalt, would have been rejected from the outset given its high MBV and SV. The mix manufactured with the olivine basalt and hydrated lime would also have been rejected based on the TSR being marginally lower (i.e. 79%) than 80%. Notably, the olivine basalt with hydrated lime would also have been rejected if the minimum 15,000 passes to an SIP criterion was applied, even though the combination demonstrated acceptable performance based on the 12.5 mm rut depth HWT criterion.

Figure 5.2: Austroads protocol assessment for aggregates with hydrated lime



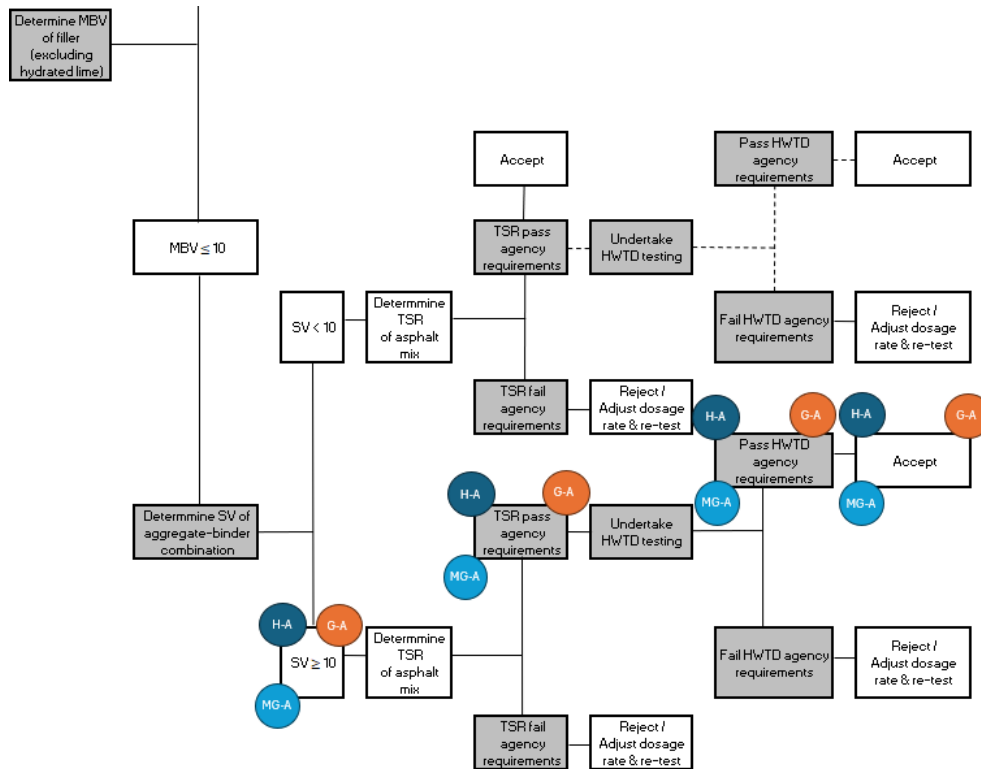
Source: Adapted from Source:Austrroads (2024:Figure 6.2), 'Assessment protocol', Austrroads.

Figure 5.3 and Source: Adapted from Source:Austrroads (2024:Figure 6.2), 'Assessment protocol', Austrroads.

Figure 5.4 show that the use of the amine-based and silane-based agents would be acceptable based on the Austroads protocol (considering the precision of the test methods) for the hornfels, greenstone and

