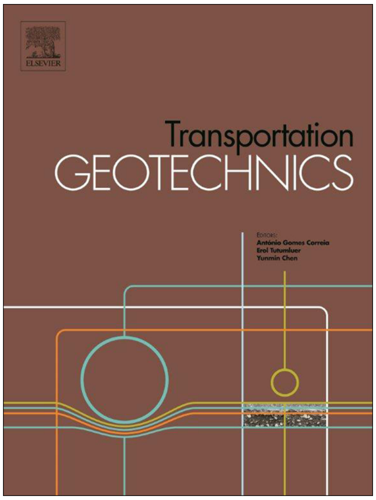

Effect of Aircraft Traffic on the Structure and Response of Asphalt

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PII: S2214-3912(14)00036-1
DOI: http://dx.doi.org/10.1016/j.trgeo.2014.10.001
Reference: TRGEO 30

To appear in:

Received Date: 8 June 2014
Revised Date: 26 August 2014
Accepted Date: 10 October 2014

Please cite this article as: G. White, Effect of Aircraft Traffic on the Structure and Response of Asphalt, (2014), doi: http://dx.doi.org/10.1016/j.trgeo.2014.10.001

Effect of Aircraft Traffic on the Structure and Response of Asphalt

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Key Words

Trafficking; Airport Pavement; Asphalt; Interface Shear Resistance.

Abstract

As part of a broader investigation into distress in the asphalt surface layer at a major Australian airport, significant testing was performed on cores taken from both trafficked and un-trafficked zones within two different asphalt mixes. Samples were compared for aggregate orientation, relative density, resilient modulus, wheel tracking, interface shear resistance and cyclic shear creep. There was a significant difference between the results from the trafficked and un-trafficked samples. It appeared that the changes to the asphalt caused by 'straight-through' aircraft trafficking increased the asphalt surface's resistance to the severe shear forces induced by heavy braking and cornering of aircraft. It is suggested that where operationally practical, the surface should be exposed to frequent and heavy straight-through traffic for as long as possible prior to allowing harsh braking and turning operations. This would reduce the risk of early life horizontal deformations occurring in the heavy braking zones.

1 Introduction

As part of a broader investigation into distress in the asphalt surface layer at a major Australian airport, significant testing was performed on cores taken from the trafficked and un-trafficked portions of two different asphalt mixes. The two asphalts were of the same approximate age, binder and mix specification, with the source of the fine aggregate (dust) being the only substantial difference. The two dust sources are referred to as Quarry T and Quarry M. The surface was generally 50-60 mm thick and comprised airport-quality asphalt. At the time of coring and testing, the surface was approximately two years old. Both mixes were manufactured using M1000 Multigrade binder complying with the requirements of Australian Standard (AS) 2008, Australia's standard specification for non-polymer modified binders for asphalt paving. One asphalt mix was observed to be performing well while the other was suffering from multiple areas of isolated horizontal deformation, characterised by curving of the sawn grooves in the heavy aircraft braking zones. **Table 1** shows the key characteristics and mix design parameters for the two materials.

Table 1 Key Asphalt Parameters

Parameter	Asphalt Mix	
Dust source	Quarry T	Quarry M
Observed performance	Sound	Horizontally deforming
Methyl Blue Value for Dust source (%)	4	8
Multigrade Binder Content (%)	5.8	5.8
Hydrated Lime Content (%)	1	1
Maximum nominal size (mm)	14	14
Passing 75 µm sieve (%)	6.1	6.5
Marshal Stability (kN)	15.3	17.5
Marshal Flow (mm)	3.3	3.1

A significant difference was noticed in forensic test results from areas of the pavement that were frequently trafficked by aircraft and those that were not. This prompted a specific assessment of the effect of aircraft traffic on the internal structure and response of the surface layer.

The samples were recovered from the two runways at the airport. The airport was found to accommodate in the order of 220,000 aircraft movements per annum, reasonably evenly distributed across the two runways. As a major international airport, the regular operating traffic included B737, B767, A330, B747, B777 and A380 aircraft. These aircraft generally have tire pressures in the order of 1.4 to 1.5 MPa on wheel loads of 20 to 25 tonnes. Cores were recovered from trafficked portion along both runways at 3-4 m (trafficked) and 8-10 m (un-trafficked) offsets from the runway centre line.

