

Adequacy of Runway Asphalt Overlay Interface Construction

Greg White^{1,2}

1. *Fulton Hogan, Brisbane, Australia*
2. *University of the Sunshine Coast, Sippy Downs, Australia*

ABSTRACT

Aircraft braking forces have increased and will continue to increase in the future. This has resulted in increased shear stresses at the interface between the surface layer and the underlying pavement. An increase in reports of delamination failures has followed. Shear stresses induced by an extreme aircraft braking event were compared to measured interface shear strengths. Interface shear strength was measured from cores recovered from runway surfaces typical of major Australian airports. The runways were exposed to aircraft operations also typical of major Australian airports. The resulting stress-strength ratios identified an area 50 mm in front of the leading edge of the tyre as the critical location for delamination failure where stress-strength ratios approached 1.0. Interface cohesion is provided by tack coat adhesion and contributes to interface shear strength. It is recommended that a premium tack coat material, such as JetBond™, be specified for future airport overlay projects.

Keywords: Airport asphalt overlay; Surface delamination; Surface de-bonding; Octahedral shear stress

1. INTRODUCTION

Since their first introduction in the early 1900s, aircraft have become ever larger and heavier. Particularly since WWII, aircraft wheel loads and tyre pressures have increased significantly [1-2]. The trend to higher aircraft tyre pressures is not expected to abate in the near future. At the same time, the pressure to minimise runway occupancy times during landing operations has led to increased use of rapid exit taxiways [3]. As a result, aircraft braking forces have increased and will continue to increase in the future.

The increase in braking forces during aircraft landing operations has resulted in an increase in shear related distress. Delamination or de-bonding of asphalt surfaces from underlying pavements has been reported more frequently, despite improvements in interface construction techniques [4]. The shear stresses transferred from braking tyres to the pavement surface and through the surface layer can initiate such failures at inadequately bonded interfaces. There have been reports of delamination failures at Japanese airports, predominantly occurring during summer and usually in the heavy aircraft braking zones [5]. Tsobakawa et al. [6] reported surface delamination failures at Nagoya Airport in 2000 and Naha Airport in 2005. Although both failures were reported to occur in the summer and were assessed as being de-bonding failures, the root cause was not reported. Significant delamination of the surface on an international airport in southern Africa was investigated by Horak et al. [7]. It was concluded that wet weather and poor drainage during construction inhibited the adhesion between layers. Australia has not escaped this issue and delamination type failures have been reported recently at Brisbane, Sydney and Adelaide airports.

Material specification and construction practices for airport overlays have not changed substantially since the 1960s. In the 1970s, significant slippage failures occurred on airports in Australia, primarily in the heavy braking zones. This prompted the development of a policy on how to manage and repair surface slippage failures, including those due to de-bonding and delamination [8].

Current practice aimed at reducing the risk of delamination of overlays at Australian airports includes:

- Removing the aged and contaminated asphalt surface by cold milling.
- Minimising the milling water to reduce the generation of slurry on the exposed surface.
- Thorough cleaning and drying of the milled surface by brooming, vacuuming and blowing.
- Complete coverage of the exposed surface with 0.15 to 0.20 l/m² of residual bitumen from bitumen emulsion tack coat.
- Minimisation of traffic on the tack coated surface to reduce pick-up of tack coat by tires.

This practice has generally resulted in good interface bond with relatively few reported surface failures attributed to delamination. Cationic Rapid Setting (CRS) bitumen emulsion containing 60% C170 bitumen is the traditional tack coat product used for airport overlays. Despite their availability, only minor additional cost and overwhelming evidence from the USA to demonstrate their contribution to improved overlay bond strength, modified bitumen emulsion tack coats, often referred to as Trackless Tacks, have not been adopted by Australian airports.

The aim of this research was to measure and evaluate the adequacy of the bond between an asphalt overlay and an underlying pavement layer achieved through typical airport overlay construction practices. This work was based on near-surface shear stresses calculated by computer-based pavement analysis software. Firstly, analysis software and existing knowledge on shear stress is presented. The typical strength of the bond is then outlined. Stress-strength ratios are calculated at various key locations as an indicator bond adequacy before potential tack coat material improvement is suggested.

2. BACKGROUND

During aircraft ground manoeuvring, takeoff and landing operations, forces are transferred between the aircraft tyre and the pavement surface [9]. Shear stresses in the upper 100 mm of flexible pavements have been shown by various researchers to be important to pavement performance [10]. Computer-based analysis tools are commonly used for calculating stresses in pavements. The tools used by researchers vary significantly in their capabilities. Different measures of stress may also be adopted as the basis for comparison of critical conditions.

2.1 Modelling tools

Both Layered Elastic (LE) and Finite Element (FE) methods have been used to calculate stresses and strains in pavements and on their surfaces. Discrete element methods have been less commonly adopted. FE models are less accurate for calculating stresses at interfaces and discontinuities between elements, whereas LE tools lose accuracy at the load boundaries and at the pavement surface [11].