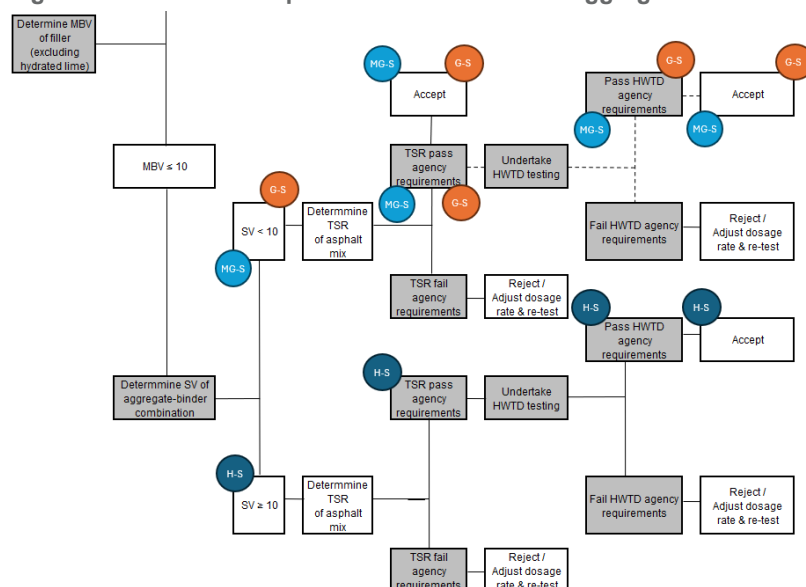
metagreywacke aggregates. Notwithstanding the MBV and SV criteria, the olivine basalt would have passed the protocol with both the amine and saline agents based on the TSR and HWT test results. However, if the stricter HWT of 15,000 passes to a 12.5 mm rut dept and SIP were applied, the olivine basalt with the amine agent would have been rejected. The silane agent with olivine basalt would have still been accepted if the stricter HWT criteria were used.

Figure 5.3: Austroads protocol assessment for aggregates with amine-based agent



Source: Adapted from Source:Austrroads (2024:Figure 6.2), 'Assessment protocol', Austrroads.

Figure 5.4: Austroads protocol assessment for aggregates with silane-based agent



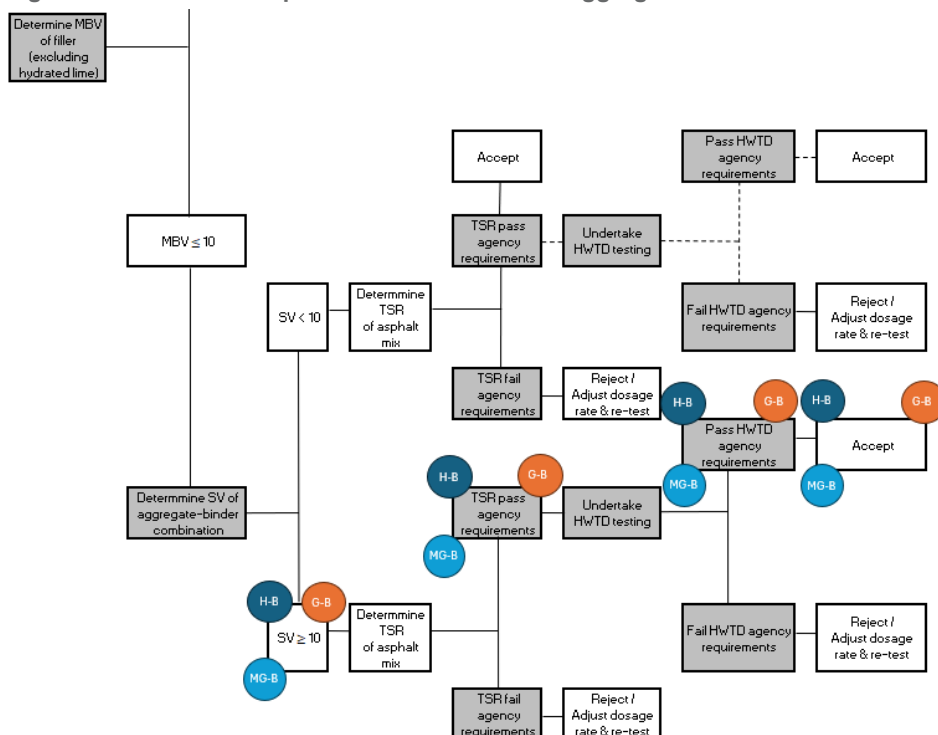
Source: Adapted from Source:Austrroads (2024:Figure 6.2), 'Assessment protocol', Austrroads.

Figure 5.5 shows that the hornfels, greenstone and metagreywacke aggregates were expected to have acceptable moisture susceptibility when the bio-oil agent was used. It is worth noting that the greenstone with the bio-oil would have failed the more stringent minimum 15,000 passes to a 12.5 mm rut depth HWT criterion.