The aim of this research was to compare various properties and responses of trafficked and un-trafficked asphalt. Firstly existing knowledge is summarised, covering asphalt structure characterisation, the structural factors affecting asphalt performance, interface shear and cyclic shear resistance, as well as previous investigations that considered the impact of traffic. The adopted research methods are then

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described and the results from each of the test methods are presented and compared using statistical analysis techniques. Finally, conclusions are made and the implications for future work are described. The cause of the Quarry M dust asphalt's poor performance is specifically excluded fom this work.

2 Background

Asphalt is a material of very complex mechanical behaviour. Asphalt's internal composition is the agglomeration of binder, active filler, fine and coarse aggregate. The mastic exhibits plastic, elastic and viscous properties which are inherently temperature dependent (Drescher et al. 2010). While the mastic dominates many mix properties, both the mastic and the aggregate skeleton are important to asphalt performance (Hassan et al. 2012). In fact, by mass, aggregate comprises some 95% of asphalt's structure and can therefore have a significant impact on the mechanical properties of a surface layer (Chen et al. 2005).

2.1 Characterisation of Aggregate Skeleton

The aggregate skeleton within asphalt can be measured directly through microstructure assessment or via bulk materials characteristics using macrostructure measurements (Chen et al. 2005). For microstructure assessment two main approaches are commonly adopted:

- **X-ray Computer Tomography (XCT)**. XCT provides an accurate 3D assessment of an aggregate structure. XCT is able to differentiate between a broad range of engineering materials with an accuracy of up to 5 µm (Tashman et al. 2007). Due to its non-destructive nature, XCT can be used to assess the same sample before, during and after wheel tracking or other performance test. It also offers the advantage of being able to measure air void distribution (Masad et al. 1999a).
- **Digital image analysis**. Digital image analysis is well established within the study of geomechanics of materials such as clays (Masad & Button 2000). Digital image processing includes three major steps; image acquisition, image processing and image analysis (Tashman et al. 2007). Common software can rapidly calculate the number of contact points, aggregate orientation distribution and aggregate segregation measures (Coenen et al. 2012). Requiring only a digital camera and software, digital image analysis offers an economical and rapid assessment of the aggregate skeleton, but only on a 2D basis.

Significant research has been conducted on the structure of asphalt skeletons using both techniques. Image analysis was used by Hamzah et al. (2013) to compare the aggregate skeletons produced by different compaction methods. Lv et al. (2011) analysed the voids, aggregate orientation and segregation of numerous asphalt mixes using similar techniques. In contrast, Masad et al. (1999a) used XCT to assess the air voids distribution and segregation of various asphalt mixtures prepared with various compaction methods. The effect of different compaction methods on asphalt structure was also investigated by Kutay et al. (2010) using XCT. Tashman et al. (2005) used XCT to characterise the aggregate structure, but only as a means of verifying a viscoplastic model for asphalt deformation.

2.2 Structural Factors Affecting Performance

Research has shown asphalt performance to be affected by variation in the orientation and spatial distribution of coarse aggregate particles (Coenen et al. 2012). The number and length of contact points is known to influence asphalt's shear strength (Masad et al. 1999b) as does the distribution of the air voids within the sample (Masad et al. 1998). Coarse and fine aggregate angularity provides an indication of aggregate internal friction and deformation resistance (Holleran et al. 2008). For asphalt samples of identical mix design and construction process, changes in the orientation of the particles within the aggregate skeleton can explain differences in performance (Chen et al. 2005).

2.3 Aggregate Orientation

Aggregate orientation cannot be expressed as a single value or described by a single parameter (Hunter et al. 2004). Many researchers have used a combination of average angle of inclination ($\hat{\theta}$) and vector magnitude (Δ) (Masad et al. 1998; Hamzah et al. 2013; Tashman et al. 2007; Bessa et al. 2012; Chen et al. 2005; Reyes & Zanzotto 2007; Lv et al. 2011). These concepts were advanced to their current form by Curray (1956) and are defined in Equations 1 and 2.

$$\Delta(\%) = \frac{100}{n}\sqrt{\left(\sum sin\,2\theta_k\right)^2 + \left(\sum cos\,2\theta_k\right)^2} \quad \text{.......... Equation 1}$$

$$\hat{\theta}(°) = \frac{\sum|\theta_k|}{n} \quad \text{.......... Equation 2}$$

Where n = the number of aggregate particles in the sample section, each with a major axis angle of inclination of θ_k. Δ varies from 0 to 100 where 0 represents a completely random distribution of aggregate particle orientation and 100 represents all particles being in the same alignment. $\hat{\theta}$ varies from 0° to 90° while θ_k ranges from -90° to 90° (Masad et al. 1998).

