Cracking in specialist surfacing systems
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JP Wu, SR Cook and PR Herrington
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NZ Transport Agency
Private Bag 6995, Wellington 6141, New Zealand
Telephone 64 4 894 5400; facsimile 64 4 894 6100
research@nzta.govt.nz
www.nzta.govt.nz

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Abbreviations and acronyms

AASHTO	American Association of State Highway and Transportation Officials
AC	asphaltic concrete
ASTM	American Society for Testing and Materials
ANOVA	analysis of variance
BBA	British Board of Agrément
BSI	British Standards Institution
CTE	coefficient of thermal expansion
DSR	dynamic shear rheometer
HAPAS	Highway Authority Product Approval Scheme
HFS	high friction surfacing
HSNO	hazardous substances and new organisms
ISO	International Organisation for Standardisation
P25	NZTA P25:2011 Pilot specification for calcined bauxite
P25PN	NZTA P25PN:2011 Notes for pilot specification for calcined bauxite
P33	NZTA P33: Draft specification for coloured surfacings
PAV	pressure ageing vessel
PSV	polished stone value
SCRIM	sideway-force coefficient routine investigation machine
SH	state highway (in New Zealand, eg SH1)
Transport Agency	New Zealand Transport Agency
TRL	Transport Research Laboratory (UK)
TSRST	thermal stress restrained specimen test
UTEP	University of Texas, El Paso

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Executive summary

Specialist surfacings such as high-friction and coloured traffic-calming surfaces have gained huge popularity since their introduction. However, the reputation of these specialist systems in New Zealand is also plagued by premature failures due to cracking and other related modes. Many of the failure modes have in fact originated from or are at least associated with the performance of the underlying pavement substrate. The purpose of this research project was to assess test methods where the emphasis was on the performance of the underlying substrate and its interaction with the specialist surfacing systems to ensure best outcomes.

For the development of a test to predict the potential failure of a specialist surfacing system, it is necessary to assume the system meets product specifications and guidelines are properly followed during construction. Specialist surfacing systems are multi-layered structures which can fail cohesively and/or adhesively. Hence, for them to work effectively, bond strengths between the binder and the aggregate as well as that of the systems and their underlying substrate are very important. Hence, predicting failures due to the breakage of one of those bonds was the focus of this research.

A number of commercial resin systems, namely epoxy, polyurethane and methyl methacrylate were tested using the tensile bond (pull-off) test and % elongation (tensile) test based on ASTM standard test methods C1583-13 and D638-10. Thermal effects were also investigated by conducting thermal cycling experiments.

One of the strengths of the tensile bond test is that it can be conducted in a controlled environment as well as in a field. This enables direct measurement of the adhesive and cohesive strength of the pavement layers, and provides good indication of the ‘weakest link’. The test method has shown good sensitivity across various materials, and it is simple to conduct.

For all the specialist surfacing systems tested, the tensile bond tests resulted in cohesive failures in the asphalt substrate regardless of the mix design. The cohesive strength of the asphalt substrate increases as the binder viscosity increases. This is also confirmed by ageing experiments where the aged asphalt substrates have much higher cohesive strength, leading to adhesive failure of the surfacing system when the adhesive bond becomes lower than that of the cohesive bond strength.

Based on the results, a general guideline to prevent premature failure (such as delamination and cohesive substrate failure) has been formed with the following criteria:

- The specialist surfacing system is applied according to best practice, ie the surface must be clean and dry, and the resin system mixed according to the supplier’s notes. Both of these minimise the risks of adhesive and/or cohesive failure of the resin system.
- The adhesive and cohesive strengths of the resin on substrate are greater than the cohesive strength of the substrate itself. This leads to load transfer from the thin specialist surfacing down to the substrate (to prevent delamination).
- The cohesive strengths of the substrate at various temperatures have to meet or exceed the expected traffic forces at various climate conditions (to prevent cohesive substrate failure).

Provided the three criteria are met, the risks of premature failure by either adhesive or cohesive mechanisms can be minimised.

In addition to the bond strength test, a conventional tensile test (elongation test) was also assessed using various binder systems as test subjects. Elastic properties are important when the surface layer is subjected to loads after delamination. The tensile test can be used as a complementary technique to the tensile bond test. The loading rate is controlled to the nearest 0.001mm/min and it has the capability of

switching from strain rate controlled to stress controlled. The use of an environmental chamber also ensures the property measured is characteristic of the specified climate. It was concluded that the best application of this test method was for quality assurance, to ensure the resin used is what was specified.

One aspect which was not investigated is each resin system's ability to withstand ageing (ie oxidation, UV exposure and other weathering effects). It was decided this property should be considered as part of the product/material certification process. It may warrant a mention in the pilot specification.

As a result of reviewing the existing test standards and the experimental results from the current work, a draft test method has been developed for consideration and further refinement. It is recommended that a tensile bond (pull-off) test is incorporated in the pilot specifications (NZTA P25/P33) to ensure adhesive bond strength meets the cohesive strength of the substrate.

It is recommended the test apparatus has the function of controlling the loading rate, and the equipment (load cell and loading speed) is calibrated/verified on a regular basis to ensure consistency. There are several types of tensile loading test apparatus available on the market. The recommendation is to use models with at least a 12kN load cell (or an equivalent tensile stress capacity of 6MPa based on a 50mm diameter area) and a controllable loading rate for consistency. In addition, some form of sampling must be done to ensure measurements are based on a representative set of samples.

In addition, it is recommended the pull-off test is conducted prior to the application of the specialist surfacing system, to ensure the underlying substrate is of sufficient strength to withstand potential traffic loading.

Calculated using the experimental data from this research work, a preliminary benchmark has been set so the asphalt substrates have to withstand tensile stresses of at least 750kPa (or 1.5kN on a 50mm diameter test area) when tested at 23ºC. There are two ways to achieve this:

1. Use a binder with a higher cohesive strength based on the temperature range experienced in the field.
2. Allow ageing of the asphalt substrate. This prevents applications of specialist surfacing systems on freshly laid substrate, which is deemed unsuitable in any case.

Since the temperature will be likely to vary in a field testing environment, there are two different approaches to the test regime:

1. A calibration chart based on temperature has to be developed for field testing.
2. An alternative to field testing is to take cores back to a controlled laboratory environment and test the field cores at 23ºC (or whatever temperature is required for benchmark results).

It is recommended the test method be further refined so the test can be conducted in the field. Further work is needed to develop a comprehensive database (calibration chart) to allow for temperature variations in field.

It is suggested the next step involves field trials at various sites around the country that are potential candidates or are currently surfaced with specialist surfacing systems to determine substrate strength and its relationship with age and mix type.

Further work is recommended to quantify the minimum binder performance requirement to achieve the necessary cohesive strength in order to create a benchmark for the specification for specialist surfacing systems. In addition, the oxidation/ageing characteristics of the specialist surfacing binder system (resin) should align with the defect liability period.

Abstract

Specialist surfacings such as high-friction and coloured traffic-calming surfaces have gained huge popularity since their introduction. However, the reputation of these specialist systems in New Zealand is also plagued by premature failures due to cracking and other related modes. Many of the failure modes have in fact originated from or are at least associated with the performance of the underlying pavement substrate. The purpose of this project was to assess test methods where the emphasis was on the performance of the underlying substrate and its interaction with the specialist surfacing systems to ensure best outcomes. A number of commercial resin systems, namely epoxy, polyurethane and methyl methacrylate were tested using methods based on ASTM standard test methods C1583-13 and D638-10. Thermal effects were also investigated by conducting thermal cycling experiments. The intention was to develop a test that could be implemented in the field. As a result, a draft test specification has been developed as part of the research work to better understand the performance of the surfacing systems and their underlying substrates to minimise some of the common premature failures.

1 Introduction

Currently in New Zealand, there is a pilot performance-based specification for calcined bauxite systems (NZTA P25: 2011) (P25) and a draft specification for coloured safety surfacings is in development (NZTA P33) (P33). The purpose of this research was to extend the scope of these specifications to minimise premature failure of specialist surfacings.

Specialist surfacing systems are commonly used in applications where high-friction is required to prevent vehicles from skidding and/or for traffic calming purposes such as coloured surfaces used at bus stops and bicycle lanes. A current limitation of the P33 specification is that surfacing performance is strongly dependent on substrate condition and this is not dealt with in any detail in the specification. Internationally, the most widely known product certification scheme for specialist surfacings is administered by the British Board of Agrément (BBA), which runs the Highway Authority Product Approval Scheme (HAPAS) and issues HAPAS certification to manufacturers of specialist surfacing systems. This ensures consistent performance and durability of these systems and is recognised across the world, including in New Zealand. While HAPAS covers several key properties of specialist surfacing materials, the potential for failure in the substrate is not directly identified in the certification process. Hence, there remains a need for additional tests to extend the scope of the existing specifications.

The objectives of the research were to:

- complete a literature review on cracking and other related failure modes of specialist surfacings
- develop a test or tests for specialist surfacings, predicting the potential for cracking and related failure modes identified for inclusion in calcined bauxite and coloured surfacing specifications
- develop a draft specification and notes which include the test as described above to ensure the specialist surfacing products are applied accordingly and thus meet their life expectancy.

2 Literature review

2.1 Background

The concept of using epoxy-resin as the binder in surface treatment was first investigated in the USA in the mid-1950s. A development of the system, in which calcined bauxite aggregates (1.2 to 2.8mm) are held in a bitumen-extended epoxy-resin binder, was introduced into the UK in the 1960s (James 1963; Hatherly and Lamb 1970) to provide improved skid resistance on crash-prone sites. Since then specialist surfacings such as high friction surfacing (HFS) and coloured surfacing have been proven to be very effective (Denning 1978; Simpson 2008).

As a result of the growing market for specialist surfacing systems, a number of alternative binders are being offered and the number of suppliers that offer resin-based systems has increased (Nicholls 1998). In New Zealand, HFS has been used to reduce crashes on sites with high crash rates since the 1990s. Similarly, coloured surfacing has become very common for designated traffic lanes such as bus and cycle lanes. Hudson and Mumm (2003) reported the benefit of a HFS system on a section of Wainuiomata Hill Road in Lower Hutt where the number of crashes reduced significantly after the original porous asphalt surface was resurfaced with calcined bauxite HFS.

Izeppi et al (2010) investigated a number of HFS systems available in the US market and showed it is reasonable to expect some of the systems to maintain high friction values for up to 10 years of service based on historical data. Unfortunately, there are some sites which do not last the targeted life for a variety of reasons. Nicholls (1998) investigated the performance of four types of resin systems in road trials in the UK. It was found that debonding (delamination) from the asphalt substrate is a potential problem with all HFS systems. Similar modes of failure were observed in New Zealand (Waters 2011) where HFS systems failed prematurely.

In recent research work conducted by Arnold et al (2014), two test methods were investigated to measure the flexural properties of specialist surfacing resins used in New Zealand: a Leutner shear test to measure bond strength and a flexural beam test to measure flexural modulus and flexural strength. The shear test showed all resins achieved full bond strength (the same as the asphalt mix shear strength) when the asphalt surface was water cut, suggesting that substrate surface preparation is important for good adhesive bonding. The flexural beam test demonstrated the high flexural strengths of the specialist surfacing resins, indicating that the thin surfacing should cope with high pavement deflections and the underlying asphalt would crack before the specialist surfacing did. While the results were promising, further investigation was recommended to review the failure modes and develop other candidate test methods. The New Zealand Transport Agency (the Transport Agency) sought the development of a practical specification that would include a test to predict potential failure, namely cracking or delamination, of the specialist surfacing and its underlying substrate.

An overview of the failure modes and the current test regime for specialist surfacing system is discussed in this literature review. The outcome of this review resulted in the selection of a candidate test methodology, which was further developed for incorporation into a draft specification for specialist surfacing.

2.2 Specialist surfacing

The binders used in these systems are typically epoxy-resin or polyurethane-resin based, but there are other forms including rosin-ester and acrylic-resin (Nicholls 1998; Izeppi et al 2010).

Epoxy-resin comes as a two component system. One component contains the resin with a portion of oils that reduce the viscosity of the resin and acts as an extender. The other part contains the curing agent (hardener). Typical curing time varies between three and four hours for applications at pavement temperatures greater than 10ºC.

Polyurethane-resin was developed to achieve a quicker curing time at lower temperatures than other existing systems. It is a chemically curing, multiple-component system. Such systems are generally hand applied with aggregate spread over the binder layer.

Rosin-ester is a pre-blended system where the resin and the aggregates are already mixed and bagged together. On site, the dry blend only needs to be heated and spread in hand-held box-screeds on the road surface. The material requires little or no sweeping. Due to its thermoplastic nature, it stiffens quickly within 15 minutes and thus minimises traffic delays.

Acrylic-resin is another two-component system but with a much faster curing time than epoxy-resin. The curing process does not begin until the aggregate, which contains the curing agent, is spread over the surface.

Nicholls (1998) assessed the performance of these four types of resins in road trials in the UK by visual assessment, sideway-force coefficient routine investigation machine (SCRIM) measurement, and texture depth. The overall ranking showed epoxy-resin and polyurethane-resin systems performed the best, then the acrylic-resin system, followed by the rosin-ester system.

All specialist surfacing systems are applied onto an existing substrate as an overlay. This substrate is usually an existing pavement of asphalt or concrete that has been cleaned and prepared. While newly laid substrate can be used, a trafficked substrate is recommended (BBA 2008). The preferred substrates vary from product to product, but, asphalt is generally preferred because it is monolithic, that is, it is a whole, single 'slab' of pavement, with few, if any joints. Accordingly, substrates made from discrete units with joints between each unit are not suitable for use as the substrate for a resin-based system. Some suppliers offer primers to prepare other substrate surfaces to ensure good adhesion of the systems.

For HFS, calcined bauxite aggregate with high polished stone value (PSV) is normally used. The small chip (1–5mm) is very durable and provides many sharp edges with high surface friction. For coloured surfacing, the PSV requirement is not as demanding and therefore a variety of aggregates may be used.

2.3 Failure modes

Specialist surfacing systems are very expensive (NZ$40–$60/m^2) when compared with other surfacing treatments. For specialist surfacings to be cost effective, the system has to last seven years or more. While some historical data has shown the systems can last the targeted life of up to 10 years (Izeppi 2010), there are many examples of premature failures.

Nicholls (1998) reports that delamination (also known as debonding) has been found on various HFS sites throughout the UK with many of the systems investigated, especially rosin-ester and polyurethane-resin. This appears to be a particular problem when the systems are laid too thick so the surfacing layer has sufficient strength to act independently from the underlying substrate.

