SLIPPERY ASPHALT RUNWAYS AFTER REJUVENATION

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ABSTRACT

The normal ageing of flexible hot-mix asphalt runways leads to the surface layer of hot-mix asphalt becoming oxidised and brittle. It is usually overlaid or replaced with a new layer of hot-mix asphalt every 10-25 years of service. The time of overlay can be extended for several years by applying a rejuvenator, such as a bitumen emulsion or a coal tar based product. This technology has been used in the roads and airfield sectors, but rejuvenation can lead to slippery runways when wet. It reduces microtexture and macrotexture, and does not reduce wheel ruts or correct drainage problems. Even grooved runways can become slippery when wet after rejuvenation.

Recent accident and incident investigations are used to show the effect of rejuvenation on runway slipperiness. ICAO recommends to States through Standards and recommendations that the runway should posses a multitude of properties so as to give good wet weather performance. The inter-dependence and importance of all of these is shown, together with new limitations of continuous measuring friction equipment in detecting certain types of slipperiness. The detection of slippery runways after rejuvenation is discussed, and the case against rejuvenation of hot-mix asphalt runways is made.

1 BACKGROUND

1.1 Aircraft braking action

Aircraft braking action results from the friction force between the tyres and the runway surface. The friction force is affected by aircraft speed, wheel speed (i.e., free-rolling, skidding or locked), tyre condition and pressure, runway condition (i.e., surface friction characteristics); the load applied on the wheel; and the efficiency of operative brakes. Surface friction characteristics have traditionally been described with the simplified runway friction coefficient. Braking force is then equal to the load applied on the braking wheels multiplied by the runway friction coefficient. Wet runways have lower friction coefficients than dry runways, and the difference increases with speed. Runway friction can also be affected by rejuvenation which effectively acts as a dry contamination. All of these can lead to reduced braking action.

1.2 Aquaplaning/hydroplaning

Aquaplaning (also known as hydroplaning) is a major contributor to runway overrun accidents. It significantly reduces the runway friction coefficient (by up to 95 per cent compared to a dry runway) and braking action [1]. Aquaplaning is often associated with periods of heavy rain, localised thunderstorm activity, shifting winds, and reduced visibility. Aquaplaning results in a partial or total loss of contact between the tyre and runway as the tyre rides above the runway surface on a film or wedge of standing water. There are three types of aquaplaning, each with varying severities [2].

- Viscous – caused by a thin film of water on the runway that acts as a lubricant and reduces the runway friction coefficient (Mu). Viscous aquaplaning is the most common type of aquaplaning and can occur on damp or contaminated runways at low taxi speeds or higher.
- Dynamic – caused by hydrodynamic force lifting the tyre off the runway, resulting in the aircraft 'water-skiing' and a substantial loss of friction. Dynamic aquaplaning can occur with standing water as little as 3 mm deep (to be greater than the tyre tread depth), and at higher ground speeds (greater than the critical dynamic aquaplaning speed).
- Reverted-rubber – occurs when a wheel 'locks up' on landing and is dragged across a wet runway. Steam is generated by friction that lifts the tyre off the runway, and heats the tyre surface until it reverts back to its unvulcanised (i.e. uncured, sticky and deformable) state. Reverted-rubber aquaplaning can occur at any speed over 35 kph and reduces the Mu value similar to that when landing on an icy runway. This is akin to viscous skidding in that it occurs with a thin film of water and a smooth runway surface.

1.3 Wet weather friction

Leaving out the winter contaminants, snow and ice, we concentrate on hot mix asphalt pavements with any form of moisture present. The greatest resistance to skidding of hot mix asphalt was found to be that with a "sand paper" texture of the surface. From a theoretical analysis in 1934 it was deduced that to be reasonably free from the danger of skidding, a road surface when wet should have a straight skid coefficient of 0.4 or higher at 65 kph and a static or side skid coefficient of 0.5 or higher at 50 kph [3]. Subsequent investigation, when evaluated in 1958 consistently showed the poorest resistance to skidding was when there was an excess of bitumen present on the surface, and according to many studies, the best skidding characteristics are in hot mix asphalt possessing an extremely dense "sandpaper" texture. The other dominant factor contributing to slipperiness of bituminous pavements was the use of uncrushed aggregates allowing a film of water to exist between the tyre and the polished aggregate. [4] It was found that for most aggregates a typical water film thickness will vary from 0.01 to 0.02 of an inch thick. [5] Further that this film could be removed rather easily until the last 0.001 of an inch. Under certain circumstances this minute film can greatly decrease the resisting force otherwise developed by each aggregate particle.