With the ready availability of digital cameras and computational software to analyse the images, much effort has recently been made assessing the orientation of aggregate particles resulting from different compaction methods. These efforts peaked in response to the introduction of the Superpave gyratory compactor in the USA (Coenen et al. 2012). Studies have assessed aggregate orientation with respect to the horizontal and vertical axis, as well as radially (for circularly compacted samples prepared in the lab).

Compaction effort has been shown to significantly change the aggregate orientation and structure (Hamzah et al. 2013). For example, with increasing gyrations of a gyratory compactor the average angle of inclination reduced from 41 to 33 over 100 cycles and then increased again to around 38. At the same time the vector magnitude increased from 15 to 44 and then dropped to 22 (Masad et al. 1999a). The mode of compaction is also significant. Lv et al. (2011) reported average angles of inclination of 33 to 36 for gyratory compacted samples and 35 to 47 for vibratory compacted samples of various grading envelopes. In the same study, vector magnitudes of 25 to 30 for gyratory compacted samples but only 15 to 25 for vibratory compaction were reported. Vibratory compacted values of average angle and vector magnitude were also concluded to be more sensitive to grading changes than results from gyratory compacted samples were.

2.4 Effect of Traffic

A large number of studies have investigated the aggregate skeleton of asphalt. Comparatively little work has been done to assess the change in orientation or asphalt response under the action of post-construction traffic. Collop et al. (2009) found that a year of trafficking increased the internal shear strength of asphalt by an average of 30%. Similarly, Oeser et al. (2008) showed that densification of asphalt lead to increased particle contacts and a resultant ‘hardening’ of the mix.

While little has been reported on the effect of traffic in the field, laboratory wheel tracking has been investigated by a number of researchers. Kondo et al. (2003) investigated the movement and reorientation of aggregate particles during Cooper’s wheel tracking test. Aggregate particles were found to move in vertical, horizontal and rotational directions, giving a zero average net movement. Holleran et al. (2008) similarly reported significant reorientation of aggregate particles during wheel tracking in stone mastic asphalt mixes containing elongated particles. The particles tended to a more horizontal alignment under repeated loading.

Chen et al. (2005) reported aggregate reorientation during the wheel tracking test in three phases (primary, secondary and tertiary). This closely reflected rut depth growth and is similar to the widely recognised three phases of asphalt flow (Al-Qadi et al. 2009). During the primary phase, the aggregate rotated to a stable orientation. In the secondary phase, the particles remained stable. In the tertiary phase, significant reorientation and movement occurred as the asphalt deformed and rutted substantially.

2.5 Interface Shear Resistance

The broader investigation specifically addressed the interface shear resistance of the surface layer to the underlying asphalt material. Interface shear resistance has been investigated by a number of researchers using direct shear with and without normal stress, as well as by torsional shear and tensile stress methods (TRB 2012). Researchers have commonly measured Interface Shear Strength (ISS) and Interface Shear Modulus (ISM) as indicators of interface shear resistance. These concepts are well described by Collop et al. (2003).

When comparing ISS and ISM values from various studies, it is important to understand the test temperature and the normal stress applied. These parameters have a significant impact on the results. Other factors that affect ISS include the asphalt materials (Collop et al. 2009), the rate of loading (Sutanto et al. 2007) and the interface’s texture (Santagata et al, 2008).

Interface Shear Work (ISW) is a less commonly used measure of interface shear resistance. ISW is calculated as the areas under the load versus displacement graph over a pre-determined amount of displacement. ISW is influenced by the ISS, the ISM and the post-elastic-peak behaviour of the interface. Some researchers have suggested ISW is governed by the friction between the two layers after de-bonding has occurred (Canestrari et al. 2005).

2.6 Cyclic Shear Resistance

In this context, cyclic shear resistance is a measure of the two layered asphalt system’s performance under a repeated shear stress. While significant research has been conducted on the monotonic behavior of asphalt layer interfaces, there is comparatively little published work on their behavior under repeated loading (Diakhate et al. 2008). For a two layered sample, a cyclic shear test would identify the weakest element in the system, which may be the surface layer, the interface or the underlying asphalt.