In Australia, Simpson (2005; 2006a) reported that most of the treatments displayed cracking from the underlying pavement reflecting into the surface layer, and some sites displayed aggregate or chip loss (stripping) around the cracks. The cracks all appeared to be initiated in the substrate. There were also areas where the surface treatment had been delaminated cleanly from the substrate.

In a separate investigation in the US, Izeppi et al (2010) also identified delamination as one of the ways that HFS systems fail, along with ravelling (chip loss) of the material and polishing of the high PSV aggregates.

In New Zealand, Waters (2011) published a review of local sites that had failed prematurely and identified three predominant modes of failure of HFS systems which also applied to coloured surfacings since their introduction to New Zealand in the 1990s:

1. Delamination failures – where the whole system falls off cleanly due to poor adhesion between the binder and the underlying substrate.
2. Chip loss – where calcined bauxite chip falls off with or without the HFS binder attached.
3. Cohesion failures – where the HFS system peels off with the top surface of the substrate due to poor cohesive strength of the substrate.

There is general consensus that specialist surfacing systems around the world can fail in these modes: delamination (debonding), chip loss, cracking and cohesion failure of the substrate.

In addition, Nicholls et al (2010) reported a comprehensive study of the durability of thin asphalt surfacing systems in various sites across the UK after nine years of monitoring. The most common categories of defects were particle loss, cracking and delamination, which mirrors those of specialist surfacing systems. Stripping was considered to be insignificant.

2.3.1 Delamination failures

Delamination means the specialist surfacing system comes off in one layer with no substrate attached. This can occur when there is poor adhesion bond between the binder and the substrate (Waters 2011). Delamination can also occur when the surface treatment is too thick (Nicholls 1998) or applied more than once (Simpson 2005) preventing the traffic load to transfer into the substrate. Figure 2.1 illustrates a pothole caused by unsuccessful bonding of the specialist surfacing overlay to the asphalt substrate. When the surfacing system delaminates, the delaminated layer is also at risk of cracking since traffic loads may exceed the strength of the surfacing system.

Figure 2.1 Example of delamination in coloured surfacing

Courtesy of AJ McCormack & Sons

The common causes of delamination according to Izeppi et al 2010 and Waters 2011 are:

- surface contamination of the substrate
    - oil drips, diesel spills and road detritus, etc prevent good adhesion of the binder to the underlying substrate surface
    - flushing, bleeding, or low/no surface texture available for sufficient mechanical bond.
- surface moisture
    - rainfall, moisture from cleaning, moisture trapped within the substrate and dewfall. For some systems if the binder reacts with moisture on the substrate surface, then it may fail to cure adequately
    - the risk of rain and dewfall damage may increase when the specialist surfacing is applied at night as a requirement to reduce disruption to the road users.

2.3.2 Chip loss/stripping

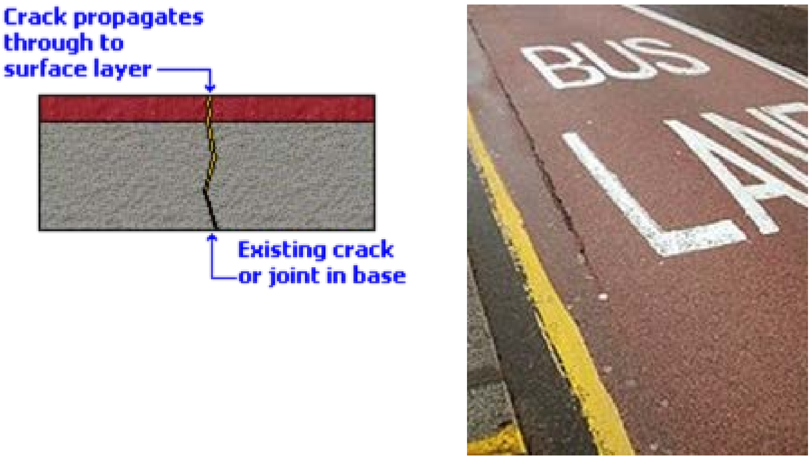
Similar to chipseals, specialist surfacing systems can fail cohesively and/or adhesively at the aggregate – binder interface. Chip loss is commonly associated with high-speed sites (Nicholls et al 2010). In addition, cohesive failures within the binder can be due to improper curing as a result of incorrect binder mixing ratio, insufficient curing time, or low temperature (Izeppi et al 2010). Adhesive failures between the aggregate and the binder can be due to surface contamination (including moisture) of the aggregate, chemical incompatibility of the aggregate and binder, and other construction issues such as the binder setting before application of the aggregate. In addition, over-application of chip or under-application of binder can also result in chip loss.

2.3.3 Crack failures

2.3.3.1 Reflective cracking

Reflective cracking (figure 2.2) occurs when an existing crack or joint in the substrate enables a higher-than-normal movement as a result of traffic loading and it propagates through to the surface layer as the resin-based layer is stretched beyond its designed specification. This is often seen on thin surfacing systems applied over jointed concrete substrates (Nicholls et al 2010). Binder material properties such as tensile strength and percentage elongation at break become important indicators of the surfacing layer's ability to cope with cracking.

Figure 2.2 (Left) Schematic diagram of reflective cracking; (right) Illustration of reflective cracking



Courtesy of AJ McCormack & Sons

2.3.3.2 Stress- induced/fatigue cracking

Cracking in specialist surfacing systems can be due to high stress and/or fatigue. If the adhesive bond is good, then the load is more likely to be transferred to the substrate, which means that any stress-induced or fatigue cracking of the substrate will be likely to propagate through the specialist surfacing layer by reflective cracking (Simpson 2005; 2006a; 2006b). For typical deflections, the fatigue resistance of a specialist surfacing system exceeds that of the substrate. However, if the adhesive bond is poor which often results in delamination, the strains generated in the thin specialist surfacing are much greater and cracking will occur. Cracking of the thin surfacing system layer will generally be a function of the substrate on which it is laid rather than of the overlying thin surface system (Nicholls et al 2010). Unless, of course, if the surfacing system is over-applied, then the thick layer can act independently and is more prone to delamination and cracking (Nicholls 1998).

Despite the lack of mention in the literature of specialist surfacing systems, top-down cracking should be considered as it is another common stress-induced failure mode in asphalt surfaced pavements (Roque and Ruth 1990; Uhlmeyer et al 2000; De Freitas et al 2005). Arnold et al (2014) suggest that top-down cracking in asphalt surfaced pavements may be explained by bending-induced surface tension as the surfacing and its underlying substrate deform under a heavy wheel load and/or shear-induced near-surface tension at the tyre edge.

2.3.3.3 Thermally induced cracking

A mismatch in thermal expansion coefficient (CTE) can lead to high thermally induced stress at the interface between the surfacing material and the substrate. If the internal stress generated is sufficiently high to break the adhesive bond between the two materials then delamination and subsequently cracking of the surface material may occur. If the adhesive bond strength exceeds the cohesive strength of the surfacing then thermally induced cracking will occur without delamination. The general consensus amongst the project steering group was that given the relatively small percentage of New Zealand roads using specialist surfacing and the corresponding climate conditions, failures by thermal cracking can occur but do not currently pose a significant threat in New Zealand. In countries with extremely cold climates, moisture trapped below the impermeable specialist surfacing system can undergo freeze-thaw action which may lead to severe ravelling or delamination (Izeppi et al 2010). In NSW, Australia, there have been reports of thermal cracking in specialist surfacing (Neaylon 2014). As there was no sign of cracking in the underlying asphalt substrate, nor any significant delamination, it was concluded that the failure was due to mismatch of the CTEs of the specialist surfacing system and the substrate.

2.3.4 Cohesion failures

Given the improved practice of HFS construction in New Zealand in recent years, there are fewer reported failures due to delamination and chip loss. Waters (2011) reported that in the majority of cases from the late 1990s and early 2000s, the premature failure was caused by cohesive failure within the top 20mm of the underlying asphalt. Specialist surfacing systems are designed for high trafficked sites with significant shear stress on the surface. When specialist surfacing is well bonded to the substrate, the high traffic stress is transferred to the underlying substrate. In this case, a cohesive failure means that the cohesive strength within the substrate is weaker than the bond between the specialist surfacing and the substrate.

2.3.5 Summary

Specialist surfacing systems can fail cohesively and/or adhesively. Hence:

- In order to predict the potential of cohesive failures within the substrate, the cohesive bond within the substrate has to be tested. This is particularly critical when the adhesive bond between the surface layer and the substrate is good and thus any stress on the surface layer is likely to be transferred into the substrate.

- In order to predict the potential of adhesive failures such as delamination and chip loss, a test that assesses the adhesive bond strength of the binder is required.
- There is also potential for the surface layer to fail by cracking. In this case, the binder properties such as tensile strength become important.
- In addition, a mismatch between the coefficients of thermal expansion can lead to stresses in the interface of the specialist surfacing and its underlying substrate, and potentially breaking the bonds.

2.4 Current specifications and test procedure

2.4.1 Current state-of-the-art in New Zealand

According to P25, the surfacing system (surfacing as well as the substrate) is expected to have a life of six to eight years with zero or minimal maintenance. The specification does not apply to coloured surfacings, which are covered by a separate performance specification (P33) currently under development by the Transport Agency in consultation with the industry.

In section 2.1 of the current P25 pilot specification, the definition for calcined bauxite systems includes the substrate as one of the components. While a best practice for ‘substrate surface preparation’ is prescribed in the pilot notes, NZTA P25PN: 2011 (P25PN), there is no specific performance test requirement for the substrate. The only relevant statement made on the substrate performance criteria is in section 3: Performance requirements: ‘The substrate shall be strong enough to resist failure planes through the substrate’. However, the exact strength is not quantified. The intention of this research work was to recommend a practical test under section 3: Performance requirements.

Currently the calcined bauxite systems are required to meet performance measures, such as skid resistance and binder/aggregate retention, for the first two years as the defect liability period. In the case of skid resistance, this is measured by SCRIM coefficient and macrotexture. For binder and aggregate retention/loss, the ability of aggregate to adhere to binder and/or the failure of binder to adhere to substrate or substrate failure, is measured against a defined percentage of a defined area within the site (see P25 for further details).

There is currently no approval system for HFS products or installers in New Zealand. The P25 specification does, however, require contractors to provide the following documentation for the supply and installation of calcined bauxite system (HFS systems):

1. Internationally recognised certification, if available (eg Roads and Bridges Agrément Certificate under the BBA HAPAS, classified as type 1 (see table 2.1)
2. Written references from local authorities if certification in accordance with (1) above is not available
3. Evidence that the resin binder manufacturer, or their New Zealand agent, has agreed to the Contractor’s use of their product, and any conditions attached to this
4. Test results from at least one calcined bauxite site within New Zealand or overseas which is more than three months old, and comprises the same calcined bauxite system and its components
5. Quality assurance documentation
6. Health, Safety and Environmental Plan; HSNO materials safety data sheets which meet the New Zealand Code of Practice
7. Installation method statement.

While ‘tensile strength’ and ‘% elongation at break’ are mentioned in P25PN as potential tests to be carried out by International Accreditation New Zealand laboratories as part of the quality assurance documentation, there is no specific mention of the exact test method and no pass/fail criteria is specified.

2.4.2 Product assessment and certification

Currently the most internationally recognised certification for specialist surfacing products is administered by the BBA under HAPAS.

Suitable areas for use of these systems are classified into three types (see table 2.1) by the UK Highways Agency, and, when applied appropriately, are expected to give a service life of 5 to 10 years.

Table 2.1 Classification of sites for specialist surfacing systems

Site category	**Site description**	**Maximum traffic levels (commercial vehicle per lane per day)**		
		Type 1/T_H	Type 2/T_M	Type 3/T_L
Q	Approaches to and across minor and major junctions, approaches to roundabouts	3,500	1,000	250
G1	Gradient 5% to 10%, longer than 50m			
S1	Bend radius <500m – dual carriageway			
R	Roundabout			
G2	Gradient >10%, longer than 50m	2,500	750	175
S2	Bend radius <500m – single carriageway			
K	Approaches to pedestrian crossings and other high risk situations	2,500	500	100

Sources: Highways Agency (2004); BBA (2005; 2008)

The assessment and certification process, which consists of the six stages listed below, is detailed in the guidelines documents (BBA 2005 and BBA 2008).

1 Assessment of applicant’s data

2 Assessment of factory production control

3 Laboratory testing (and optional tests)

4 System installation trial

5 System performance trial (if applicable)

6 Certification

The following section reviews the laboratory testing and optional tests along with other tests available for studying the ability of the surfacing systems to cope with different modes of failure.

2.4.3 Current laboratory tests

The laboratory testing required by the HAPAS process, as described in the *TRL report 176* (Nicholls 1997), consists of:

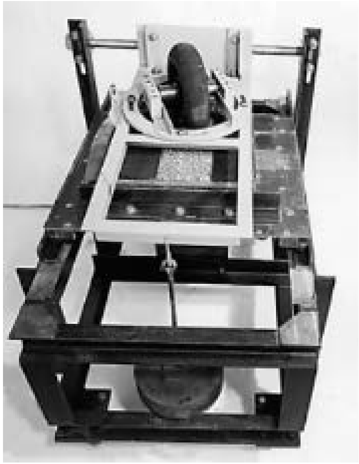
- simulative tests – scuffing, wear and tensile adhesion
- conditioning tests – heat ageing, freeze/thaw, and diesel susceptibility
- thermal movement test
- optional tests – installation temperature, substrate texture depth and concrete substrate.

All of the tests, except for thermal movement and some of the optional tests, are carried out using a standard asphalt slab, fabricated according to specifications in Nicholls (1997). This ensures the certification process is carried out using a benchmark substrate, and the properties measured are that of the surfacing system.

2.4.3.1 Scuffing

The test consists of a wheel tracker type apparatus as shown in figure 2.3 with a loaded pneumatic tyre wheel positioned on an angle to the direction of the moving test specimen. It simulates the turning action of traffic and thus the scuffing motion on the HFS. It is designed to assess the bond of the HFS to the underlying substrate. The test has been validated (Nicholls 1997) to identify potential for de-bonding (delamination).

Figure 2.3 Scuffing wheel- tracking test machine



Source: Nicholls (1998)

2.4.3.2 Wear

This test is designed to simulate the long-term wear and chip loss caused by turning traffic. The test is conducted at 10°C on a circular testing machine as illustrated in figure 2.4. The wear resistance is measured by texture depth and skid resistance value before and after 100,000 wheel passes.