1.4 ICAO provisions for wet weather friction

ICAO starts by recommending that "The surface of a paved runway shall be so constructed as to provide good friction characteristics when the runway is wet" [6: section 3.1.23]. The four legs of good wet weather friction are macrotexture, microtexture, geometry and drainage. So ICAO recommends a minimum macrotexture, minimum limits for runway slopes and crossfall to ensure drainage, and limits on irregularities and ruts to reduce ponding of water. They also recommend limits for friction testing. Microtexture is not provided for specifically, but follows from the use of crushed aggregate in the design phase.

1.5 Slippery asphalt runways after rejuvenation

There is a risk of creating slippery conditions on an asphalt runway after applying bituminous or coal-tar rejuvenation products. Recent aviation accidents and incidents have highlighted problems with the use of rejuvenation products, and limitations in the use of friction measuring devices to detect these conditions. The terms used in this paper are fog spray (also termed dilute bitumen emulsion), bitumen emulsion (also termed asphaltic emulsion) and hot-mix asphalt (also termed HMA, asphaltic concrete or asphalt).

2 RELEVANT AIRCRAFT INCIDENTS AND ACCIDENTS

2.1 USA accidents and incidents

In 1959 when landing, a T-33 light jet aircraft ran off the end of the runway. This was during light rain, on a rejuvenated runway (with bitumen emulsion). Braking was tried but was ineffective; the pilot commented that it was the slickest runway he had ever landed on. The surface friction characteristics were subsequently measured under dry conditions using a pendulum type decelerometer. It revealed a coefficient of friction of about 0.4, which would normally be judged as reasonable [7]. A literature survey in 1970 mentions lack of braking action at two wet rejuvenated runways (with fog seal) [8]. In 1969 a DC-8 jet aircraft overran the end of the dry runway in a rejected takeoff during a touch-and-go manoeuvre on a runway newly treated with bitumen emulsion without any abrasive additive [9]. The runway surface displayed a glazed (bitumen rich) smooth and slippery appearance when compared to the texture of adjacent unsealed surfaces. Subsequent measurement of surface friction characteristics using a pendulum type decelerometer under dry conditions gave low readings but could not detect any significant difference between the treated runway and adjacent untreated surfaces.

2.2 Chile accident

In February 1991 a BAE 146-200 jet aircraft overran a wet runway and went into the sea [10]. One month prior the runway had been rejuvenated/treated with a partial slurry seal application with a full fog seal treatment on top as the finishing coat, leaving two strips of bitumen-rich pavement surfaces on either side of the centreline. The investigation indicated that those areas of poor braking were those with the fog seal on top of the slurry seal. In October 1991 the surface was tested using British Pendulum Test and Sand Patch method giving information on microtexture and macrotexture respectively. The measurements were judged to be conclusive indicating substandard micro and macrotexture along the centreline of the runway caused by the rejuvenation. In March 1992 a side-force continuous friction measurement device was brought to the accident site. The areas of fog seal had changed due to oxidation and some surface restoration had taken place. Nevertheless, measurements showed results below the Minimum Friction Level indicated by ICAO for the type of device used.

2.3 Norway incident

In July 1995 a bitumen emulsion rejuvenator was applied to dense graded hot-mix asphalt runway at a Norwegian airport. Due to intervention from non-skilled personnel, a second application of rejuvenator was added to the central part of the runway. This resulted in slippery conditions experienced by flight crew in landing aircraft. No serious incident or accident took place. Continuous aggressive brushing of the runway with rotating steel-brushes reduced the potential dangerous slippery runway surface condition. A continuous friction measuring device (CFME) was used to measure the surface friction, and was not able to detect the slippery conditions when compared to the Minimum Friction Level indicated by ICAO for the device used. At the time, it was theorised that the cause of the slipperiness had to be found within the applied rejuvenator combined with moisture/water.