There is no standard test method for cyclic shear resistance. Santagata et al. (2008) developed a triple layered (double interface) shear fatigue test to derive shear fatigue laws for interfaces. The double interface arrangement was adopted as this provided a near-pure shear stress across the interface. Petit et al. (2012) used the same double-interfaced shear fatigue test protocol to assess the difference between warm and hot mix asphalts. White (2014) cut cores on a 45° angle to the surface producing an inclined interface at the mid-height. Cyclic compression was used to induce a repeated shear stress through the sample and across the interface. This method was termed the Inclined Repeated Interface Shear (IRIS) test.

3 Investigation Methods

The methods utilised in this investigation were focused on the comparison of nominally identical samples except for their exposure to frequent aircraft traffic. Two similar asphalt mixes were considered. The two mixes were known to perform significantly differently under aircraft braking forces in the field. Because this investigation utilised existing data collected as part of a broader investigation, the results were effectively ‘data mined’. There was no opportunity to perform additional testing. Some comparisons were only possible for Quarry M dust asphalt. In such cases data was not available for the Quarry T dust asphalt.

3.1 Basis of Comparisons

Asphalt samples can be compared in a number of ways. The methods used generally either measure; the properties of the various constituents within the mix, the relative proportions and distribution of those constituents, the macro properties of the asphalt or the response of the asphalt to various load conditions. Because comparisons were being made between trafficked and un-trafficked samples from the same two asphalt materials, assessment of the constituents and their proportion/distribution within the samples was not performed. The broader investigation found no evidence of significant systemic differences within the nominally identical materials.

Of the data available, the following were considered likely to be influenced by trafficking and were therefore utilised as the basis for comparing the trafficked and un-trafficked samples:

- **Relative Density**. Trafficking may have increased the asphalt’s density in comparison to un-trafficked asphalt, which would remain similar to its as-constructed density.
- **Aggregate Orientation**. Trafficking may have altered the structural skeleton through reorientation of the aggregate particles to a more ordered and horizontal alignment.
- **Resilient Modulus**. An increase in density or reorientation of the aggregate particles would likely result in an increase in the modulus.
- **Wheel Tracking**. An increase in the density under traffic would effectively ‘consume’ an amount of the densification potential under wheel tracking. Any structural improvement due to reorientation of the aggregate to a more stable skeleton would also reduce wheel tracking rut potential.
- **Interface Shear Resistance**. Increased embedment of the surface layer aggregate into the underlying surface may increase the interface’s shear resistance.
- **Cyclic Shear Resistance**. Increased embedment of the surface layer aggregate into the underlying surface, as well as increasing the density/modulus, could both result in improved resistance to cyclic shear of the two layered system.

3.2 Test Methods

Existing AS test methods were utilised where available. Where no AS test was available, another established Australian or foreign test method was adopted. In the case of the interface shear resistance a protocol was developed, similar to the direct shear test method described by Canestrari et al. (2005) as the ASTRA test. For the cyclic shear resistance test, a new test and protocol were developed in an attempt to mimic the in-service shear stress conditions using the equipment available in the local laboratory.

3.2.1 Relative Density

The relative density of each sample was measured from cores recovered from the surface. The 100 mm diameter cores were trimmed just above the interface and the density measured and compared to the laboratory prepared Marshall density for the corresponding Lot of asphalt from the project quality assurance records. All samples were prepared according to AS 2891.1 and tested in accordance with the Australian Airports Association Method of Test 002.

3.2.2 Aggregate Orientation

Aggregate orientation was evaluated by 2D digital image analysis using the software i-Pas 2, developed at the University of Wisconsin-Madison and described by Sefidmazgi et al. (2012). The software examines a digital image of a cross section of the asphalt sample and requires a number of key mix parameters such as voids in the mineral aggregate, binder content and grading. The software then analyses the image and calculates the contact lengths, geometry, location and angle to the horizontal of each aggregate particle. From this data, the vector magnitude and average angle of inclination were calculated.

3.2.3 Resilient Modulus

The resilient modulus was measured from cores recovered from the surface. The 100 mm diameter cores were trimmed just above the interface and then tested by the indirect tension method in accordance with AS 2891.13.1. Standard test conditions were utilised and a test temperature of 25°C was adopted as is common practice in Australia for modulus testing of airport asphalt.