FE methods allow more precise modelling of tyre tread patterns, load distributions over the tyre contact areas, and interface conditions. Many studies have shown these factors can significantly influence the stress distribution and peak stress imparted on the pavement surface [12-15]. However, Horak et al. [16] suggested that circular contact areas of uniform stress distribution were a reasonable simplification for many applications. Various computer based tools are available to perform the numerical calculations using both LE and FE techniques. The most commonly reported tools include ANSYS, ABAQUS, BISAR and mePADS/GAMES.

Of the LE tools, the GAMES routine within the mePADS software developed by Maina & Matsui [17] has been used in a number of applications. LE tools are less commonly used in surface layer modelling due to inaccuracies at the surface and at the edge of the loaded area [11]. However, the GAMES routine was specifically developed to provide more accurate modelling of stresses and strains near the surface. Comparison with results published in the Advanced Models for Analytical Design of European Pavement Structures (AMADEUS)

report [18] returned good correlation and provided confidence in the GAMES-calculated pavement responses [19]. Maina et al. [11] used GAMES to compare square and rectangular loads while Horak et al. [7] modelled the risk of shear slippage deeper in the pavement. Horak et al. [16] used GAMES to assess surface layer delamination. The mePADS/GAMES software is well suited to modelling near-surface stresses and strains in pavement structures.

2.2 Stress and Strains

The calculation of stresses and strains in pavement structures is not a recent development. The use of computer-based software merely allows the processing of large numbers of complex calculations to be performed far quicker than any manual method. This has allowed more complex mathematics, such as those embedded within LE and FE methods, to be incorporated into research and design tools.

Current design methods for airport pavements generally only consider the vertical force applied to the pavement surface by the aircraft, assumed to apply uniformly over a circular contact area. This simplification is not realistic [10, 15, 20]. De Beer et al. [13] found some stresses to be up to six times higher when modelling an actual tyre in comparison to a circular and constant contact pressure model free of non-vertical forces. Al-Qadi & Wang [12] determined that the surface shear stress varied from 103% to 147% of those induced by an equivalent uniform contact pressure model when tyres were accurately modelled in three dimensions. Longitudinal and transverse horizontal stresses were found to be 12% and 48% respectively, of the vertical stress under a rolling tyre [15]. When considering surface layer and interface performance, it is critical that the non-vertical stresses associated with braking and turning aircraft are considered.

2.3 Octahedral Shear Stress

When 3D stress states are taken into account, the coordinate system is rendered arbitrary as the combination of longitudinal and transverse stresses change the orientation of the critical shear stress. For a generally cross-anisotropic material such as asphalt, the orientation of the shear stress with maximum magnitude will be the orientation of critical surface performance. The ability to consider and compare complex combinations of three dimensional stresses is simplified by the use of the Octahedral Shear Stress (OSS).

OSS combines the effect of nine stresses at a given point. It represents the effective stress state better than any other single parameter [21] as it represents the strength of the effective deviatoric stress state. OSS provides a sound indicator of pavement response and is well suited to 3D analysis tools [13, 22]. OSS (τ_{OCT}) is calculated from Eq.(1). In the plane across which the shear stresses are zero, the OSS will be greatest and Eq.(1) reduces to Eq.(2). This is known as the principal stress plane. The associated Octahedral Normal Stress (ONS) is calculated as Eq.(3), which becomes Eq.(4) on the principal stress plane [23].

$$\tau_{OCT} = \frac{1}{3} \left[(\sigma_x - \sigma_y)^2 + (\sigma_y - \sigma_z)^2 + (\sigma_z - \sigma_x)^2 + (\delta_{xy}^2 + \delta_{yz}^2 + \delta_{zx}^2) \right]^{1/2} \dots\dots\dots \text{Equation 1}$$

$$\tau_{OCT} = \frac{1}{3} [(\sigma_1 - \sigma_2)^2 + (\sigma_2 - \sigma_3)^2 + (\sigma_3 - \sigma_1)^2]^{1/2} \dots\dots\dots \text{Equation 2}$$

$$\varphi_{OCT} = \frac{1}{3} [\sigma_x + \sigma_y + \sigma_z] \dots\dots\dots \text{Equation 3}$$

$$\varphi_{OCT} = \frac{1}{3} [\sigma_1 + \sigma_2 + \sigma_3] \dots\dots\dots \text{Equation 4}$$

- Where:
- τ_{OCT} = octahedral shear stress
 - φ_{OCT} = octahedral normal stress
 - $\sigma_x \sigma_y \sigma_z$ = normal stresses
 - $\delta_{xy} \delta_{yz} \delta_{zx}$ = shear stresses
 - $\sigma_1 \sigma_2 \sigma_3$ = major, intermediate and minor principal stresses

The origins of OSS in pavement analysis lie in granular base course materials [24]. Witczak & Uzan [25] first introduced calculated OSS as an input to stress-dependent modulus models for granular pavement layers [22]. The USA's Mechanistic-Empirical Pavement Design Guide FE tool uses OSS in its generalised stress dependent model for granular material modulus [26]. A number of researchers have also adapted OSS into asphalt material analysis. De Beer et al. [13] used OSS as an indicator of critical stress state in thin asphalt surfaces and the change in OSS as the pavement progressed from an un-cracked to a cracked condition was modelled. Perdomo & Button [23] used OSS to predict asphalt rutting. OSS has also been recommended as an indicator of asphalt fatigue life [22].

