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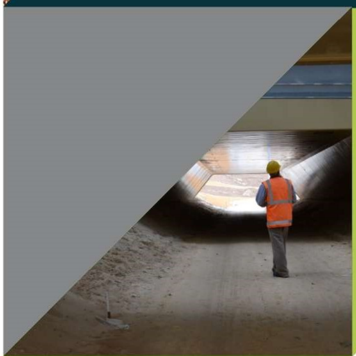
WESTERN AUSTRALIAN ROAD RESEARCH AND INNOVATION PROGRAM

Review of Applicable Bond Strength Tests for Assessing Delamination Potential



Ester Tseng

AN INITIATIVE BY:

THE GOVERNMENT OF WESTERN AUSTRALIA

mainroads WESTERN AUSTRALIA

arrb

ABN 68 004 620 651

Victoria
80A Turner Street
Port Melbourne VIC 3207
Australia
P: +61 3 9881 1555
F: +61 3 9887 8104
info@arrb.com.au

Western Australia
191 Carr Place
Leederville WA 6007
Australia
P: +61 8 9227 3000
F: +61 8 9227 3030
arrb.wa@arrb.com.au

New South Wales
2-14 Mountain St
Ultimo NSW 2007
Australia
P: +61 2 9282 4444
F: +61 2 9280 4430
arrb.nsw@arrb.com.au

Queensland
21 McLachlan St
Fortitude Valley QLD 4006
Australia
P: +61 7 3260 3500
F: +61 7 3862 4699
arrb.qld@arrb.com.au

South Australia
Suite 713,
127 Pirie Street
Adelaide SA 5000
Australia
P: +61 8 8235 5000
F: +61 8 8223 7406
arrb.sa@arrb.com.au

Review of Applicable Bond Strength Tests for Assessing Asphalt Delamination Potential

2018-008

for Main Roads Western Australia

Reviewed		
Project Leader	Ester Tseng	
Quality Manager	Geoff Jameson	

014088_PAV_WARRIP_Bond Strength Test-Final

June 2019

SUMMARY

The current Austroads pavement thickness design procedure assumes interfaces between asphalt layers are fully bonded. In other words, no slippage is considered between layers, with displacements at the top and bottom asphalt layers assumed to be exactly the same at the interface depth. In practice, however, full bond is not always achieved. Poor interlayer bond condition can significantly reduce the capability of the pavement to support traffic, leading to a reduced pavement life.

With the implementation of EME2 and warm mix asphalt (WMA) technologies, as well as the increasing adoption of full depth asphalt pavements in the WA network, Main Roads Western Australia (MRWA) is concerned that poor bond between deeper asphalt layers may result in costly pavement rehabilitation and reconstruction requirements.

With no bond strength test method or minimum criteria currently adopted by MRWA, the aim of this study is to assist MRWA in the adoption of a test method to assess the bond strength achieved between asphalt layers. This report presents a review of (laboratory and field) destructive bond strength tests and an overview of available (field) non-destructive tests. Additionally, the report summarises standard test methods and recommended minimum strength limits identified in the literature.

Based on the literature review conducted, it is recommended that destructive methods are considered for quality control and the ranking of tack coat and tack coat applications, while non-destructive methods are considered for evaluating long lengths of pavement where the presence and location of delamination need to be determined, as well as an indication of its severity.

Among the many destructive test procedures described in this report, laboratory direct shear and direct tensile tests with controlled conditions appear to be the most appropriate for a routine construction quality control test and for the ranking of tack coat products and application rates. Preferably, both shear and tensile tests should be investigated. However, if a single test is to be used, a shear test is preferred as it not only assesses the adhesiveness between the layers but also it allows friction to be considered.

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1 INTRODUCTION

Sufficient bonding between pavement layers is fundamental for achieving good pavement performance. Most pavement design and evaluation techniques assume that adjacent pavement layers are fully bonded together, and that no displacement is developed between them. However, full bond is not always achieved. Theoretical evaluation and research have shown that poor interlayer bonding affects stress/strain distributions within a pavement structure and reduces the capability of the pavement to support traffic and environmental loadings. West, Zhang and Moore (2005) indicated that a reduction in interface bond by only 10% can result in a decrease in fatigue life of 50%.

Linear elastic modelling of a typical full depth asphalt pavement cross-section under an 80 kN single axle dual tyre load (Austroads 2018) indicated that the allowable loading, in terms of pavement deformation, is reduced by 40–96% when debonding occurs (although it is noted that, in practice, this allowable loading does not limit the life of full depth asphalt pavements, as the predicted asphalt fatigue life is shorter). The lower value (40%) corresponds to debonding at the top asphalt layer interface, whereas the higher value (96%) corresponds to debonding of all asphalt interfaces. The same analysis carried out for asphalt fatigue indicated a reduction in life from 27–83%.

Factors that affect bonding between layers include, amongst others, interface texture and condition, the nature and extent of trafficking, tack coat type and application rate, asphalt mix type, temperature, emulsion curing time and the presence of contamination (Johnson 2015; Raposeiras et al. 2013; White 2015). Main Roads Western Australia (MRWA) have recorded instances where the interface condition was not ideal, i.e. wet interface, which has led to loss of bond between asphalt layers.

MRWA are currently investigating the possible application of high modulus binder technology in the form of EME2 and the implementation of warm mix asphalt (WMA) technologies. The use of EME2 and WMA raises several concerns with regards to bonding strength. EME2 results in a smoother-than-normal interface texture, potentially reducing friction and bond strength between layers. Bitumen foaming and some WMA additives utilise water in the mixing process. Because of the possible incomplete vaporisation of water during the mixing and laying process, the presence of residual water may lead to stripping under traffic. In addition, the lower temperature at which WMA is placed potentially inhibits heat transfer to the underlaying layer to enhance bonding.

This report describes test methodologies for interface bond strength sourced from the literature, including their advantages and disadvantages. Recommendations are made regarding possible test methods which could be further investigated for possible adoption in WA.

The report includes the following sections:

Section 2 – Current Australia practice.

Section 3 – Existing destructive asphalt bond strength test methods.

Section 4 – Brief overview of non-destructive methods.

Section 5 – Review of standard test methods.

Section 6 – Summary of minimum bond strength limits identified in the literature.

Section 7 – Summary of findings and recommendations.

2 AUSTRALIAN PRACTICE

2.1 Austroads and Australian Asphalt Pavement Association (AAPA)

Neither Austroads nor AAPA provide guidance with respect to testing and quantifying asphalt interlayer bond strength.

The importance of the use of tack coat to ensure good bond between asphalt layers and advice on tack coat binder types, application rates, surface preparation and application procedures can be found in Pavement Work Tips No. 51 – Asphalt tack coating (Australian Asphalt Pavement Association & Austroads 2013) and the Austroads guide to pavement technology part 8: pavement construction (Austroads 2009).

2.2 Main Roads Western Australia (MRWA)

MRWA does not currently specify any test methods for determining asphalt interlayer bond strength or minimum strength requirements.

MRWA requires a tack coat to be applied between two asphalt layers. A sprayed seal is usually required between the wearing course and the intermediate course, with the tack coat applied prior to and subsequent to the construction of the seal (MRWA 2015, 2017 & 2018).

MRWA Specifications 204 and 510 (MRWA 2017 & 2018) require a tack coat application rate of 0.6 L/m^2, mixed 50:50 by volume with water (residual binder application rate of 0.3 L/m^2).

2.3 New South Wales Roads & Maritime Services (RMS)

RMS requires a tack coat application prior to laying an asphalt layer. The recommended application rates vary depending on the subsequent asphalt type, as summarised in Table 2.1 (RMS 2009, 2012a, 2013a, 2013b, 2013c & 2013d).

RMS does not require testing of asphalt interlayer bond strength but has a standard test method for tack coat bond strength (Test Method T620, RMS 2012b). The test is conducted in the field to provide data on the performance of tack coatings on specific surfaces prior to asphalt placement. It consists of a shear test where the tack coat is applied to the asphalt surface and an asphalt cylinder briquette is compacted on top of the tack coat using a rammer. Four cylinders are prepared, of which two are treated with water. A spring balance pulley block and a rope is attached to the wheel of a utility which pulls the briquette, thus applying a shear load at the interface. The load at which each test cylinder separates from the surface is recorded. The test is not in RMS specifications and is not widely used (based on email from Su Tao from RMS on 16 April 2019).

Su Tao from RMS (on email dated 15 April 2019) indicated that RMS has not done any asphalt interlayer testing. RMS QA Specification B343 (RMS 2014) provides minimum tensile and shear strength requirements for waterproof membranes on bridge decks (waterproof membrane to concrete deck and asphalt to waterproofing membrane). The minimum shear adhesion strength between the asphalt and waterproofing membrane varies from 0.4 MPa for –10 °C to 0.1 MPa for 50 °C. The minimum tensile bond strength is 0.2 MPa.

2.4 Queensland Department of Transport and Main Roads (TMR)

TMR does not require testing of asphalt interlayer bond strength. To minimise the risk of debonding, TMR Technical Specification MRTS30 *Asphalt pavements* (TMR 2019) requires the application of a tack coat between asphalt layers, emphasizing that the surface must be clean, dry and free from loose and other deleterious materials. The suggested application rate range is 0.10–0.30 L/m^2 residual binder at 15 ºC. The tack coat is not required when a new asphalt layer is placed on asphalt or sprayed bituminous treatments that have: (1) been placed on the same day or the previous day, (2) not been subjected to traffic and, (3) has a clean appearance. A sprayed bituminous surfacing (instead of tack coat) is typically placed below an open-graded asphalt layer to provide a waterproof layer.

TMR (2019) cites the extraction of cores from the pavement to show that a strong bond has been achieved despite the asphalt being placed at temperatures below the minimum requirements. However, no quantitative approach is included to assess what qualifies as 'strong bond'.

TMR used to have a test method to test bond strength between asphalt layers but this method was not widely used, and it has been withdrawn (according to Jason Jones of TMR in an email dated 11 April 2019).

TMR also has a field test procedure to ensure that asphalt geosynthetic products are bonded to the asphalt. The procedure, called 'Spring balance testing', consists of hook attached to a spring balance that is used to pull the geotextile, as illustrated in Figure 2.1. If 9 kg or more is required to pull the geotextile upwards, then paving can continue. Otherwise, corrective action in accordance with the manufacturer's recommendation must be undertaken (TMR 2018)

Figure 2.1: Spring balance testing

Source: TMR (2018).

According to Jason Jones of TMR (email dated 11 April 2019), poor bond between asphalt layers is observed in Queensland mainly when an asphalt overlay is applied to an older (and smoother) asphalt surface. This occurs mainly in high shear environments, such as sharp curves, approaches to bus stops and roundabouts, or where heavy vehicles are turning or decelerating. These issues could be minimised by texturizing the old asphalt surface prior to the application of an overlay.

2.5 South Australia Department of Planning, Transport and Infrastructure (DPTI)

DPTI does not require testing of asphalt interlayer bond strength. To minimise the risk of debonding, DPTI *Specification Part R28 Construction of asphalt pavements* (DPTI 2018) requires a tack coat to be applied if the asphalt layers are not placed on the same day. The required application rate range is between 0.2 and 0.4 L/m^2 of residual binder.

According to email from Johnny Tran of DPTI on 9 April 2019, there has not been any recent issues with delamination. Asphalt rehabilitation works are usually conducted at night with two to three layers of asphalt constructed per night and the wearing course often placed after the application of a tack coat.

Johnny Tran also mentioned that, in the past (around 2004), DPTI used the Leutner shear test device to test interface bond strength at a temperature of 25 ºC; however, they found it difficult to determine what would be a suitable strength requirement.

2.6 VicRoads

VicRoads does not have any requirements for testing of the bond strength between asphalt layers. VicRoads Standard Section 407 *Hot mix asphalt* (VicRoads 2017) requires the application of tack coat at a rate 0.15 to 0.30 L/m^2 (60% bitumen content) or 0.30 to 0.60 L/m^2 (30% bitumen content). The tack coat should be applied to a clean and dry surface. A tack coat is not required if the asphalt is being spread over a clean, freshly-laid asphalt; a clean, primed surface; or where the thickness of the layer exceeds 50 mm.

Andrew Walker from VicRoads (during a telephone conversation on 10 April 2019) indicated that VicRoads does not experience many issues related to debonding between asphalt layers.

2.7 Summary

None of the Australia road agencies surveyed currently adopt a test method for assessing the bond strength between asphalt layers. A summary of Australian road agency requirements relating to tack coats is presented in Table 2.1.

Table 2.1: Tack coat requirements by different road agencies

Road agency	Relevant test procedure	Asphalt interlayer requirements	Tack coat application rate
MRWA[(1)] (Western Australia)	▪ Not encountered	▪ Tack coat ▪ Sprayed seal applied to the uppermost layer of 14 mm asphalt intermediate course (with tack coat prior to and subsequent to the sprayed seal application)	▪ 0.6 L/m^2 of the dilute emulsion (0.3 L/m^2 residual binder)
RMS[(2)] (New South Wales)	▪ Test method T620 – Tack coat bond strength (RMS 2012b)	▪ Tack coat	▪ Prior to dense-graded, open-graded and crumb rubber asphalt: 0.15 to 0.30 L/m^2 residual binder (application rate may be reduced upon request due to the existing underlying pavement material, such as primerseal or seal). ▪ Prior to stone mastic asphalt: 0.15 to 0.40 L/m^2 residual binder (sprayed seal warranted in some cases). ▪ Prior to thin open-graded asphalt: 0.5 to 1.0 L/m^2 residual binder.
TMR[(3)] (Queensland)	▪ Spring balance test: used to test the bond strength of asphalt geosynthetic products to the underlying layer prior to placement of following asphalt layer (TMR 2018)	▪ Tack coat except when a new asphalt layer is placed an asphalt or sprayed bituminous treatment that has been placed on the same day or previous day, has not been subjected to traffic and has a clean appearance. ▪ Sprayed bituminous surfacing (instead of tack coat) below open-graded asphalt.	▪ 0.10 to 0.30 L/m^2 residual binder.
DPTI[(4)] (South Australia)	▪ Not encountered ▪ Previous experience using Leutner apparatus (direct shear test)	▪ Tack coat except if the asphalt layers are placed in the same day.	▪ 0.2 and 0.4 L/m^2 residual binder.
VicRoads[(5)] (Victoria)	▪ Not encountered	▪ Tack coat except if the asphalt is being spread over a clean, freshly laid asphalt; a clean, primed surface; or where the depth of the layer exceeds 50 mm.	▪ 0.15 to 0.30 L/m^2 (60% bitumen content) or 0.30 to 0.60 L/m^2 (30% bitumen content).

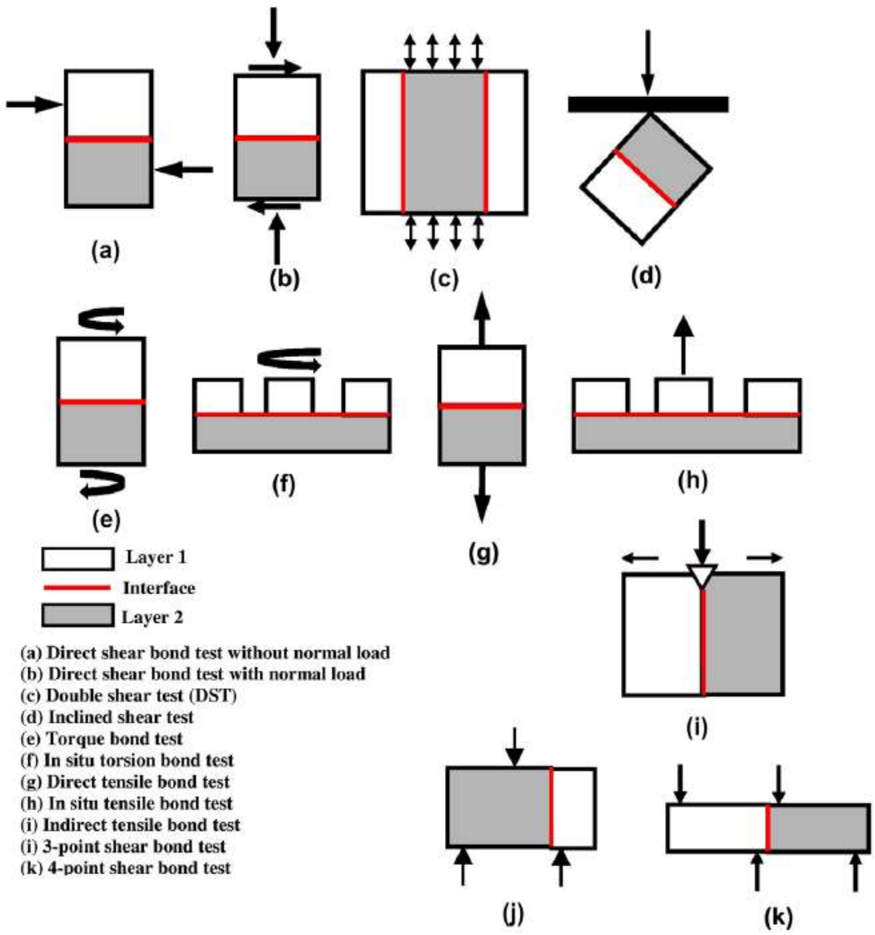
1 Source: MRWA (2015, 2017 & 2018).
2 Source: RMS (2009, 2012a, 2012b, 2013a, 2013b, 2013c & 2013d).
3 Source: TMR (2018 & 2019).
4 Source: DPTI (2016).
5 Source: VicRoads (2017).

3 EXISTING DESTRUCTIVE ASPHALT BOND STRENGTH TEST METHODS

3.1 Introduction

Many different test configurations have been used to assess bond strength between asphalt layers. The most common tests include the application of direct shear, direct tension or torque on dual layer specimens or in the field. Some less common variations include the application of a compression stress combined with shear, the use of three layer specimens, fracture testing and indirect shear testing. The different types of destructive test methods for assessing asphalt interface bond strength are summarised in Figure 3.1 and detailed in Sections 3.2 to 3.4.

Figure 3.1: Schematic diagram of different test methods for interface bonding



Source: Rahman et al. (2017).

3.2 Shear Bond Tests

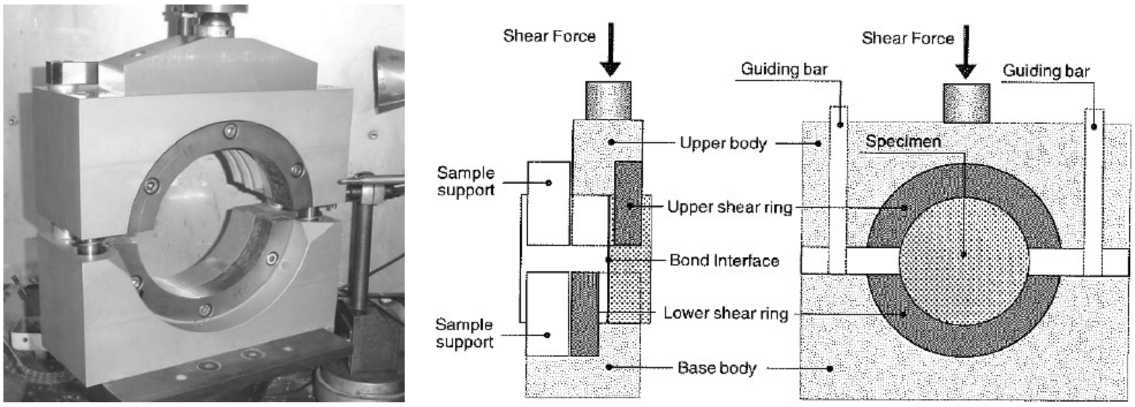
3.2.1 Direct Shear Bond Tests

Direct shear tests are the most popular type of interface bond strength tests. A shear force is applied parallel to the interface of two asphalt layers. Shear testing is conducted in the laboratory. It is quick, repeatable and can be conducted using common laboratory equipment. For those reasons, it is the most common test method available to investigate bond strength between asphalt layers (Asphalt Institute 2014).