3.2.4 Wheel Tracking

200 mm diameter cores recovered from the surface were tested under the Australian protocol for the Cooper's wheel tracker. The samples were trimmed just above the interface and held in a jig that allowed the wheel tracker to traverse across the sample surface as detailed in Austroads AG:PT/T220. The Australian test is performed at a load of 700 N over 10,000 cycles. Samples were conditioned to 60°C as detailed in Austroads AG:PT/T231.

3.2.5 Interface Shear Resistance

Interface shear resistance was measured by a direct shear test of the interface from cores obtained from the surface. Interface strength (ISS), modulus (ISM) and work (ISW) were calculated. ISS was calculated as the peak shear load divided by the initial cross sectional area. ISM was measured as the gradient of the elastic portion of the graph of shear stress versus shear strain. ISW was calculated as the area under the shear force versus shear deformation graph during the first 10 mm of deformation.

Up to eight cubic samples were cut from each 200 mm core and tested at various normal stresses, ranging from approximately 20 kPa to 700 kPa. This allowed Mohr-Coulomb type envelopes to be generated for each core. Square sectioned samples are not commonly used for direct shear strength testing but were selected to avoid any point-loading associated with imperfectly matching circular sections.

Direct shear testing was performed on samples conditioned to 55°C to represent the mean summer pavement temperature. The samples were sheared at a constant 50 mm per minute rate of deformation.

3.2.6 Cyclic Shear Resistance

Cyclic shear resistance was measured using the IRIS test as described by White (2014). Sample preparation involved cutting a 75 mm core on a 45° angle to the surface and then trimming the top and bottom perpendicular to the core's axis of symmetry. Generally two 75 mm samples were obtained from a single 200 mm core.

The resulting 75 mm cylinders included an interface at 45° to the core's axis, at around the mid-height of the sample. Testing was performed on samples conditioned and maintained at 55°C. The adopted loading regime was:

- Load rate/frequency. 0.1 second haversine loading.
- Rest time. 0.9 seconds.
- Confining stress. 138 kPa.
- Cyclic axial (deviatory) stress. 828 kPa.

Each sample was tested under sub-maximal cyclic load until 20,000 cycles or failure occurred as either interface de-bonding or horizontal deformation in excess of 100 mm. The sample deformation was logged against load cycles.

The number of cycles until tertiary flow initiation was recorded. The deformations after 400 and 2000 load cycles were also reported. Following testing, the failure location (separation at the interface or deformation within the mix) was assessed by visual inspection of dissected cores and was recorded.

3.3 Statistical Analysis

The various tests results were compared using a range of statistical techniques. For direct comparison of results where the only explanatory variable was the dichotomous factor ('trafficked' or 'un-trafficked') a Student's T-test was utilised. As the data was not paired, sample sizes for each group could be different and the variances were not known to be equal, a single-sided Welch's version of the T-test was performed (Lawson & Erjavec. 2001).

For the direct shear resistance testing, both the dichotomous ('trafficked' or 'un-trafficked') and the applied normal stress, were both considered as explanatory variables. It is well established that interface shear resistance increases linearly with increasing normal stress (Uzan et al. 1978). Rather than separately compare the results for tests performed at different levels of normal stress, a linear regression analysis was performed. Each of the measures of interface shear resistance was modelled as a linear function of the normal stress and whether or not they were trafficked. The statistical significance of the trafficking was obtained from the p-value associated with its coefficient from the regression analysis (Ramsey & Shafer

2002). Prior to final regression analysis, any outliers were identified using Cook's distance and by inspection of the plots of residuals and removed from the data set. The normality and variance of the residuals were also checked at that time.

For the cyclic shear resistance testing the failure mode was more informative than the numerical measurements. The frequency of each failure mechanism was therefore compared rather than any specific statistical analysis of the deformations and load cycles recorded.

4 Results and Analysis

The analysis of the results was performed 'parameter-by-parameter' using the statistical techniques described above. The consistence of the effect of aircraft traffic across each of the various parameters was then considered along with a likely mechanism of structural evolution.