The olivine basalt with the bio-oil agent failed the MBV, SV and TSR criteria and, therefore, would have been rejected based on the criteria in the protocol. Nevertheless, the olivine basalt with the bio-oil passed the 12.5 mm rut depth at 10,000 passes criterion in the HWT test, but failed the more stringent 15,000 passes criterion.

Notably, all the aggregate–bio-oil combinations, except for the metagreywacke aggregates, would have failed the assessment based on the minimum 15,000 passes to an SIP criterion.

Figure 5.5: Austroads protocol assessment for aggregates with bio-oil



Source: Adapted from Source:Austroads (2024:Figure 6.2), 'Assessment protocol', Austroads.

The analysis shows that the TSR results primarily determined the outcome of the assessment using the current HWT criteria adopted by TMR in TN 213. This makes any subsequent HWT testing potentially redundant based on the current criteria. However, if the more stringent 12.5 mm rut depth and SIP to 15,000 passes criteria are adopted, the HWT results would determine to assessment outcome for certain aggregate–BAA combinations.

5.2 TMR interim adhesion agent assessment protocol

TMR has implemented an interim assessment procedure for registering nonstandard dense graded asphalt mixes containing BAAs as an alternative to hydrated lime. The procedure is documented in TN 213 and comprises:

- a desktop assessment, including evidence of proven performance in a similar application elsewhere
- constituent materials testing, including MBV and voids in dry compacted filler testing
- binder–aggregate adhesion testing using the SV test
- asphalt mix performance testing using the TSR and HWT tests.

The binder-adhesion test results should be reported only, whereas the asphalt performance tests are used to demonstrate equivalent (or better) performance to the standard mix design. The nonstandard mix containing the proposed BAA must also meet the following HWT criteria:

- ≤ 12.5 mm rut depth at 20,000 passes for polymer modified and M1000 multigrade binders
- ≤ 12.5 mm rut depth at 15,000 passes for C600 bitumen
- ≤ 12.5 mm rut depth at 10,000 passes for C320 bitumen.

The HWT criteria listed above were based on the criteria adopted by the Texas Department of Transportation (refer to Table 3.2). The C320 and C600 bitumens used in Australia are similar to a PG64 and PG70 binder, respectively, whereas the local PMBs and multigrade binders are similar to a PG76 (or higher) binder in the USA.

MRTS30 requires that dense graded asphalt mixes contain a minimum of 1% or 1.5% hydrated lime based on the source of the baghouse fines. As such, the use of lime would be considered as the baseline against which alternative adhesion agents are measured in the protocol. It is also noted that the olivine basalt fines had a MBV of 22.5, which exceeded the maximum of 18 in MRTS30 for the combined filler excluding hydrated lime and, therefore, may not provide satisfactory performance when hydrated lime is included as an added filler.

Table 5.2 provides a summary of the outcomes of the TMR protocol for the aggregate–BAA combinations tested. Based on the relative performance of the BAAs compared to hydrated lime, the amine agent would be suitable for the greenstone and metagreywacke aggregates, whereas the bio-oil exhibited acceptable performance with the metagreywacke aggregates only. When considering the standard HWT criteria included in the protocol in isolation, both the amine and bio-oil agents would be considered suitable for all the aggregates assessed, noting that the HWT performance of the bio-oil with the hornfels was marginal. However, when considering a stricter HWT criterion (i.e. minimum 15,000 passes to a 12.5 mm rut depth), the amine agent exhibited marginal performance with the hornfels and olivine basalt aggregates, whereas the bio-oil would be acceptable for the greenstone and metagreywacke aggregates only.

Notably, the silane agent exhibited equivalent or better performance compared to the hydrated lime for all the aggregate types assessed, irrespective of the HWT criterion used.