Cyclic shear testing of an asphalt mixture can provide the cohesion (c) and internal angle of friction (ϕ) based on Mohr-Coulomb failure theory. These parameters can be combined with the calculated ONS to calculate the octahedral shear strength ($\tau_{OCT STR}$) of the mixture as Eq.(5) [23]. The Octahedral shear strength represents the OSS value at which the asphalt mixture is expected to fail in slip circle shear during a single load event. When considering interfaces, which are parallel to the surface, Eq.(5) can be adapted to determine the interface octahedral shear strength by adopting c and ϕ values from a direct shear strength test of the interface between two asphalt layers [3].

$$\tau_{OCT STR} = \frac{2\sqrt{2}}{3-\sin\phi} [\varphi_{OCT} \times \sin\phi + c \times \cos\phi] \dots \dots \dots \text{Equation 5}$$

Where: $\tau_{OCT STR}$ = octahedral shear strength of the asphalt mixture

3. RESEARCH METHODS

A computer-based modelling tool was used to perform the stress calculations. Of the LE tools, mePADS/GAMES was considered to be the most viable in terms of near-surface stress modelling. It has been verified against AMADEUS and used by a number of researchers in similar applications. If a more complex FE method was selected then the readily available and widely used ABAQUS would be preferred. While more mathematically powerful and precise, FE tools are far more demanding in terms of inputs and parameters. The LE-based mePADS/GAMES was selected over ABAQUS for this research.

The shear stresses at the interface were calculated under an extreme braking aircraft. The OSS on the horizontal plane was used as the primary indicator of interface shear. OSS values were calculated at a depth of 45 mm below the surface to represent the near-interface stresses of a nominal 50 mm surface layer. OSS values were calculated under and in front of the aircraft tyre on a grid. The grid was concentrated either side of the tyre edge at the longitudinal and transverse centres of the tyre as shown in Figure 1. In addition to the calculated OSS values, the ONS was also calculated and used to subsequently calculate the interface shear strength and associated stress-strength ratio.

Aircraft braking forces for a typical Australian commercial aircraft have been investigated by White [27]. These forces were adapted for this research. Separately, White [28] reported direct shear strength results for the interface of a typical Australian airport overlay. The data presented allowed the range of typically achieved interface c and ϕ values to be calculated. Testing was performed at 55°C as the estimated summer mean interface temperature.

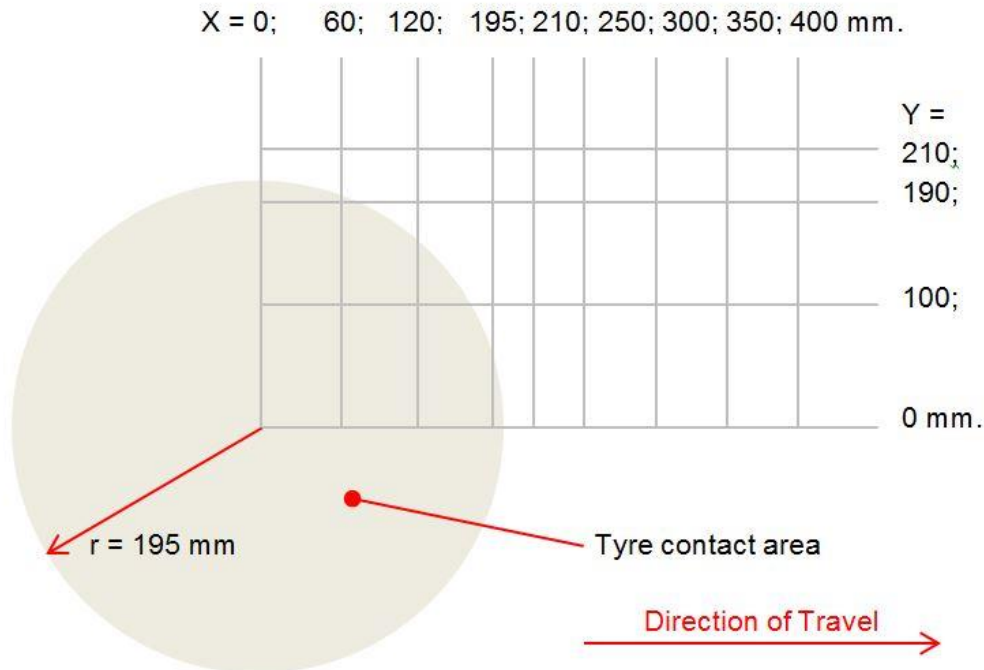


FIGURE 1 Shear Stress Measurement Grid

4. RESULTS AND ANALYSIS

4.1 Aircraft Braking Forces

White [27] calculated braking forces of various aircraft under normal and extreme landing conditions at a major Australian airport. The calculations were based on information gathered from experienced pilots. Under extreme braking conditions, aircraft autobrakes target a deceleration rate of 4.3 m/s^2 . The resulting (single wheel) vertical and horizontal surface forces and tyre pressure during extreme braking by a B767 aircraft were calculated to be [27]:

- Vertical force. 160 kN.
- Horizontal force. 52 kN.
- Contact (tyre) pressure. 1,350 kPa.

4.2 Pavement Structure

Most capital city airports in Australia were constructed or significantly developed in the 1940s in support of WWII. Many have been significantly upgraded since. The original thin asphalt surfaces have generally been covered with a number of overlays to now provide substantial asphalt thicknesses at the top of the pavement. The following pavement structure was adopted as being typical of a capital city airport on poor ground conditions in Australia. As this research focused on the stresses in the uppermost 50 mm surface layer, the underlying structure was of little practical consequence.

- Asphalt surface layer. 50 mm thick with a modulus of elasticity (E) of 3,500 MPa.
- Additional asphalt layers. 100 mm, $E = 2,500 \text{ MPa}$ representing 2 x 50 mm layers.
- Fine crushed rock base. 250 mm, $E = 300 \text{ MPa}$.
- Fine crushed rock sub-base. 1150 mm, $E = 150 \text{ MPa}$.
- Subgrade. CBR 3%, $E = 30 \text{ MPa}$.

4.3. Interface Shear Strength

Three typical airport asphalt overlays were cored and the interfaces tested in direct shear at various normal stresses. This allowed Mohr-Coulomb envelopes of shear strength to be generated. Figure 2 illustrates these envelopes. The cores were recovered from runways

comprising different asphalt mixes and exposed to different levels of traffic. None of these conditions significantly affected the measured Interface Shear Strength (ISS). From Figure 2 the c and ϕ values for the ISS were calculated and are shown in Table 1. The sample codes indicate the runway from which the cores were obtained (A, B or C) and the sample number from within that runway (a or 2). The design and construction of the overlays were typical of major Australian airports and included [28]:

- Short night shift possession periods and the requirement to return the runway to service each night.
- Removal of the existing grooves and surface by texturing with cold planing machines 5-10 mm prior to overlay.
- Thoroughly cleaning the existing surface prior to tack coating with 0.2 l/m² residual bitumen as CRS C170.
- Paving of nominal 50 mm thickness of 14 mm sized airport quality asphalt with a premium binder.

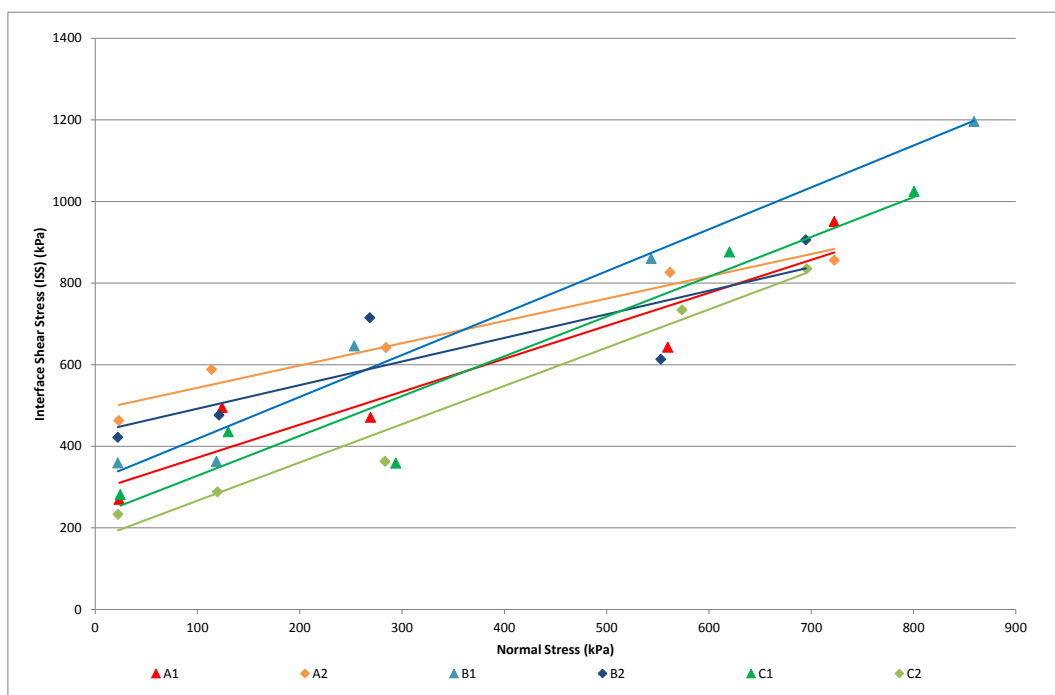


FIGURE 2 Interface Direct Shear Results

TABLE 1 Characteristic Interface c and ϕ Values

Parameter	Cohesion (c)	Friction Angle (ϕ)
Maximum	489	46
Minimum	173	29
Average	322	38
Standard Deviation	120	7

Values one standard deviation either side of the average were selected as being representative of the majority of interfaces. This resulted in 202-442 kPa and 31-46° as the range of representative values of c and ϕ , respectively.