Figure 2.4 Circular road machine no.1

Source: Nicholls (1998)

2.4.3.3 Tensile adhesion

This test determines the tensile force required to break the adhesive bond between the surfacing system and the substrate or between the aggregate and the binder, whichever is less. For this test, the specialist surfacing system (including aggregate) is applied on the standard asphalt slab, and a 100mm x 100mm steel plate is glued on top of the surfacing system. The test plate is then pulled off using a tensile pull-off apparatus where the load required is measured. In practice, the adhesive used for the steel plate has to have a tensile strength of at least 4N/mm^2 (MPa). Two test temperatures (-10ºC and 20º) are used. Other variations of pull-off tests and bond strength tests are discussed later in this chapter.

2.4.3.4 Conditioning tests

There are three types of conditioning tests: heat ageing, freeze/thaw and diesel susceptibility. They are all designed to assess the surfacing system's resistance to environmental ageing. All three tests utilise the scuffing test as described earlier to determine the effects of different environmental conditioning.

2.4.3.5 Thermal movement

This is a test to determine the thermal expansion coefficient of the HFS system, excluding the underlying substrate. The test is conducted in the temperature range from 5ºC to 45ºC. This simple test involves measurements of the distance between two reference points placed on the binder system at various temperatures, namely 5ºC, 15ºC, 35ºC, and 45ºC. The reference points move as the temperature changes. The test is repeated three times to produce a mean value of the thermal expansion coefficient.

2.4.3.6 Optional tests

The optional tests are designed to confirm the manufacturer's claims of using the surfacing system under non-standard conditions such as installation temperature, substrate texture depth and concrete as the substrate. The performance is assessed by conducting the scuffing test and/or tensile adhesion test on the asphalt or concrete slabs prepared to the conditions as claimed.

The tests, as part of the BBA/HAPAS certification process, are fit-for-purpose from a product approval point of view. However, they exclude the effect of the underlying substrate, and thus cannot predict the cohesive failure of the substrate nor the actual adhesive bond between the system and the real substrate.

It is also impractical to assume that contractors have access to machines such as the wheel tracker or the circular road machine used for the wear test. The tensile adhesion test discussed above has been demonstrated to be useful in determining adhesive bond of the surfacing system. However, it was found to be inadequate in addressing cohesive issues of the substrate, which is why the Leutner shear test or another field bond test is suggested.

The thermal movement test is a very simple but effective method to measure thermal expansion coefficient, and it has potential to determine thermally induced failures. However, it needs further work to focus on the extent of mismatch between the binder and its substrate. This may be achieved simply by measuring the thermal expansion coefficient of the substrate using the same technique. A mismatch could indicate internal stress build-up during heating/cooling cycles, which can ultimately lead to failure.

2.4.4 Other tests

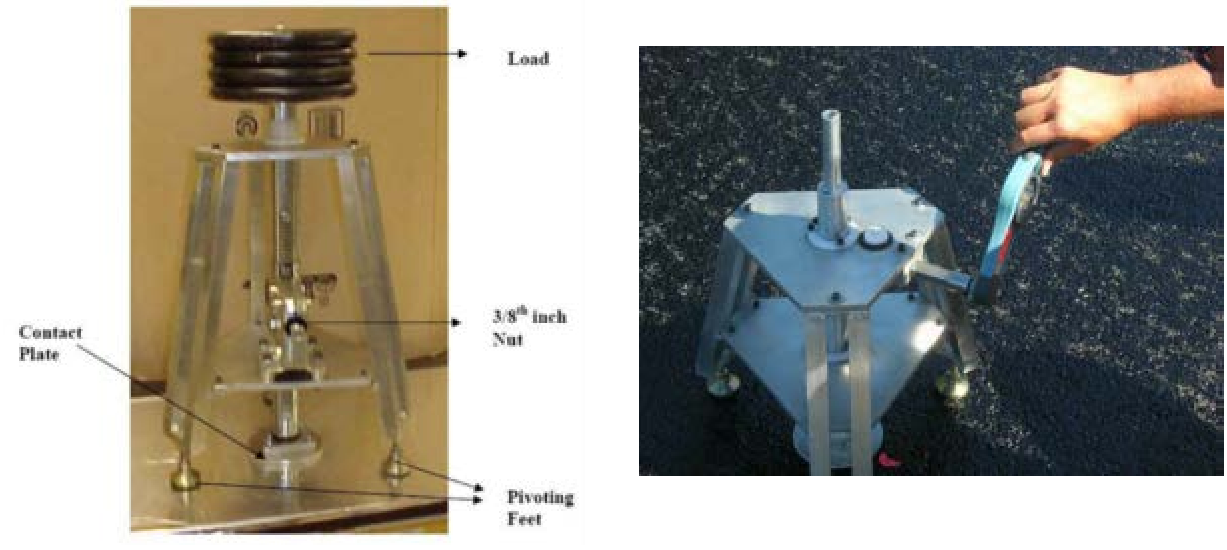
2.4.4.1 Peel- off test

Originally, a peel-off test was developed as part of the Transport Research Laboratory (TRL) testing procedure to evaluate the bond between the high-friction surface and the substrate (Nicholls 1997). However, it was excluded from the procedure as it has not been fully assessed yet. It was suggested that a shear test that mimics the forces applied to the surface by vehicles stopping abruptly might be more appropriate.

2.4.4.2 UTEP pull- off test

The UTEP pull-off test was developed at the University of Texas at El Paso (UTEP) to evaluate tack coats (Tashman et al 2006). It measures the bond strength of the tack coat by applying a torque to break the contact plate, as shown in figure 2.5, away from the tack coat material.

Figure 2.5 (Left) UTEP pull- off device; (right) the device with torque wrench in the field



Source: Tashman et al 2006)

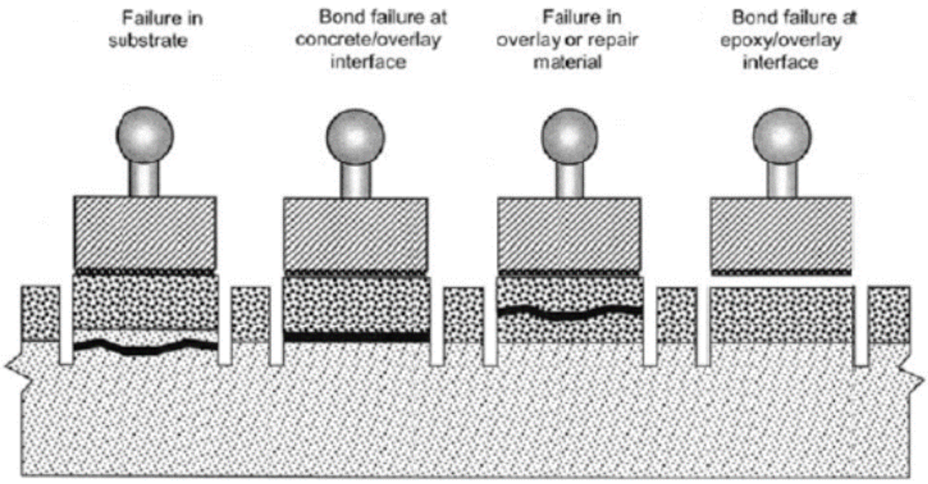
2.4.4.3 ASTM C1583 pull- off method

ASTM C1583-13 (ASTM 2013a) is a standard direct tension test used for measuring tensile strength of concrete surfaces and the bond strength or tensile strength of concrete repair and overlay materials on bridge decks (Young et al 2014). Like many other bond test regimes, a steel disc/plate is adhered to a scored circle on the road surface, and a hydraulic or pull device (figure 2.6) is attached. The force at failure will indicate the type of failure and bond strength of the test subject as illustrated in figure 2.7.

Figure 2.6 (Left) A pull- off bond test device; (right) the device in action

Source: Young et al 2014

Figure 2.7 Bond test failure modes according to ASTM C1583- 13

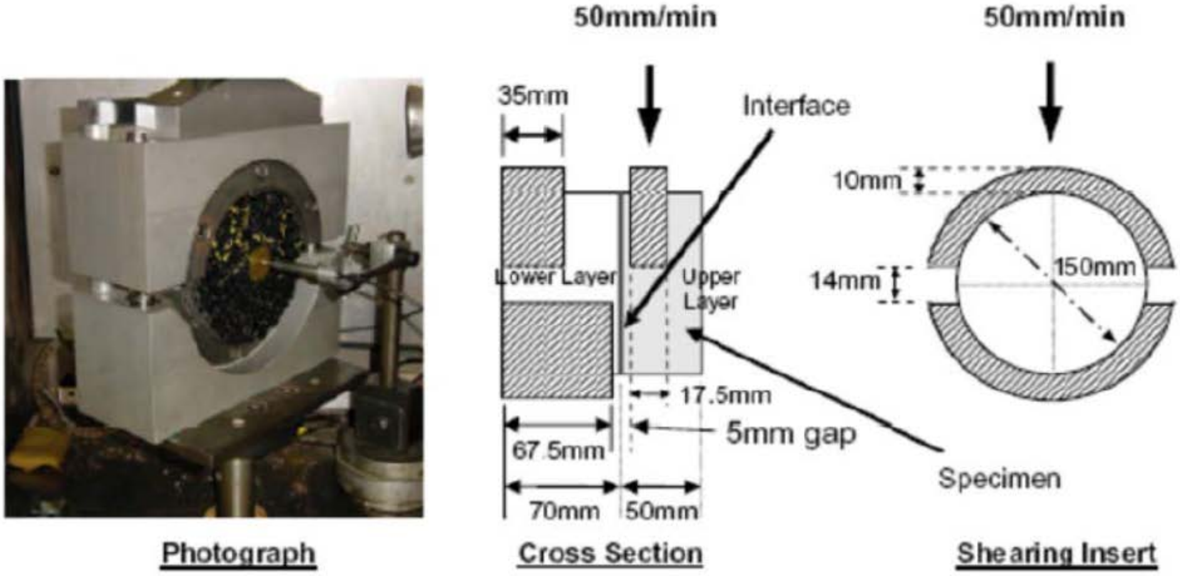


Source: ASTM (2013a)

2.4.4.4 Leutner shear test

The Leutner test was developed in Germany (Leutner 1979) in the late 1970s to conduct shear test on bond between two asphalt layers using a standard material testing system. Figure 2.8 illustrates the testing set up in principle. The test applies a constant displacement rate across the interface between two layers of materials, and the resulting shear force is measured. The peak shear stress, displacement at peak shear stress and shear stiffness (modulus) are typically measured or calculated. There are several variations of this shear test, and numerous studies have demonstrated the potential of such test in measuring the bond strength of stress alleviating membrane interlayers (Molenaar et al 1986), interfaces between pavement layers (Collop et al 2003; 2009), and HFS systems and asphalt mixes (Arnold et al 2014).

Figure 2.8 Leutner shear test



Photograph Cross Section Shearing Insert

Source: Collop et al 2009

2.4.4.5 Torque bond test

The torque bond test was developed in Sweden for field testing of asphalt interfaces and has been adopted in the UK as part of the approval system for thin surfacing systems (Walsh and Williams 2001). It is generally used on interfaces between thin surfacing and its underlying layer and would be ideal for the specialist surfacing systems. For this simple procedure, the pavement is cored to a depth that includes the interface under investigation. A metal plate is glued to the top of the core and a torque applied to the top of the core until failure. The measured torque at failure will indicate the thin surfacing bond strength or potentially the cohesive strength of the underlying substrate if that fails first (Wheat 2007). Tashman et al (2006) modified the test by clamping the core specimens in a device shown in figure 2.9 for testing in a laboratory. The weakness of this test is the lack of control in loading speed (Xiao et al 2012).

Figure 2.9 Torque bond testing device

Source: Tashman et al 2006

2.4.4.6 Flexural beam test

Arnold et al (2014) investigated the flexural beam test method for specialist surfacing resins and found that the majority of the specialist surfacing resins commonly used in New Zealand are very flexible at two test temperatures (5ºC and 20ºC). The resins can tolerate high strains (>40,000 microns). However, while the test results show that the majority of the binder systems available are flexible enough to cope with high deflections, the test method did not address adhesive or cohesive bond strengths between the specialist surfacing resin and the underlying substrate. A recommendation was made by Arnold et al (2014) to investigate the suitability of an elongation measurement which is much simpler and potentially more appropriate for measuring ductility.

The pavement curvature (D_0-D_{200}) was also discussed in Arnold et al (2014). Based on the high ductility of the specialist surfacing resins, it was concluded that D_0-D_{200} would have to enter the ‘rutting’ range, ie >5mm to cause enough strain to crack the specialist surfacing material. It is important to note that typically a D_0-D_{200} value of more than 0.2mm can invoke high enough strains to cause cracking as well as fatigue failure of a typical asphalt.

2.4.4.7 Tensile test/% elongation at break

This is a very common test method for measuring material behaviour under tension. One of the properties commonly used by specialist surfacing manufacturers is % elongation at break. This gives the % strain (extension over original length) of the test subject at failure under certain test conditions.

The BBA product certification guideline refers to BS 6319-7:1985 (BSI 1985) and BS EN ISO 527-1:2012 (BSI 2012) for measuring tensile properties of the binder systems. The principle of the test is to subject the test specimen of a defined dumb-bell geometry to a tensile force until failure of the specimen occurs. The test is normally conducted at 20ºC with the specimen conditioned at the temperature for at least 16 hours. The test result is considered invalid if the line of fracture occurs outside the middle third of the specimen. At least three valid measurements are required to report a valid tensile strength. For BS EN ISO 527-1:2012, the testing machine should comply with ISO 7500-1 (ISO 2004) and meet the specifications given in the standard. The test speeds are given in a recommended range of 0.125–500mm/min.

ASTM D638-10 (ASTM 2010), which is technically equivalent to BS EN ISO 527-1:2012, is the most recent ASTM standard for measuring tensile properties of unreinforced and reinforced plastics in the form of standard dumb-bell-shaped test specimen. The standard defines conditions for specimen pre-treatment, temperature, humidity, and testing machine speed. It is suitable for testing samples of thickness up to 14mm. However, for thin sheets and films of less than 1mm thickness, ASTM D882-12 (ASTM 2012) is the preferred method.

2.4.4.8 Crack bridging ability

ASTM standard test method C1305-08 (ASTM 2008) is designed to determine the ability of a waterproofing membrane layer to bridge a crack in the substrate. It is, however, debatable whether or not the specialist surfacing systems should be able to bridge cracks in the pavement substrate. This may be more suited to crack repair products.