Canestrari et al. (2012), in a study including 14 laboratories from 11 countries, achieved satisfactory precision with the direct shear test, with repeatability standard deviation of 0.05 MPa and reproducibility standard deviation of 0.12 MPa.

The most common device to test direct shear bond is called Leutner shear tester. It consists of a guillotine apparatus that can be attached to common laboratory equipment, such as a standard Marshall or California Bearing Ratio (CBR) loading device. A force is applied on one asphalt layer of the sample through a U-shaped arm while the other layer remains stationary, producing a shear stress at the interface. Figure 3.2 shows the Leutner direct shear device.

Figure 3.2: Leutner shear tester



Source: Canestrari et al. (2012) and Hakimzadeh (2015).

The shear stress is usually calculated as the shear force divided by the interface area, as per Equation 1:

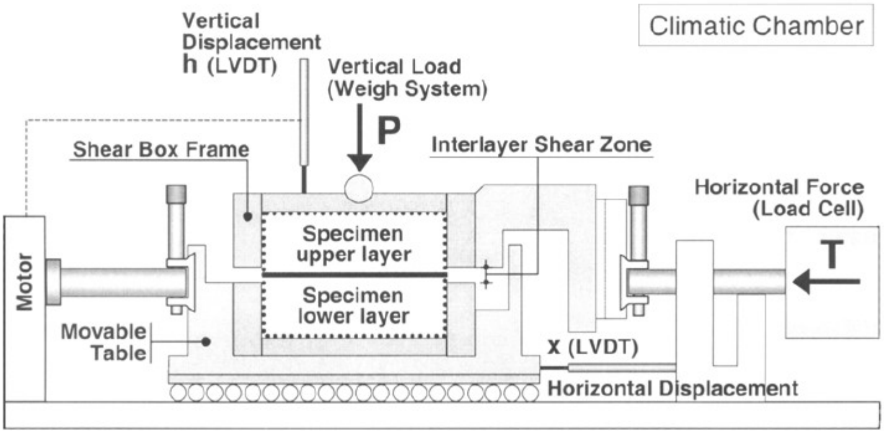
$$\tau = \frac{F_{max}}{A} \qquad 1$$

where

τ	=	Shear stress (MPa)
F_{max}	=	Maximum shear force (N)
A	=	Cross-sectional area (mm)

Another shear device commonly used is the direct shear box, which was originally developed to test the shear strength of soils. The shear box is composed of two prismatic boxes, which support the upper and lower asphalt layers. The interface is placed between the two parts which then slide, generating a shear force. A compressive stress perpendicular to the interface can also be applied to simulate the effect of traffic loading in the pavement. A shear box device is illustrated in Figure 3.3.

Figure 3.3: Direct shear box type of device



Source: West et al. (2005).

Many different researchers have proposed variations of these devices. Some shear devices allow the inclusion of a normal force. This allows a dilatancy effect, as well frictional properties and aggregate interlocking to contribute to the bonding characteristics (Chang et al. 2014; Sutanto 2010).

West et al. (2005) found that normal pressure affects bond strength differently at various temperatures. At high temperatures (60 °C), the authors observed bond strength to increase with normal stress. However, at intermediate and low temperatures (25 °C and 10 °C) the bond strength was not considerably sensitive to the normal pressure levels. Canestrari et al. (2012) reported friction to linearly increase with normal stress.

Several authors found it beneficial to include a gap between the shearing plates. The gap minimises potential problems related to the interface plane not being exactly parallel to the shearing plane. It also minimises crushing of the aggregates at the edge of the specimen (Chang et al. 2014; Mrawira & Damude 1999; Sholar et al. 2003; Sutanto 2010). Various gap widths have been reported in the literature. According to Sholar et al. (2003), the gap should be large enough to minimise skewness effects but, if excessively large, it can result in bending. According to Raab, Partl and Abd El Halim (2010) wider gaps increase eccentricity, resulting in a combined bending-shear moment. If the gap is too wide, the shear plane is less defined, and failure may occur at a weaker point outside the interface. The authors warned that a gap width of 5 mm or more, as used in some studies (Choi et al. 2005; Sholar et al. 2003; Sutanto 2010; West et al. 2005), may lead to results that reflect a combined inlayer and interlayer properties.

Another variable that influences test results is the shape and size of the specimen tested. Chang et al. (2014) found that larger diameters specimens (150 mm compared to 100 mm) result in less variability, especially for mixes with larger nominal maximum aggregate size. Canestrari et al. (2012) reported shear stress values using 150 mm diameter cores to be about 14% lower than the results of tests using 100 mm diameter cores. According to Gaspa, Vasconcelos and Bernucci (2016), this is due to the higher concentration of stresses on smaller samples.

Temperature also affects shear strength, with several studies reporting that peak shear strength decreases with increasing temperatures (Abuaddous et al. 2016; Canestrari et al. 2012 & 2018; Dony et al. 2016).

Muench and Moomaw (2008) noted that shear tests are usually conducted at a much slower shear rate than what is produced in-service by traffic, and that this may result in a discrepancy between the laboratory results and what happens in the field. Canestrari et al. (2012) conducted shear stress tests on 77 cores varying displacement rates from 1.27 to 200 mm/min and concluded that shear increases with test speed.

Abuaddous et al. (2016) conducted simple shear tests using the Leutner equipment at five different deformation rates (from 1 to 25 mm/min) with two specimen diameters (100 mm and 150 mm) at three different temperatures (5 °C, 20 °C and 40 °C). The authors concluded that these parameters (deformation rate, specimen size and temperature) were inter-related. The slope of a regression line in a log-log plot relating shear deformation rate and shear strength depends on the specimen diameter and on the temperature.

Shear tests can involve the application of constant or cyclic strain. The first (constant strain test) measures the bond strength between two asphalt layers. The second (cyclic strain test) measures fatigue resistance at the interface. According to Waisome (2017), the first group is an adequate representation of the mode of failure that occurs at interfaces located 15 to 40 mm beneath the pavement surface, where strains and stresses are higher. At deeper locations, stresses are lower, and shear strength may not realistically represent the gradual loss of bond that occurs. Repeated lower shear stresses and vertical confinement may cause the interface to fail. The author suggested that non-brittle bonding materials may perform best at greater depths.

Tozzo et al. (2014 cited in Waisome 2017) compared cyclic and monotonic test results but could not find a correlation between shear stress, normal stress and the number of cycles to failure. Crispino et al. (1997) found dynamic shear reaction modulus to be three times higher than the static shear reaction modulus.

Details on direct shear tests encountered in the literature are included in Appendix A.1 (Direct shear tests without normal load), Appendix A.2 (Direct shear tests with normal load) and Appendix A.3 (Inclined shear tests).

3.2.2 Double Shear Tests

The double shear test (DST) was developed at the University of Limoges, France. It uses prismatic 3-layer laboratory-manufactured specimens with two asphalt interfaces. The outside layers are fixed while the central part is subjected to a displacement, resulting in (near) pure shearing forces at the two interfaces. The load can be unidirectional monotonic static or unidirectional cyclic (Canestrari et al. 2012). Figure 3.4 presents a schematic of the double shear test.

The shear stress is calculated as the maximum shear force divided by two times the cross-sectional area of the prism, as per Equation 2.

$$\tau = \frac{F}{2.a.b} \qquad (2)$$

where

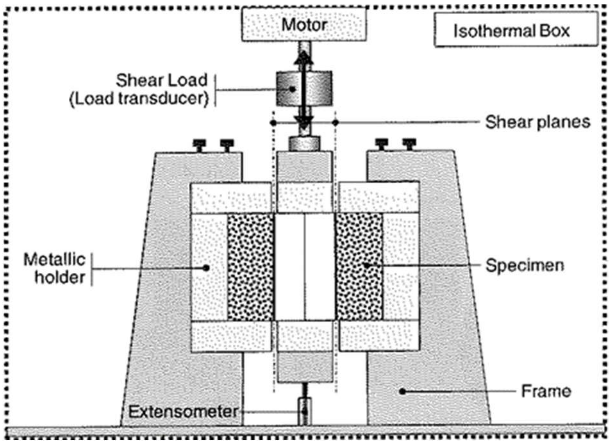
τ = Shear stress (MPa)

F = Shear force (N)

a, b = Width and height of the specimen (mm)

Source: Canestrari et al. (2012).

Figure 3.4: Double shear test



Source: Canestrari et al. (2012)

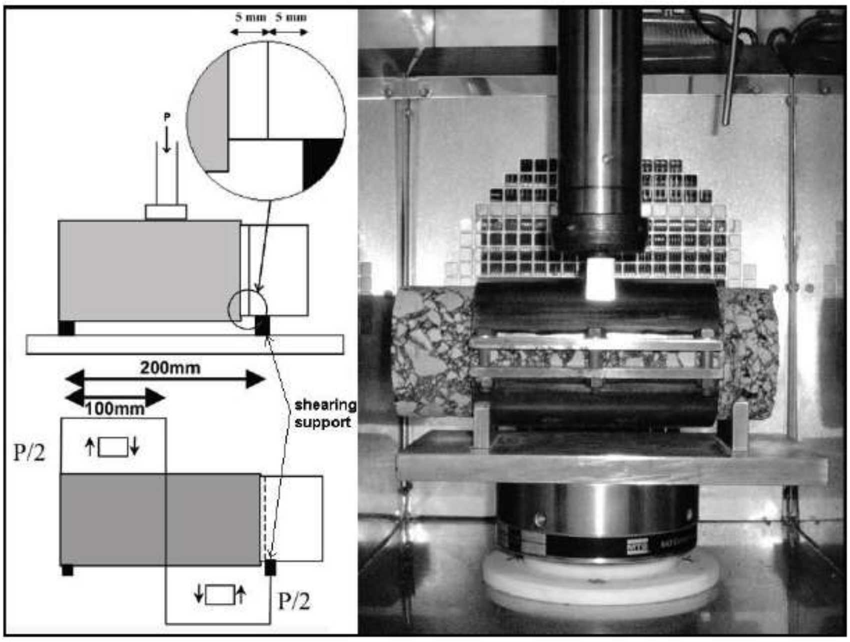
As observed with the simple direct shear tests, Canestrari et al. (2012) also noted that shear stress decreased with increasing temperatures with the DST. The authors observed a linear relation between the results from the direct shear tests and the DST for temperatures between 10 °C and 30 °C, with the DST results being about 30% higher than the shear test results.

Additional details on the DST are included in Appendix A.4.

3.2.3 Three-Point Shear Test – Laboratorio de Caminos de Barcelona (LBC) Shear Test

The three-point shear test was developed at the Laboratorio de Caminos de Barcelona (LCB), Spain. It is a Leutner-based test modified to provide a pure shear test configuration. A dual-layered specimen is placed over two supports spaced 200 mm apart. A vertical load is then applied to the specimen at the middle of the two supports until failure. The test measures shear strength, shear modulus and cracking energy. The test and forces diagram are illustrated in Figure 3.5. The interface is positioned 5 mm from the edge of the mould, and the shearing support 5 mm from the interface (i.e. 10 mm between the mould and the shearing support). The proximity of the support allows the bending moment to be almost zero at the interface (Ahn 2014; Canestrari et al. 2012; Mohammad et al. 2012; Raposeiras et al. 2013; Sutanto 2010).

Figure 3.5: LCB shear test configuration



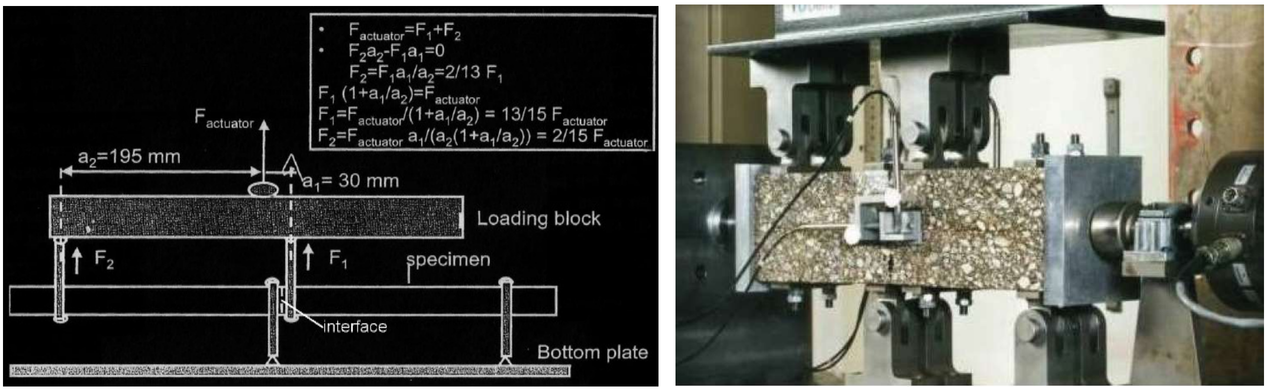
Source: Sutanto (2010).

Additional details on the LCB test are included in Appendix A.5.

3.2.4 Four-point Interface Shear Test

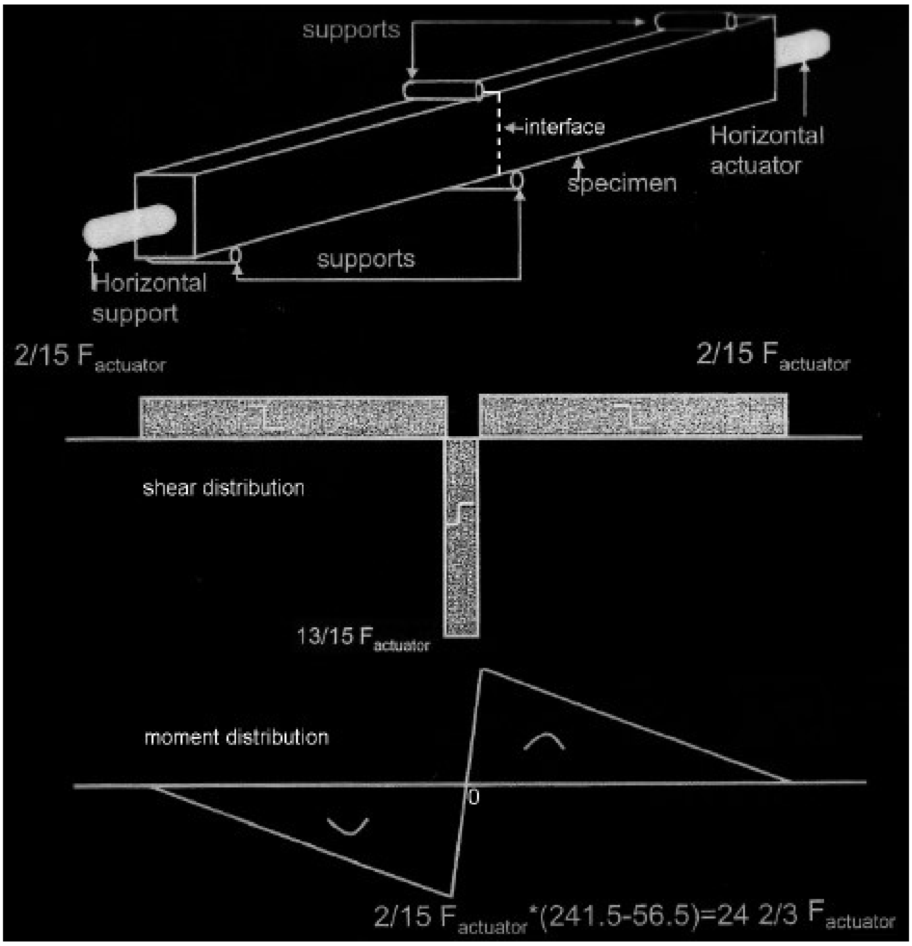
The four-point interface shear test was developed at Delft University, Netherlands. It allows a uniform shear stress distribution and no bending moment where the interface is located. The configuration of the test is illustrated in Figure 3.6. Shear and moment distributions in the test are illustrated in Figure 3.7.

Figure 3.6: Configuration in the four-point shear test



Source: Erkens (2002 cited in Sutanto 2010).

Figure 3.7: Shear and moment distributions in the four-point shear test



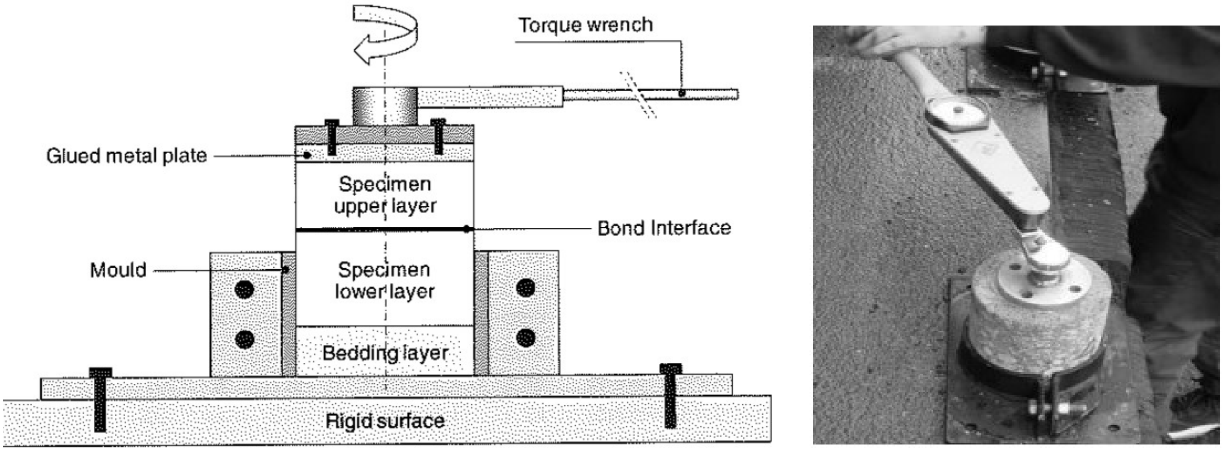
Source: Erkens (2002 cited in Sutanto 2010).

3.3 Torque Bond Test

Torque (or torsional) testing can be conducted in the field or in the laboratory. When conducted in the field, the pavement is partially cored to a certain depth beneath the interface level (20 mm according to the British Board of Agrément, 2004), a disc is glued to the surface and a torsional force is applied until failure. When conducted in the laboratory, the top and bottom of the specimen are glued, and torsional force is applied until failure occurs.

The most common set-up consists of a manual torque force applied using a wrench attached to the top plate. Although it is possible to test 100 mm and 150 mm diameter cores, Canestrari et al. (2012) recommend using the smallest specimens as it minimises the required effort to produce a twisting failure. The torque bond test is illustrated in Figure 3.8.

Figure 3.8: Torque meter



Source: Canestrari et al. (2012) and Hakimzadeh (2015).

During the test, the peak load as well as the cross-sectional area of the specimen are recorded. The bond torque resistance is calculated following Equation 3.

$$\tau = \frac{12M.10^3}{\pi D^3} \qquad 3$$

where

τ	=	Shear stress (MPa)
M	=	Torque momentum at failure (N.m)
D	=	Core diameter (mm)

Source: Canestrari et al. (2012)

Some procedures also include a confinement (compression) stress perpendicular to the interface being tested.

As per peak shear stress, peak torque was also found to decrease with increasing temperature (Canestrari et al. 2012; Choi et al. 2005). Therefore, results obtained outside of a temperature-controlled environment (which is the case with field testing) must be interpreted with care.