4.1 Relative Density

Relative density data was available from both trafficked and un-trafficked areas of the pavement containing Quarry M dust as presented in **Table 2**. With a T-test p-value of 0.05 and by comparison of the mean values, it was determined that the trafficked areas of the Quarry M dust asphalt had a statistically significantly higher relative density than the un-trafficked areas of the same asphalt. On average, trafficked areas had a 1.5% higher relative density. A moderate increase in density of a viscoplastic material under repeated heavy loading was intuitively expected.

Table 2 Relative Density Summary for Quarry M dust Asphalt

Statistic	Trafficked	Un-trafficked
Mean	99.5%	98.0%
Standard Deviation	1.3%	1.3%
p-value	0.05 for 30 degrees of freedom (df)	

4.2 Aggregate Orientation

Table 3 summarises the vector magnitude and average angle of inclination results from both trafficked and un-trafficked areas of the Quarry M dust mix. With a T-test p-value of less than 0.01 and by comparison of the means, it was determined that the trafficked areas of the Quarry M dust asphalt had a statistically significantly lower average angle of inclination than the un-trafficked areas of the same asphalt. Similarly, with a p-value of 0.02, the trafficked Quarry M dust samples showed statistically significantly higher vector magnitudes than un-trafficked samples. Frequent aircraft traffic had caused the aggregate particles to become more horizontally aligned. It is also noted that the vector magnitude values for both trafficked and un-trafficked samples are at the upper end of those reported in literature. This may reflect the high quality of the asphalt mix and the high level of compaction required during construction of an airport surface layer. Most vector magnitudes reported in the literature were measured on asphalt mixes compacted in the laboratory and manufactured to road specifications.

Table 3 Aggregate Orientation Summary for Quarry M dust Asphalt

Statistic	Average Angle of Inclination ($\bar{\theta}$)		Vector Magnitude (Δ)	
	Trafficked	Un-trafficked	Trafficked	Un-trafficked
Mean	32.8°	39.8°	69.1%	59.0%
Standard Deviation	0.93°	2.73°	4.6%	6.4%
p-value	< 0.01 for 7 df		0.02 for 7 df	

4.3 Resilient Modulus

Resilient Modulus data from both trafficked and un-trafficked areas of both the Quarry M dust and the Quarry T dust is summarised in **Table 4**. With a T-test p-value of 0.04 and by comparison of the means the trafficked areas of the Quarry M dust asphalt had a statistically significantly higher resilient modulus than the un-trafficked areas. It was anticipated that trafficking would increase the resilient modulus of the asphalt as a result of the increase in density and reduction in air voids. For the Quarry T dust asphalt, the p-value was higher, at 0.08 which is marginal in terms of statistical significance and may have been the result of the relatively small sample size. The higher variance in the test data for these field cores could also be a factor.

Table 4 Resilient Modulus Summary

Statistic	Quarry M dust Asphalt		Quarry T dust Asphalt	
	Trafficked	Un-trafficked	Trafficked	Un-trafficked
Mean	3,675 MPa	3,158 MPa	4,295 MPa	3,496 MPa
Standard Deviation	668 MPa	371 MPa	709 MPa	569 MPa
p-value	0.04 for 30 df		0.08 for 5 df	

4.4 Wheel Tracking

Table 5 presents the wheel tracking data from both trafficked and un-trafficked areas of the surface containing Quarry M dust. With a T-test p-value of less than 0.01 and by comparison of the means the trafficked areas of the Quarry M dust asphalt exhibited statistically significantly less rutting under wheel tracking than the un-trafficked areas. The wheel tracking test is intended to measure the remaining potential for rutting within an asphalt sample. For a trafficked sample it was not surprising that the remaining rut potential had already decreased. It was also expected that the un-trafficked wheel tracking results would be similar to those measured on laboratory prepared samples, assuming that the laboratory compactive effort closely replicated that achieved in the field. The laboratory prepared wheel tracking result for the Quarry M dust asphalt was 3.4 mm, which was similar to the un-trafficked average of 3.3 mm.

Table 5 Wheel Tracking Summary for Quarry M dust Asphalt

Statistic	Trafficked	Un-trafficked
Mean	1.9 mm	3.3 mm
Standard Deviation	0.6 mm	0.2 mm
p-value	< 0.01 for 6 degrees of freedom (df)	

4.5 Interface Shear Resistance

Direct shear test results were available for the interface of trafficked and un-trafficked samples from both the Quarry M and Quarry T dust asphalts. Linear regressions were performed on interface strength (ISS), modulus (ISM) and work (ISW) separately. One outlier was removed from the Quarry T dust data prior to the regression analysis being performed. The dichotomous variable (trafficked or un-trafficked) was modelled as a dummy variable called ‘traffic’ with an assigned value of 1 (for trafficked samples) or 0 (for un-trafficked samples).