Table 5.2: Outcome of TN 213 assessment – 12.5 mm rut depth criterion

Aggregate type	BAA type	Relative performance compared to hydrated lime	No of passes to 12.5 mm rut depth (10,000 criterion)	No of passes to 12.5 mm rut depth (15,000 criterion)	No of passes to 12.5 mm rut depth (20,000 criterion)
Hornfels	Amine	Fail	Pass	Marginal	Fail
	Bio-oil	Fail	Marginal	Fail	Fail
	Silane	Pass	Pass	Pass	Pass
Greenstone	Amine	Pass	Pass	Pass	Pass
	Bio-oil	Fail	Pass	Pass	Fail
	Silane	Pass	Pass	Pass	Pass
Olivine basalt	Amine	Fail	Pass	Marginal	Fail
	Bio-oil	Fail	Pass	Fail	Fail
	Silane	Pass	Pass	Pass	Pass
Metagreywacke	Amine	Pass	Pass	Pass	Pass
	Bio-oil	Pass	Pass	Pass	Pass
	Silane	Pass	Pass	Pass	Pass

A similar analysis using the number of passes to a SIP criterion was also undertaken, as shown in Table 5.3.

Notably, all the aggregates with the silane agent passed the SIP criteria. Similarly the metagreywacke passed the SIP criteria, irrespective of the type of BAA used.

The hornfels aggregate with the amine agent failed the relative performance to hydrated lime and minimum 15,000 passes to a SIP criteria but passed the 10,000 passes SIP criterion. The same aggregate with bio-oil failed all the SIP criteria.

The greenstone with the amine agent passed the SIP criteria. However, the same aggregate with the bio-oil failed the relative performance to hydrated lime and more stringent minimum 15,000 to a SIP criteria.

The amine and bio-oil agents exhibited marginal performance with the olivine basalt based on a comparison with hydrated lime and the minimum 10,000 number of passes to a SIP criterion. However, both these agents with the olivine basalt failed the minimum 15,000 passes to a SIP criterion.

Table 5.3: Outcome of TN 213 assessment – SIP criterion

Aggregate type	BAA type	Relative performance to hydrated lime	No of passes to SIP (10,000 criterion)	No of passes to SIP (15,000 criterion)
Hornfels	Amine	Fail	Pass	Fail
	Bio-oil	Fail	Fail	Fail
	Silane	Pass	Pass	Pass
Greenstone	Amine	Pass	Pass	Pass
	Bio-oil	Fail	Pass	Fail
	Silane	Pass	Pass	Pass
Olivine basalt	Amine	Marginal	Marginal	Fail
	Bio-oil	Marginal	Marginal	Fail
	Silane	Pass	Pass	Pass
Metagreywacke	Amine	Pass	Pass	Pass
	Bio-oil	Pass	Pass	Pass
	Silane	Pass	Pass	Pass

Based on the assessment outcomes presented above, it would appear that the requirement to demonstrate equivalent or better performance for the BAAs compared to hydrated lime is more conservative than relying on the HWT 12.5 mm criterion alone. The SIP criterion generally resulted in a similar assessment outcome when compared to the stricter 15,000 passes to a 12.5 mm HWT criterion.

6. Conclusions and Recommendations

This project evaluated the applicability of the interim Austroads (2024) and TMR laboratory protocols for assessing the effectiveness of different BAAs using Queensland-specific materials. A comprehensive laboratory testing program was undertaken using 4 aggregate sources, 4 different BAA types, and a range of different laboratory tests (including MBV, plate stripping, boiling water, TSR and HWT tests).

6.1 Conclusions

The following conclusions were made from the laboratory investigation and analysis:

- The MBV results of several of the aggregates did not correlate well with the plate stripping and TSR test results for the binder without any adhesion agent. The MBV test was, however, able to identify the poor moisture sensitivity of the olivine basalt aggregate without any BAA.
- All the aggregates tested without any BAA exhibited poor performance using aggregates in their as-received condition in the plate stripping test, based on an SV criterion of 10%. SVs obtained for the different BAAs were also above the 10% threshold, except for the aggregates with the silane agent. Indications are that the SV criterion of $\leq 10\%$ may be too stringent if dusty aggregates are tested. Nevertheless, the plate stripping test was able to distinguish between the performance of certain aggregate–BAA combinations, which demonstrated its usefulness as an initial screening tool.
- The boiling water test, despite its international use as a screening tool, showed very limited sensitivity and was unable to meaningfully differentiate the stripping potential between the different aggregate–BAA combinations.
- The TSR test provided more discriminating results and aligned reasonably well with MBV trends, identifying both high-risk aggregates and the beneficial effects of adhesion agents. However, some inconsistencies were observed, particularly for aggregates without any BAA passing the MBV threshold but failing the TSR limit. The TSR results highlighted the dependency of stripping performance on the aggregate–BAA combination proposed.
- The TSR and HWT tests ranked the performance of the specimens without any BAAs reasonably consistently, depending on the criteria adopted for the HWT test. However, the ranking was less consistent between the tests for the specimens containing BAAs, especially when the bio-oil was used.
- All the specimens, irrespective of aggregate and BAA type (including no BAA), exceeded the minimum 10,000 passes to a 12.5 mm rut depth HWT criterion included in TN 213. Given that some of the aggregate–BAA combinations performed poorly in the TSR and plate stripping tests, the 10,000 passes criterion does not appear to be sufficiently conservative for the mixes in Queensland.
- The SIP criterion used by some jurisdictions in the USA was able to demonstrate the need for a BAA with the hornfels aggregates even though the specimens without any BAA passed the 12.5 mm rut depth HWT criterion. This demonstrated the potential benefit of also including an SIP criterion for the HWT test, similar to international practices.
- The study identified potential repeatability concerns with the HWT test, which resulted in the need for re-testing several specimens.
- The laboratory testing showed that some alternative BAAs can provide equivalent or better performance than hydrated lime. However, the effectiveness of the agents is aggregate type–dependent.
- There does not appear to be a single standard test method currently available in Australia that can reliably and consistently predict the moisture sensitivity of asphalt mixes with different BAAs in the laboratory.
- The interim Austroads assessment protocol, subject to some modifications, appears to be suitable for assessing the effectiveness of different BAAs in Queensland.

6.2 Recommendations

Based on the project findings, the following is recommended for consideration by TMR:

- The plate stripping test should be retained in the Austroads and TMR assessment protocols as a screening tool. However, the 10% SV criterion appears to be too stringent if the aggregates will be tested in their 'as-received' condition. It is recommended that the acceptance criteria be relaxed or that testing washed aggregates instead be further investigated.
- The minimum number of passes to a rut depth of 12.5 mm in TN 213 should be increased to at least 15,000 passes for a C320 bitumen to ensure that BAAs will provide equivalent or better performance to hydrated lime. It is also recommended that TMR considers the introduction of an SIP criterion for the HWT test. However, the methodology to identify the SIP should be investigated further as the current methodology for identifying the SIP in Q325 is considered to be overly subjective.
- The repeatability of the HWT test should be further investigated with a view to develop appropriate precision criteria.
- The need for benchmarking the performance of alternative BAAs against hydrated lime could be reconsidered if the Austroads protocol, including mandatory HWT testing, is adopted.

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Appendix A Laboratory Test Results

A.1 Plate stripping test results

The plate stripping test results are presented in Table A.1 to Table A.4.

Table A.1: Plate stripping test results – Hornfels aggregate

Parameter	C320 without BAA	C320 with amine agent	C320 with bio-oil	C320 with silane agent
SV – sample 1 (%)	100	56	100	12
SV – sample 2 (%)	100	53	99	10
Average SV (%)	100	55	100	11

Table A.2: Plate stripping test results – Olivine basalt aggregate

Parameter	C320 without BAA	C320 with amine agent	C320 with bio-oil	C320 with silane agent
SV – sample 1 (%)	59	17	62	1
SV – sample 2 (%)	68	10	56	2
Average SV (%)	64	14	59	2

Table A.3: Plate stripping test results – Metagreywacke aggregate

Parameter	C320 without BAA	C320 with amine agent	C320 with bio-oil	C320 with silane agent
SV – sample 1 (%)	100	24	100	2
SV – sample 2 (%)	100	38	100	0
Average SV (%)	100	31	100	1

Table A.4: Plate stripping test results – Greenstone aggregate

Parameter	C320 without BAA	C320 with amine agent	C320 with bio-oil	C320 with silane agent
SV – sample 1 (%)	100	33	100	2
SV – sample 2 (%)	100	22	100	1
Average SV (%)	100	28	100	2

A.2 Boiling water test results

The boiling water test results are presented in Table A.5.