2.4.4.9 Shear modulus by dynamic shear rheometer

AASHTO T315-12 (AASHTO 2012) describes a test that is commonly used for testing rheological properties such as shear moduli of bitumen binders using a dynamic shear rheometer (DSR). It may be adopted to test the ductility of specialist surfacing binders. However, the main concern is that the torque capacity of a standard DSR may be too low for some of the non-bitumen binders once cured.

2.4.4.10 Tests for thermally induced failures

In addition to the thermal movement test as developed by TRL (Nicholls 1997), there are many other potential candidates for test regimes. Arnold et al (2014) suggests that ASTM D7051-05 (ASTM 2013b) may be suitable for further investigation into predicting thermal induced failures, where the coefficient for thermal expansion is an important property to measure and understand.

Xu and Solaimanian (2008) developed a test method for measuring thermal expansion and contraction of asphalt concrete as the property played a significant role in the thermal fatigue and low-temperature cracking of AC pavements in the US.

Low-temperature cracking performance of asphalt mixes can also be assessed using the thermal stress restrained specimen test (TSRST) according to AASHTO standard TP10-93 (AASHTO 1993). Based on data collected from four test roads across the US as part of a Strategic Highway Research Program contract, Kanerva et al (1994) concluded that cracking behaviour of the test roads could be explained with TSRST fracture temperatures and the TSRST could be used in the prediction of low-temperature cracking of asphalt-aggregate mixtures. Mohammad et al (2013) applied TSRST to asphalt mixes modified with bio-derived binders to determine the low temperature cracking performance.

There is a wide range of tests for determining low temperature properties developed for bitumen binders and asphalt mixes. Apart from TSRST, there is also the bending beam rheometer test (Shenoy 2002), direct tension test, semi-circular bending (Im et al 2013), asphalt binder cracking device (Kim et al 2006), and the DSR (Wen and Bhusal 2013). Tabatabaee and Bahia (2014) have modified some of these techniques to test asphalt pavements for crack prevention. While fracture-based tests are generally accepted as the most promising to predict low-temperature cracking, there is merit in refining the existing thermal movement test (Nicholls 1997) which is a much simpler technique for investigating thermal expansion coefficient mismatch.

2.5 Candidate tests for development

Premature failures of specialist surfacing systems can be due to poor construction method and failure to follow manufacturers' guideline. However, this can only be minimised by implementing good quality control through specification and selecting competent contractors. The current specifications include test methods appropriate for determining functions such as skid resistance of the specialist surfacings, but do not address failure modes.

For development of a test to predict the potential for failure of a specialist surfacing system, it is necessary to assume the system meets product specifications and guidelines are properly followed during construction. For the specialist surfacing system to work effectively, bond strengths between the binder and the aggregate as well as that of the system and the substrate are very important. Hence, predicting failures due to the breakage of one of those bonds was the focus of this research.

The following candidate tests were recommended for further consideration:

2.5.1 Adhesion/cohesive strengths

2.5.1.1 Pull- off/ASTM C1583

The pull-off test based on ASTM C1583-13 (2013a) is attractive because it is a standard test method commonly used for measuring tensile strength of concrete surfaces and the bond strength or tensile strength of concrete repair and overlay materials on bridge decks. It can be easily adopted to specialist surfacing on asphalt substrates, and thus predict potential of delamination, chip loss and other adhesive strength-related failures. The only concern is whether a direct tensile force is realistic enough to simulate the traffic loading on the specialist surfacing system, which is designed for high friction and thus high shear loading should be more relevant.

2.5.1.2 Leutner shear test/torque bond test

Arnold et al (2014) conducted the Leutner shear test on several specialist binder products as well as asphalt mix cores. The test not only measures the adhesive strength of the binders but also the cohesive strength of the asphalt substrate. This test could be conducted prior to construction, when cores of the substrate on site are taken. The specialist surfacing system is then applied according to the manufacturer's guidelines. The results would help to predict the potential for delamination due to poor adhesive strength as well as cohesive failure of the substrate.

The torque bond test is an alternative 'shear-type' test where its application is very similar to the ASTM C1583-13 pull-off method. Its appeal lies in the ability to do field testing as well as providing a shear type loading to the test specimen. The only weakness of this method compared with the Leutner shear test is that the loading rate or test temperature is not controlled, although the latter at least may be resolved by further modification of the equipment.

2.5.2 Crack resistance

2.5.2.1 Tensile test/% elongation at break

While flexural beam testing (Arnold et al 2014) can distinguish different levels of ductility in the resins, it makes more sense to conduct a simpler test such as direct tensile testing. This test measures the ability of the resin-based binder to elongate under tension, which can be related to its ability to bridge cracks. While this property is not considered a priority, it does affect how the surfacing behaves under loading.

In specialist surfacing systems, the potential of failure by cracking appears to be driven by the underlying substrate provided the surfacing is thin and adheres well to the substrate. The tensile test can be conducted at different temperatures and therefore a ductile-to-brittle transition temperature may be captured. The test results will provide confidence the binder is able to cope with expected traffic deflections and deform elastically over the expected temperature range.

2.5.3 Thermal cracking resistance

2.5.3.1 Thermal expansion coefficient mismatch

An extension to the 'thermal movement' test as part of the HAPAS test regime (Nicholls 1997) may be used to measure any mismatch between the coefficient of thermal expansion of the surfacing system and that of the underlying substrate. The key is to develop a pass/fail criteria for the maximum allowable mismatch.

3 Test development

3.1 Introduction

Based on the literature review, the pull-off test offers the best functions, in terms of identifying the weakest bond strength in a multi-layer structure such as specialist surfacing systems. The practicality of the pull-off test is the other main advantage over the other candidate test methods. Not only is the test method based on an established international standard (ASTM C1583-13), it is also easily adaptable from a laboratory environment to a field environment.

The test developmental plan was to investigate the effect of the following variables:

- mix design
- binder grade/viscosity
- oxidation/ageing
- thermal cycling (freeze/thaw).

3.2 Pull-off test

The pull-off test apparatus (figure 3.1) at Opus Research consists of a hand-cranked unit with a 12kN load cell. The apparatus is designed to work with 50mm diameter aluminium studs which are glued onto the test substrate (figure 3.2). At the point of failure, a digital readout of the force at break is displayed and recorded in kN after conversion using a calibration chart.

Please consult appendix A for full details of the test methodology.

Figure 3.1 Illustrations of a pull- off bond tester

Figure 3.2 Example of an asphalt substrate with calcined bauxite system in preparation

3.2.1 Mix design (substrate)

For the purpose of assessing this test method, various types of asphalt mix were chosen. Asphalt surfaces are the most commonly used substrates for specialist surfacing systems in New Zealand. While chipseals and concrete surfaces may be used as the underlying substrate, chipseal surfaces require specific resin systems to be able to cope with the viscoelastic nature of the seal. Concrete surfacing is not very common in New Zealand.

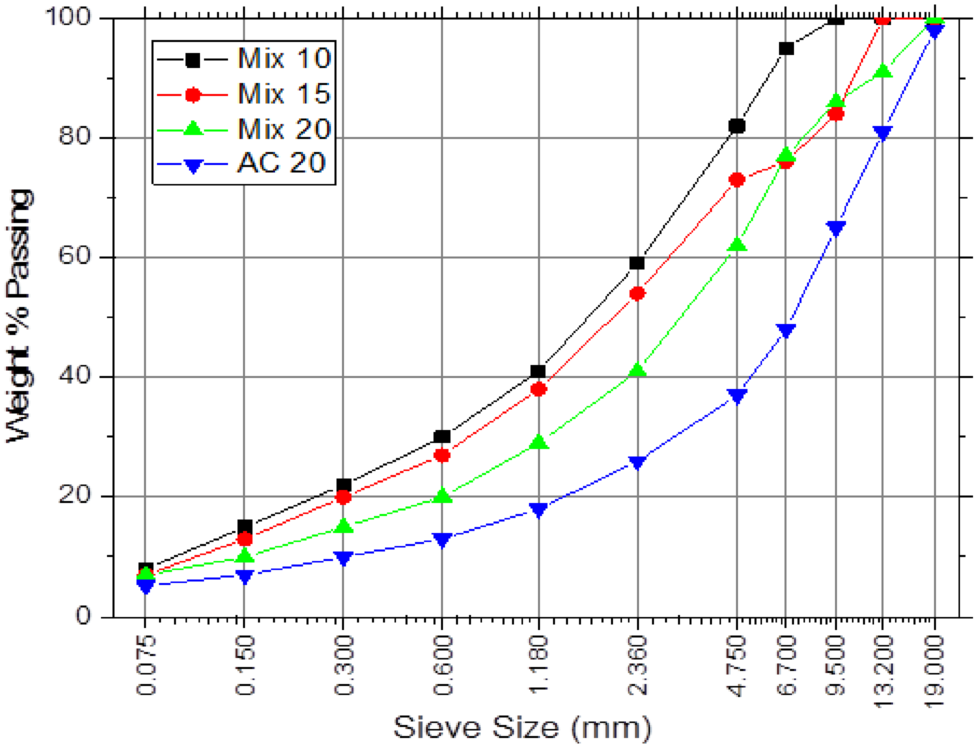
Four different types of asphalt mix were sampled from an asphalt plant in Wellington: mix 10, which is now designated as DG7 in the M10 specification (NZ Transport Agency 2014), mix 15, mix 20 and AC20. Marshal blocks (100mm diameter) were prepared using 75 blows per side. All of the mixes used an 80–100 penetration graded asphalt binder. Binder contents and grading of the mixes tested are given in table 3.1. Several large 150mm diameter field cores (of the same mix 20 asphalt (figure 3.3) were extracted from SH1 (Coast Road, Paekakariki, Wellington).

Figure 3.3 Illustration of a mix 20 asphalt sample cored from SH1 near Wellington and used as test substrate for a calcined bauxite system

Table 3.1 Asphalt mix grading and binder content

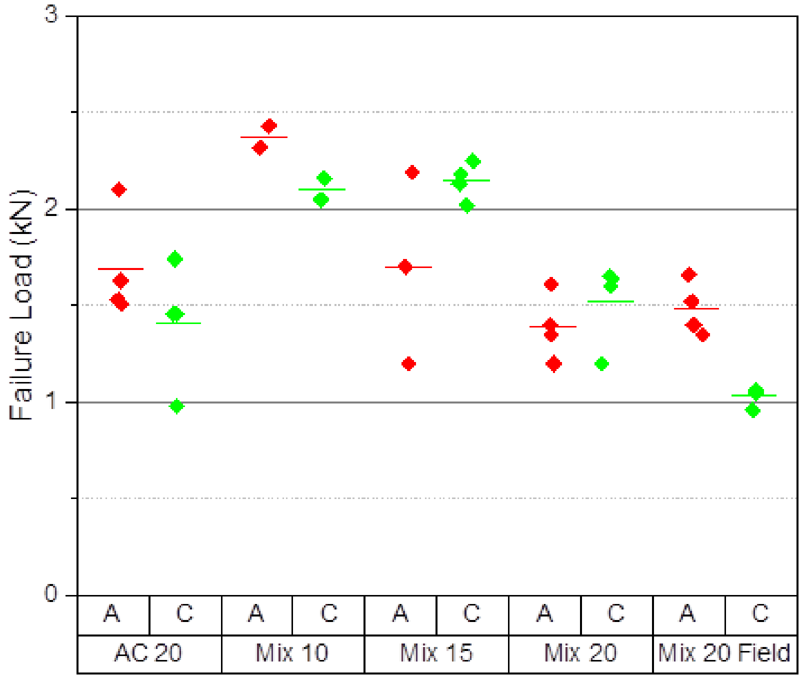
	% Mass passing			
Sieve size (mm)	**Mix 10**	**Mix 15**	**Mix 20**	**AC 20**
19	100	100	100	98
13.2	100	100	91	81
9.5	100	84	86	65
6.7	95	76	77	48
4.75	82	73	62	37
2.36	59	54	41	26
1.18	41	38	29	18
0.6	30	27	20	13
0.3	22	20	15	10
0.15	15	13	10	7
0.075	8	7	7	5.2
Binder content (% mass)	6.4	5.9	5.4	5.4

Figure 3.4 Gradation chart of various asphalt mix designs



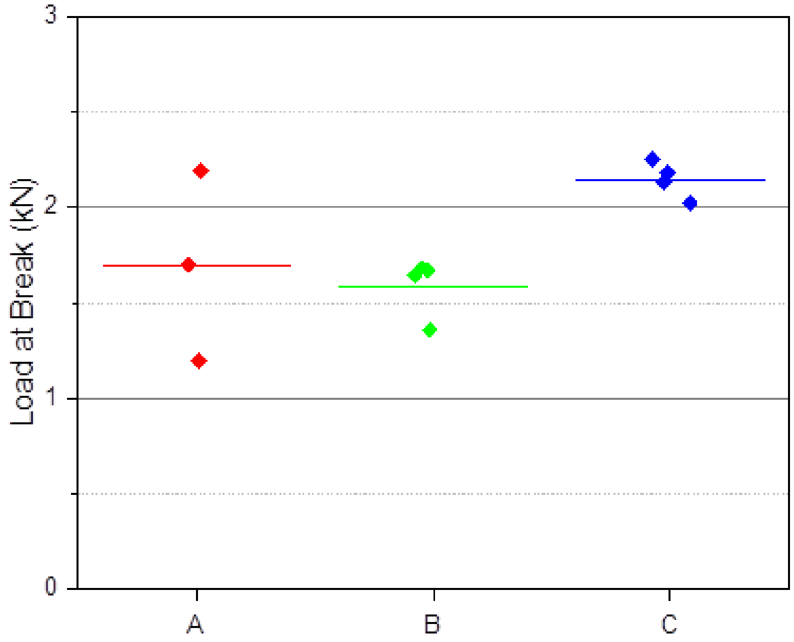
As expected, tests resulted in some scatter due to the variability in compaction as the majority of the test blocks were made in the laboratory. On the other hand, the field cores produced much more consistent readings. Despite the variance in actual failure loads, all of the systems failed cohesively within the asphalt substrate.

Figure 3.5 Failure loads of test substrates with A=polyurethane based and C=epoxy based calcined bauxite systems



In terms of absolute values, there is a minor difference in the cohesive failure loads between the blocks; the figures are typically between 1 to 2.5kN (equivalent to 0.5 to 1.3MPa on a 50mm-diameter area). However, based on analysis of variance (ANOVA) results, neither the mix gradations nor the types of specialist surfacing resin (figure 3.6) appear to have a significant impact on the cohesive failure loads of the substrate.