4.4 General Stress Distribution

The general distribution of horizontal shear stress calculated by mePADS/GAMES is shown in Figure 3. In mePADS/GAMES the centre of the tyre defaults to the origin ($X=0, Y=0$), compressive stresses are negative and tension stresses are positive, stresses are in kPa and strains are in microstrain. X is the longitudinal direction of travel and Y is the transverse

direction across the pavement. The braking force was applied in the X direction to simulate aircraft braking.

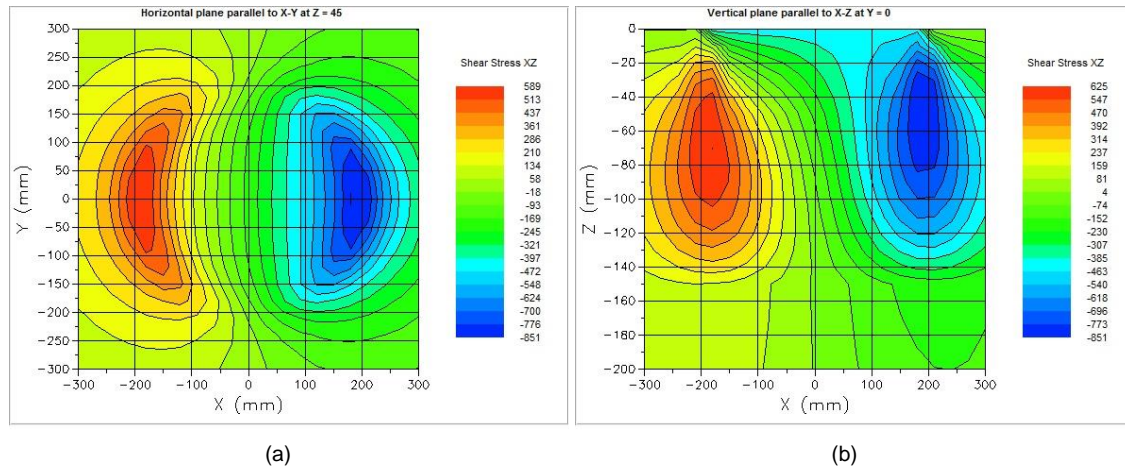


FIGURE 3 Calculated XZ Shear Stresses in the (a) horizontal and (b) vertical-longitudinal planes

The effect of braking can be seen in Figure 3(a) where the shear stress at the leading edge of the tyre (851 kPa) is significantly higher than the equivalent shear stress at the trailing edge (589 kPa), noting the tyre is moving from left to right. The zone of constant shear stress near the surface under the tyre can also be seen in Figure 3(b). The peak of the shear stress occurred at a depth ranging from 30 mm to 80 mm. Figure 3 shows that the maximum shear stress occurred directly under the leading edge of the braking aircraft tyre through a depth range that included all practical airport surface layer interfaces.

4.5 Calculated OSS at the Interface

The interface OSS values were calculated using Eq.(1) and are presented in Table 2. Equivalent calculated ONS values from Eq.(3) are in Table 3. The calculated OSS peaked just in front of the centre of the leading edge of the tyre. At this location, the ONS was also high. Similar levels of OSS were calculated across the central 200 mm of the leading edge of the tyre which is consistent with the general stress distribution in Figure 3.

TABLE 2 Calculated OSS on the Horizontal Plane (kPa)

Y (Transverse)	X (Longitudinal)								
	0 mm	60 mm	120 mm	195 mm	210 mm	250 mm	300 mm	350 mm	400 mm
0 mm	222	275	289	478	550	539	404	303	235
100 mm	185	243	300	537	540	465	357	276	220
190 mm	317	384	465	413	392	337	275	226	188
210 mm	386	428	443	376	358	310	257	214	180

TABLE 3 Calculated ONS on the Horizontal Plane (kPa)

Y (Transverse)	X (Longitudinal)								
	0 mm	60 mm	120 mm	195 mm	210 mm	250 mm	300 mm	350 mm	400 mm
0 mm	1,498	1,541	1,483	1,122	1,006	746	544	418	333
100 mm	1,371	1,407	1,312	912	825	642	489	386	312
190 mm	904	911	789	590	555	472	389	322	270
210 mm	757	768	682	533	505	437	365	306	259