Details of torque bond tests encountered in the literature are provided in Appendix B.

3.4 Tensile Bond Tests

3.4.1 Direct Tensile Test

Tensile bond tests, also called pull-off tests, can be conducted in the field or in the laboratory. When conducted in the field, the pavement is partially cored to a certain depth beneath the interface level, a disc is glued to the surface and a tensile force is applied until failure occurs. When conducted in the laboratory, the top and bottom of the specimen are glued, and the tensile force is applied at the top until failure occurs. Some procedures also require conditioning via a seating load. During the test, the peak load as well as the cross-sectional area of the specimen are recorded.

Cutting below the interface level aims at eliminating the influence of the surrounding area. Finite element analysis carried out by Xiao et al. (2012) indicated that, if the lower layer is not cut, the surrounding area can significantly influence tensile strength.

Tensile tests isolate the effect of the tack coat adhesion from other material properties that influence shear or torque test results, such as gradation, maximum aggregate size and surface roughness.

Although quick and repeatable, results from tensile bond tests are often found to be too scattered. This may be related to (Canestrari et al. 2012, Chang et al. 2014, Rahman et al. 2017, Sutanto 2010, Tschegg et al. 1995):

- the eccentricity of the load (inclined testing piston or asphalt interface)
- the size of the specimens (small core diameters)
- large aggregate sizes
- strain concentrations resulting from constrained transverse strains where the load is introduced
- variable testing temperatures when conducted in the field.

Shuler (2018) reported a tendency for failure to occur at the interface between the steel plate and the asphalt specimen, with 30% of the samples tested by the author failing at the grip. He conducted tests on cores from two pavements identified as poorly bonded and well bonded and concluded that the variation in test results was unacceptably high and did not allow distinction between the well-bonded and poorly-bonded samples.

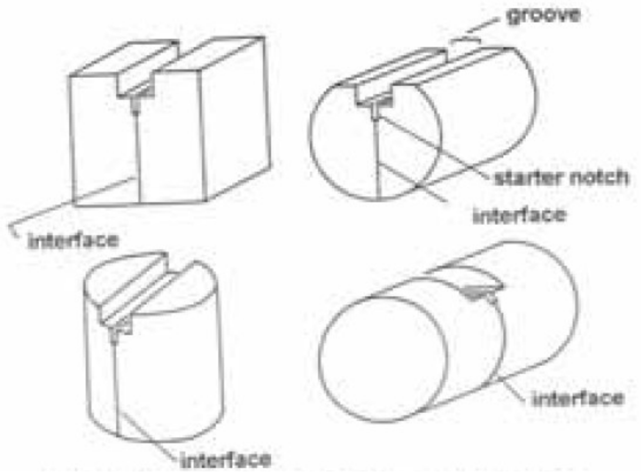
Details of direct tensile tests identified in the literature are provided in Appendix C.1.

The wedge splitting test is an indirect tensile laboratory test developed by The University of Vienna, Austria. It consists of a vertical load applied through a wedge to a dual-layered specimen with a groove and a starter notch. The load is applied at a constant rate until the specimen separates. The test generates load-displacement curves, thus allowing differentiation between the brittle and ductile behaviour of the materials. The maximum horizontal force and specific fracture energy are measured to characterize the fracture-mechanical behaviour of the layer bonding. The specimen can be cubic or cylindrical, with the interface located in different locations as illustrated in Figure 3.9. Specimens can be laboratory-fabricated or cored/cut from the pavement. The test set-up is illustrated in Figure 3.10.

Two disadvantages of this test are:

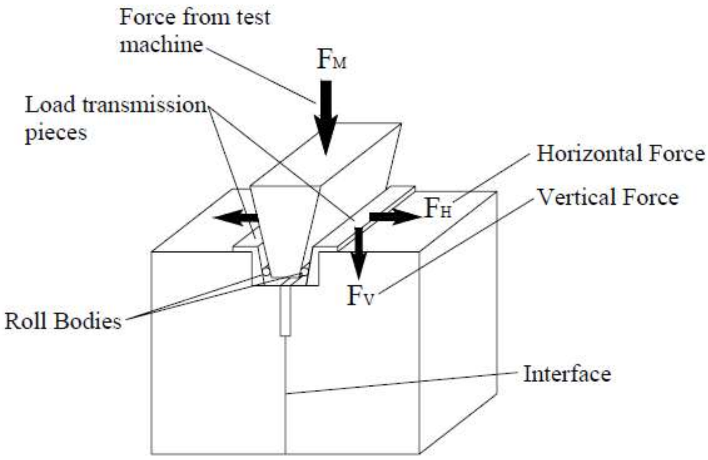
- the stresses in the specimen do not represent field conditions (the effect of aggregate interlock at the interface is not assessed)
- the preparation of the specimen requires considerable effort (Ahn 2014; Canestrari et al. 2012; Mohammad et al. 2012; Sutanto 2010; Tschegg et al. 1995).

Figure 3.9: Specimen shapes for wedge splitting tests



Source: Tschegg et al. (1995).

Figure 3.10: Wedge-splitting test



Source: Buchanan and Woods (2004).

3.4.2 Other Crack Resistance Tensile Bond Tests

The University of Illinois at Urbana-Champaign, USA, developed three other tests to measure crack resistance at interfaces:

1. interface bond test (IBT)
2. three-point bending notched beam
3. four-point bending notched beam.

The last two allow a combination of tension and shear forces to act simultaneously to evaluate crack resistance at the interface (Hakimzadeh 2015). More details are included in Appendix C.2.

3.4.3 Direct Tensile Test on Tack Coats

Direct tensile tests can also be performed directly on tack coats or tack coated surfaces for ranking of tack coat products and application rates. A list of direct tensile tack coat tests is included in Appendix C.3.

3.5 Summary

The advantages and disadvantages of the main types of bond tests are summarised in Table 3.1.

Choi et al. (2005) reported a good correlation between the results of shear strength measured using the Leutner test with a 5 mm gap and the peak torque measured using the torque test. However, Canestrari et al. (2012) found that torque bond test results between two laboratories varied significantly and did not enable a reliable comparison between the torque bond test and the shear test results. The correlations of torque bond test results from each laboratory with shear test results also resulted in very low coefficients of determination (R^2).

Hakimzadeh, Buttlar and Santarromana. (2012) found that different testing methods can result in different rankings of interface strength. They found that the optimum tack coat application rate determined using the interface bond test (maximising tensile bond fracture energy) was twice that determined using the torsional shear test. Additionally, it was observed that the ranking of tack coat materials was opposite when the tension results and the shear test results were compared. According to the authors, a milled surface can present a high shear strength even when tension tests suggest poor bond strength. Hakimzadeh, Buttlar and SantarromanaHakimzadeh (2012) suggested that further studies should be performed to develop a system that would allow the pavement bond based on the results of both shear and tension tests to be optimized.

No conclusive studies were identified to optimise tack coat application at interfaces based on a combination of different test methods. Hakimzadeh, Buttlar and SantarromanaHakimzadeh . (2012) suggested that, for the rehabilitation of uncracked or unjointed underlying pavements in warmer climates, shear properties should have a higher weighing factor whilst, for cracked pavements in colder climates, tensile bond properties should have a higher weighing factor.

Table 3.1: Advantages and disadvantages of bond strength tests

Bond test method	Advantages	Disadvantages
Direct shear tests	▪ Quick and simple (Asphalt Institute 2014; Rahman et al. 2017; Sutanto 2010). ▪ Repeatable (Asphalt Institute 2014; Sutanto 2010). ▪ Can be conducted using common laboratory equipment with an attachment (Asphalt Institute 2014; Road Science 2011). ▪ Measured effects of interface sliding (Road Science 2011). ▪ Most widely promoted (Asphalt Institute 2014; Chang et al. 2014; Rahman et al. 2017). ▪ Cleanly ranks materials (Asphalt Institute 2014).	▪ Can only be performed in the laboratory. ▪ Does not separate friction from bond (Road Science 2011). ▪ Shear stress distribution on the interface is not uniform (Choi et al. 2005; Rahman et al. 2017) ▪ Results depend on the gap between shearing plates and the influence of gap width depends on asphalt type (Canestrari et al. 2012). ▪ Complexity associated with the application of a normal stress (where required) and shear load is not suitable for routine testing (Choi et al. 2005; Sutanto 2010). ▪ Possible load eccentricity causes additional momentum. ▪ Usually results in recommended low tack coat application rates, contrary to field experience (Road Science 2011).
Three-point shear test – LBC shear test	▪ Reduced bending moment at the interface ('pure shear' configuration).	▪ Results are variable, which makes it more difficult to distinguish between good and poor performance. ▪ Not able to test a short core specimen.
Torque (torsional) tests	▪ Portable, can be performed in situ or in the laboratory (Asphalt Institute 2014; Chang et al. 2014; Sutanto 2010). ▪ Quick (Asphalt Institute 2014; Sutanto 2010).	▪ Poor repeatability (Asphalt Institute 2014; Sutanto 2010). ▪ Varying temperature when testing is conducted in the field. ▪ Limited to the uppermost interface of the pavement (Choi et al. 2005; Rahman et al. 2017). ▪ Fracture occurs at the weakest plane, which is not necessarily the interface (Sutanto 2010). ▪ The adhesive between the metal plate and the upper surface of the core needs to be sufficiently strong not to allow failure to occur at this interface. ▪ Non-uniform stress distribution (from zero at the centre to the maximum at the outside) causes the failure to initiate at the outside and propagate towards the centre of the core (Rahman et al. 2017). ▪ Inaccurate torque rate with manual operation (Rahman et al. 2017). ▪ Occurrence of axial bending (Rahman et al. 2017). ▪ High manual force required in the manual test (Rahman et al. 2017). ▪ A small compression load needs to be applied to minimise the risk of lifting due to difficulties in applying the torque force parallel to the interface.

Bond test method	Advantages	Disadvantages
Direct tensile tests	▪ Portable, can be performed in situ or in the laboratory (Asphalt Institute 2014; Sutanto 2010). ▪ Quick (Asphalt Institute 2014). ▪ Repeatable (Asphalt Institute 2014). ▪ Cleanly ranks materials (Asphalt Institute 2014). ▪ Commonly used in other industries (Road Science 2011). ▪ Reduces friction between surfaces effect (Road Science 2011).	▪ Results are often too scattered (Chang et al. 2014; Sutanto 2010; Tschegg et al. 1995). ▪ Eccentricity of the load (Chang et al. 2014; Rahman et al. 2017; Road Science 2011; Tschegg et al. 1995). ▪ Varying temperature when testing conducted in the field (Tschegg et al. 1995). ▪ Fracture occurs at the weakest plane, which is not necessarily the interface (Road Science 2011, Tschegg et al. 1995). ▪ Preparation process is time consuming (specially the application of epoxy between the plate and the specimen) (Chang et al. 2014). ▪ Does not allow the application of a confinement pressure and investigation on the friction properties provided by the aggregate interlocking at the interface (Chang et al. 2014; Tschegg et al. 1995). ▪ Mechanical properties of heterogeneous materials (brittleness and ductile fracture) are not considered. ▪ Tensile separation mode rarely found in the field (Sutanto 2010).
Indirect tensile test (crack resistance bond test) and other crack resistance bond tests	▪ Allows characterisation of the fracture-mechanical behaviour of the material (Rahman et al. 2017; Tschegg et al. 1995). ▪ Depending on the test method, allows a combination of tensile and shear forces to act simultaneously.	▪ Complexity associated with the preparation of the specimens not suitable for routine testing (Rahman et al. 2017; Sutanto 2010). ▪ Results are often too scattered (Sutanto 2010).

The factors that can affect test results and that need consideration when defining a testing procedure include:

- temperature: bond strength generally decreases with increasing temperatures (Abuaddous et al. 2016; Canestrari et al. 2012 & 2018; Dony et al. 2016)
- loading rate: peak strength and fracture energy increases with increasing loading rate (Abuaddous et al. 2016; Canestrari et al. 2012 & 2018; Hakimzadeh 2015)
- normal stress applied: affects bond stress differently at varying temperatures; bonding strength increases with increasing vertical loading as friction parameters increase (Canestrari et al. 2012; Mousa et al. 2017)
- specimen size: peak strength decreases with specimen size (Abuaddous et al. 2016; Canestrari et al. 2012; Gaspa et al. 2016)
- test configuration (including gap between shearing plates, location of load with regards to the interface, presence of bending moments, bond between specimen and plate, etc).

From a study involving the testing of five different configurations of shear tests at seven laboratories, Canestrari et al. (2018) concluded that, if the vertical stress is considered, interface shear strength values obtained at different test speeds and temperatures can be superimposed, allowing for comparison between results using different shear devices.

4 EXISTING NON-DESTRUCTIVE ASPHALT BOND TEST METHODS

4.1 Introduction

Many non-destructive (ND) test methods for the detection of delamination between asphalt layers have been explored. ND methods are suitable for locating debonding in a large area, where extensive coring and testing is not practical. However, there are limitations relating to the capacity of each method to locate delamination and quantify its severity. This section presents a brief review of some of the ND test methods encountered in the literature.

4.2 Electromagnetic

4.2.1 Ground Penetrating Radar (GPR)

GPR is a geophysical non-destructive technique that transmits electromagnetic waves to the ground and receives reflected waves from the pavement layers.

According to Celaya et al. (2010), GPR wavelength is too long to resolve the 1 to 2 mm wide delamination cracks. Although some studies show some progress in using GPR to detect delamination, further investigation is required. Testing carried out by Celaya et al. (2010) on a 3 m by 40 m pavement section showed that GPR could detect only about 33% of the debonded areas.

Some studies found that GPR could only detect bond failures when the interlayer had reached the stage of a thin, and moist, cohesionless layer (Lepert et al. 1992 cited in pp. 2-60 of Sutanto 2010; Heitzman et al.2013).

Simonin and Villain (2016) reported some progress in the monitoring of artificial debonding within an accelerated pavement test facility (IFSTTAR's pavement carrousel) using GPR.

4.3 Impulse Methods

Impulse methods measure the deflection generated by a vertical load applied to the pavement. Higher deflections are expected if poor bond exists, as the layers will act independently (Celaya et al. 2010, Heitzman et al.2013).

Among the impulse methods are the Falling Weight Deflectometer (FWD), Heavy Weight Deflectometer (HWD) and the impulse response method (Impulse Hammer).

4.3.1 Falling Weight Deflectometer (FWD) and Heavy Weight Deflectometer (HWD)

The FWD and HWD impart a load pulse to the pavement and the vertical deflection at different offsets from the load is measured. The HWD uses heavier loads (30–320 kN), and is usually used for airfield pavements, whereas the FWD (4–120 kN) is used for road pavements.

Hakim (2002) developed a back-calculation method to predict both the pavement layer stiffnesses and bonding condition between layers from FWD data. The method comprises two stages:

1. Deflection database is developed using a combination of layer moduli assuming constant bond modulus between bituminous layers (1000 MN/m^3). The location of the interfaces should be known based on construction records or coring. A multiple regression analysis is carried out to calculate layer moduli that give the best correlation with the FWD-measured deflections.

2. Another deflection database is developed with the bituminous layer moduli slightly changed from the values in step 1 and the bond stiffness between the bituminous layers varying from complete de-bonding to full adhesion (10–105 MN/m^3). Deflection bowls with the lowest errors compared with the measured values are selected as representative of the pavement.

Amir, Michael and Jean-Michel (2016) carried out a study using HWD measurements from an experimental pavement facility where a local sliding interface was artificially created between the asphalt surface and the base layers. First, back-calculation analysis was conducted for a sound pavement (with no debonding). The back-calculated moduli were used in a forward calculation to obtain deflections for a debonded pavement. The calculated deflections were consistent with the in situ results. The local sliding interface results were found to affect the central deflections more than the outer deflections. The authors, however, recognized that visual inspection or complementary tests were required, since higher deflections can also be a result of other factors such as material distress.

A study by Gomba (2004) on FWD data collected from the National Airport Pavement Test Facility in Atlantic City, New Jersey, concluded that the back-calculated modulus of the layer above the interface can be used to identify interface delamination, as this value will be lower when debonding occurs. The author defined a parameter called ‘tack coat failure ratio’ (TFR) as the ratio between the back-calculated moduli of the asphalt layer above and below the interface. This factor was found to correlate with the ‘effective slip’, defined as the ratio of the difference in radial stress (between points just above and below the interface) to the maximum difference in radial stress at the interface at full slip.

Testing carried out by Celaya et al. (2010) on a 3 m by 40 m pavement section showed that the FWD back-calculation method could detect about 46% of the debonded areas.

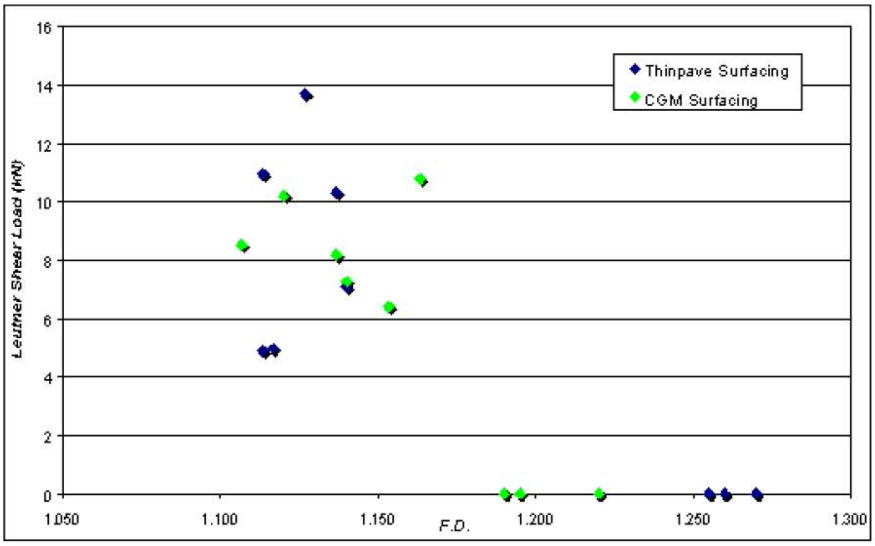
According to the Heitzman et al.(2013) in the USA, the use of FWD impulse duration and geophone spacing is not appropriate for thin top layers, and the variability of layer thicknesses and moduli can mask the detection of delamination.

4.3.2 Impulse Hammer Test

The impulse hammer (impulse-response method) applies a load to the pavement surface and measures the vertical dynamic response 90–100 mm from the load using an accelerometer. Debonded systems have higher frequency vibrations and take longer to reach zero compared to bonded systems (Celaya et al. 2010; Mohammad et al. 2012; Sangiorgi, Collop and Thom 2003; Sutanto 2010).

Sangiorgi et al. (2003) developed an interpretation approach of the data using fractal theory to obtain a quantitative indicator of bond conditions. Following the proposed methodology, a unique characteristic parameter called fractal dimension (FD) between 1 and 2 is calculated from the Impulse Hammer test data. The FDs varied from approximately 1.1 for well-bonded areas to about 1.3 for debonded areas. Reasonable correlation was found between the Impulse Hammer results and the Leutner test results, although the scatter was quite high, as shown in Figure 4.1.

Figure 4.1: Correlation between Impulse Hammer test fractal dimension results and Leutner test results



Source: Sangiorgi et al. (2003).

However, Celaya et al. (2010) noted that the results needed to be considered relative to the response of areas known to be well bonded. The authors also noted that the cases encountered in the literature were based on controlled condition studies, and more research was needed to verify the applicability of the method in the field. Testing carried out by Celaya et al. (2010) on a 3 m by 40 m pavement section showed that the impulse-response method could detect about 59% of the debonded areas. Most of the defects detected corresponded to fully debonded areas (both shallow and deep).