Figure 3.6 Mix 15 blocks with 3 different specialist surfacing systems (A and B = polyurethane based, C = epoxy based)



3.2.2 Effect of binder grade

Bitumen binder is graded by ‘penetration’ in New Zealand, each penetration grade has a characteristic range of viscosity which it is known to have an effect on the cohesive strength of a hot mixed asphalt. To demonstrate such effect, two grades of asphalt binders were compared using the proposed pull-off test method.

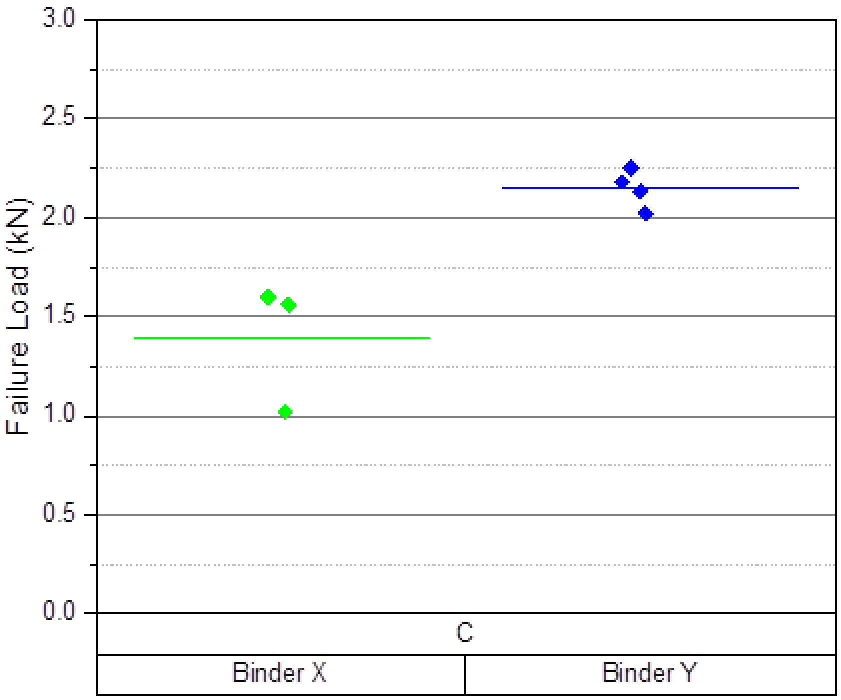
Binders X and Y were chosen and mixed with mix 15 aggregate (greywacke from Kiwi Point, Wellington) at 125°C until the aggregates were completely covered. Each block, which contained approximately 1kg of the aggregate mix with 5.5wt% binder, was compacted by a Marshall hammer for 75 blows each side. The blocks were left in a constant temperature room (23°C) for seven days before the resin system (including calcined bauxite chips) was applied. Properties of the binders are given in table 3.2.

Table 3.2 Extracted binder properties

Binder	Viscosity at 23°C (Pa.s)(0.005s^{-1})	Viscosity at 55°C (Pa.s)(0.005s^{-1})
X	810,700	900
Y	3,330,000	3,000

Both sets of blocks failed cohesively within the substrate, but those with the more viscous binder (3,000 Pas compared with 900 Pas for the softer grade) had significantly higher failure loads (figure 3.7).

Figure 3.7 Comparison of two different binders using the same mix design (mix 15) and the same high friction surfacing system (C)



The results highlight the relevance of binder properties to the substrate performance and the ability of the test procedure to clearly distinguish the different substrate strengths.

Further tests were conducted to investigate the effect of ageing of the asphalt during service. The sensitivity of the test method was tested by comparing results off freshly laid substrates against aged substrates oxidised by an accelerated ageing process in a laboratory environment. Methodology and results are discussed in the following section.

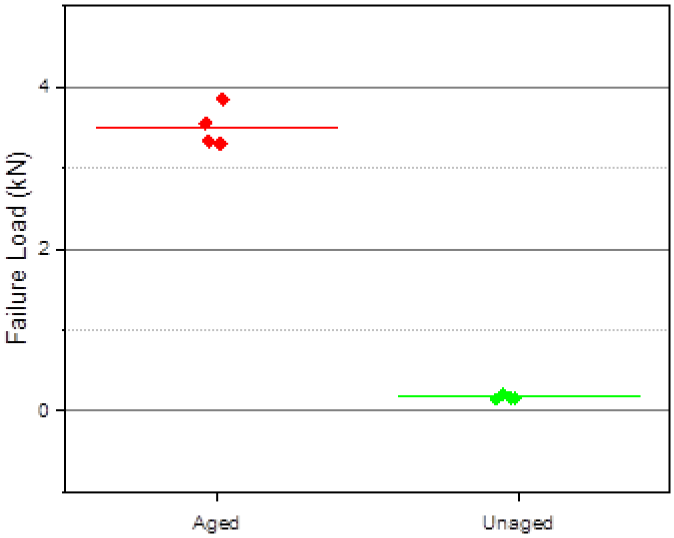
3.2.3 Effect of oxidation

The stiffness and viscosity of a binder can increase as a result of oxidation through ageing in the field. This will influence the cohesive strength of the asphalt substrate and thus impact on the selection process of substrate appropriate for a specialist surfacing. Asphalt blocks were intentionally aged in an oven for 40 days before the specialist surfacing systems were applied. The pull-off test results showed adhesive failure at the interface between the resin and substrate, indicating the cohesive strength of the substrate had exceeded that of the adhesive bond strength of the resin on the substrate.

Figure 3.8 (Left) Cohesive failure in the mix 15 substrate versus; (right) adhesive failure of the specialist surfacing system after ageing for 40 days

Two sets of mix 15 blocks (four blocks per set) were prepared. One set was tested straight away, two days after compaction. The other set was left in the 85ºC oven for 40 consecutive days before the specialist surfacing was applied and the strength measured. Figure 3.9 shows that the freshly compacted blocks were relatively weak and failed cohesively at a load of about 0.2kN. The oven-treated substrates were substantially stronger. The force reading exceeded 3kN before each block failed at the interface between the aluminium stud and the substrate. The adhesive failure at the interface between the resin and substrate indicated the cohesive strength of the substrate had exceeded that of the adhesive resin – substrate bond.

Figure 3.9 Effect of accelerated oxidation on cohesive strength of asphalt substrate



To confirm the results obtained with laboratory compacted specimens, tests were also conducted using 150mm cores of asphalt pavement were taken from northbound sections of Coast Road, SH1 (Paekakariki) north of Wellington six weeks after being laid. These field cores consist of mix 20 with 80–100 penetration grade bitumen. Two specialist surfacing systems were tested (one polyurethane-based and one epoxy-based formulation). Both sets of aged blocks failed at the calcined bauxite system/substrate interface (figure 3.10). Based on previous work with open graded mixes the 40-day oven treatment resulted in significant hardening of the binder equivalent of up to about 12 years in the field. Oxidation led to a substrate with high cohesive strength that well exceeded the adhesive strength of any of the specialist surfacing systems as well as that of the glue for the aluminium stud.

Figure 3.10 Example of an aged mix 20 core with an epoxy- based calcined bauxite system

Figure 3.11 Failure loads of aged (40- day treatment) mix 20 field cores increased as a result of ageing but the failure mechanism also changed from cohesive (substrate) to adhesive

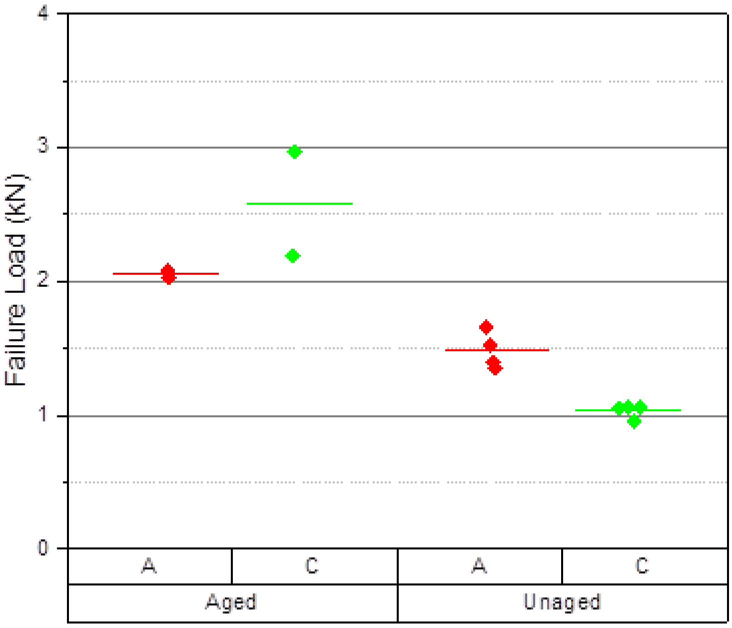


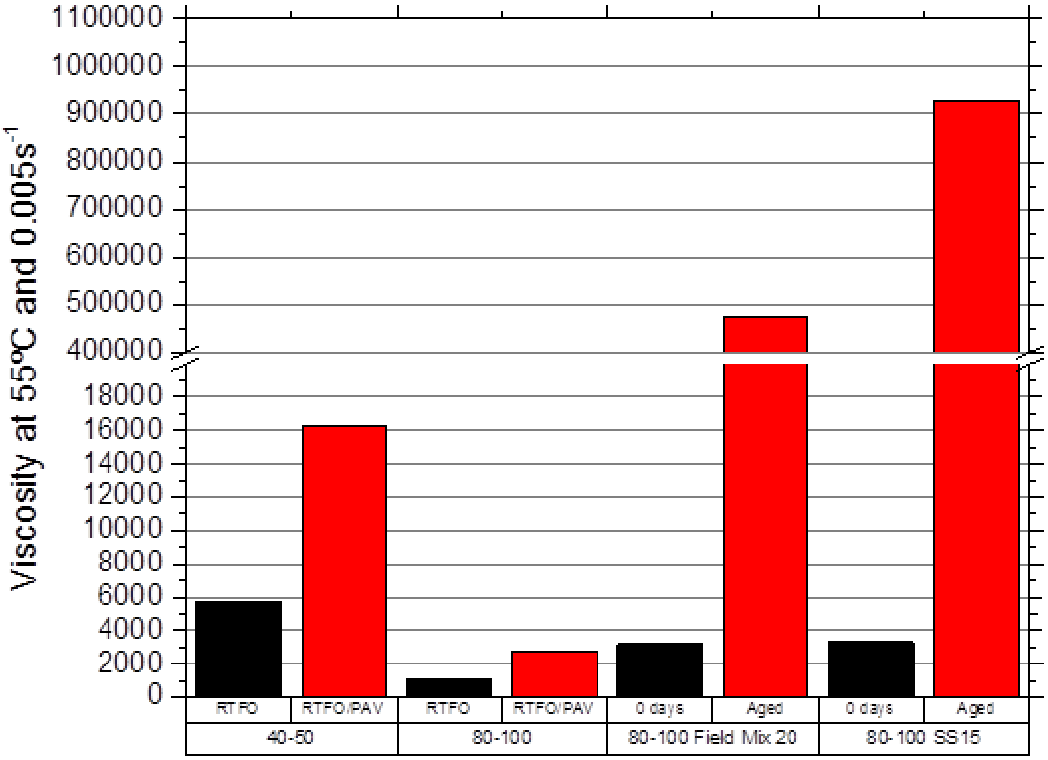
Figure 3.11 shows a summary of dynamic viscosity measurements of binder extracted from the field cores before and after ageing. For comparison with the binders extracted from the field, core samples of 40–50 and 80–100 bitumen were measured after rolling thin film oven and pressure ageing vessel (PAV) treatment. The rolling thin film oven treatment is a standard treatment to simulate the oxidation process during the manufacture of hot mix asphalt. PAV treatment is used to simulate field ageing. However, an earlier study (Herrington et al 2014) indicated that the PAV treatment according to the Transport Agency T/13 method specified in NZTA M1:2011 (NZ Transport Agency 2011c) (60ºC for 80 hours), only produced ageing equivalent to less than a year in the field.

The key observations are:

1 The initial binder viscosity of the field cores is similar to that of the laboratory-made blocks. It reaffirms the consistency of the pull-off test given that both mixes were made at the same Wellington plant and using the same 80–100 binder.

2 The aged binders in the field cores were extremely viscous, causing the substrates to gain significant cohesive strength and thus leading to adhesive failure at the interface.

Figure 3.12 Dynamic viscosity at 55ºC for bitumen binders with various treatments (SS15 = mix 15 blocks)



Further oxidation experiments were conducted using laboratory prepared mix specimens aged at various times up to 10 days at 85ºC. While the samples all failed cohesively within the substrates, the cohesive strengths all increased compared with the unaged specimens. Results for 10-day aged mix 10 samples are shown in figure 3.13.