Table A.5: Boiling water test results

Aggregate type	Retained coating (%)				
	C320 (control)	C320 with lime	C320 with amine agent	C320 with bio-oil	C320 with silane agent
Hornfels aggregate	99	97	97	98	98
Olivine basalt aggregate	97	98	98	98	100
Greenstone aggregate	98	100	100	100	100
Metagreywacke	100	100	100	100	100

A.3 Tensile strength results

The TSR test results are presented in Table A.6 to Table A.9.

Table A.6: TSR test results – Hornfels aggregate

Parameter	C320 (control)	C320 with lime	C320 with amine agent	C320 with bio-oil	C320 with silane agent
Average tensile strength – dry (kN)	758	866	876	762	783
Average tensile strength – wet (kN)	711	796	834	700	849
Average degree of saturation (%)	72	73	79	78	75
TSR (%)	94	92	95	92	108
Visual observation	Minimal stripping on fine aggregate	Minimal stripping on fine aggregate	Moderate stripping	Minor stripping	Minimal stripping on coarse aggregate

Table A.7: TSR test results – Olivine basalt aggregate

Parameter	C320 (control)	C320 with lime	C320 with amine agent	C320 with bio-oil	C320 with silane agent
Average tensile strength – dry (kN)	1,045	931	778	994	1,032
Average tensile strength – wet (kN)	784	733	708	741	859
Average degree of saturation (%)	72	73	71	75	76
TSR (%)	75	79	91	75	83
Visual observation	Moderate to severe stripping	Moderate stripping	Minimal to moderate stripping	Minor to moderate stripping	Minor to moderate stripping

Table A.8: TSR test results – Metagreywacke aggregate

Parameter	C320 (control)	C320 with lime	C320 with amine agent	C320 with bio-oil	C320 with silane agent
Average tensile strength – dry (kN)	1,032	820	1,224	783	763
Average tensile strength – wet (kN)	946	727	1,056	768	864
Average degree of saturation (%)	69	75	75	73	75
TSR (%)	86	89	86	98	113
Visual observation	No visible stripping	No visible stripping	No visible stripping	No visible stripping	Mild stripping on coarse aggregate

Table A.9: TSR test results – Greenstone aggregate

Parameter	C320 (control)	C320 (with lime)	C320 with amine agent	C320 with bio-oil	C320 with silane agent
Average tensile strength – dry (kN)	1316	1106	975	1075	1120
Average tensile strength – wet (kN)	1044	1091	1191	901	1022
Average degree of saturation (%)	76	65	70	77	77
TSR (%)	79	99	122	84	91
Visual observation	Minor stripping	Minimal stripping	No visible stripping	Minor stripping	Minor stripping

A.4 Hamburg Wheel Tracking test results

Table A.10 to Table A.13 present the HWT test results. Where samples were re-tested, the results in **bold** were used in the analysis.

Table A.10: HWT test results – Hornfels aggregate⁽¹⁾

Parameter	C320 (control)	C320 with lime	C320 with amine agent	C320 with bio-oil	C320 with silane agent
No. of passes to 12.5 mm rut depth	15,200/15,444	> 20,000/> 20,000	12,160/17,820	8,120/12,464	> 20,000/16,632 (> 20,000/> 20,000)
No. of passes to 20 mm rut depth	19,190/> 20,000	> 20,000/> 20,000	15,352/20,000	11,678/16,482	> 20,000/> 20,000 (> 20,000/> 20,000)
Rut depth at 10,000 passes (mm) ⁽²⁾	6/6	6/7	8/6	17/9	7/10 (8/7)
Rut depth at 15,000 passes (mm) ⁽²⁾	12/12	6.5/7.5	19/9	> 20/18	9/12 (8/7.5)
Rut depth at 20,000 passes (mm)	> 20.0/17.2	7.5/8.5	> 20.0/20.0	> 20.0/> 20.0	9.6/14.0 (9.4/8.0)
Stripping inflection point (passes) ⁽²⁾	10,640/12,872	–	10,032/16,236	6,496/9,840	–