4.4 Vibration Methods

Vibration methods rely on vibrating the pavement using controlled frequencies and measuring its displacement or reflections (echoes). Celaya et al. (2010) cited the stiffness gauge and the high-frequency sweep among vibration methods with the potential to detect delamination between asphalt layers. None of these methods have been proved to be effective in detecting delamination between asphalt layers (Celaya et al. 2010).

4.5 Sonic/ultrasonic Seismic Methods

Seismic sonic/ultrasonic methods generate elastic waves in the pavement layers and detect its reflections. Among the seismic methods available are the Impact-Echo (IE), Spectral Analysis of Surface Waves (SASW) and Ultrasonic Surface Waves (USW), all of which have been successfully used in the assessment of bonding conditions between asphalt layers (Celaya et al. 2010).

4.5.1 Impact-Echo (IE)

The impact-echo (IE) method involves the application of a high-frequency mechanical (sound) wave into the pavement and the measurement of reflections (echo) from the interfaces of materials having different elastic properties. If debonding is present, reverberation is disrupted and lower frequency modes of vibration occur (Celaya et al. 2010, Heitzman et al. 2013).

According to Heitzman et al. (2013), IE is only effective in identifying discontinuities deeper than 100 mm when the pavement is cold and it has limited ability to provide a degree of severity. Nazarian et al. (1997 cited in pp. 26 of Celaya et al. 2010) also mention that the method is not applicable to very thin layers or when the difference in moduli of adjacent materials is small.

4.5.2 Spectral Analysis of Surface Waves (SASW)

The Spectral Analysis of Surface Waves (SASW) method involves applying short, high-frequency waves into the pavement which are received by two receivers spaced at different distances from the wave source. The information collected is used to develop a curve comparing wavelength with frequency (dispersion curve) for the surface wave. The wavelength is related to the depth of penetration, and therefore related to the surface wave velocity. If debonding is present, a sharp drop in velocity at a particular depth can be observed (Heitzman et al. 2013).

SASW was found to successfully identify discontinuities within the upper 130–180 mm of the pavement. However, it requires a reasonable knowledge of the material modulus at the test temperature and complicated analysis. It is also limited in providing a degree of severity (Heitzman et al. 2013).

4.5.3 Ultrasonic Surface Waves (USW)

The Ultrasonic Surface Waves (USW) method is a variation of SASW using very high frequencies (Celaya et al. 2010). USW can detect delamination and identify the approximate depth of the debonded layers. However, it cannot detect partially-debonded defects and defects at depths greater than 100 mm (Celaya et al. 2010; Heitzman et al. 2013).

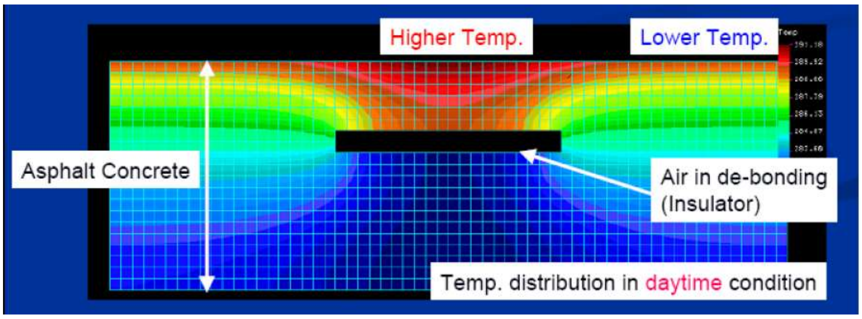
Testing carried out by Celaya et al. (2010) on a 3 m by 40 m pavement section showed that the USW method could detect about 53% of the debonded areas, with most defects detected being shallow (both partial and full debonding).

4.6 Thermal Methods

4.6.1 Infrared Thermography

Infrared thermography (IR) is a technique that detects infrared radiations emitted from objects at different temperatures to develop a temperature distribution map. Near-surface flaws or voids can be picked up as a hot or cold spot. If air is trapped in a delaminated pavement, it can act as an insulator, blocking heat transfer between asphalt layers and allowing IR to detect the presence of delamination, as illustrated in Figure 4.2 (Celaya et al. 2010).

Figure 4.2: Example image of thermal analysis



Source: Tsubokawa et al. (2007 cited in Celaya et al. 2010).

According to Celaya et al. (2010), although detection of debonding with IR is possible, the method cannot provide exact dimensions or the depth of localised defects. The degree of effectiveness of the method is also reliable on favourable environmental and surface conditions; for example, a coarsely-segregated area may be interpreted as a delaminated zone.

Heitzman et al. (2013) tested two IR thermography devices and concluded that the change in thermal response obtained was not significant enough to identify delamination.

4.7 Summary

A summary of ND methods, its advantages and concerns, is presented in Table 4.1. More details are included in Appendix D.

The literature shows that ND can be successfully used in the detection of debonded areas. However, as cautioned by Celaya et al. (2010) and the Heitzman et al. (2013) in the US, no ND method can detect all debonding in the pavement and/or distinguish between types of pavement discontinuities. Some methods are better at detecting shallow defects and are not suitable for deeper defects, whereas some can only detect fully-debonded defects and are not sensitive to less prominent debonding. Often, coring and destructive testing are still required to confirm the nature of the discontinuity or other pavement properties, such as layer thicknesses and stiffnesses.

Although some studies have made progress in using ND methods to quantitatively assess debonding between asphalt layers, the accuracy and reliability of these methods seem to be much lower than that of destructive testing. The results obtained using ND methods are dependent on many factors, such as how the pavement is modelled, the presence of other defects in the pavement, pavement materials, surface and environmental conditions.

Celaya et al. (2010) assessed the ability of GPR, FWD, thermography, sonic-seismic methods and impulse response to detect debonding in two airfield pavements and concluded that the FWD, Impulse Response method (with a site-specific temperature adjustment) and ultrasonic surface wave method were the most promising methods for the detection of debonded sections.

Table 4.1: List of feasible technologies for detecting delamination of HMA layers

Method	Device	Advantages	Concerns
Electromagnetic	GPR	Rapid test, provides full areal coverage.	Cannot directly detect delamination even at 1 or 2 GHz.
.Impulse	FWD	Available and well understood, rapid test.	Impulse duration too long to focus on top thin layers, variability in thickness and modulus of sublayers may mask the detection of delamination. Point load.
	Impulse response	Have been successful to detect different levels of debonding in HMA, rapid test, needed components are readily available.	Even though automated analysis available, automated equipment is not available.
Vibration	Stiffness gauge	Input is controlled, equipment available.	Coupling to asphalt problematic, load is too light, frequency range is too low.
	High-frequency sweep	Reasonably priced equipment is available for other applications.	Automation may be required, has not been used on asphalt.
	Impact-echo	Proven technology for detection of delamination in concrete, automated equipment is available. Full coverage: rolling.	Limited use for detecting asphalt delamination, coupling of energy to coarser mixes, walking speed.
Seismic/sonic	SASW	Automated equipment is available, feasibility has been shown in asphalt.	Coupling of energy to coarser mixes, only used to detect delamination in top layers (upper 130–180 mm).
	Ultrasound	Proven technology for detection of delamination in concrete, automated equipment is available.	Has not been used on asphalt, frequency content may be too high to interact with coarse aggregates.
Thermal	Thermography	Rapid test, provides full areal coverage, automated equipment and interpretation.	Highly dependent on environmental conditions such as wind speed, ambient temperature, and sunlight, can only be used to detect shallow delamination.

Source: Based on Celaya et al. (2010) and Heitzman et al. (2013).

5 STANDARD TEST METHODS

A limited number of standard bond strength test methods were identified in the literature. Most of the test methods involve direct shear testing.

Standard direct shear test methods were found in Europe (draft European Standard, Germany, Switzerland and Italy) and in some US states. Leutner-based devices with a shear load rate of approximately 50 mm/min are the most commonly adopted, with varying gap between shearing plates, specimen sizes (100 or 150 mm) and test temperature (usually around 20 °C to 25 °C).

The in-service torque test is required in the UK as part of the approval system for thin surfacing systems. Two draft test methods were found, a British standard (Appendix A.3 of the British Board of Agrément Guidelines Document for the Assessment and Certification of Thin Surfacing Systems for Highways), and a draft European Standard (prEN 12697-48, British Standards Institute 2013).

Other test methods encountered in standard test methods include:

- the pull-off (tensile) test (Austrian Standard)
- the 3-point shear test using the LCB device (Spanish Standard)
- the tensile, compressed shear and cyclic compressed shear tests (draft European Standard).

A detailed list of standard test methods is included in Appendix E.

6 LIMITS ON ASPHALT INTERFACE BOND STRENGTH

Asphalt interface bond strength limits identified in the literature were quite variable. Minimum shear strength limits from 0.21 to 1.41 MPa and tensile strength limits from 0.21 to 1.5 MPa were encountered. Some researchers and regulators recommend different minimum values for interfaces between different asphalt layers. Higher values generally correspond to shallower interfaces, as shear stresses developed closer to the load are generally higher.

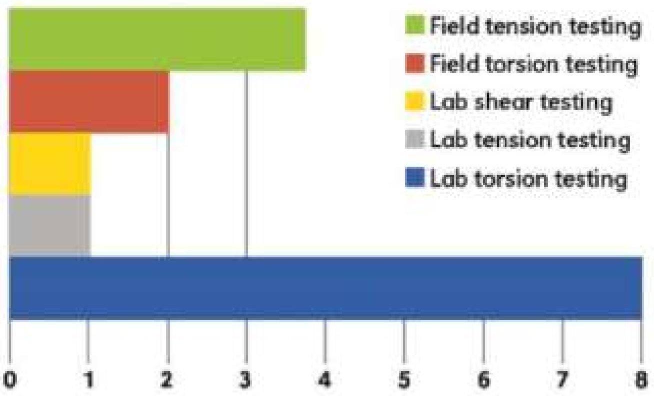
As discussed in Section 1, linear elastic modelling of a typical full depth asphalt pavement cross-section under an 80 kN single axle dual tyre load (Austroads 2018) indicated that the maximum horizontal shear stress at the two top asphalt interfaces (30 mm depth and 70 mm depth) were similar in magnitude (top interface slightly higher). The maximum horizontal shear stress at the interface between the two asphalt intermediate courses (120 mm depth) was about 25% lower. The analysis only considered vertical loads, but it is expected that shear stresses generated by horizontal loads, such as breaking and turning vehicles, would also decrease with depth at some degree.

A detailed list of recommended and specified limits on minimum bond strength requirements are included in Appendix F.

The actual level of strength at which debonding starts to become an issue is not clear. None of the specified or recommended limits are supported by compelling evidence (Muench & Moomaw 2008). West et al. (2005) indicated that a bond strength of less than about 0.34 MPa can be considered poor while bond strengths above 0.64 MPa could be considered good. On the other hand, finite element analysis conducted by Mohammad, Elseifi and King (2015) indicated that a laboratory result of 0.27 MPa represented acceptable performance of the pavement in the field considering a safety factor of 1.4 against variability in measurements and construction.

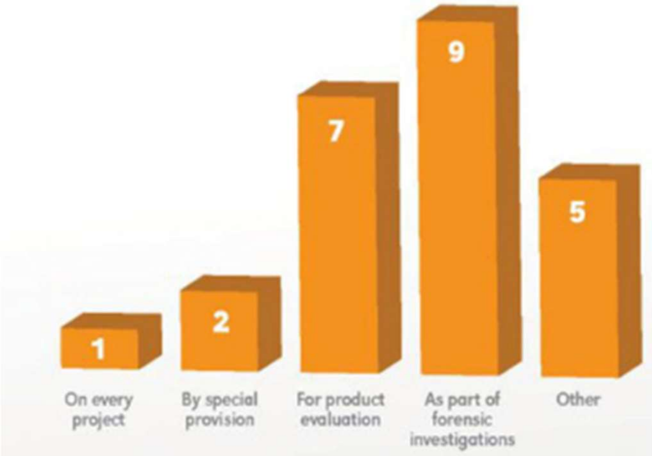
Johnson (2015) collected information on the number of US states using a bond strength testing method, including when these test methods are used, whether normal load is used and what limit values are specified. The information is illustrated, respectively, in Figure 6.1, Figure 6.2, Figure 6.3 and Figure 6.4. It shows that the most common test conducted in the USA is the laboratory torsion test; it is most commonly carried out as part of a forensic investigation or as part of a product evaluation. Minimum specified tensile strength values vary from 0.21–0.27 MPa (30 to 40 psi). Minimum specified shear strength varies from 0.34–0.69 MPa (50 to 100 psi), with most states adopting the most conservative value (0.69 MPa).

Figure 6.1: Number of US states using bond strength testing method



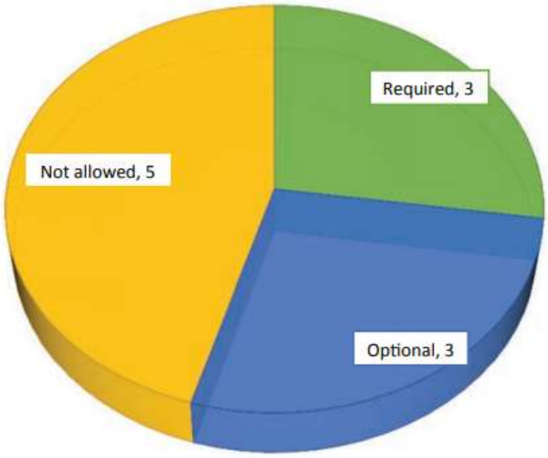
Source: Johnson (2018).

Figure 6.2: When US agencies perform interface bond testing



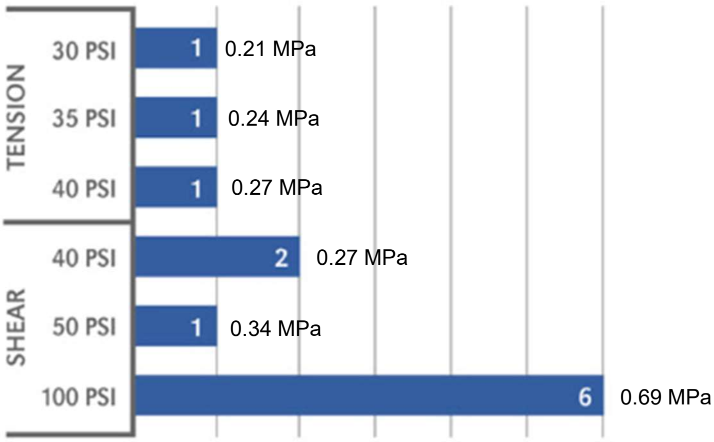
Source: Johnson (2018).

Figure 6.3: Use of a normal load while bond testing in US



Source: Gierhart & Johnson (2018).

Figure 6.4: Number of US states specifying a minimum test value



Source: adapted from Johnson (2018).

The Kansas Department of Transportation (KDOT) implemented a tensile test method (KT-78) in 2011 (KDOT 2011). They have reported that, since the test requirement was implemented, contractors started limiting construction traffic on tacked surfaces and doing a better job of cleaning milled surfaces with multiple brooms, resulting in better pavements. KDOT initially had a penalty associated with tensile strengths less than 0.24 MPa, which was waived after a couple of seasons of usage, reportedly because they were not able to correlate it to field performance (Gierhart & Johnson 2018).

The Texas Department of Transportation (TxDOT) has been testing interlayer bond strength since 2004. However, no target value is specified. TxDOT collects shear test results for informational purposes and uses bond testing to evaluate new products and procedures. They have noted that a high bond strength does not always correspond to best performance in the field, citing an example where cracking propagated through an overlay more severely where higher bond strength values were found (Gierhart & Johnson 2018).

The West Virginia Department of Transport (WVDOT) started using a shear bond test in 2013. They specify a minimum shear strength of 0.69 MPa (100 psi) but do not have any penalties relating to non-conformance. Even without having penalties, however, the requirement was found to improve practice, with the percentage of test results higher than 0.69 MPa increasing over time (Gierhart & Johnson 2018).

7 CONCLUSIONS AND RECOMMENDATIONS

Destructive and non-destructive methods to detect and quantify debonding between asphalt layers have been identified and reviewed in this report. Destructive methods include coring and testing of pavement sections using shear, torque or tensile forces. Testing can be done in situ or in the laboratory. In situ testing is portable and minimises the effect of coring in the bond strength results; however, the test conditions are not controlled and can result in poor repeatability. Laboratory testing can be performed in a temperature-controlled environment, minimising scatter in the results associated with testing at different temperatures.

Among the many test procedures described in this report, laboratory direct shear and direct tensile tests with controlled conditions appear to be the most appropriate for a routine construction quality control test and for ranking of tack coat products and application rates. Preferably, both shear and tensile tests should be investigated, as suggested by Hakimzadeh, Buttlar and Santarromana (2012). However, if a single test is to be used, then a shear test is preferred as it not only assesses the adhesiveness between the layers but also allows friction to be considered.

Based on discussions with MRWA, it is understood that the main concern is with the deeper interfaces between asphalt layers, as shallower interfaces can more easily and frequently undergo maintenance works. Shear stresses decrease with depth. The literature indicates that, for interfaces located deeper in the pavement (150–400 mm from the pavement surface), a gradual loss of bond occurs with repeated lower shear stresses (Waisome 2017). Therefore, it is recommended that MRWA considers cyclic loading tests as well as (monotonic) peak stress tests. Although its complexity may not be appropriate for routine testing, it may be desirable to investigate the potential relationship between monotonic and cyclic failure.

It should also be noted that the studies reviewed in this report were conducted on interfaces between two asphalt mixes with a tack coat in between, whereas in Western Australia, some shallower interfaces include a seal in addition to the tack coat. Ideal testing conditions (i.e. gap between shear plates) for different interface configurations would have to be investigated.

A range of minimum bond strength requirements have been proposed, but limited data support these values. Additionally, a large variety of destructive test procedures have been used under varying conditions, which hinders any comparison between the limits proposed by different authors. Minimum bond strength and fatigue performance requirements should be validated by testing local pavements. In general, minimum bond strength requirements decrease as the interface is further from the surface, as the shear stress decreases with increasing depth. At higher depths, some authors recommend fatigue tests rather than bond strength tests, as a gradual loss of bond is more likely to occur with repetitive lower stresses.

Non-destructive methods have been used in many studies and they proved effective in detecting debonding between asphalt layers. However, the literature indicates that no non-destructive method can fully detect debonding, with some methods limited in the depth of the interface they can detect and some limited to the detection of fully debonded layers only. Some methodologies allow quantitative assessment of debonding, but the accuracy of those methods compared to destructive methods is questionable. Non-destructive test results are dependent on many factors, such as how the pavement is modelled, the presence of other defects in the pavement, environmental and pavement conditions.

Based on the literature review conducted, it is recommended that destructive methods are considered for quality control and ranking of tack coat and tack coat application purposes, while non-destructive methods are considered for evaluating long lengths of pavement where the presence and location of delamination need to be determined, as well as an indication of its severity.