Figure 3.13 Increasing cohesive failure loads of 10- day aged mix 10 blocks compared with unaged blocks of the same mix design

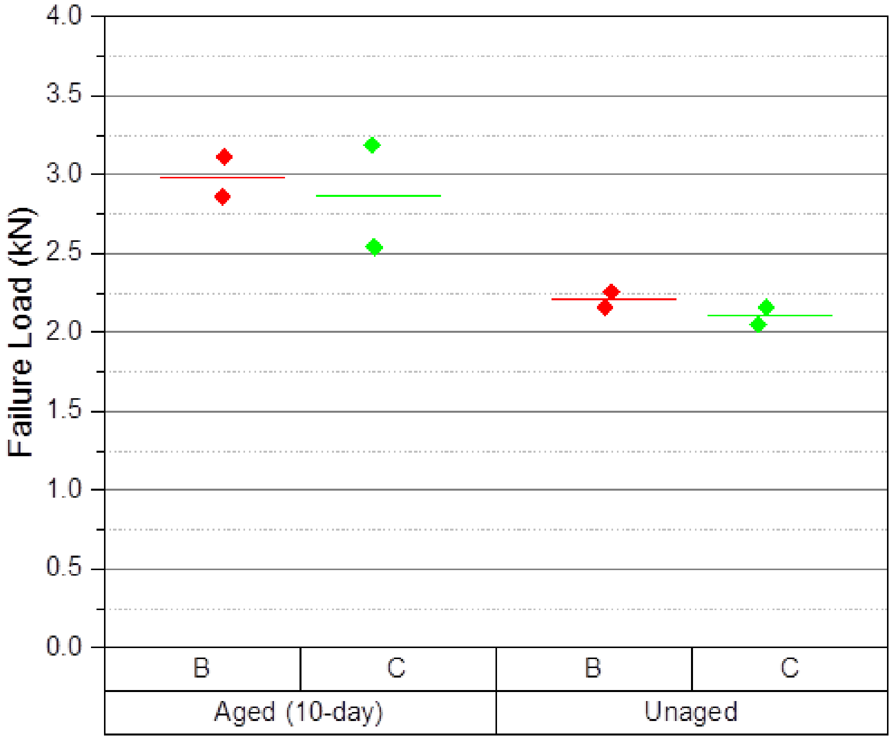


Figure 3.14 Failure load versus viscosity of bitumen binder

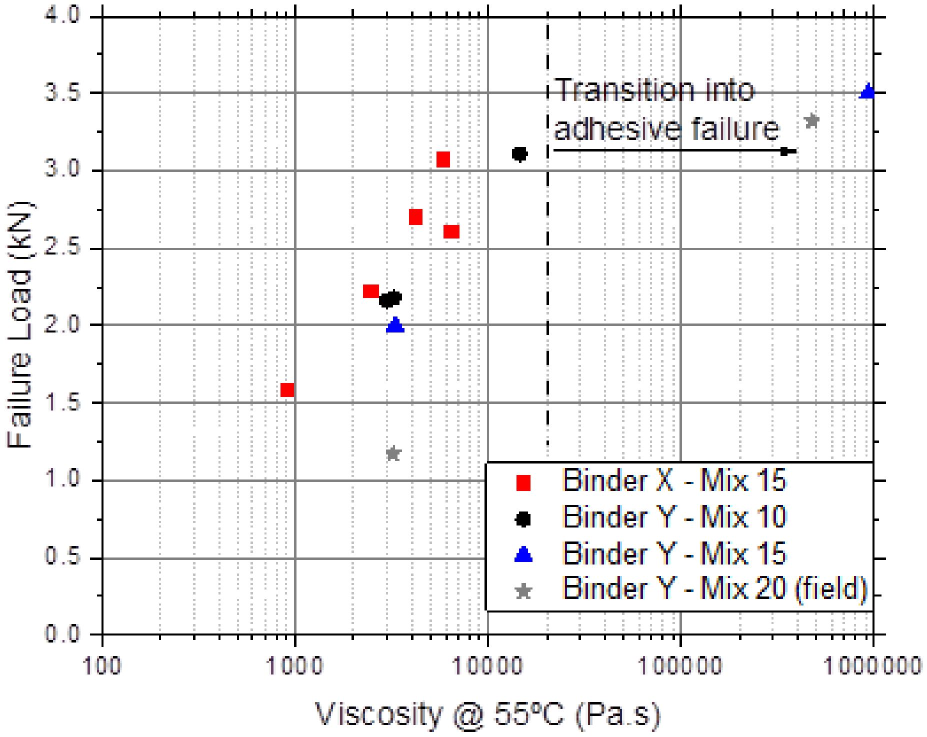
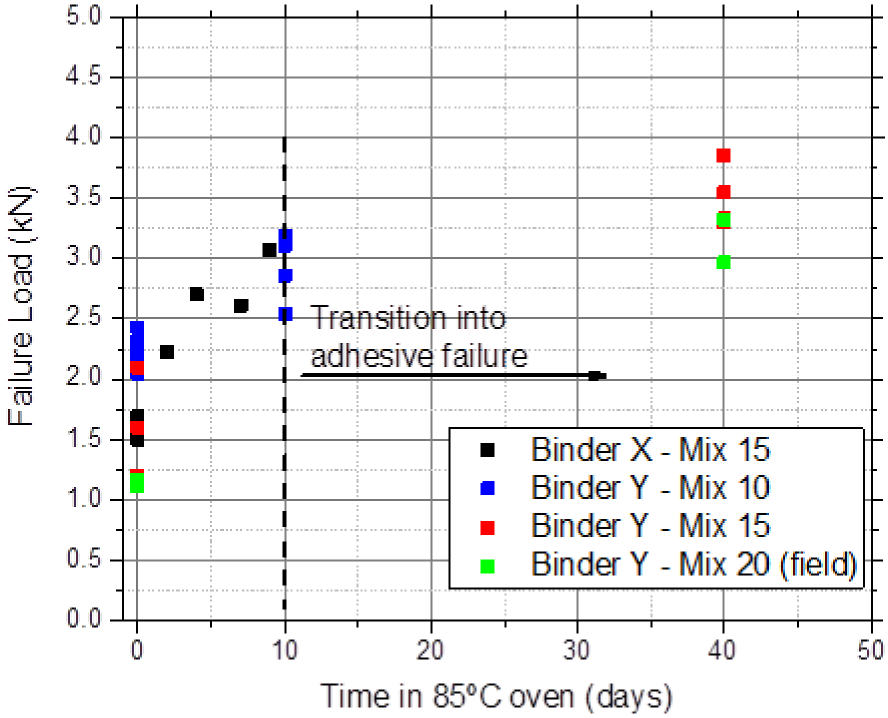


Figure 3.15 Failure load versus ageing treatment duration

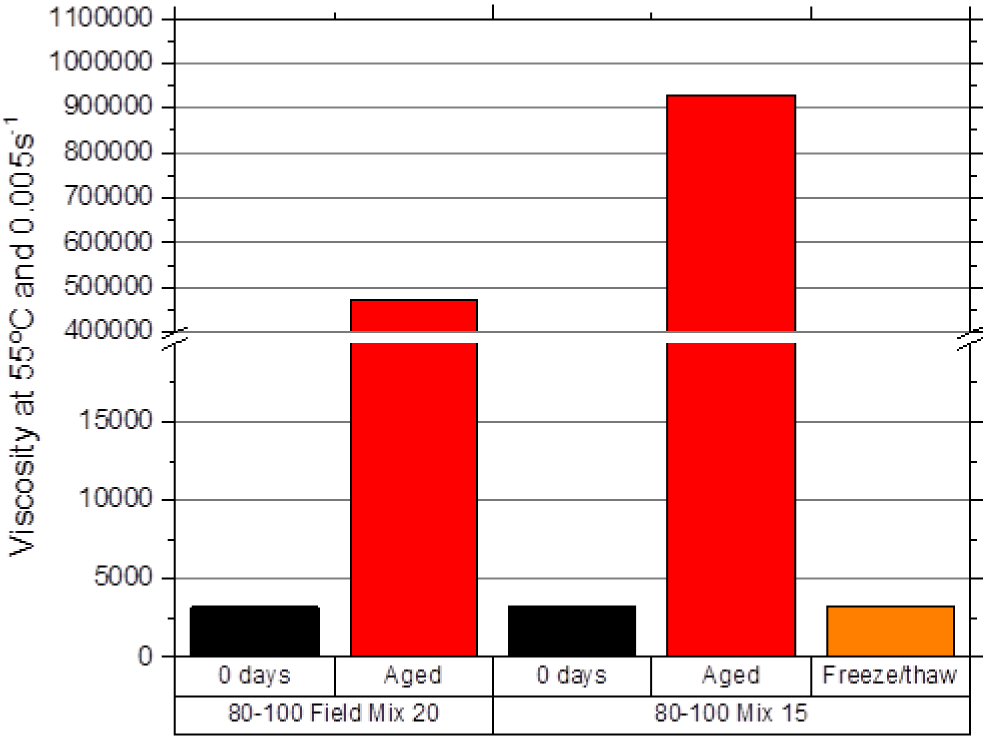


The effect of oxidation for all the mixes tested is shown as a function of the extracted binder viscosity in figure 3.14 and in terms of oven ageing time in figure 3.15. After 10 days of ageing at 85ºC, the failure mechanism began to transition from cohesive substrate failure to adhesive failure at the interface between the substrate and the resin system. This reinforces the need to measure substrate properties prior to the application of specialist surfacing systems in order to prevent premature failures.

3.2.4 Effect of freeze/thaw

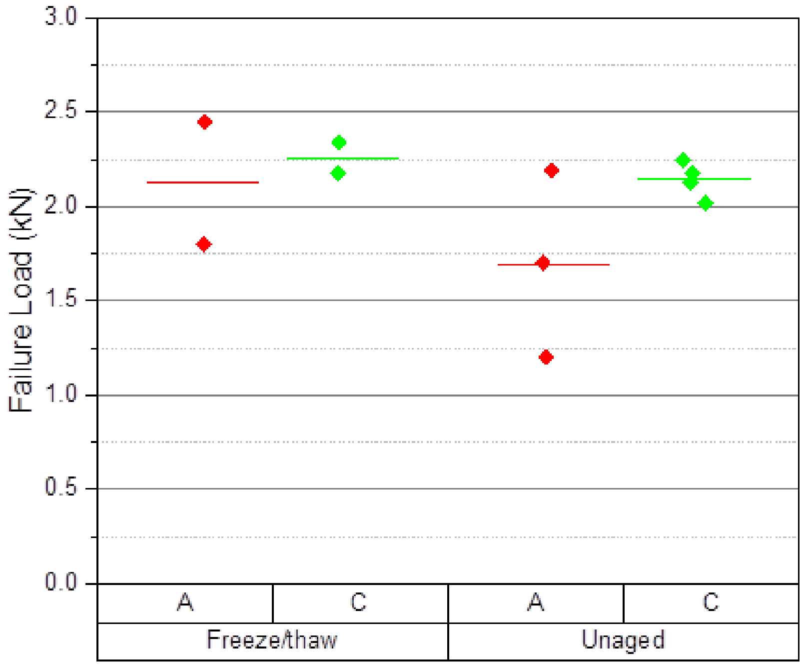
The effect of freeze/thaw cycling on the cohesive and adhesive bonds of the surfacing layers was investigated by subjecting assembled mix 15 asphalt blocks-specialist surfacing specimens to 10 cycles of thermal treatment which consisted of 10 heating/cooling cycles on 10 consecutive days. Each cycle of the treatment includes 16 hours in a freezer (at -18.9ºC) and eight hours (at 40ºC). The thermal cycling experiment did not have any impact on the viscosity, ie did not incur additional oxidation/ageing (figure 3.16). This is a positive result as this means that the effect of thermal cycling can be assessed independently.

Figure 3.16 Viscosity of 80- 100 bitumen binder was unaffected by the freeze/thaw thermal treatment



Potentially differences in the thermal expansion/ contraction of the materials may result in stresses that damage the surfacing-substrate bond. Results are presented in figure 3.17.

Figure 3.17 Effect of 10 freeze/thaw cycles on the failure strength of specialist surfacing systems on mix 15 asphalt substrates

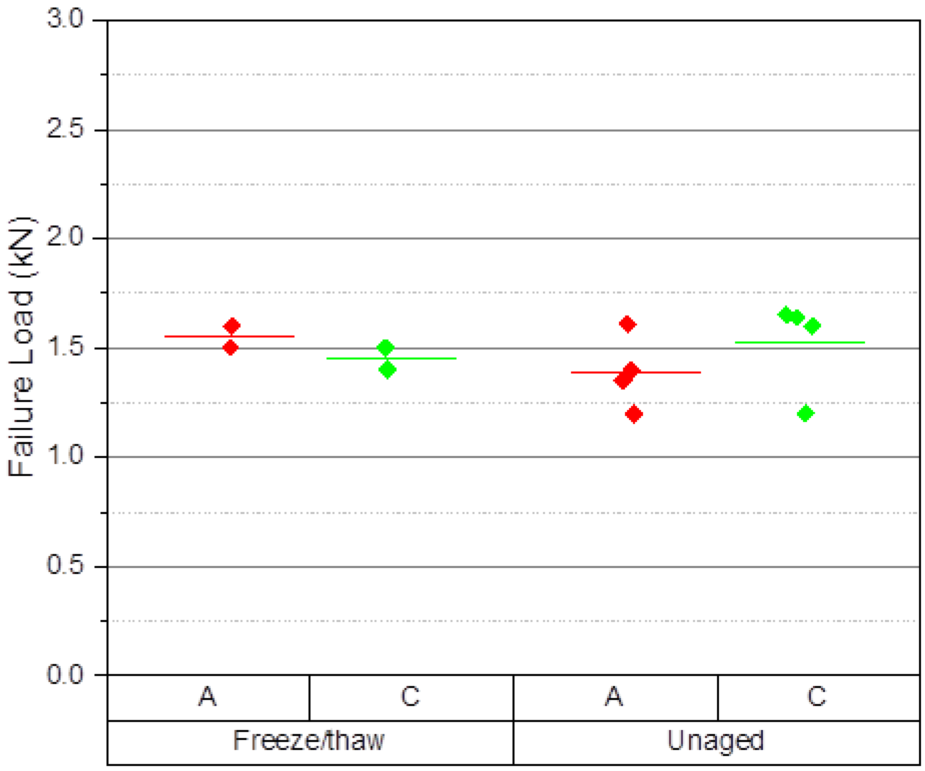


Gradual thermal cycling does not appear to have a significant effect on the cohesive/adhesion bond strength of the system and its substrate. Cohesive failure of the substrates was observed with and without thermal cycling. The load data suggests the heating cycles may have a positive effect on the strength as it promotes ageing. On the other hand, the thermal cycling treatment of 10 cycles may be too short to give conclusive results. It is also possible that a certain degree of recovery/healing takes place during the 'hot' cycles. In addition, there is potentially a scaling effect where the small size laboratory samples may mask the effects of thermally induced expansion or contraction.

A separate set of experiments was carried out on blocks of mix 20 using resins A and C (figure 3.18). It produced similar results to the mix 15. Failure still occurred in the substrate after the freeze/thaw cycling.

The results indicate that the thermal expansion coefficient mismatch between specialist surfacing systems and the substrate is insignificant in the New Zealand climate. However, further investigation using larger samples or field trials is recommended to verify the effect of specimen size.

Figure 3.18 Effect of 10 freeze/thaw cycles on the failure strength of specialist surfacing systems on mix 20 asphalt substrates



3.2.5 Bond strength of the specialist surfacing system

The adhesive bond strengths of a polyurethane resin-based system and of an epoxy-based system were measured by using a roughened steel plate as a substrate. The tests were conducted at 23ºC in a constant temperature room. While the surface chemistry is different from that of an asphalt substrate, the measurement demonstrated that the adhesive and cohesive strengths of the resins (>6MPa, maximum limit of the pull-off tester) are much higher than those of the asphalt mixes (0.5-1.5MPa). This was verified by tensile testing of the resins which is discussed in section 3.3.

3.2.6 Strengths and weaknesses

The pull-off test is a well-established test method, designed to detect the weakest bond in a multi-layered structure. One of its strengths is that it can be conducted in the field. The method enables direct measurement of the adhesive and cohesive strength of the pavement layers, and provides good indication of the ‘weakest link’. The test method has shown good sensitivity across various materials and it is simple to conduct.