4.6 Adequacy of Interface Shear Strength

The lower, average and upper representative c and ϕ values calculated from direct shear testing of the interfaces in Table 1 were used to calculate the octahedral shear strength of

the interface, from Eq.(5), at each point on the analysis grid. The stress-strength ratios were then calculated at each grid location. The critical location (maximum stress-strength ratio) was found to be on the centre line of the tyre ($Y = 0$ mm) approximately 10 mm in front of the leading edge of the tyre ($X = 210$ mm). The stress-strength ratios were 0.85, 0.63 and 0.52 for the lower, average and upper representative interface octahedral shear strengths on the horizontal plane. The stress-strength ratios for the lower representative interface stresses are presented in Table 4.

TABLE 4 Stress-Strength Ratios for Lower Representative c and ϕ (%)

Y (Transverse)	X (Longitudinal)								
	0 mm	60 mm	120 mm	195 mm	210 mm	250 mm	300 mm	350 mm	400 mm
0 mm	0.21	0.25	0.27	0.56	0.85	0.78	0.68	0.60	0.21
100 mm	0.18	0.24	0.31	0.73	0.81	0.74	0.65	0.58	0.18
190 mm	0.44	0.52	0.70	0.76	0.71	0.65	0.58	0.53	0.44
210 mm	0.60	0.66	0.74	0.74	0.68	0.62	0.57	0.51	0.60

A stress-strength ratio of 0.85 for the lower representative c and ϕ values indicated that the interface would be stressed close to its capacity, but would not fail during a single load event. For the average and upper representative values the factor of safety was 1.6 and greater than 1.9 respectively.

5. POTENTIAL IMPROVEMENTS

Interface shear strength is partially provided by the adhesive bond of the interface between the two layers, represented by the cohesion value (c). The tack coat between the two layers provides this tensile strength. The optimal tack coat would adhere well to new and old asphalt and resist softening across a broad range of temperatures. It would also be resistant to 'pick-up' during unavoidable trafficking by asphalt delivery trucks and pavers during the overlay process. This would require rapid curing. Traditional tack coat used in Australia is CRS C170 bitumen emulsion containing 60% bitumen.

A Premium Tack Coat (PTC) known as JetBond™ has been developed. Although available for over a decade, this product has seen only limited use. It was used to provide enhanced interface strength during the resurfacing of the V8 race car track in Townsville in 2009. It has also been verified in a number of field trials [29] and by comparison to other tack coat options in the laboratory [30].

During the field trials, PTC was demonstrated to exhibit significantly less tracking (after emulsion breaking) by asphalt paving equipment than conventional tack coats. There was no visible pick-up by pavers after 30 minutes, despite pavement surface temperatures exceeding 50°C and a heavy application rate of 0.2 L/m² residual bitumen [29]. Laboratory direct shear testing of interfaces showed the PTC to exhibit a 5-6 fold increase in shear strength when compared to conventional emulsion at 25°C and 40°C test temperatures, as reproduced in Figure 7 [30]. Typical properties are presented in Table 3.

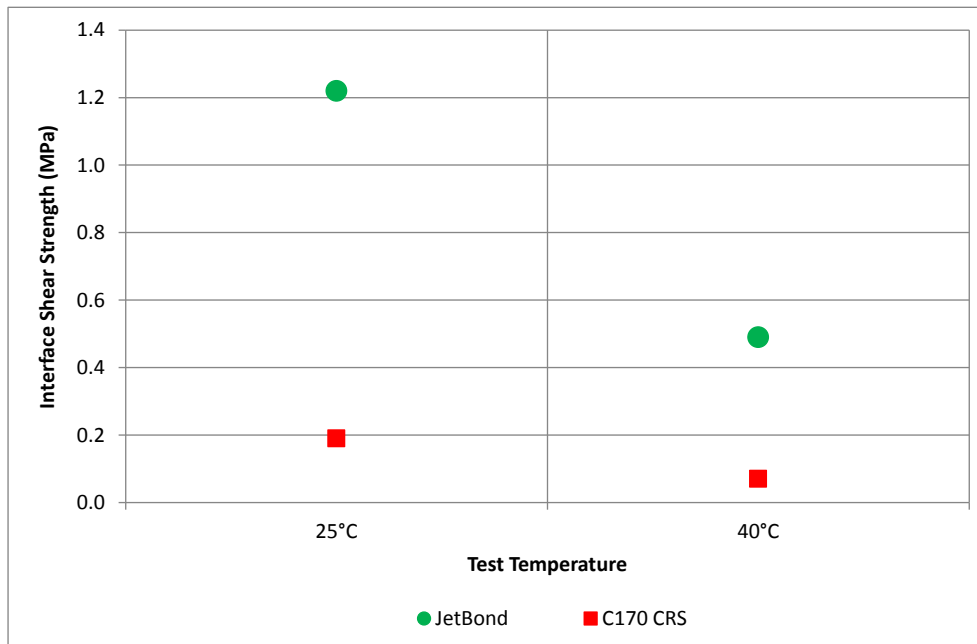


FIGURE 4 JetBond and CRS emulsion Interface Shear Strengths

FIGURE 5 Typical PTC and C170 CRS Residual Binder Properties

Property	PTC	C170 CRS
Nominal Portion of Bitumen (%)	40	60
Softening Point (°C)	83	49
Consistency at 60°C (Pa.s)	3,500	170
Penetration at 25°C (p.u)	50	70