2.4 South African accident

2.4.1 Accident

On 7 December 2009 an Embraer 135-LR landed at George Airport 11/29 runway in South Africa which had been recently rejuvenated with a fog seal. The aircraft was cleared for an instrument landing (ILS) approach for Runway 11. The prevailing weather conditions at the time were overcast, with light rain. According to the air traffic controller (ATC) on duty at the time, the landing appeared normal, however the aircraft did not vacate the runway to the left as per normal operation but instead veered to the right and went past the ILS localizer. The aircraft collided with eleven approach lights before it burst through the aerodrome perimeter fence, with the aircraft coming to rest in a nose-down attitude on a public road [11].

The pilots involved had landed at George in wet conditions many times before, but this was the first landing conducted by them in wet runway conditions since the rejuvenation was completed. The day of this accident was the first time that the George area had received a proper rain shower following the rejuvenation of the runway, which was concluded on 6 November 2009.

The runway length was 2000 m with an upslope of 0.4%. According to figures provided by the manufacturer, the aircraft should have been able to have come to a complete stop in a distance of 1895 m. The deceleration obtained was on average -0.1g where levels of more than -0.15g were required to stop the aircraft in the distance available. The EMB 135 aircraft (ZS-SJW) was not fitted with a thrust reverser system and is fully reliant on the braking system of the aircraft (including spoilers) to bring the aircraft to a stop. All indications are that the aircraft was serviceable and that the anti-skid braking system of the aircraft worked as it should have, but that due to the slippery surface, the system was unable to apply sufficient brake pressure to effectively stop the aircraft. Although pilots may be applying maximum braking, the system will limit the actual brake pressure to prevent the wheels from locking. The tyres did display some evidence of aquaplaning, as there was a partial scalding effect to the tread rubber and the surface of the tread rubber had some evidence of reversion and peeling of the compound (Figure 1).

	
Aircraft final stopping position	Rubber reversion on tyre

Figure 1 – George accident

2.4.2 Runway rejuvenation

The rejuvenation was by application of a bitumen emulsion - fog spray (SS-60 Stablemix Bitumen Emulsion) to the runway surface. The average application rate for the runway surface was 0.56 l/m² with a slight run-off observed from the runway edges. The runway had some slots cut into the surface in an isolated area, but was considered effectively ungrooved. After the accident, it was observed that the macrotexture at George had been reduced by the application of bitumen emulsion, and that most of the microtexture, had been covered by it.

2.4.3 Friction tests

Just before the rejuvenation and accident, on 1 September 2009 a friction test was done of the runway using a Grip Tester MK-2 (C-type), with 1.0 mm self-wet and at 65 kph. The average friction was 0.69 (between ICAO design objective level of 0.74 and maintenance level of 0.53) [6]. After the fogspray, but before the accident, on 6 November, similar testing showed an average friction of 0.40, below the minimum friction level (MFL) range of 0.43 as listed in the ICAO friction level table for a test at 65 kph. On 9 December 2009, two days after the accident, similar testing showed an average friction of 0.77, which met the design objective level of 0.74. Testing was repeated on 15 February 2010, and showed an average friction of 0.70 [11]. This repeat testing was conducted under close scrutiny and the CMFE was in-calibration and properly operated. Sand patch macro-texture results on 15 February 2010 had a range from 0.24 mm-0.69 mm, with an average of 0.47 mm; this is significantly less than the ICAO recommendation of 1.0 mm minimum for a new surface [6].

2.4.4 Boeing 737-400 landing and rejected takeoff test

In view of the uncertainty created by the varying friction test results, a full scale landing test followed by a rejected take off (RTO) test was executed on 12 March 2010 using a Boeing 737-400. The tests were conducted after aerodrome operating hours during raining/heavy drizzle conditions. The aircraft was empty with only crew onboard with an additional captain in the jump seat. The pilot had previous simulator training and had experienced one high speed RTO in a B737 under dry conditions [11].

On landing, according to the 737-400 Aircraft Flight Manual (AFM) the aircraft should have stopped within 1103 m. Distance achieved was 1199 m. The result presents an underperformance of 95 m or 8.6 per cent.