There is a flaw to the test method used in this study, which is the loading rate. The hand-cranked unit is subject to operator consistency. As was identified in the tensile testing (discussed in the next section), the failure strength as well as the mechanism are dependent of the loading rate. However, the new generation of pull-off testing apparatus currently on the market are mostly automated.

A preliminary minimum cohesive bond strength for asphalt substrate has been set at 1.5kN (for a 50mm diameter area) after examining the bond test results across all mixes and systems in this study. There is a need to correlate the bond strength test results with in-service forces, to ensure that the benchmark is sufficient to withstand high stress areas where specialist surfacing systems are used. Based on the laboratory results, it can be stipulated that asphalt mixes with higher cohesive strength (ie designed for higher traffic stresses and/or aged) are most appropriate for specialist surfacing systems. Further work is recommended to confirm this criteria in the field.

3.3 Tensile test (stiffness and elongation)

Tensile testing is a very widely used method to determine the stiffness of a material. It is currently used as one of the optional tests in the HAPAS certification process. However, there is no requirement to conduct such a test at the point of application. For this project, tensile test complements the pull-off bond test as it is used to examine the strength of the resin material. The tensile strength test was selected as it was recommended in previous Transport Agency research work on specialist surfacings (Arnold et al 2014). The test was perceived as a simpler method for measuring ductility of the resin system than the flexural beam test. There is a need to confirm the ductility of the resin materials independently, in scenarios where the specialist surfacing systems have delaminated and are exposed to full traffic forces without the ability to transfer the loads to the underlying substrate.

The tensile tester at Opus Research is from the Shimadzu EZ-TEST series. It is equipped with a 5kN load cell and an environmental chamber controlled by a fluid (figure 3.19). The testing temperature was controlled to the nearest 0.1ºC. 120mm long dog-bone test pieces were prepared by pouring mixed resin systems into pre-prepared silicone rubber moulds (figure 3.20). The dimensions of the dog-bone were adopted from the ASTM standard C638-10 (ASTM 2010)

Figure 3.19 The Shimadzu EZ- Test LX with a custom- made environmental chamber

Figure 3.20 Examples of different types (D, A, C, B) of resin used in calcined bauxite systems in New Zealand

3.3.1 Effect of temperature

Four different resins were tested to demonstrate their behaviours under tension at various temperatures at a constant loading rate of 50mm per minute. The four resins exhibited various behaviours as expected. It is important to understand that at low temperatures, these resins are not expected to stretch as much as they do at ambient and above-ambient temperatures. It is also important to note that in practice, provided there is good adhesion between the specialist surfacing system and the substrate, the loading exerted on the thin surfacing is normally transferred down to its underlying substrate.

In this case, this tensile test method is appropriate for understanding how the resin material performs when it is detached from the substrate, whereas the pull-off test (tensile bond test) is designed to measure the adhesive bond strength or the cohesive bond strength of the system.

Figure 3.21 (Left) a dog- bone specimen of Resin B mounted in the tensile tester; (right) the same specimen with brittle fracture post- tensile test

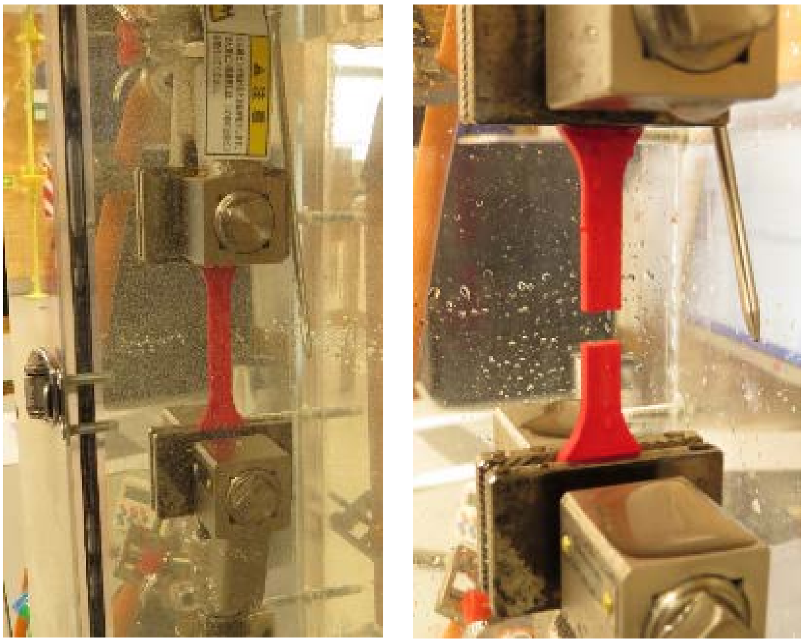
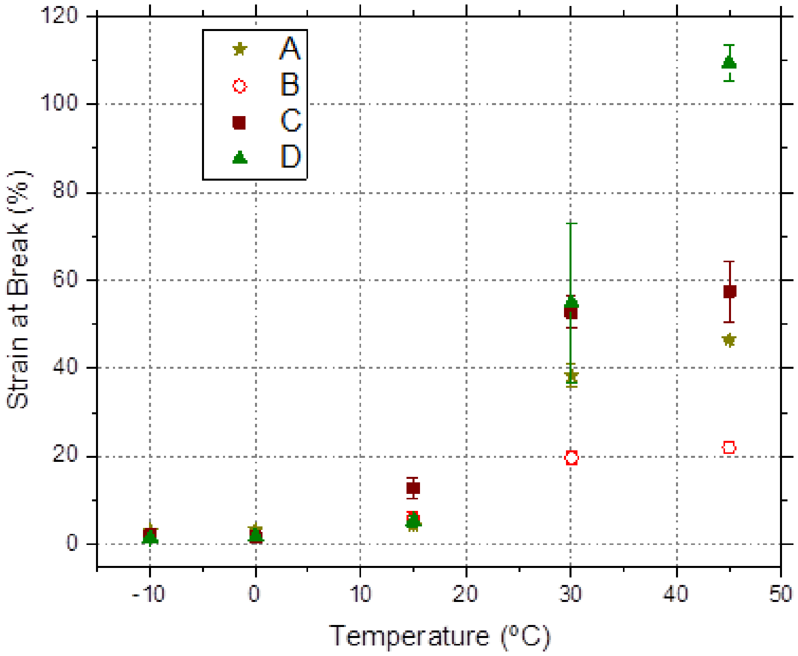


Figure 3.21 above illustrates a test specimen made of resin B before and after tensile test at 0ºC. The brittle fracture surface is typical of most tests conducted at temperatures below 15ºC. At least two tests were done under each test condition and the averages are plotted in figures 3.22 and 3.23.

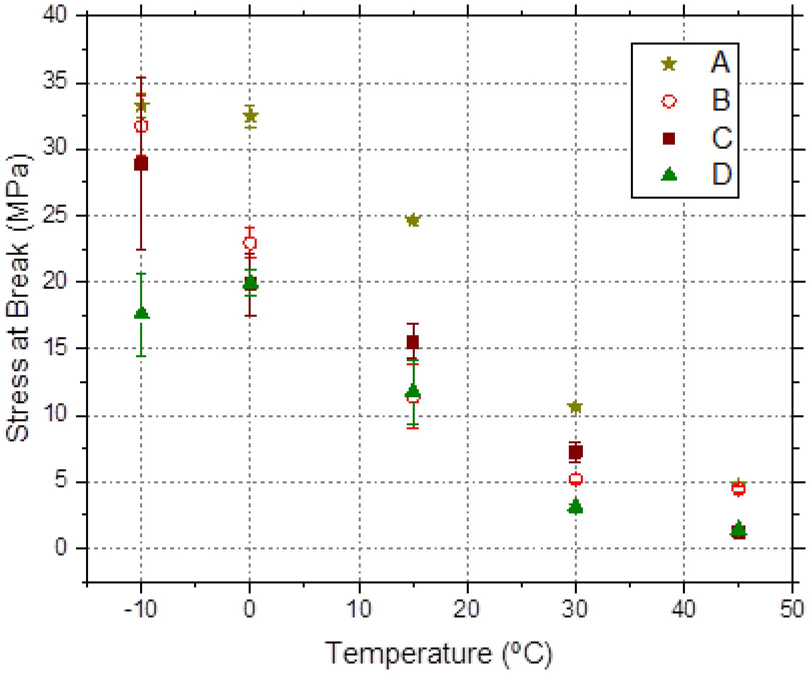
Figure 3.22 Temperature dependency of tensile strain at break



There is a large variation in the high-temperature (45°C) strain value between the four resin systems (figure 3.22). This is solely due to the type of resin material and its composition (structure, degree of cross-linking), affecting its ductility at various temperatures. However, as the test temperature drops, the strain values at break for all four systems converge to <5% at temperatures below zero at which the microstructure of each material becomes less mobile. The poorer ductility exhibited by the specialist surfacing resins at sub-zero temperatures is similar to that of bituminous binders when tested at lower temperatures.

The results suggest that apart from the cohesive strength of the substrate, high temperature climate conditions also need to be considered when selecting the type of specialist surfacing system.

Figure 3.23 Temperature dependency of tensile stress at break



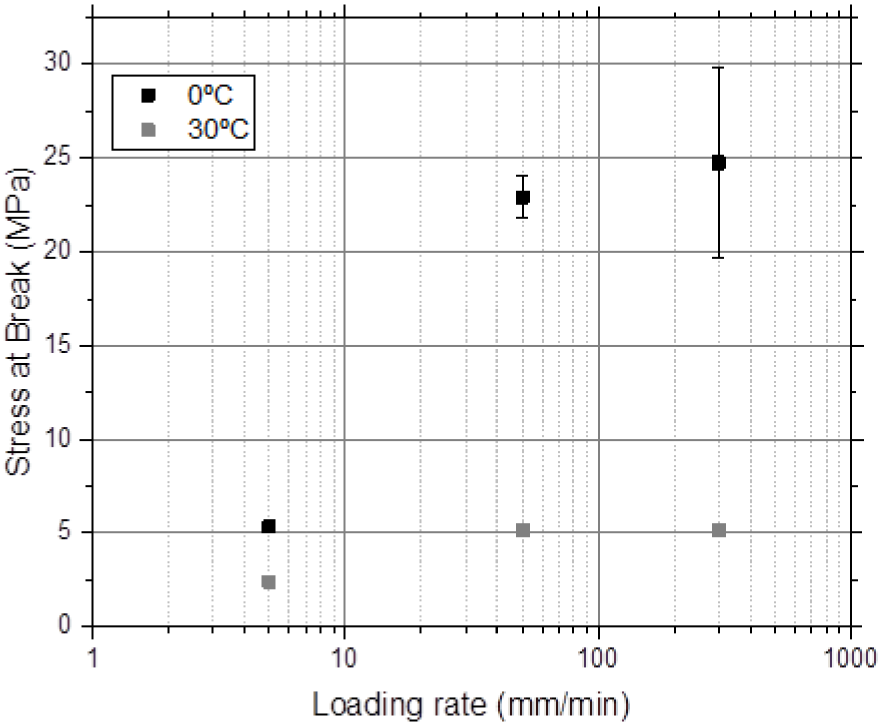
Similarly, the tensile strength at break is clearly dependent on the test temperature, meaning that each resin behaves differently due to temperature variation. In general, these resin materials are much more brittle at lower temperatures but can withstand higher stresses prior to failure.

The pull-off test data (>6MPa) matches well with the temperature dependency of tensile stress at break (figure 3.23) as the stress value at 23°C is expected around 5–15MPa.

3.3.2 Effect of loading rate

This experiment was an attempt to demonstrate the effect of the loading rate on the tensile properties. In reality, most of the stresses from traffic movement are instantaneous, ie extremely fast loading rates that are much greater than the capability of most test machines. Despite the limitation, it was observed (figure 3.24) that a significant increase in the loading rate has resulted in an increase in the resin elastic properties (tensile stress at break and thus stiffness). The lower stress and stiffness resulting from the decreased loading rate may be explained by relaxation and creep mechanisms common in polymeric materials.

Figure 3.24 Loading rate dependency of tensile stress at break for resin B



3.3.3 Strengths and weaknesses

The strength of the tensile test is its precision. The loading rate is controlled to the nearest 0.001 mm/min and it has the capability of switching from strain rate controlled to stress controlled. The environmental chamber also ensures that the properties measured are characteristic of the specified climate. While the tensile test was excellent in distinguishing the ductility of each resin system, it does not measure the bond strength to the multi-layered structure. It is recommended that this technique is used as a quality assurance test, to ensure the elastic properties of the resin used are what was specified.

One aspect which was not investigated is each resin system's ability to withstand ageing (ie oxidation, UV exposure and other weathering effects). It was decided this property should be considered as part of the product/material certification process. It may warrant a mention in the pilot specification (P25) under the notes section 5(e) for binders.

4 Conclusions

Specialist surfacing systems are multi-layered structures which can fail cohesively and/or adhesively. Hence, in order to evaluate the weak point in a multi-layered structure, a tensile bond test was chosen as a candidate test method.

The tensile bond test is a well-established test method, designed to detect the weakest bond in a multi-layered structure. One of its strengths is that it can be conducted in a controlled environment as well as in a field. This enables direct measurement of the adhesive and cohesive strength of the pavement layers, and provides good indication of the 'weakest link'. The test method has shown good sensitivity across various materials and it is simple to conduct.

For all specialist surfacing systems tested, the tensile bond tests resulted in cohesive failures in the asphalt substrate regardless of the mix design. The cohesive strength of the asphalt substrate increases as the binder viscosity increases. This is also confirmed by ageing experiments where the aged asphalt substrates have much higher cohesive strength, leading to adhesive failure of the surfacing system when the adhesive bond strength becomes lower than that of the cohesive bond strength. It can be concluded that the binders with high viscosities, either via higher initial bitumen penetration (eg 40–50 or 60–70 grades) and/or oxidative ageing, will provide a higher cohesive strength substrate than a higher penetration, unoxidised binder. Based on the results, a general guideline to prevent premature failure (such as delamination and cohesive substrate failure) includes the following criteria:

- The specialist surfacing system is applied according to best practice, ie the surface must be clean and dry and the resin system mixed according to the supplier's instructions. Both of these criteria are to minimise the risk of adhesive and/or cohesive failure of the resin system.
- The adhesive strength of the resin-substrate interface and the cohesive strength of the resin are greater than the cohesive strength of the substrate itself. This leads to load transfer from the thin specialist surfacing down to the substrate (and prevents delamination).
- The cohesive strength of the substrate at various temperatures has to meet or exceed the expected traffic forces at various climate conditions (to prevent cohesive substrate failure).