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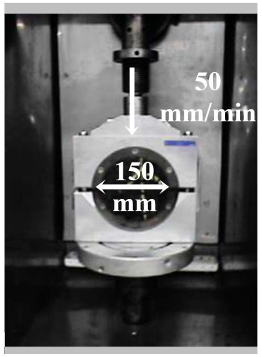
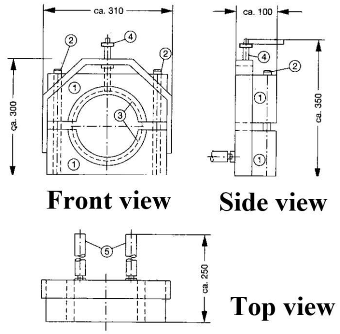
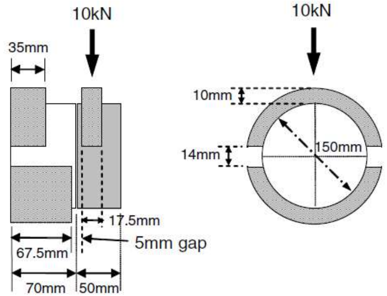
APPENDIX A SHEAR BOND TESTS

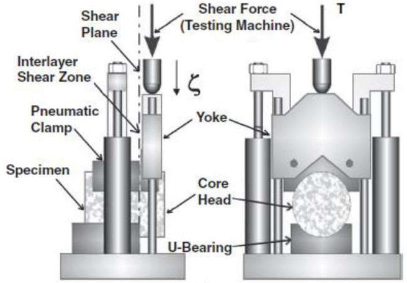
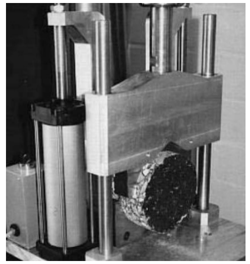
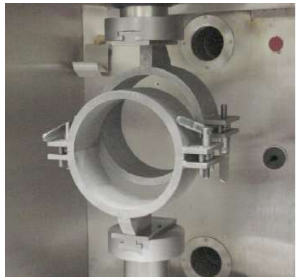
A.1 Direct Shear Tests without Normal Load

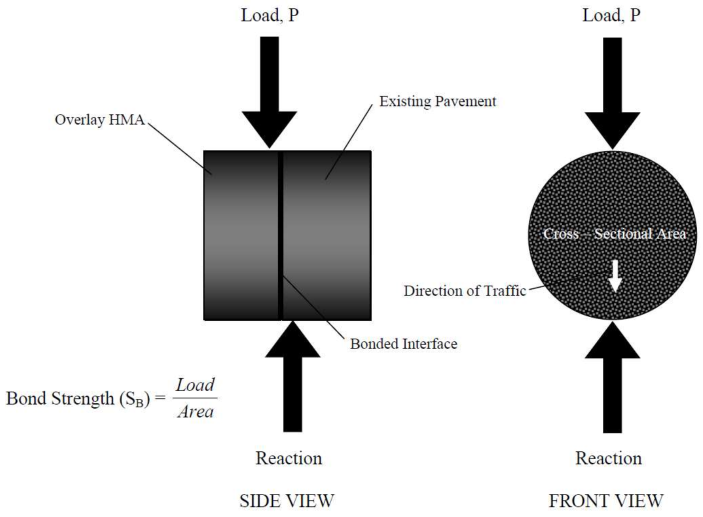
Table A 1: Direct shear tests without normal load

Test device	Description	Specimen size	Gap width	Displacement rate	Related standard test method	Sources
Leutner shear tester	▪ Developed in Germany. ▪ Test can be performed in standard Marshall or CBR loading devices. ▪ Cylindrical sample placed in a shear cast. ▪ A vertical load is applied to the top layer while the bottom layer stays stationary. ▪ Test at 20±1 °C. ▪ Clamping manually tightened. ▪ German standard: – minimum thicknesses of the lower layer: 70 mm – minimum thickness of the upper layer: 25 mm.	150 ± 2 mm diameter	No gap	50 ± 3 mm/min	German Standard ALP A-Stb Teil 4	Ahn (2014), Canestrari et al. (2012), Chang et al. (2014), Mohhamad (2012), Raposeiras et al. (2013), Sutanto (2010), White (2015)
		  Source: Sangiorgi et al. (2002).				

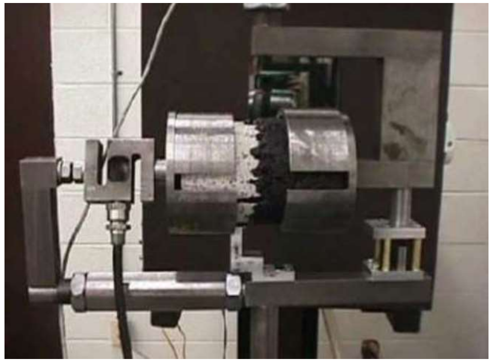
<table>
<tr><th>Test device</th><th>Description</th><th>Specimen size</th><th>Gap width</th><th>Displacement rate</th><th>Related standard test method</th><th>Sources</th></tr>
<tr><td rowspan="2">Modified Leutner by Choi et al. (2005)</td><td rowspan="2">Leutner based device.
Introduced a 5 mm gap into the shear place to prevent crushing of large aggregate particles as well as to improve the repeatability of results.
Recommends minimum upper layer thickness of 30 mm and lower layer thickness of 60 mm (to avoid bulging at the top half of the specimen).
Test at 20±0.5 °C.
Clamping manually tightened.</td><td>150 ± 2 mm diameter</td><td>5 mm</td><td>50 ± 2 mm/min</td><td></td><td>Choi et al. (2005), Sutanto (2010)</td></tr>
<tr><td colspan="5">

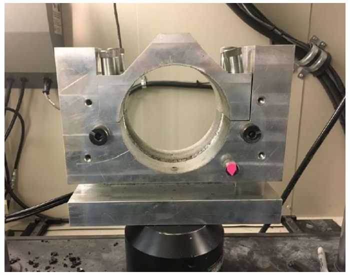
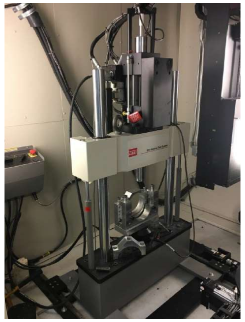
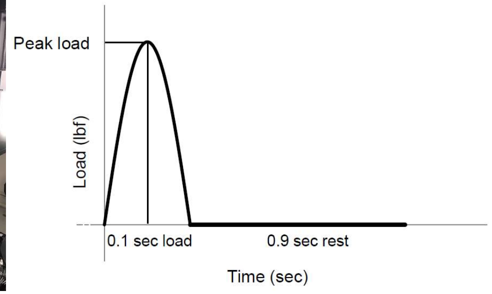
Source: Choi et al. (2005).</td></tr>
<tr><td>Modified Leutner by Sutanto (2010)</td><td>Leutner based device.
Further modification of the Leutner test (following Choi et al. 2005 modification) to allow for testing of thin surfacing course systems with a layer thickness less than 30 mm.
A 30 mm thick 150 mm diameter steel grooved plate is attached to the surface of a core specimen.</td><td>150 ± 2 mm diameter</td><td>5 mm</td><td>50 ± 2 mm/min</td><td></td><td>Sutanto (2010)</td></tr>
</table>

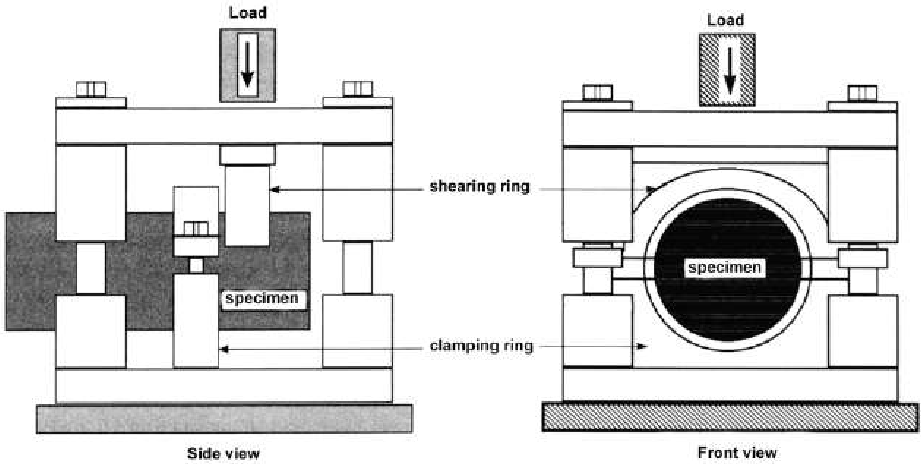
Test device	Description	Specimen size	Gap width	Displacement rate	Related standard test method	Sources
Layer Parallel Direct Shear Tester (LPDS) **Raab and Partl (2004)**	▪ Leutner-based device with more accurate clamping mechanism. ▪ Developed by EMPA, Swiss Federal Laboratories for Materials Science and Technology. ▪ Device can be fitted to a Marshall testing machine or any standard universal testing machine. ▪ Clamping hydraulic tightened (one part of the core is laid on a circular u-bearing and held with a well-defined pressure by a semicircular clamp). ▪ Swiss standard: – minimum thickness of the upper layer: 25 mm – maximum deviation of specimen surface: 2 mm. ▪ Controlled temperature.	150 ± 2 mm diameter	2.5 mm	50.8 ± 3 mm/min	Swiss Standard SN 671961	Ahn (2014), Canestrari et al. (2012), Canestrari et al. (2018), Chang et al. (2014), Hooda and Monika (2017), Mohammad et al. (2012), Raposeiras et al. (2013), Sutanto (2010), Waisome (2017), Wes et al. (2005), White (2015)
		   Source: Canestrari et al. (2005), Raab and Partl (2004 cited in Ahn 2014), West et al. (2005).				
FDOT shear tester	▪ Leutner-based device. ▪ Device can be fitted to a universal testing machine or a Marshall press or CBR loading device. ▪ Modified version of the Iowa Department of Transportation shearing device for Portland cement concrete. ▪ Developed in 2003 following the request of the FDOT engineers to investigate the performance of bond strength for paving works done on wetted tack coat due to the rainwater. ▪ Test at 25 °C.	150 ± 2 mm diameter	4.8 mm	50.8 mm/min	FDOT FM 5-599	Ahn (2014), Canestrari et al. (2012) Chang et al. (2014), Sholar et al. (2003), Sutanto (2010), Waisome (2017), West et al. (2005)
		 Source: Sholar et al. (2003).				
Alabama Department of Transportation	▪ metal cylindrical specimen holder and a sliding metal loading head with a concave surface	150 mm diameter Thickness of each layer 50 to 150 mm.	6.3 ± 0.8 mm	50.8 mm/min	ALDOT-430 (9/23/2008)	

<table>
<tr><th>Test device</th><th>Description</th><th>Specimen size</th><th>Gap width</th><th>Displacement rate</th><th>Related standard test method</th><th>Sources</th></tr>
<tr><td>(ALDOT) Standard Test Method</td><td>Attached to a Marshall Stability test apparatus or other mechanical or hydraulic testing machine.
A minimum of 3 random locations need to be selected.
The pavement should be allowed to cool before coring.
Cores shall be taken full depth so that no prying action is needed to extract the cores from the pavement.</td><td colspan="5">


Source: ALDOT (2008).</td></tr>
<tr><td>SuperPave Shear Test (SST)</td><td>Based on the Uzan et al. (1978) device but with some modifications for testing cylindrical samples.
Records shear loads and corresponding shear displacement to obtain shear stress-displacement curve as well as shear strength of the interface.
Load controlled rather than strain controlled.</td><td>150 mm diameter</td><td></td><td>222.5 N/min (load controlled)</td><td></td><td>Sutanto (2010), White (2015)</td></tr>
</table>

Test device	Description	Specimen size	Gap width	Displacement rate	Related standard test method	Sources
Virginia shear fatigue test	▪ Developed by Virginia Polytechnic Institute & State University and the Virginia Tech Transportation Institute. ▪ Cyclic shear load applied. ▪ test at 25 °C or ambient temperature. ▪ Determines the number of shear loading cycles at failure, maximum shear stress against the number of cycles of failure and optimal tack coat application rate. ▪ Upper asphalt layer is gyratory compacted on the top of the core after application of the geocomposite and tack coat.	94 mm diameter		0.381 mm deflection, 0.10-s half-sine wave followed by a relaxation period of 0.9 s (the total cycle is 1 s)		Ahn (2014), Mohammad et al. (2012)
		 Source: Donoval et al. (2000 cited in Ahn 2014).				

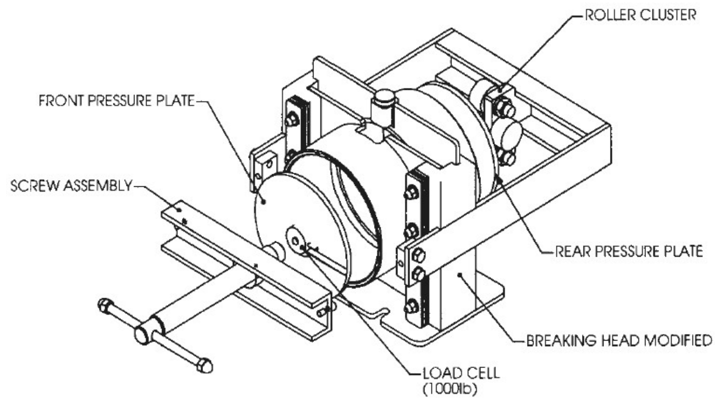
Test device	Description	Specimen size	Gap width	Displacement rate	Related standard test method	Sources
Florida Interface Shear Tester (FIST) **Waisome (2017)**	▪ Leutner-based device. ▪ Modification of existing interface shear strength test device developed by the Louisiana State University (LISST). ▪ Installed on an MTS servo-hydraulic load frame. ▪ Addition of a thicker and elongated bottom plate to reduce the eccentricity of the load, increase flexural strength of the device, and provide a better location to attach it to the MTS system. ▪ Loading frame and reaction frame with a removable top collar. ▪ Monotonic and cyclic shear loading modes. ▪ Loading period of 0.1 seconds (0.05 seconds load, and 0.05 seconds unloading), followed by a rest period of 0.9 seconds. ▪ Half-sine load. ▪ 8.2 kN compressive load (0.2 kN seating and 8.0 kN load pulse) to represent 60.0% of the average strength of the specimens. ▪ Test at 25 °C.	   Source: Waisome (2017).	6.3 mm	51 mm/min		Waisome (2017), White (2015)
Mrawira and Damude (1999)	▪ Modified version of the test apparatus from ASTM D-143, which is used to test shear strength of wood samples. ▪ Guillotine style where a uniform lateral load is applied through a pivoting load surface. ▪ Core trimmed from the field with a new asphalt mix compacted over the trimmed surface using a Marshall hammer	101.6 mm diameter	8 mm	1 mm/min		Canestrari et al. (2012), Sholar et al. (2003)

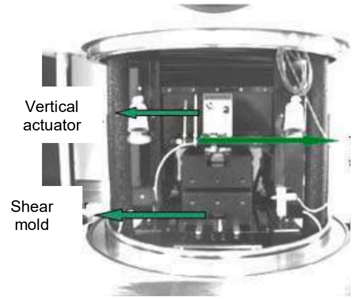
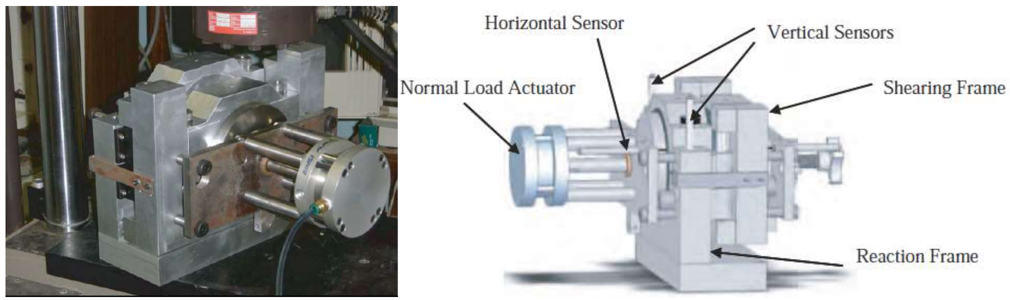
<table>
<tr><th>Test device</th><th>Description</th><th>Specimen size</th><th>Gap width</th><th>Displacement rate</th><th>Related standard test method</th><th>Sources</th></tr>
<tr><td rowspan="2">Austrian shear test</td><td rowspan="2">▪ Leutner-based device.
▪ Developed and used as standard test in Austria.
▪ At least 2 bonded layers.
▪ Test at 25±1 °C.
▪ Clamping manually tightened.</td><td>100 ± 2 mm diameter</td><td></td><td>50 ± 3 mm/min</td><td>Austrian Standard RVS 11.065 Teil 1 [FSV, 1999]</td><td>Sutanto (2010)</td></tr>
<tr><td colspan="5">

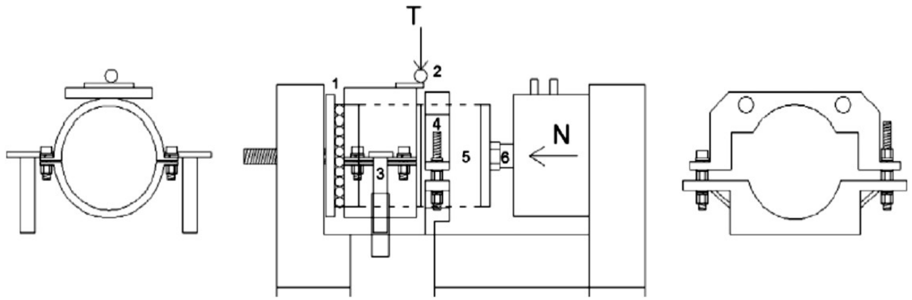
Source: Sutanto (2010).</td></tr>
</table>

A.2 Direct Shear Tests with Normal Load

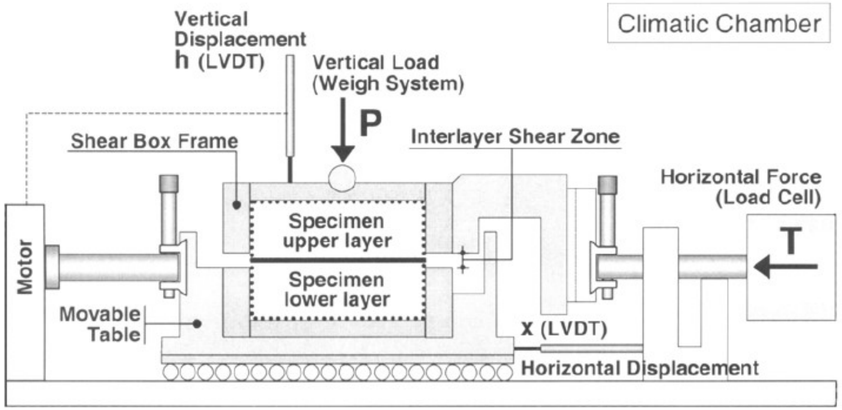
Table A 2: Direct shear tests with normal load

Test device	Description	Specimen size	Gap width	Displacement rate	Related standard test method	Sources
Direct shear test or Interface shear mold Uzan et al. (1978)	▪ prismatic samples with two layers. ▪ bottom layer attached to the test table. ▪ load vertically applied to the top layer combined with a constant horizontal load applied to the upper mould.	Prismatic 15 cm × 10 cm × 5 cm plus tack coat and 6 cm of mix on top.		2.5 mm/min		Buchanan and Woods (2004), Raposeiras et al. (2013), Sholar et al. (2003), Sutanto (2010), West et al. (2005)
National Center for Asphalt Technology (NCAT) bond strength device	▪ Leutner-based device. ▪ developed by the National Center for Asphalt Technology (NCAT). ▪ attached to a universal testing machine, Marshall press or CBR equipment. ▪ 453.6 kg (1000 lb) load cell attached to the body of the device to measure the amount of confinement force needed, which later may be converted into confinement pressure taking into consideration the surface area in contact. ▪ adopted by the Alabama Department of Transportation (ALDOT) since 2008. ▪ ttest at 25 °C. ▪ minimum thickness of the upper layer: 76.2 mm. ▪ thickness of each layer must be between 50 mm and 150 mm.	150 mm diameter	6.35 ± 0.8 mm	50.8 mm/min	ALDOT-430	Chang et al. (2014), Hakimzadeh (2015), Sutanto (2010), Waisome (2017), West et al. (2005), White (2015)
		 Source: West et al. (2005).				
Louisiana Transportation	▪ Developed by LTRC.	150 mm diameter	2.54 mm	222.5 N/min (stress control mode)		Mohammad et al. (2012)