Based on a residual bitumen application rate of 0.2 l/m², the effective material cost of the PTC has been calculated to be 50% higher than the cost of conventional C170 CRS at the same residual bitumen rate. However, the tack coat material cost represents only 0.2% of the cost of a typical airport asphalt overlay. The effective cost of using a PTC is therefore around 0.1% of the typical project cost. This would be around \$8,000 on a typical \$8 M runway overlay.

6. CONCLUSIONS

Representative *c* and ϕ values were calculated for airport asphalt overlay interfaces constructed in Australia. Imposed surface forces were also calculated for an aircraft performing a severe braking operation on a major Australian runway. The analysis of interface shear strength adequacy utilised measured interface shear strengths from runway surfaces that are representative of major airports in Australia.

The stress-strength ratios demonstrated that even assuming the lower representative *c* and ϕ values, the interface shear strength was adequate to resist the calculated shear stresses on the horizontal plane just above the interface. However, the factor of safety was close to 1.0. It must be noted that the heavy braking condition is reserved for emergency operations and is therefore not performed on a regular basis. The actual factor of safety would be higher due to the reduced braking force required during normal operations.

The PTC known as JetBond™ has been demonstrated in the laboratory to provide higher interface shear strengths across a range of service temperatures. The use of PTC on future runway asphalt overlays would significantly increase the factor of safety associated with interface delamination at insignificant additional cost. It is acknowledged that using a PTC is

not the only solution to providing improved overlay bond strength. However, given the relatively low cost and significant benefit, a PTC is a readily and immediately available option. It is recommended that designers modify their specifications to require a PTC for future airport overlays.

7. ACKNOWLEDGEMENTS

Direct shear testing was managed by Tom Gabrawy of Fulton Hogan's national asphalt research laboratory. JetBond™ product and test data was provided by John Lysenko of Fulton Hogan's national bitumen research laboratory. The efforts of both are gratefully acknowledged.

8. REFERENCES

- [1] Roginski, MJ 2007, 'Effects of aircraft tire pressures on flexible pavements', *Proceedings Advanced Characterisation of Pavement and Soil Engineering Materials*, Athens, Greece, 20-22 June, Taylor and Francis, pp. 1473-1481.
- [2] Fabre, C, Balay, J, Lerat, P & Mazars, A 2009, 'Full-scale aircraft tire pressure test', *Proceedings Eight International Conference on the Bearing Capacity of Roads, Railways and Airfields*, Urbana-Champaign, Illinois, USA, 29 June - 2 July, pp. 1405-1413.
- [3] White, G 2015, 'State of the Art: Interface Shear Resistance of Asphalt Surface Layers', *International Journal of Pavement Engineering*, submitted but not yet published.
- [4] TRB 2012, *Optimization of Tack Coat for HMA Placement*, National Cooperative Highway Research Program, Report 712, Transport Research Board, Washington DC, USA.
- [5] Hachiya, Y & Sato, K 1997, 'Effect of tack coat in bonding characteristics at interface between asphalt concrete layers', *Proceedings Eight International Conference on Asphalt Pavements*, Seattle, Washington, USA, 10-14 August, vol. 1, pp. 349-362, International Society of Asphalt Pavements.
- [6] Tsubokawa, Y, Mizukami, J, Esaki, T & Hayano, K 2007, 'Study on infrared thermographic inspection of de-bonded layer of asphalt flexible pavement', *Proceedings FAA Worldwide Airport Technology Transfer Conference*, Atlantic City, New Jersey, USA, 16-18 April, Federal Aviation Administration.
- [7] Horak, E, Emery, S, Maina, J & Walker, B 2009, 'Mechanistic modelling of potential interlayer slip at base and sub-base level', *Proceedings Eighth International Conference on the Bearing Capacity of Roads, Railways and Airfields*, Urbana-Champaign, USA, 29 June - 2 July, pp. 543-550.
- [8] DoC 1978, *Repair and Maintenance of Slippage Cracking of Bituminous Aerodrome Pavements*, Department of Construction, Commonwealth of Australia, April.
- [9] Khapane, PD 2003, 'Simulation of asymmetric landing and typical ground manoeuvres for large transport aircraft', *Aerospace Science and Technology*, vol. 7, pp. 611-619.
- [10] Su, K, Sun, L, Hachiya, A & Maekawa, R 2008, 'Analysis of shear stresses in asphalt pavements under actual measured tire – pavement contact pressure', *Proceedings 6th International Conference on Road and Airfield Pavement Technology*, Sapporo, Japan, 20-23 July, Pavement Engineering Society (Singapore), pp. 11-18.
- [11] Maina, JW, Ozawa, Y & Matsui, K 2012, 'Linear elastic analysis of pavement structure under non-circular loading', *Road Materials and Pavement Design*, vol. 13, no. 3, pp 403-421.
- [12] Al-Qadi, IL & Wang, H 2011, 'Prediction of tire pavement contact stress and analysis of asphalt pavement response: a decoupled approach', *Proceedings Asphalt Pavement Technology*, Tampa, Florida, USA, 27-30 March, Association of Asphalt Paving Technologists, pp. 289-315.
- [13] De Beer, M, Fisher, C & Jooste, FJ 2002, 'Evaluation of non-uniform tyre contact stresses on thin asphalt pavements', *9th International Conference on Asphalt Pavements*, Copenhagen, Denmark, 17-22 August.