1. Results in brackets are re-tested values.
2. Estimated value from deformation curve.

Table A.11: HWT test results – Olivine basalt aggregate⁽¹⁾

Parameter	C320 (control)	C320 with lime	C320 with amine agent	C320 with bio-oil	C320 with silane agent
No. of passes to 12.5 mm rut depth	13,024/>20,000 (8,892/11,856)	16,632/17,028	11,544/> 20,000 (> 20,000/17,820) (12,000/17,226)	14,586/11,880	16,632/> 20,000 (> 20,000/> 20,000)
No. of passes to 20 mm rut depth	17,776/> 20,000 (11,492/15,292)	> 20,000/> 20,000	20,000/20,000 (> 20,000/> 20,000) (15,180/> 20,000)	17,918/13,332	> 20,000/> 20,000 (> 20,000/> 20,000)
Rut depth at 10,000 passes (mm) ⁽²⁾	8/2.5 (16/11)	5/6	10/5 (4/5) (7.5/7)	5/8	7/6 (3.5/4)
Rut depth at 15,000 passes (mm) ⁽²⁾	16/(3.5 (> 20/19))	10/10	20/6 (5/8) (19/12)	14/> 20	11/6 (5/5)
Rut depth at 20,000 passes (mm)	> 20.0/5.9 (> 20.0/> 20.0)	19.4/15.4	20/9.2 (6.0/15.0) (> 20.0/16.2)	> 20.0/> 20.0	18.1/6.7 (5.4/6.1)
Stripping inflection point (passes) ⁽²⁾	8,448/13,264 (6,042/6,688)	10,396/10,296	4,884/4,356 (–/12,970) (9,180/10,296)	10,680/10,956	13,702/– (–/–)

1. Results in brackets are re-tested values.
2. Estimated value from deformation curve.

Table A.12: HWT test results – Metagreywacke aggregate⁽¹⁾

Parameter	C320 (control)	C320 with lime	C320 with amine agent	C320 with bio-oil	C320 with silane agent
No. of passes to 12.5 mm rut depth	> 20,000/> 20,000	> 20,000/> 20,000	> 20,000/> 20,000	> 20,000/> 20,000	> 20,000/> 20,000
No. of passes to 20 mm rut depth	> 20,000/> 20,000	> 20,000/> 20,000	> 20,000/> 20,000	> 20,000/> 20,000	> 20,000/> 20,000
Rut depth at 10,000 passes (mm) ⁽²⁾	4/3	6/5	4/3	4/3.5	3.5/3.5
Rut depth at 15,000 passes (mm) ⁽²⁾	4/3.5	7.5/6.5	5/3.5	5/4	4/4
Rut depth at 20,000 passes (mm)	4.7/3.8	8.6/6.8	5.5/4.15	6.1/4.9	4.6/4.4
Stripping inflection point (passes) ⁽²⁾	–/–	–/–	–/–	–/–	–/–

1. Results in brackets are re-tested values.
2. Estimated value from deformation curve.

Table A.13: HWT test results – Greenstone aggregate⁽¹⁾

Parameter	C320 (control)	C320 with lime	C320 with amine agent	C320 with bio-oil	C320 with silane agent
No. of passes to 12.5 mm rut depth	15,444/15,246	> 20,000/> 20,000 (19,008/> 20,000)	12,768/> 20,000 (> 20,000/> 20,000)	17,028/18,612	> 20,000/> 20,000
No. of passes to 20 mm rut depth	20,000/> 20,000	> 20,000/> 20,000 (> 20,000/> 20,000)	16,968/> 20,000 (> 20,000/> 20,000)	> 20,000/> 20,000	> 20,000/> 20,000
Rut depth at 10,000 passes (mm) ⁽²⁾	5/5	4/4 (5/4.5)	6/3.5 (2/3.5)	4/3	3.5/4
Rut depth at 15,000 passes (mm) ⁽²⁾	12/12	6/4 (8/5)	17/5.5 (2.5/4.5)	9/7.5	3.5/5
Rut depth at 20,000 passes (mm)	20.0/19.0	10.5/4.7 (13.9/8.3)	> 20.0/4.9 (5.0/7.1)	17.7/15.3	4.7/6.1
Stripping inflection point (passes) ⁽²⁾	10,890/10,500	16,236/– (9,900/17,424)	9,072/– (17,424/17,424)	11,102/12,012	–/–

1. Results in brackets are re-tested values.
2. Estimated value from deformation curve.