Provided these three criteria are met, the risks of premature failure by either adhesive or cohesive mechanisms can be minimised.

There was a limitation in the testing device used in this study. The unit is operated by a crank handle, meaning that it is subject to operator consistency. It was established during the tensile testing work that the failure strength as well as the extent of plastic deformation are dependent on the loading rate. This can be mitigated with the use of a new generation of pull-off testing apparatus that is currently on the market with automated loading mechanisms.

In addition to the bond strength test, a conventional tensile test (elongation test) was also assessed using various binder systems as test subjects. The tensile strength test was selected as it had been recommended in previous Transport Agency research work on specialist surfacings (Arnold et al 2014). The test was perceived as a simpler method for measuring strength and ductility than the flexural beam test. It was chosen to confirm the ductility of the resin materials independently, in scenarios where the specialist surfacing systems have delaminated and are exposed to full traffic forces without the ability to transfer the loads to the underlying substrate.

The tensile strength and elastic properties of the resin are particularly important when the surface layer is subjected to loads after delamination. The advantage of the tensile test is its precision. The loading rate is controlled to the nearest 0.001 mm/min and the procedure can be switched from strain rate controlled to stress controlled. The use of an environmental chamber also ensures that the property measured is characteristic of the specified climate. The method is also very well documented as a standard material test method. However, while the tensile test was excellent in distinguishing the ductility of each resin system, it did not account for the bond strength to the multi-layered structure. It was concluded that the best application of this test method is for quality assurance, to ensure the resin used is what was specified.

One aspect which was not investigated is each resin system’s ability to withstand ageing (ie oxidation, UV exposure and other weathering effects). It was decided this property should be considered as part of the product/material certification process. It may warrant a mention in the pilot specification.

Another failure mechanism which was not investigated in the present work was fatigue cracking. Based on the flexural beam test results from the earlier specialist surfacings study (Arnold et al 2014), it was considered that the asphalt substrate remains the weaker link even under fatigue loading conditions.

A draft test specification for the tensile bond was prepared so the test method can be incorporated into the pilot performance-based specification for specialist surfacing systems to help minimise failures associated with the substrate.

5 Recommendations

As a result of reviewing the existing test standards and the experimental results from the current research project, a draft test method (Txxx) has been developed for consideration and further refinement (appendix B). It is recommended that a tensile bond (pull-off) test is incorporated in the pilot specifications (NZTA P25/P33) to ensure the adhesive bond strength meets the cohesive strength of the substrate.

It is recommended that the test apparatus has the function of controlling the loading rate, and the equipment (load cell and loading speed) is calibrated/verified on a regular basis to ensure consistency. There are several types of tensile loading test apparatus available on the market. The recommendation is to use models with at least 12kN load cell (or an equivalent tensile stress capacity of 6MPa based on a 50mm diameter area) and a controllable loading rate for consistency. In addition, some form of sampling must be done to ensure measurements are based on a representative set of samples.

In addition, it is recommended that the pull-off test should be conducted prior to the application of the specialist surfacing system, to ensure the underlying substrate is of sufficient strength to withstand potential traffic loading.

Calculated using the experimental data from this research work, a preliminary benchmark has been set so the asphalt substrates have to withstand tensile stresses of at least 750kPa (or 1.5kN on a 50mm diameter test area) when tested at 23ºC. There are several ways to achieve this:

1. To use a binder with higher cohesive strength based on the temperature range experienced in the field
2. To allow ageing of the asphalt substrate. This prevents applications of specialist surfacing systems on freshly laid substrate, which is often deemed unsuitable in any case.

Since the temperature will be likely to vary in a field testing environment, there are two different approaches to the test regime:

1. A calibration chart based on temperature has to be developed for field testing.
2. An alternative to field testing is to take cores back to a controlled laboratory environment and test the field cores at 23ºC (or whatever temperature produces the benchmark results).

It is recommended that the test method be further refined so the test can be conducted in the field. Further work is needed to develop a comprehensive database (calibration chart) to allow for temperature variations in field.

It is suggested the next step involves field trials at various sites around the country, which have been selected as potential candidates or which are currently surfaced with specialist surfacing systems to determine substrate strength and its relationship with age and mix type.

Further work is recommended to quantify the minimum binder performance requirement to achieve the necessary cohesive strength in order to create a benchmark for the specification for specialist surfacing systems. In addition, the oxidation/ageing characteristics of the specialist surfacing binder system (resin) should align with the defect liability period. Further work is also recommended to confirm that the fatigue lives of specialist surfacing resins are higher than those of the asphalt. This can be carried out using 3- or 4-point bending test apparatus.

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Appendix A: Experimental procedure

A1 Determination of bond strength

A1.1 Preparation of substrate

1 Preheat asphalt mix and compaction moulds at appropriate temperatures (depending binder properties).

2 For lab-made asphalt blocks, make each block by Marshall Hammer compaction for 75 blows per side.

3 For field-acquired cores, cut the base of the core flat and leave to dry.

Figure A.1 Marshall block of mix 15 asphalt

A1.2 Preparation of surface

A1.2.1 Preparation to determine tensile strength of asphalt substrate:

1 Prepare the surface using a buffing wheel to remove excess bitumen and to expose aggregate surface.

2 Remove all surface contaminants to obtain a clean, undamaged surface.

3 Leave the block in a constant temperature (23ºC) room for 48 hours before further treatment.

A1.2.2 Preparation to determine bond or tensile strength of the specialist surfacing system:

1 Prepare the surface in accordance with 1.2.1.

2 Apply and cure the specialist surfacing system in accordance with supplier's instructions.

3 Example: for a 100mm diameter block, use 12.5g of the mixed resin (based on an application rate of 1.6kg per m^2). Spread the resin carefully and evenly and then sprinkle calcined bauxite aggregate (1–3mm) on top of the resin surface. Remove excess chip after the resin cures.

Figure A.2 Asphalt block surfaced with a calcined bauxite system

4 Leave the block in a constant temperature (23ºC) room for 48 hours before further treatment.

A1.3 Preparation of test specimen

1 Clamp the block into a steel circular mould and then bolt it to the floor using two dyna bolts that have been placed in the floor.

Figure A.3 Setup of a test specimen for coring cut

2 Attach the 54mm core barrel (internal diameter of 50mm) to the portable corer and then line this up on to the blocks centre.

3 Start the coring equipment and let the core barrel balance itself before starting to lower into the block.

4 Using the coring equipment, carefully drill a circular cut to a depth of 35mm perpendicular to the surface. Leave the test specimen intact, attached to the substrate. Measure the diameter of the test specimen in two directions at right angles to each other. Record the average diameter to the nearest 0.2 mm.

Figure A.4 Coring equipment and the test specimen setup

5 Once the cut has been made, remove any standing water; clean the surface of any debris from the drilling operation and allow to dry.

Figure A.5 Test specimen with a circular cut

6 Attach the aluminium disc to the top of the test specimen using an epoxy adhesive (Sika Anchorfix-3+). Ensure the disc is centred with the test specimen and the axis of the disc is parallel to the axis of the test specimen. Cure the epoxy adhesive following manufacturer's instructions. Do not allow the adhesive to run down the side of the test specimen into the annular cut; if this occurs, do not test the specimen and prepare another. At temperatures below 20°C, it is permitted to gently heat the metal disc to no more than 50ºC to facilitate spreading of the adhesive and to accelerate curing. Do not heat the test specimen with a direct flame.

Figure A.6 Test specimen with aluminium disc attached

A1.4 Test procedure

1. Attach the tensile loading device to the disc using the coupling device.
2. Apply the tensile load to the test specimen so that the force is parallel to and coincident with the axis of the specimen.
3. Apply the tensile load at a constant rate.
4. Measure the peak tensile load (or load at failure). Record the results.
5. Record the failure mode (cohesive, adhesive, etc.)

Appendix B: Draft test methodology

Draft Txxx
Test methods for asphalt substrate bond strength

XX XXXXXXXX 2016

B1 Scope

1 This test method is suitable for both field and laboratory use to determine one or more of the following:

  a the near-surface tensile strength of the substrate as an indicator of the adequacy of surface preparation before application of a specialist surfacing system

  b the bond strength of a specialist surfacing system to the substrate

  c the tensile strength of a specialist surfacing system, after the material has been applied to a surface.

2 This test method involves use of potentially hazardous materials and equipment, and should only be undertaken by properly trained laboratory personnel following appropriate health and safety practices.

B2 Related documents

1 ASTM C1583-13 Standard test method for tensile strength of concrete surfaces and the bond strength or tensile strength of concrete repair and overlay materials by direct tension (pull-off method)

2 ASTM D4541-09 Standard test method for pull-off strength of coatings using portable adhesion testers

3 ASTM C900-15 Standard test method for pullout strength of hardened concrete.

B3 Terminology

B3.1 Definitions

1 Failure mode – indicator of the weakest component of the asphalt/surface system. In applications to this test procedure, failure can occur within the asphalt substrate, at the surface binder/substrate interface.

2 Pull-off tensile strength – the stress required to remove a pull-off stub attached to a prefabricated surface by an epoxy adhesive with force applied in the normal direction. Used in this procedure as a parameter to evaluate the quality of the bond.

B4 Summary of method

1 This test is performed on the surface of a prepared asphalt substrate before application of a specialist surfacing system, or on the surface of a specialist surfacing system after the material has been applied to the prepared asphalt surface.

2 The test specimen is formed by drilling a shallow core into and perpendicular to the surface of the substrate, and leaving the intact core attached to the substrate. A steel or aluminium disc is bonded to the top surface of the test specimen.

3 A tensile load is applied to the metal disc until failure occurs. The failure load and the failure mode are recorded and the nominal tensile stress at failure is calculated.

B5 Significance and use

1 This test method determines the tensile strength of asphalt substrate near to the prepared surface, which can be used as an indicator of the adequacy of surface preparation before applying a specialist surfacing system.

2 When the test is performed on the surface of a specialist surfacing, it determines the bond strength to the substrate or the tensile strength of either the specialist surfacing system or substrate, whichever is weaker.

3 The method may also be used to evaluate the adhesive strength of bonding agents.

4 When the test is performed on the surface of a material applied to the substrate, the measured strength is controlled by the failure mechanism requiring the least stress. Thus it is not possible to know beforehand which strength will be measured by the test. For this reason, the failure mode has to be reported for each individual test result and tests results are averaged only if the same failure mode occurs.

B6 Equipment

1 Core drill, for preparing test specimen

2 Core barrel, with diamond impregnated bits – nominally 50mm inside diameter.

3 Steel or aluminium disc, nominally 50mm diameter and at least 20mm thick.

4 Tensile loading device, with a load-indicating system and nominal capacity of 12 kN and capable of applying load at the specified rate. The loading device includes a tripod or bearing ring for distributing the force to the supporting surface.

  a Within the operating range, the indicated tensile force shall be within 2% of the force measured by a calibrated testing machine or load cell. Verify the tensile loading device at least once a year and after repairs and adjustments. See ASTM C900-15 for suitable verification schemes.

  b A coupling device shall be used to connect the metal disc to the tensile loading device. The coupling device shall be designed to withstand the tensile load capacity without yielding, and to transmit the tensile force parallel to and in line with the axis of the cylindrical test specimen without imparting torsion or bending to the test specimen.

B7 Materials

1 Select a solvent-free, epoxy-based adhesive material for bonding the metal disc to the test specimen. It should be a fast-curing paste or gel meeting the requirements of Specification C881/C881M for Type IV, Grade 3, except that a shorter gel time is permitted.

B8 Sampling

1 Obtain three individual test results with similar failure modes for each test site.

2 Ensure the field test site is large enough so all methods applied in the full-scale operation, including surface preparation, are used for preparing test specimens. The test site should be at least 1m by 1m and representative of actual field conditions, ie wheel paths as well as non-wheel paths.

3 Ensure the centre-to-centre distance of adjacent test specimens is at least two disc diameters. The distance from the centre of a test specimen and a free edge of the test object should be at least one disc diameter.

B9 Determination of bond strength

B9.1 Preparation of surface

1 Preparation to determine tensile strength of substrate:

  a Remove all surface contaminants and loose or deteriorated substrate to obtain a clean, undamaged surface.

  b Prepare the surface using the same method to be used in the full-scale operation.

  c Ensure the surface is in the same condition regarding dryness and cleanliness as specified for the actual work.

2 Preparation to determine bond or tensile strength of the repair or overlay material:

  a Prepare the surface in accordance with step 1 above.

  b Apply and cure the specialist surfacing system in accordance with the manufacturer's specifications.

B9.2 Preparation of test specimen

1 Using the coring equipment, drill a circular cut perpendicular to the surface. For tests of substrate, drill to a depth of at least 10mm. For tests of a specialist surfacing system, drill to at least 10mm below the asphalt-overlay interface. The test specimen is left intact, attached to the substrate. Measure the diameter of the test specimen in two directions at right angles to each other. Record the average diameter to the nearest 0.2mm.

2 Remove any standing water; clean the surface of any debris from the drilling operation and allow it to dry.

3 Attach the metal disc to the top of the test specimen using the epoxy adhesive. Ensure the disc is centred with the test specimen and the axis of the disc is parallel to the axis of the test specimen. Cure the epoxy adhesive following the manufacturer's instructions. Do not allow the adhesive to run down the side of the test specimen into the annular cut; if this occurs, do not test the specimen

prepare another. At temperatures below 20°C, it is permitted to gently heat the metal disc to no more than 50ºC to facilitate spreading of the adhesive and to accelerate curing. Do not heat the test specimen with a direct flame.

B9.3 Test procedure

1. Attach the tensile loading device to the steel disc using the coupling device.
2. Apply the tensile load to the test specimen so the force is parallel to and coincident with the axis of the specimen.
3. Apply the tensile load at a constant rate so the tensile stress increases at a rate of 35 ± 15 kPa/s (~70N/s on a 50mm diameter specimen).
4. Measure the peak tensile load (or load at failure). Record the results.
5. Record the failure mode (cohesive, adhesive, etc.)

B10 Calculation

1. Failure strength (MPa) = failure load (N) / area in (mm^2)

B11 Reporting

B11.1 The test report should contain the following:

1. Purpose of the test:
    a. To assess the substrate before application of specialist surfacing system with regards to the adequacy of surface preparation and the strength of the near-surface region of the substrate
    b. To determine the controlling failure mode and corresponding strength when a specialist surfacing system is bonded to the substrate
2. Identification of all materials used in the test
3. Test conditions – location of test, weather conditions, and surface temperatures
4. The failure mode and the tensile or bond strength for each individual test reported to the nearest 0.05 MPa.