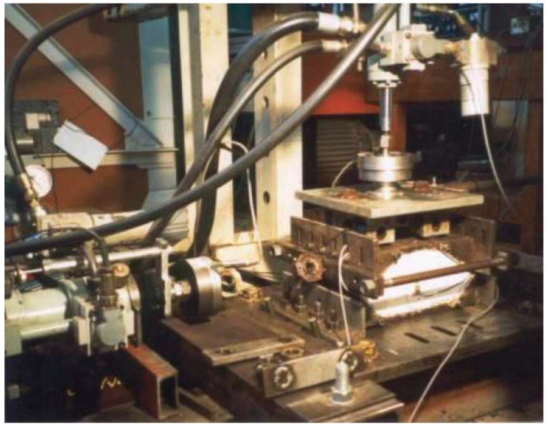
Test device	Description	Specimen size	Gap width	Displacement rate	Related standard test method	Sources
Research Center (LTRC) Direct Shear Test	▪ horizontal shear load applied to a dual-layer specimen. ▪ climate chamber (–20 °C to 80 °C).	 Source: adapted from Mohammad et al. (2012).				
Louisiana Interface Shear Strength Test (LISST) Mohammad et al NCHRP Project 9-40 (2012)	▪ Leutner-based device. ▪ Developed as part of the National Cooperative Highway Research Program (NCHRP) Project 9-40, Optimization of Tack Coat for Hot-Mix Asphalt (HMA). ▪ Shearing and reaction frame attached to a universal testing machine. ▪ Average coefficient of variation (NCHRP study) less than 10%. ▪ Temperature chamber if required. ▪ Normal load actuator attached to the mould. ▪ Normal pressure up to 207 kPa on a 150 mm specimen.	100 or 150 mm diameter	12.7 mm	2.5 mm/min	AASHTO TP 114	AASHTO (2018), Chang et al. (2014), Mohammad et al. (2015), NCHRP (2018b), White (2015)
		 Source: Mohammad et al. (2012).				
	▪ Monotonic and cyclic shear loading modes.	100 mm diameter	10 mm	2.5 mm/min		Canestrari et al. (2018), Tozzo et al. 2014 (from Waisome 2017)

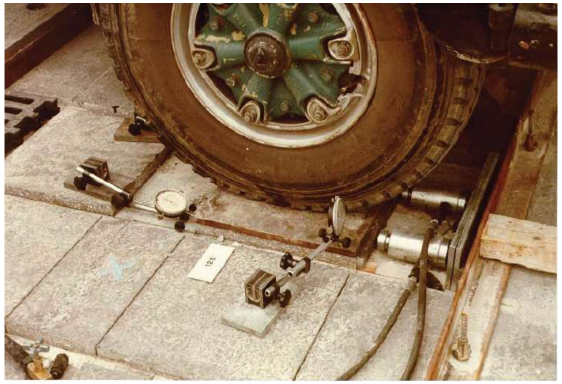
Test device	Description	Specimen size	Gap width	Displacement rate	Related standard test method	Sources
Sapienza Direct Shear Testing Machine (SDSTM)		 Source: Tozzo et al. (2014 cited in Waisome 2017)..				

Test device	Description	Specimen size	Gap width	Displacement rate	Related standard test method	Sources
Ancona Shear Testing Research and Analysis (ASTRA) device	▪ Based on the Uzan et al. (1978) device but with some modifications for testing cylindrical samples. ▪ Developed at the Università Politecnica delle Marche in Italy. ▪ Direct shear box type of device, complying with the Italian Standard UNI/TS 11214 (usually used for soil testing). ▪ Climatic chamber. ▪ If carried out at different normal loads, a Mohr-Coulomb failure envelope can be obtained. ▪ Uses a dead load through a lever and weight system to provide normal pressure.	94 mm to 100 mm diameter OR prismatic with maximum cross-sectional area of 100 × 100 mm^2		From 0.0008 mm/min to 9.5 mm/min, typically 2.5 mm/min	Italian Standard UNI/TS 11214 (2007)	Canestrari et al. (2018) Chang et al. (2014), Mohammad et al. (2012), Raposeiras et al. (2013), Sutanto (2010), Waisome (2017), West et al. (2005), White (2015)



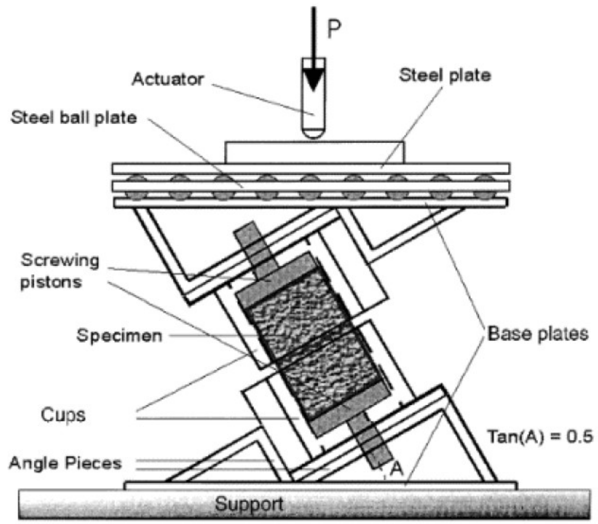
Source: West et al. (2005).

Test device	Description	Specimen size	Gap width	Displacement rate	Related standard test method	Sources
Dynamic Shear Box	▪ Developed at the University of Nottingham, UK. ▪ Double layered slab. ▪ Cyclic shear loading.	320 mm by 200 mm  Source: Carr (2001 cited in Sutanto 2010).				Sutanto (2010)

<table>
<tr><th>Test device</th><th>Description</th><th>Specimen size</th><th>Gap width</th><th>Displacement rate</th><th>Related standard test method</th><th>Sources</th></tr>
<tr><td rowspan="2">EMPA in situ shear test</td><td rowspan="2">▪ Shear load generated by hydraulic or pneumatic actuator.
▪ Vertical loading provided by the rear truck wheel load.
▪ Typically used to assess the interface bond of an asphalt layer laid over concrete.
▪ Horizontal and vertical displacements are monitored and recorded.</td><td></td><td></td><td></td><td></td><td>Sutanto (2010)</td></tr>
<tr><td colspan="5">
Source: Raab and Partl (1999 cited in Sutanto 2010).</td></tr>
</table>

A.3 Inclined Shear Tests

Table A 3: Inclined shear test

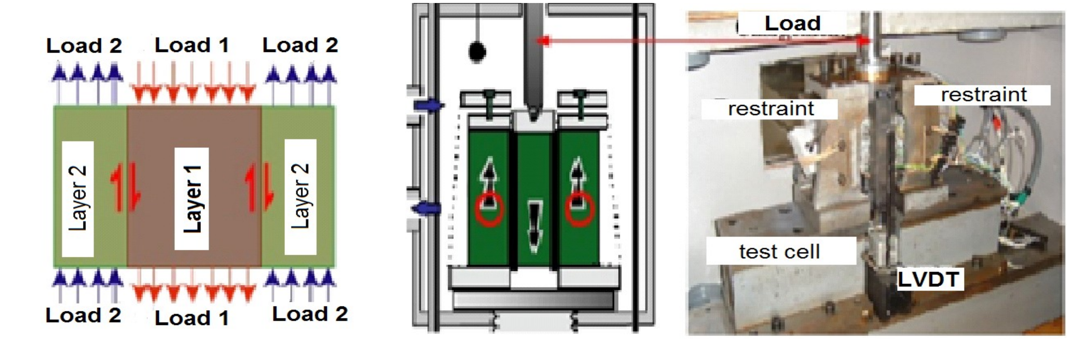
<table>
<tr><th>Test device</th><th>Description</th><th>Specimen size</th><th>Gap width</th><th>Displacement rate</th><th>Related standard test method</th><th>Sources</th></tr>
<tr><td rowspan="2">Romanoschi (1999)</td><td rowspan="2">Shear plane placed at an angle of 25.5° to the horizontal plane to allow both shear and normal stress to be simultaneously applied to the interface (shear stress at the interface is half of the normal stress).
Aapplied load between 138 and 522 kPa.
Shear fatigue (cyclic) test.
Haversine vertical load with a frequency of 5 Hz (from the total period of 0.2 seconds, the length of the haversine pulse was 0.05 sec to simulate the pass of a vehicle at 50 km/h).
Reports the number of load cycles to produce an increase of permanent shear deformation of 1 mm.</td><td>95 mm diameter</td><td></td><td>12 mm/min</td><td></td><td>Hakimzadeh (2015), Raposeiras et al. (2013), Romanoschi (1999) Sutanto (2010), Waisome (2017)</td></tr>
<tr><td colspan="5">

Source: Romanoschi and Metcalf (2001 cited in Waisome 2017).</td></tr>
</table>

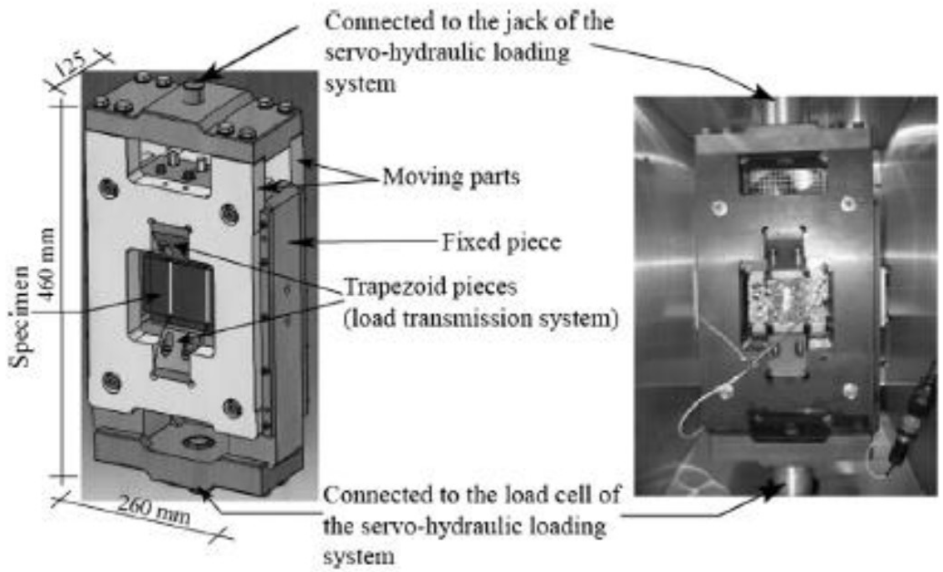
<table>
<tr><th>Test device</th><th>Description</th><th>Specimen size</th><th>Gap width</th><th>Displacement rate</th><th>Related standard test method</th><th>Sources</th></tr>
<tr><td rowspan="2">Sapienza Inclined Shear Test Machine (SISTM)</td><td rowspan="2">60° incline in the longitudinal direction of the specimen (so that the normal and shear stress response measured would relate to 30.0 mm from the edge of a tire wheel load).
Results indicated that further analysis was required to capture the ratio between shear stress and normal stress for more accurate predictions.
Test at 20 °C.
Monotonic and cyclic shear loading modes.</td><td></td><td></td><td>1.27 mm/min</td><td></td><td>Tozzo et al. (2014)</td></tr>
<tr><td colspan="5">
Source: Tozzo et al. (2014 cited in Waisome 2017).</td></tr>
</table>

A.4 Double Shear Tests

Table A 4: Double shear test

Test device	Description	Specimen size	Gap width	Displacement rate	Related standard test method	Sources
Modified Compact Shearing (MCS)	▪ Developed by the Groupe d'Etudes des Matériaux Hétérogènes (GEMH) – Génie Civil et Durabilité (GCD) laboratory at the University of Limoges, France to investigate shear fatigue on tack coats. ▪ 3-layer specimen. ▪ Two outside layers are fixed while the displacement is applied to the centre layer. ▪ Monotonic and cyclic shear loading modes. ▪ Controlled temperature and load. ▪ Test frequency 1 Hz. ▪ Test at 5 °C.	Prismatic 70×30×100 mm^3 total (outside parts are 70×30×30 mm^3 each and middle part is 70 x 30 x 40 mm^3).				Diakhate (2007), Sutanto (2010), Waisome (2017), White (2015)
		 Source: adapted from Diakhate (2007).				

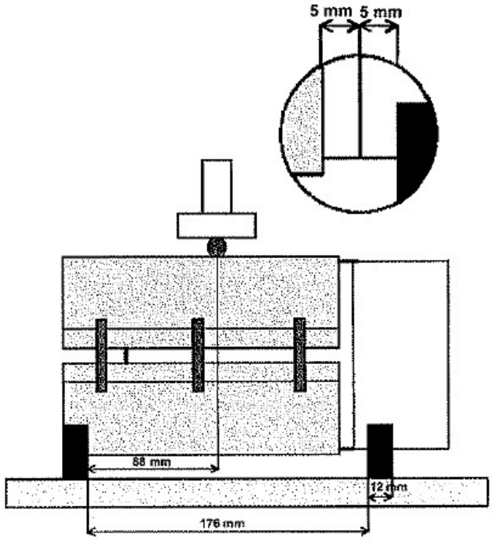
Test device	Description	Specimen size	Gap width	Displacement rate	Related standard test method	Sources
Double Shear Test (DST)	▪ Developed at the University of Limoges. ▪ 3-layer specimen. ▪ Two external layers are held and load is applied in the intermediate layer to produce shear at the joint surface between layers. ▪ Applies a relatively pure shear stress at both interfaces symmetrically (rather than producing a bending moment owing to the eccentricity effect like other shear test methods). ▪ Monotonic and cyclic shear loading modes. ▪ Controlled temperature. ▪ Shear displacement at the interfaces is measured by an extensometer. ▪ Result is a shear force-displacement curve, related to time and number of cycles.	Prismatic 70 × 120 × 50 mm^3	4 to 10 mm			Canestrari et al. (2012), Diakhate (2007) Rahman et al. (2017), Raposeiras et al. (2013), Sutanto (2010)



Source: Diakhate et al. (2011 cited in Waisome 2017).

A.5 3-Point Shear Bond Test

Table A 5: 3-point shear bond test

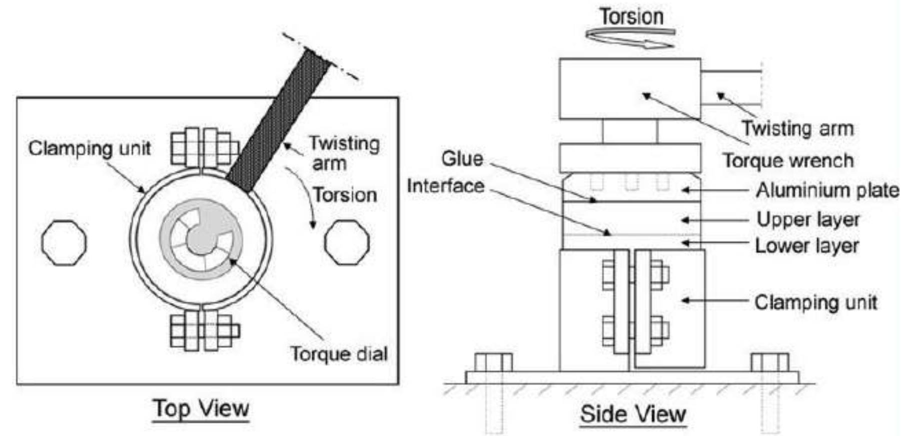
Test device	Description	Specimen size	Gap width	Displacement rate	Related standard test method	Sources
Laboratorio de Caminos de Barcelona (LCB)	▪ Leutner-based test. ▪ Laboratory testing ▪ 'pure shear' test configuration. ▪ 3-point shear bond test. ▪ Laboratory fabricated and/or pavement core.	100 mm diameter and 178 mm height	10 mm	1.27 mm/min	NLT-328/08	Ahn (2014), Canestrari et al. (2012), Mohammad et al. (2012), Raposeiras et al. (2013), Spanish Road Technology (2008), Sutanto (2010)
		 Source: Spanish Road Technology (2008).				

APPENDIX B TORQUE BOND TESTS

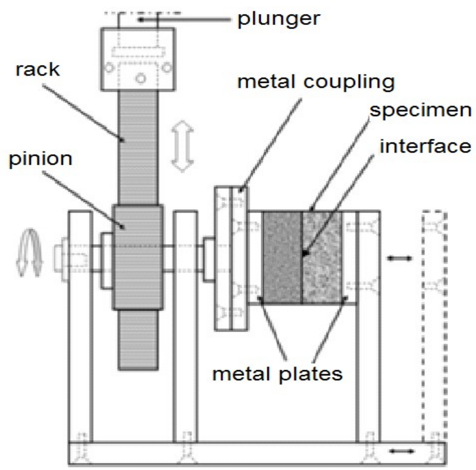
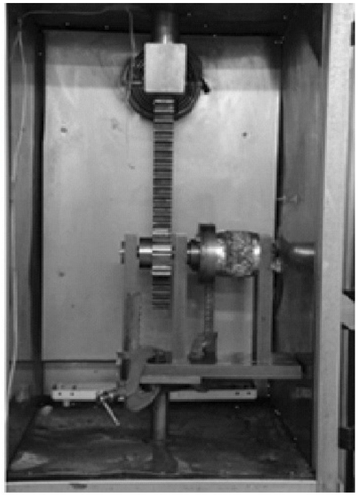
Table B 1: Torque bond tests

<table>
<tr><th>Test device</th><th>Description</th><th>Specimen size</th><th>Stress rate</th><th>Related standard test method</th><th>Sources</th></tr>
<tr><td rowspan="2">(Manual) Torque Bond Test</td><td rowspan="2">▪ Originally developed in Sweden for the in situ assessment of bond conditions and has been adopted in the UK as-part-of the approval system for thin surfacing systems.
▪ Can perform the torque test either for field specimens or specimens fabricated in the laboratory.
▪ The test is conducted by conglutinating the surface of the core to the metal plate of the device. For testing in situ, partial coring is required up to at least 20 mm below the interface of interested.
▪ Torque is applied manually at a steady rate to the specimen to induce a twisting shear failure at the interface.
▪ If the tested specimen is laboratory fabricated, it should be tested at 20 °C.
▪ Generally limited to the interface between thin surfacing and the lower layer material.
▪ No lateral support at the top part of the specimen (Sutanto 2010 states that this condition may cause lateral shear stress to act at the interface in addition to the interface shear stresses induced by the torque).</td><td>100 or 150 mm diameter</td><td>Constant rotation rate so that the torque wrench sweeps an angle of 90° within 30±15 seconds</td><td>SG3/05/234</td><td>Buchanan and Woods (2004), Chang et al. (2014), Sutanto (2010), Sutanto (2011), Tashman, Nam and Papagiannakis (2006)</td></tr>
<tr><td colspan="4">
Source: Tashman et al. (2006).</td></tr>
</table>