- [14] De Beer, M, Maina, JW, van Rensburg, Y & Greben, JM 2011, 'Towards using tire-road contact in pavement design and analysis', *September 2011 Meeting of the Tire Society*, Pretoria, South Africa.
- [15] Yoo, PJ, Al-Qadi, IL, Elseifi, MA & Janajreh, I 2006, 'Flexible pavement responses to different loading amplitudes considering layer interface conditions and lateral shear forces', *International Journal of Pavement Engineering*, vol. 7, no. 1, pp. 73-86.
- [16] Horak, E, Maina, J & Emery, S 2009, 'A case study: quantification and modeling of asphalt overlay delamination on an airport pavement', *Proceedings Eight International Conference on the Bearing Capacity of Roads, Railways and Airfields*, Urbana-Champaign, USA, 29 June - 2 July, pp. 1475-1483.
- [17] Maina, JW & Matsui, K 2004, 'Development of software for elastic analysis of pavement structure due to vertical and horizontal surface loadings', *Proceedings 83rd Meeting of the Transport Research Board*, Washington, DC, USA, 11-15 January, Transport Research Board.
- [18] EU 2000, *AMADEUS: Advanced Models for Analytical Design of European Pavement Structure*, Report RO-97-SC.2137, European Commission, 29 March.
- [19] Maina, JW, Denneman, E & De Beer, M 2008, 'Introduction of new road pavement response modelling software by means of benchmarking', *Proceedings 27th Annual South African Transportation Conference*, Pretoria, South Africa, 7-11 July.
- [20] Wang, H, Al-Qadi, IL & Stanciulescu, I 2012, 'Simulation of tyre-pavement interaction for predicting contact stress at static and various rolling conditions', *International Journal of Pavement Engineering*, vol. 13, no. 4, pp. 310-321.
- [21] Ameri-Gaznon, M & Little, DN 1990, 'Octahedral shear stress analysis of an ACP overlay on a rigid base', *Journal of Association of Asphalt Paving Technologists*, vol. 59, pp. 443-479.
- [22] Kim, M, Tutumluer, E & Kwon, J 2009, 'Nonlinear pavement foundation modeling for three-dimensional finite-element analysis of flexible pavements', *International Journal of Geomechanics*, vol. 9, no. 5, pp. 195-208.
- [23] Perdomo, D & Button, JW 1991, *Identifying and Correcting Rut-Susceptible Asphalt Mixtures*, Research Report FHWA/TX-91/1121-2F, Federal Highways Administration, February.
- [24] Uzan, J 1999, 'Granular material characterization for mechanistic pavement design', *Journal of Transportation Engineering*, vol. 125, no. 2, pp. 108-113.
- [25] Witczak, MW & Uzan, J 1988, *The Universal Airport Pavement Design System, Report I of IV : Granular Material Characterization*, University of Maryland, College Park, Maryland, USA.
- [26] Al-Qadi, IL, Wang, H & Tutumluer, E 2010, 'Dynamic analysis of thin asphalt pavements by using cross-anisotropic stress-dependent properties for granular layers', *Journal of the Transportation Research Board*, no. 2154, pp. 153-163.
- [27] White, G 2015 'Shear Stresses in an Asphalt Surface under Various Aircraft Braking Conditions', *Journal of Transportation Engineering*, submitted but not yet published.
- [28] White 2014, 'Cyclic shear deformation of asphalt at Melbourne Airport', *Proceedings 2014 Worldwide Airport Pavement Technology Transfer Conference*, Galloway, New Jersey, USA, 5-7 August, Federal Aviation Administration.
- [29] Lysenko, JE 2009, 'An effective bond coat for longer pavement life', *Proceedings AAPA Pavements Industry Conference*, Gold Coast, Australia, 16-18 September, Australian Asphalt Pavements Association.
- [30] Lysenko, JE 2006, 'Development of shear testing of a bond coat emulsion', *Proceedings CME Congress*, Lyon, France.