The ISS, ISM and ISW multivariate regression models are shown in Equations 3 to 5 for Quarry M dust samples and similarly in Equations 6 to 8 for Quarry T dust samples. In all cases *Normal* is the normal stress applied during the test in kPa and *Trafficked* is the dummy variable described above.

$$ISS_{Quarry\ T} = 138 + 0.645 \times Normal + 209 \times Trafficked\ (R^2 = 87\%) \quad \text{Equation 3}$$

$$ISM_{Quarry\ T} = 38.9 + 0.122 \times Normal + 68.8 \times Trafficked\ (R^2 = 86\%) \quad \text{Equation 4}$$

$$ISW_{Quarry\ T} = 1.78 + 0.015 \times Normal + 4.52 \times Trafficked\ (R^2 = 96\%) \quad \text{Equation 5}$$

$$ISS_{Quarry\ M} = 285 + 0.729 \times Normal + 143 \times Trafficked\ (R^2 = 77\%) \quad \text{Equation 6}$$

$$ISM_{Quarry\ M} = 119 + 0.061 \times Normal + 4.7 \times Trafficked\ (R^2 = 23\%) \quad \text{Equation 7}$$

$$ISW_{Quarry\ M} = 3.30 + 0.018 \times Normal + 3.25 \times Trafficked\ (R^2 = 81\%) \quad \text{Equation 8}$$

To demonstrate the impact of traffic on the interface shear resistance, **Table 6** provides the calculated (from Equations 3 and 6 respectively) ISS for Quarry T and Quarry M dust asphalts at two different normal stresses. Normal stresses of 0 kPa and 400 kPa were selected to represent the normal stress (at 50 mm depth) just in front of the aircraft tire and under the centre of the tire. These values were estimated from finite element model data presented by Al-Qadi & Wang (2011). From Table 6 it can be calculated that traffic increased the ISS by an average of 25-150% for these extreme limits of normal stress. It is most likely that de-bonding occurs at low or even zero normal stresses, which occurs immediately in front of a rolling tire (TRB 2012). At zero normal stress, the average increase in ISS provided by aircraft trafficking was 50-150%.

Table 6 Comparison of Interface Shear Strengths at extremes of Normal Stress

Normal Stress (kPa)	Quarry M dust Asphalt		Quarry T dust Asphalt	
	Un-trafficked	Trafficked	Un-trafficked	Trafficked
0 kPa	285 kPa	428 kPa	138 kPa	347 kPa
400 kPa	577 kPa	721 kPa	396 kPa	605 kPa

Table 7 presents the p-values associated with the statistical significance of *Normal* and *Trafficked* for each ISS, ISM and ISW model. From the p-values and the regression models it was concluded that:

- In all cases except for Equation 7, the R^2 values ranged from 77-96%. This showed that the majority of the variability observed in the test results was explained by a linear model with only the normal stress and the trafficked condition as explanatory variables. This gives a high level of confidence in the statistical validity of the results.
- Normal stress was statistically significant in all cases. Based on the work of Uzan et al. (1978) and many others that have investigated the shear resistance of interfaces between asphalt layers, this was fully expected.
- Trafficking was statistically significant in all cases except ISM for Quarry M dust. Work by Oeser et al. (2008) and Collop et al. (2009) suggested this should be expected. Further investigation would be required to determine the specific effect of trafficking on ISM. Such further investigation lies outside the scope of this current work.

Table 7 Interface Shear Resistance Regression Model p-values

Predictor	Quarry M dust Asphalt		Quarry T dust Asphalt	
	Normal	Trafficked	Normal	Trafficked
ISS	0.00	0.01	0.00	0.02
ISM	0.01	0.70	0.01	0.00
ISW	0.00	0.00	0.00	0.00

4.6 Cyclic Shear Creep

Prior to testing, it was expected that all samples would fail by deformation within the surface layer. Different materials were expected to deform at different rates. However, the various samples failed by a number of mechanisms. The mechanisms included interface separation (or de-bonding), surface layer deformation and underlying layer deformation. The latter of these was not expected. All failure modes were reported by a single parameter: displacement of the top of the sample relative to the bottom. The numerical results were consequently not enlightening. Of more interest was the frequency of failure mode as determined by visual inspection of the samples after the completion of each test, as summarised in **Table 8**.