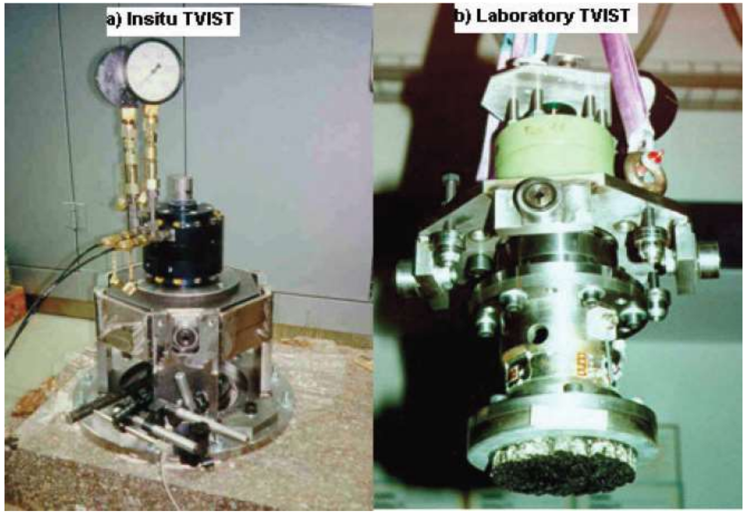
Test device	Description	Specimen size	Stress rate	Related standard test method	Sources
Texas A&M Transportation Institute (TTI) Torsional Shear Test	▪ Developed by the Texas A&M Transportation Institute (TTI). ▪ Double layered specimen. ▪ Twisting moment is applied at a constant rate. ▪ normal load is applied on the top of a double-layered cylinder specimen. ▪ Measures shear strength. ▪ Mohr-Coulomb failure envelope constructed to get the cohesion and the tangent of internal friction angle.	150 mm diameter compacted in laboratory using two half-moulds. Space between the two halves is 2 mm.	2.9 E-04 radian/sec		Ahn (2014), Mohammad et al. (2012)
Laboratory manual torque test	▪ Constant torque rate is applied by synchronising the movement of the torque dial gauge with the second hand of an analogue clock. ▪ Controlled environment. ▪ Able to test the shear strength of an interface other than the interface below the surfacing (which is not possible in the field).		600 Nm/min		Choi et al. (2005), Sutanto (2010)

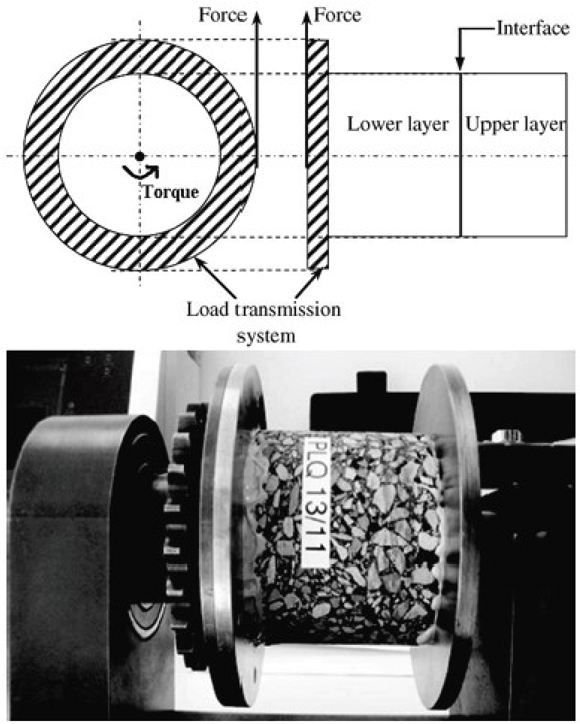


Source: Sutanto (2010).

Test device	Description	Specimen size	Stress rate	Related standard test method	Sources
Automatic torque bond test	▪ Mechanically (automatic) controlled automated torque bond test. ▪ Rack and pinion mechanism used in the automatic torque bond apparatus to transfer the applied load or displacement and convert it into a torque or rotation respectively. ▪ Monotonic or cyclic loading. ▪ The force and linear displacement of the rack are measured using the load cell and LVDT incorporated in the testing machine. ▪ 100 mm diameter and 10 mm thick cylindrical metal plates are glued to the top and bottom of the specimen. ▪ Temperature controlled cabinet. Sutanto (2011) found higher bond strength values compared to manual torque bond test when operated at a contact rate of 600 Nm/min.	100 mm diameter			Chang et al. (2014), Sutanto (2011)
		  Source: adapted from Sutanto (2011).			

Test device	Description	Specimen size	Stress rate	Related standard test method	Sources
Carleton In situ Shear Strength Test (CISSST)	▪ Developed in Carleton University, Canada. ▪ Developed to determine in situ shear strength of surfacing material, but can also be used to measure interface torque bond strength between the surfacing and the layer underneath. ▪ Torque is applied across a steel disc affixed to the pavement surface using epoxy resin. ▪ Electromechanical system develops the required torque. ▪ Mounted to a small cart-like chassis for manoeuvrability.				Abd El Halim (2004), Goodman et al. (2002), Sutanto (2010)
		 Source: Goodman et al. (2002).			

Test device	Description	Specimen size	Stress rate	Related standard test method	Sources
Torsional Vibration and In situ Testing (TVIST)	▪ Similar to CISST. ▪ Developed by EMPA, Swiss Federal Laboratories for Materials Science and Technology. ▪ Applies both torsion and vertical loadings. ▪ Available in situ and laboratory.				Sutanto (2010)
		 Source: Raab and Partl (1999 cited in Sutanto 2010).			

<table>
<tr><th>Test device</th><th>Description</th><th>Specimen size</th><th>Stress rate</th><th>Related standard test method</th><th>Sources</th></tr>
<tr><td rowspan="2">Torque Bond by Diakhate et al. (2006, 2007)</td><td rowspan="2">▪ Mechanically controlled.
▪ Chain-sprocket mechanism transfers tensile force generated by a tension testing machine and converts it into a torque (loading rate can be controlled accurately).</td><td></td><td></td><td></td><td>Diakhate (2007), Sutanto (2010)</td></tr>
<tr><td colspan="4">

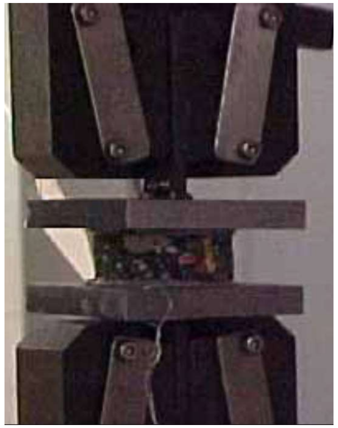
Source: Sutanto (2010).</td></tr>
</table>

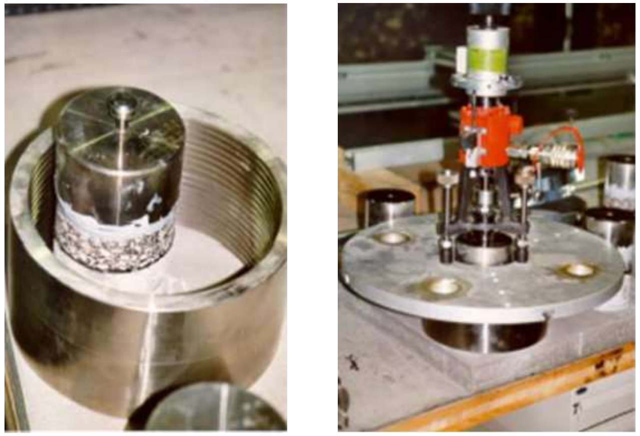
APPENDIX C TENSILE BOND TESTS

C.1 Direct Tensile Bond Tests (Laboratory and In situ)

Table C 1: Direct tensile bond tests

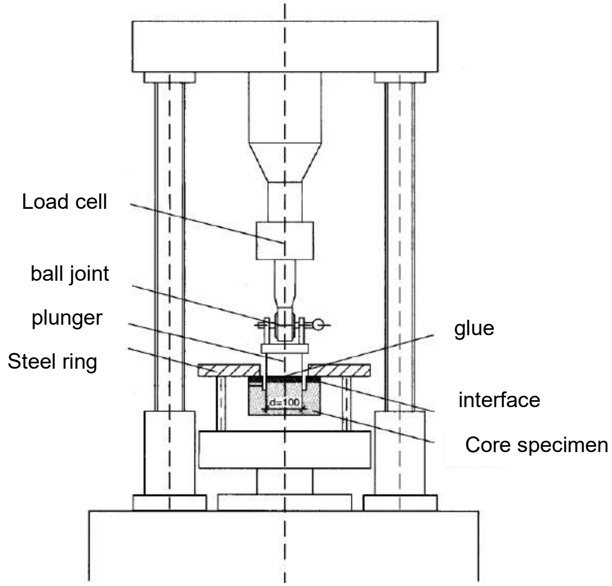
Test	Description/comments	Specimen size	Pulling rate	Related standard test method	Source
Pull-Off test by Tschegg et al. (1995)	▪ Partial coring of the pavement is conducted to a certain depth below the interface. ▪ A contact plate is glued to the surface of the coring using epoxy. ▪ Vertical load is applied until failure (de-bonding). ▪ The maximum load is recorded. ▪ Can be applied in situ or in the laboratory. ▪ Results are significantly scattered.	100 mm diameter drilled from the top surface down to 50 mm into the base layer.		BS EN 13863-2	Raposeiras et al. (2013), Tschegg et al. (1995)

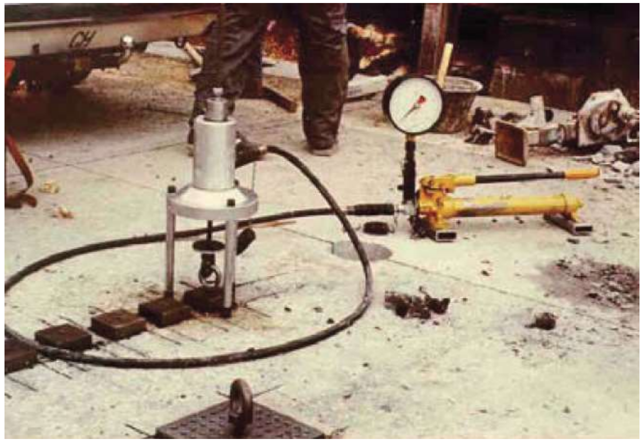
Test	Description/comments	Specimen size	Pulling rate	Related standard test method	Source
KDOT Pull-Off Test	▪ Partially adopted the procedure as stated in ASTM D4541 (Standard test method for pull-off strength of coating using portable adhesion testers). ▪ Modified from the ASTM standard test method ASTM D4541 "Standard Test Method for Pull-Off Strength of Coating using Portable Adhesion Tester". ▪ Test at 25 °C.	50 mm diameter cores	25 mm/min	ASTM D4541-09e1	Chang et al. (2014)
		 Source: Rahman and Hossain (2009 cited in Chang et al. 2014).			
Japan Pull-Off test	▪ Similar to KDOT pull-off test.	Prism 50 mm wide, 100 mm long (50 mm for each asphalt layer) and 50 mm high.	1 mm/min and 100 mm/min mentioned		Chang et al. (2014)

Switzerland Pull-Off Test	▪ A 100 mm diameter disc is glued to the upper layer of the specimen while the bottom layer is fixed to a concrete plate. ▪ A tensile load is applied to a dual-layered specimen.	100 mm diameter	100 N/s (stress-controlled test)		Canestrari et al. (2018), Chang et al. (2014), Mohammad et al. (2012), White (2015)
		 Source: Canestrari et al. (2018).			

Ahn 2014	▪ Modified pull-off test for measurement of in situ pavement interface bonding strength. ▪ Epoxy adhesive placed on the surface of the specimen. ▪ Steel disk attached to the top of the epoxy adhesive. ▪ Testing device attached to the steel disk and tensile load applied.		0.5 mm/s		Ahn (2014)
		 Source: Ahn (2014).			
Traction Test	▪ Developed by Ministère des transports du Quebec, Canada.	101.6 mm diameter	0.24 kN/s (constant load)		Buchanan and Woods (2004),

	▪ Tensile force applied to a cylindrical sample until failure. ▪ Laboratory or in situ. ▪ Measured the tensile strength of the tack coat interlayer.				Mohammad et al. (2012)
		 Source: Mohammad et al. (2012).			
Pull test method by Xiao et al. (2012)	▪ Self-designed for analysing the adhesion properties between thin surface layers (25 mm to 40 mm) and the mixture layer below. ▪ Steel plate is glued to the dried and cleaned surface. ▪ Sample is placed upside down on test table in a temperature-controlled chamber. ▪ Surface layer is pulled off and tensile force measured.	Cylindrical cuts with 50 mm diameter cored on samples to a depth of 10 mm			Xiao et al. (2012)
		 Source: Xiao et al. (2012).			
German tensile bond test	▪ Partial coring of 100 mm diameter (to approximately 10 mm below the interface) on a 150 mm core specimen.	150 mm diameter		German standard DIN2974	Sutanto (2010)

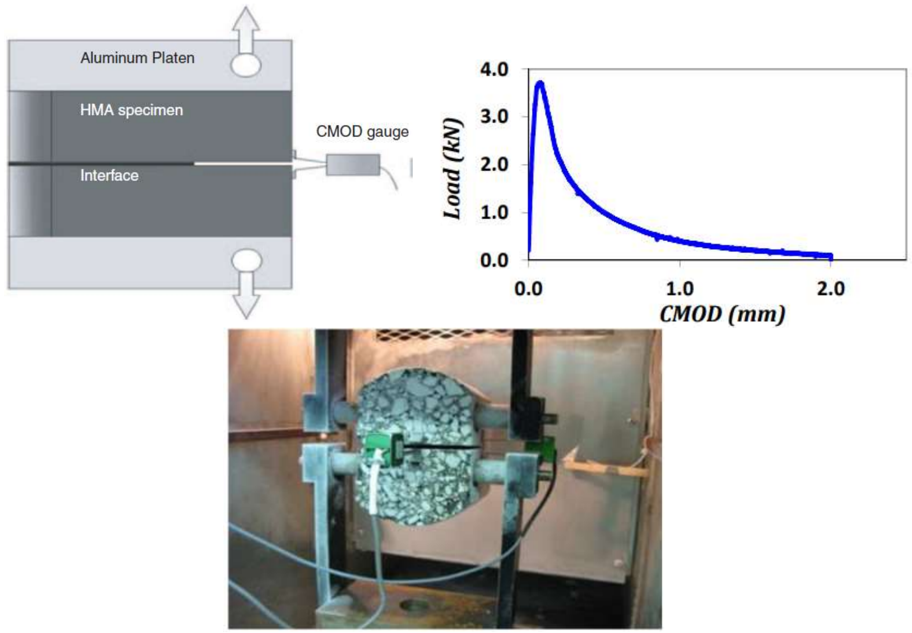
	▪ A 100 mm diameter plunger is glued to the surface of the core. ▪ A steel ring is placed around the plunger and fixed to the base support. ▪ The tension testing machine pulls the plunger in the axial direction.	 Source: adapted from DIN (2003 cited in Sutanto 2010).

In situ tensile bond test (Raab and Partl 1999)	▪ Partial core carried out until a certain depth below the interface of interest. ▪ Metal plate glues on top of the surfacing and attached to the in situ tension machine. ▪ Top layer is pulled-off in the axial direction. ▪ Used by EMPA, Swiss Federal Laboratories for Materials Science and Technology to measure tensile bond properties at the interface of an asphalt surfacing laid over a concrete lower layer.	 Source: Raab and Partl (1999 cited in Sutanto 2010).			Sutanto (2010)
Austrian pull-off test	▪ Strictly enforced in enforced in Austrian Standard. ▪ Cores are glued to metal plates at both ends and undergo direct tensile test.			Austrian Standard RVS 11.065	Buchanan and Woods, (2004), Chang et al. (2014)
Schenk-Trebel Test Litzka et al.	▪ Layers stuck to clamping jaws. ▪ It was realised that results can be erroneous due to variations in eccentricities.				Raposeiras et al. (2013)
ENDACMA tensile test	▪ Schenck-Trebel-based test device. ▪ Developed by Intecasa. ▪ Layers stuck to clamping jaws. ▪ It was realised that results can be erroneous due to variations in eccentricities.				Raposeiras et al. (2013)

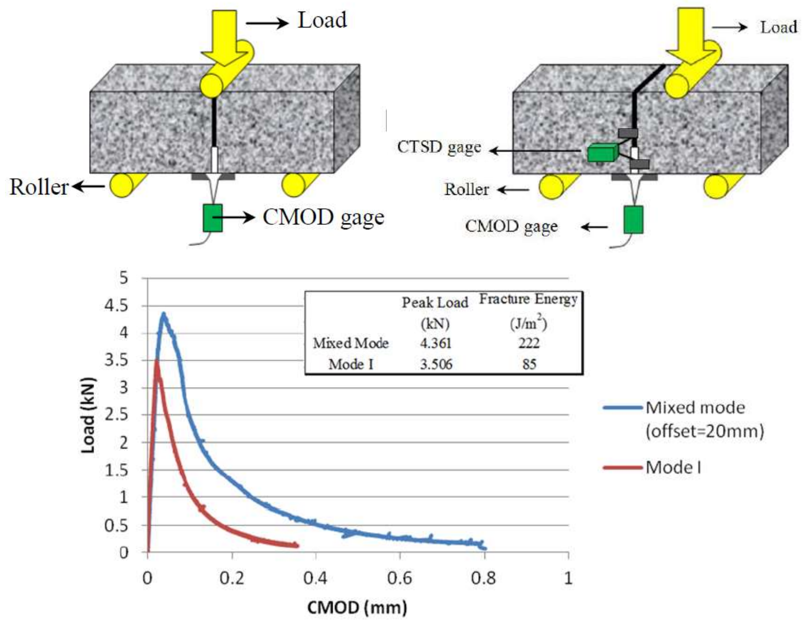
KDOT Direct Tension Test	▪ Mobile pull-off apparatus. ▪ Modified from the ASTM standard test method ASTM D4541 "Standard Test Method for Pull-Off Strength of Coating using Portable Adhesion Tester". ▪ A 37 mm diameter pipe cap machined flat with the shoulder cut to provide a 50 mm diameter surface for bonding is glued to the surface of the core with epoxy resin. ▪ A preload of approximately 5 kg is applied. ▪ Tension is applied until failure or the peak capacity of the scale is reached (227 kg). ▪ Test at 25 °C.	50 mm core to a depth 6.3–19 mm below the layer to be tested. three of these holes are drilled in a triangular fashion so that a 150 mm diameter core drill circumscribe them. The larger core is drilled either to the bottom of the pavement or 230 mm, whichever is less.	20.3 ± 2.5 mm/min	KT-78	NCHRP (2018a), Williamson (2015)
		  Source: KDOT (2011).			

C.2 Crack Resistance Tensile Bond Test

Table C 2: Crack resistance tensile bond test

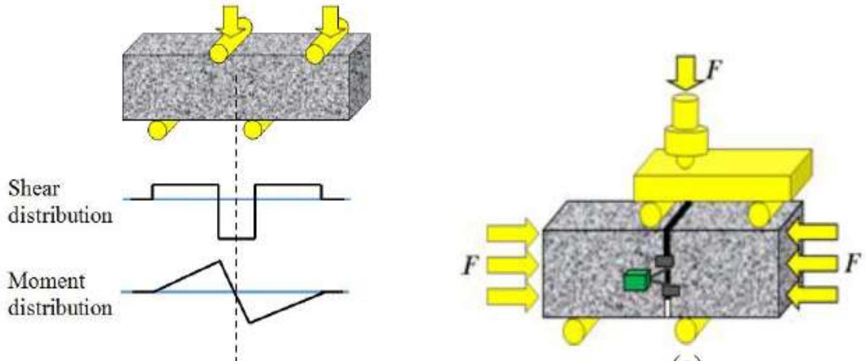
Test	Description/comments	Specimen size	Loading rate	Related standard test method	Source
Interface Bond Test (IBT)	▪ developed by the University of Illinois at Urbana-Champaign. ▪ measures the effect of tack on crack resistance. ▪ crack resistance is assessed using fracture energy. ▪ capture the effects of macrotexture as well as the adhesion properties of the tack coat material. ▪ can evaluate bonding between thin-bonded overlays.		0.1 to 0.5 mm/min	ASTM 7313 (b)	Hakimzadeh et al. (2012), Road Science (2011)
		 CMOD = crack mouth opening displacement. Source: Hakimsadeh et al. (2012), Road Science (2011).			