Table 8 Cyclic Shear Creep Failure Mode Frequency

Failure Mode	Quarry M dust Asphalt		Quarry T dust Asphalt	
	Trafficked	Un-trafficked	Trafficked	Un-trafficked
Surface layer deformation	6	1	0	0
Interface de-bonding	1	3	2	3
Underling layer deformation	0	0	1	0

The failure mode frequency data suggested that for the Quarry M dust samples, aircraft traffic prompted a change in the dominant failure mode from interface de-bonding to surface layer deformation. It appeared that the surface layer became the weakest element of the system. It then deformed rather than the interface separating and de-bonding. This is consistent with the findings of Oeser et al. (2008) and Collop et al. (2009) that the action of trafficking improved the interface's shear resistance.

In contrast, traffic did not significantly change the failure mode for the Quarry T dust samples. It appeared that the Quarry T dust sample interfaces were still improved by the traffic, as suggested by the interface shear resistance testing. The Quarry T dust asphalt was, however, so resistant to cyclic shear that the interface remained the weakest element of the system. These explanations were supported by the broader investigation which found that the Quarry M dust asphalt lacked resistance to cyclic shear stress, while the strength of the interfaces were not significantly different for the two asphalts.

5 Summary of results

Aircraft traffic significantly changed the structure of the asphalt materials investigated by generally improving the response of the asphalt surface layer. The data indicated two years of aircraft trafficking:

- Increased the relative density of the surface layer by approximately 1.5%.
- Re-orientated the aggregate particles towards a more horizontal and ordered alignment.
- Increased the resilient modulus of the asphalt by approximately 500 MPa.
- Decreased the remaining rut potential from approximately 3 mm to less than 2 mm.
- Significantly improved the interface shear resistance, particularly the ISS and ISW.

- Changed the failure mode of shear creep susceptible asphalt, subject to cyclic shear loading, from being predominantly interface de-bonding to being predominantly deformation of the surface layer.

Where data from both mixes was available, these trends were generally consistent for both the Quarry M and Quarry T dust asphalt. This consistence was despite the two asphalts' significantly different field performance under severe shear forces.

6 Conclusions

The measured changes in asphalt's structure and response due to aircraft trafficking are not inconsistent with those reported by other researchers. They indicate that under repeated heavy aircraft traffic loading:

- Aggregate particles re-orientated to a more stable arrangement, which increased the combined inter-particle contact area and locked-up the matrix.
- During this aggregate re-orientation process, the relative density of the surface layer would have increased moderately.
- The combined effect of the densification and aggregate re-orientation improved the asphalt mix as well as improving interlayer embedment and interface bonding.
- This improvement resulted in increased resilient modulus, improved interface shear resistance and improved interface resistance to cyclic shear creep.

Aircraft traffic increased the surface asphalt's future resistance to severe shear loading situations, such as during heavy braking and turning of aircraft. Despite these measured improvements, the Quarry M dust asphalt continued to perform poorly in the field. The traffic-induced improvement was not enough to overcome the Quarry M dust asphalt's susceptibility to severe shear stresses.

It is suggested that where operationally practical, new asphalt surfaces be exposed to frequent and heavy 'straight-through' traffic for as long as possible prior to allowing harsh braking and turning operations. This would reduce the risk of shear deformation occurring early in the new surface's life, when it is most susceptible to such damage. In practice this would require the prevention of sharp or locked-wheel turns and the temporary closure of taxiway intersections that require heavy braking.

Additional investigation is needed to determine the rate of improvement measured in this investigation as a function of traffic volume. Further research into the specific effect of trafficking on interface stiffness or modulus is also required as the results were inconsistent for the two asphalt mixes assessed.

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Acknowledgements

The author acknowledges the contributions made to the broader investigation by Beca Consultants and other Fulton Hogan staff and laboratories. The development of the interface shear resistance tests by Tom Gabrawy and performance of the physical testing by Tom Gabrawy and Kevin Embleton is specifically recognised. The provision of the i-Pas 2 software by the University of Wisconsin-Madison is greatly appreciated.