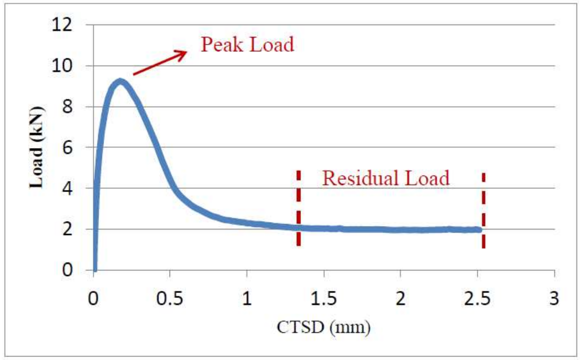
Test	Description/comments	Specimen size	Loading rate	Related standard test method	Source
Three-point bending notched beam	▪ developed by the University of Illinois at Urbana-Champaign. ▪ new configuration of the IBT used to evaluate bond between layers under tension (mode I) and under a combination of tension and shear (mixed mode).		0.1 to 0.3 mm/min		Hakimzadeh (2015)



CTSD = crack tip sliding displacement.

Source: Hakimzadeh (2015).

<table>
<tr><th>Test</th><th>Description/comments</th><th>Specimen size</th><th>Loading rate</th><th>Related standard test method</th><th>Source</th></tr>
<tr><td rowspan="2">Four-point bending notched beam</td><td rowspan="2">developed by the University of Illinois.
new configuration of the IBT used to evaluate bond between layers under a combination of tension and shear.
configuration aims at maximising shear and minimising moment at the interface location.</td><td></td><td>5 mm/min</td><td></td><td>Hakimzadeh (2015)</td></tr>
<tr><td colspan="4">

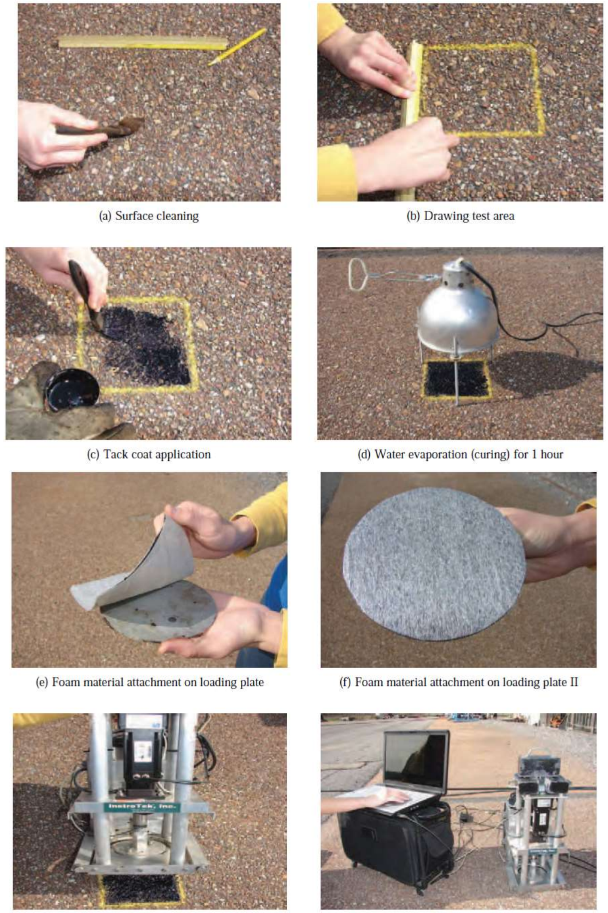
(a)

</td></tr>
</table>

C.3 Direct Tensile Bond Tests on Tack Coats

Table C 3: Direct tensile bond tests on tack coats

Test	Description/comments	Specimen size	Pulling rate	Related standard test method	Source
ATacker™ tack coat evaluation device (TCED)	▪ Developed for the Mississippi Transportation Research Centre by Instrotek Inc. ▪ The device includes a smooth, circular aluminium contact plate, torque and force gauge and the force driven lever. ▪ The sizes of the contact plates used differ accordingly to the types of tack coat materials. ▪ A pull and/or torque stress is applied to tack coated plates until failure (separation). ▪ A steel plate is placed on the surface of the bottom layer right after the tack coat is applied. ▪ When the emulsion is dry, a tensile vertical load is applied to produce de-bonding between the steel plate and the bottom layer. ▪ Tack coat applied to two plates or a plate and a pavement surface ▪ The device can perform a torque test or tensile test.	Tack material of PG binders: contact plate of diameter size 12.7 and 25.4 mm. Emulsified tack coats: contact plates of 50.8 mm and 127.0 mm diameter.			Ahn (2014), Buchanan and Woods (2004) Chang et al. (2014), West et al. (2005), White (2015)

Test	Description/comments	Specimen size	Pulling rate	Related standard test method	Source
University of Texas at El Paso (UTEP) Pull-Off Test (UPOD)	▪ Developed by the University of Texas at El Paso. ▪ Atacker-based device. ▪ Developed to inspect and quantify the bonding characteristics of the tack coat material applied on site. ▪ Tests the tacked surface rather than a two layered specimen. ▪ The pull-off device is placed on the tacked surface with the contact plate is in contact with the tack coat material after the applied tack coat has set. ▪ A dead load of 18.1 kg (40 lb) is applied for 10 minutes as confinement to ensure that the contact plate is firmly contact to the tacked surface. ▪ The dead load is removed once 10 minutes approaches and the contact plate is detached by the mean of pulling as a result of torque applying to the device. ▪ The maximum torque required to detach the contact plate is later convert to tensile strength using the calibration factor. ▪ Can be performed in the laboratory or in situ.	 Source: Hakimzadeh (2015).			Chang et al. (2014), Mohammad et al. (2012), Raposeiras et al. (2013), White (2015)

<table>
<tr><th>Test</th><th>Description/comments</th><th>Specimen size</th><th>Pulling rate</th><th>Related standard test method</th><th>Source</th></tr>
<tr><td rowspan="2">Louisiana Tack Coat Quality Tester (LTCQT) device
NCHRP 9-40</td><td rowspan="2">▪ Modified from ATacker test setup.
▪ Developed under the collaboration of Louisiana Transportation Research Centre and Instrotek Inc. as part of the National Cooperative Highway Research Program (NCHRP) Project 9-40, Optimization of Tach Coat for Hot-Mix Asphalt (HMA).
▪ Small test unit the measures the bond strength of a tack coat in the field.
▪ Controlled strain rate determined by the user at a constant temperature determined by the user.
▪ Average coefficient of variation (NCHRP study) less than 11%.
▪ The contact plate of the device should be kept in contact with the tack surface for 3 minutes, with a contact pressure of 10.8 kPa.</td><td></td><td>0.2 mm/s</td><td>A standard method was proposed to AASHTO</td><td>AASHTO (2018), Chang et al. (2014), Mohammad et al. (2012), Raposeiras et al. (2013)</td></tr>
<tr><td colspan="4">
(a) Surface cleaning (b) Drawing test area
(c) Tack coat application (d) Water evaporation (curing) for 1 hour
(e) Foam material attachment on loading plate (f) Foam material attachment on loading plate II
(g) Placement of LTCQT (h) Pull-off testing and data recording
Source: Mohammad et al. (2012).</td></tr>
</table>

APPENDIX D NON-DESTRUCTIVE METHODS

Table D 1: Advantages, disadvantages and potential use of feasible methods

Method	Device	Equipment Limitations and Capabilities								Past experience	Ability to implement procedures/ equipment without specialists
		Detectability extent (1)	Detectability threshold (2)	Detectability depth	Speed of data collection & area coverage	Speed of data analysis	Availability and accessibility of equipment	Expertise needed for data processing & interpretation	Equipment reliability		
Electromagnetic	GPR	Small	Advanced	lower than top 50 mm	Rapid/continuous (full-lane width, up to 65 km/h)	Slow	Commercially available	High	High	Mixed results	Medium
Impulse	FWD	Extensive	Advanced		5 min./point	Rapid	Commercially available	High	High	Mixed results	Medium
	LWD	Small	Advanced		2 min./point	Rapid	Commercially available	Unknown	Medium	None	Medium
	Impulse Response	Small	Onset		2 min./point	Rapid	Commercially available	High	High	Some	High
Vibration	Stiffness Gauge	Unknown	Unknown		2 min./point	Unknown	Commercially available	Unknown	high	None	Unknown
	High-frequency sweep	Unknown	Onset		unknown	Unknown	Research stage	Unknown	Unknown	None	Unknown
Seismic/sonic	Impact-Echo	Small	Onset	100–300 mm for cold-stiff asphalt	2 min./point (half-lane width, < 8 km/h)	Rapid	Commercially available	Medium	High	Some	High
	SASW	Small	Advanced	0–180 mm	2 min./point (half-lane width, < 8 km/h)	Rapid	Commercially available	Medium	High	Some	High
	Ultrasound	Unknown	Unknown		2 min./point		Commercially available	Unknown	High	None	Unknown
Thermal	Thermography	extensive	Advanced		Rapid/continuous	Rapid	Commercially available	Medium	Medium	Mixed results	Low

Source: Based on Celaya et al. (2010) and the National Academy of Sciences (2013).

1 Planar extent of debonding that should occur before they can be detected by the method.

2 Per cent of defects identified within Celaya et al. (2010) study.

APPENDIX E STANDARD TEST METHODS

Table E 1: Summary of standard test methods

Standard Test Method	Type of load	Gap between shearing plates	Specimen size	Test temperature	Normal stress	Loading rate
DRAFT prEN 12697-48	Torque (field)	NA	Top layer thickness > 15 mm, 100 mm diameter groove cores to a depth of 20 mm below the interface to be tested	To be recorded	No	Load is manually applied so that torque wrench sweeps an angle of 90° within 30±15s. Torque applied until failure of the bond or a torque of 400 Nm is exceeded.
		NA	If top layer ≥ 15 mm: 100 mm diameter with minimum depth 80 mm below the interface being tested. If top layer < 15 mm: 200 mm diameter	20±2 °C	No	
	Direct shear	≤5 mm recommended, noting that gap length influences the test results	150±2 mm or 100±2 mm diameter (noting that specimen diameter influences the test results) (thickness of top layer ≥ 20 mm and thickness of bottom layer ≥ 70 mm).	20±1 °C	No	50.0±2 mm/min up to a displacement of at least 7 mm and a maximum load of at least 35 kN.
	Tensile	NA	Applicable on thin surface layers, 150 mm diameter and 60 mm height drilled with a diamond tipped drilling machine so that the internal diameter of the ring-groove is 100 ± 2 mm	0±1 °C or 10±0.5 °C	NA	200 N/sec until failure
	Compressed shear	Determined based on the maximum diameter of the aggregate of the two mixes in contact – not less than 5 mm	97±3 mm diameter with thickness between 60 and 80 mm	20 ± 0.5 °C	Yes	2.5±0.1 mm/min Normal load: 0.2 MPa for road pavement and 0.3 MPa for airfield pavement
	Cyclic compressed shear	1±0.1 mm	98.5±3 mm diameter. Minimum thickness of each layer ≥ 40 mm	–10 °C, 10 °C, 30 °C, 50 °C,	Yes	Shear displacements: 0.01 mm, 0.025 mm, 0.05 mm, 0.1 mm, 0.2 mm, 0.01 mm Frequencies: 10 Hz, 5 Hz, 1 Hz, 0.1 Hz Normal stress: 0.9 MPa, 0.6 MPa, 0.3 MPa, 0 MPa
AASHTO TP 114 (2018) (1)	Shear (LISST equipment)	12.7 mm	150 mm diameter specimens (thickness of each layer 50 mm)		If required, up to 206.84 kPa	2.54 mm/min
FDOT FM 5-599 (2016) (Florida Department of Transportation)	Shear	6.3 mm	150 mm diameter	25±1 °C	No	50.8 mm/min

Standard Test Method	Type of load	Gap between shearing plates	Specimen size	Test temperature	Normal stress	Loading rate
ALDOT-430 (Alabama Department of Transportation)	Shear	6.3±0.8 mm	150 mm diameter core (thickness of each layer must be between 50 and 150 mm each)	25±1 °C	No	50.8 mm/min
WVDOT MP 401.07.23 (2009) (West Virginia Department of Transport)	Shear	6.3±0.8 mm	150 mm diameter (thickness of each layer between 50 and 76 mm)	24±2 °C	No	50.8 mm/min
KDOT KT-78 (Kansas Department of Transportation)	Tensile	NA	50 mm core to a depth 6.3 to 19 mm below the layer to be tested, 3 of these holes are drilled in a triangular fashion so that a 150 mm diameter core drill circumscribe them. The larger core is drilled either to the bottom of the pavement or 230 mm, whichever is less	25 °C	NA	20.3 ± 2.5 mm/min
TxDOT Tex-249-F (Texas Department of Transportation)	Shear	6.3 to 19 mm	140 to 152 mm diameter	25 °C	No	5.08 ± 0.51 mm/min
VTM-128 (Virginia Department of Transportation 2019)	Shear	6.3 mm	101.6 mm diameter	21.1 °C	No	50.8 ± 3.8 mm/min
	Tensile	NA	101.6 mm diameter	21.1 °C	NA	
BBA SG3/05/234 Appendix A.3 (Draft for development)	Torque (field)	NA	100 ± 5 mm diameter core barrel to a depth of 20 mm below the thin surfacing layer to be tested			Load is manually applied so that torque wrench sweeps an angle of 90° within 30 ± 15s. Torque applied until failure of the bond or a torque of 300 Nm is exceeded.
		NA	100 or 150 mm diameter core cut to a minimum depth of 80 mm below the bottom of the surface layer	20±2 °C	No	
Austrian Standard RVS 11.065 (Sutanto 2010)	Shear					50 ± 3 mm/min
	Tensile	NA			NA	
Swiss Standard SN 671961 (Canestrari et al. 2012)	Shear		150 mm		No	
	Tensile	NA			NA	
Swiss Standard SN 640430B (Destrée & Visscher 2016)	Shear		150 mm	20 °C		50 ± 2 mm/min

Standard Test Method	Type of load	Gap between shearing plates	Specimen size	Test temperature	Normal stress	Loading rate
German Standard ALP A-Stb Teil 4 (Sutanto 2010)	Shear		150 mm		No	
German Standard ALP A-Stb Teil 9	Tensile					
Italian Standard UNI/TS 11214 (2007) (Canestrari et al 2012)	Shear (ASTRA device)				Yes	
Spanish Standard NLT-328/08 (Spanish Road Technology 2008)	Shear		100 or 150 mm	20±1 °C	No	2.5 mm/min
	Shear (3-point shear, LCB device)	10 mm	100 or 150 mm with minimum thickness of the overlay asphalt layer 25 mm	20±1 °C	No	2.5 mm/min

1 A newer version (2018) is available for purchase.

APPENDIX F SPECIFIED AND RECOMMENDED BOND STRENGTH LIMITS

Table F 1: Summary of specified and recommended bond strength limits

Source		Country	Type of load	Specimen size	Displacement rate	Test temperature	Limit	Test method
Codija (1994 cited in Sangiorgi et al. 2002) (Recommended)		Germany	Shear (no gap)	150 mm diameter	50 mm/min		▪ Wearing course/ binder course: 15 kN (0.85 MPa) ▪ Binder course/ basecourse: 10 kN (0.57 MPa) ▪ Wearing course/ basecourse: 13 kN (0.74 MPa)	
Stöckert (2001cited in Sangiorgi et al. 2002) (Recommended)		Germany	Shear (no gap)	150 mm diameter	50 mm/min		▪ Wearing course/ binder course: 25 kN (1.41 MPa) ▪ Binder course/ bas course: 20 kN (1.13 MPa) ▪ Wearing course/ basecourse: 16 kN (0.91 MPa)	
FGSV (2003 cited in Destrée & Visscher 2016) (Specified)		Germany		150 mm diameter			▪ 0.85 MPa	
SN 640430 (2012 cited in cited in Destrée & Visscher 2016) (Specified)		Switzerland		150 mm diameter			▪ 0.85 MPa	
Sangiorgi et al. (2002) (Recommended)	New pavement		Shear (no gap)	150 mm diameter	50 mm/min	20 °C	▪ Wearing course/ binder course: 20 kN (1.13 MPa) ▪ Binder course/ base course: 12 kN (0.68 MPa) ▪ Wearing course/ base course: 18 kN (1.02 MPa)	
	After 1 year traffic		Shear (no gap)	150 mm diameter	50 mm/min	20 °C	▪ Wearing course/ binder course: 25 kN (1.41 MPa) ▪ Binder course/ base course :17 kN (0.96 MPa) ▪ Wearing course/ base course: 23 kN (1.30 MPa)	
Partl and Raab (1999)		Switzerland	Shear	150 mm diameter	50 mm/min	20 °C	▪ Surfacing/binder course: 0.85 MPa ▪ Binder course/base: 0.68 MPa	Swiss Standard SN 671961
West et al. (2005) NCAT (Recommended)		USA	Shear	150 mm diameter	50.8±3.8 mm/min	25 °C	▪ 0.69 MPa based on average of at least 3 samples ▪ Marginal bond strength results appear to be between 0.34 and 0.69 MPa ▪ Poor bond strength results are below 0.34 MPa (Preliminary ranges pending verification with further work)	
Johnson (2015) MnDOT (Recommended)		USA					▪ 0.69 MPa ▪ maximum standard deviation 0.17 MPa	

Source	Country	Type of load	Specimen size	Displacement rate	Test temperature	Limit	Test method
VDOT (2019) (Specified)	USA	Shear	101.6 mm diameter	50.8±3.8 mm/min	21.1 °C	▪ Milled surfaces: average shear strength ≥ 0.69 MPa with no single core to have a shear strength less than 0.34 MPa. ▪ Un-milled surfaces: average shear strength ≥ 0.34 MPa with no single core to have a shear strength less than 0.21 MPa.	VTM-128 (VDOT)
WVDOT (2019) (Specified)	USA	Shear	150 mm	50.8 mm/min	24 ± 2 °C	▪ 0.69 MPa	MP 401.07.23
KDOT (2015) (Specified)	USA	Tensile	50 mm diameter	20.3 mm/min	25 °C	▪ If the tensile stress of a test is less than 0.24 MPa (35 psi), suspend plant production and paving.	KT-78 (KDOT)
British Board of Agreement (SG3/05/234) (Recommended)	UK	Torque	100 or 150 mm	Load is manually applied so that torque wrench sweeps an angle of 90° within 30±15s. Torque applied until failure of the bond or a torque of 300 Nm is exceeded.	Field temperature or 20 °C at the laboratory	▪ minimum shear strength 0.40 MPa as a guideline.	British Board of Agreement (SG3/05/234)
Sutanto (2010) (Recommended)		Shear (5 mm gap)				▪ Surfacing/binder course: 1 MPa. ▪ Binder course/base: 0.5 MPa.	
Buchanan and Woods (2004), Chang et al. (2014) (Specified)	Austria	Pull-off (tensile)				▪ Tensile strength > 1.5 N/mm^2 when using modified binders and > 1.0 N/mm^2 with unmodified binders, penalties are distributed for each 0.1 N/mm^2 below specification.	Austrian Standard RVS 11.065