For the rejected takeoff, the aircraft was accelerated by means of maximum thrust to 100 knots before the rejected take off drill commenced. Braking was initially moderate according to the pilot. For the last 610 m though, the braking action can only be described as poor as the anti-skid was releasing all the time. Further to this small pools of water could be felt under the aircraft. According to the AFM the aircraft should have stopped within 975 m. Distance achieved was 1254 m which equates to an underperformance of 278 m or 28 per cent. From 70 knots down to zero, the braking action was very poor. During the test period, the recorded rain fall at the aerodrome was 3 mm over 4 hours.

2.4.5 Probable cause

The probable cause of the accident [11] was: “The use of the fog spray sealant can be considered to have been the primary probable cause of the occurrence of aquaplaning to such an extent that the crew was unable to decelerate the aircraft to a safe stop in the certificated distance.”

3 TECHNOLOGY OF REJUVENATION

3.1 Hot-mix asphalt ageing and rejuvenation

Hot-mix asphalt (HMA) ages and becomes brittle as a consequence of bitumen oxidation. There are two approaches to rejuvenation. The first is the addition of solvents (lighter bitumen fractions or oils; sometimes in emulsified format) which penetrate the HMA and flux (soften) the hard and brittle bitumen inside the HMA, restoring flexibility. The second are surface treatments which protect the asphalt surface from further oxidation and/or rebind any loose and oxidised material. In addition to generic materials such as bitumen emulsion, there are a number of proprietary rejuvenators which are often difficult to specify with a generic specification. While rejuvenation is used on roads, aprons, taxiways and parking areas, it is not commonly used on hot-mix asphalt runways. Spray applications of liquid agents on the pavement surface have the potential to reduce the frictional characteristics of the pavement surface [12].

3.2 Solvent rejuvenation for HMA

The solvent type rejuvenators are themselves fluxed with light fraction hydrocarbon compounds that aid in the absorption and penetration of the rejuvenator into the existing HMA surface immediately after application, and then after some short time evaporate from the surface. These products are applied at very low rates, typically at 0.15 l/m^2 or less.

To be effective, the solvent rejuvenator must penetrate into the pavement surface in order to be absorbed by the age hardened asphalt, but also to avoid causing a binder-slick surface, especially in wet weather [13]. This type of rejuvenation has rarely been used on civilian airports, mainly due to the slow evaporation rate of the solvents, making the surfaces sticky and soft and requiring closure of the pavement for extended periods. The skid resistance can be significantly reduced for a substantial period of time when rejuvenators are applied, especially when the rejuvenators do not penetrate [14]. The US Air Force in their standard practice for pavement recycling describe use of rejuvenator as one of three processes that should be considered on a structurally sound pavement. With respect to skid resistance following is stressed: "Application of a rejuvenator will also reduce the skid resistance of the pavement for up to 1 year. While this reduction in skid resistance should not be significant for parking aprons and taxiways, it may be significant for runways or other areas where high aircraft speeds are likely to occur. Use caution; be sure to have a full-time person on the job who is experienced in applying rejuvenators" [15].

In some cases a scatter of sand has been applied to the pavement surface to allow traffic to use it; this is common on highways but not aircraft pavements to avoid Foreign Object Debris (FOD) generation.

3.3 Surface treatment rejuvenation for HMA

Surface treatment rejuvenators are products that typically protect the asphalt surface from further oxidation and also act as a sacrificial surfacing. These materials usually reduce the macro- and micro-texture of the HMA (Figure 2), and this can have a significant impact on the runway friction.

3.3.1 Coal Tar Based Products

Coal tar based "rejuvenators" have been used on military airfield pavements in Australia without any publicly reported incidences of friction loss. However the Federal Aviation Administration in the USA requires that the friction survey tests be done on test sections when contemplating their use on a runway [16]. Coal tar residue is fluxed with a low ignition temperature carbon chemical (generally in a 50/50 mix), and is applied by spray application to the pavement surface. The solvent evaporates leaving the residual coal tar material penetrating the asphalt surface. Typically the material is applied at a rate of $0.15 l/m^2$ residual coal tar. The coal tar is chemically quite different to bitumen and provides good adhesion, is extremely resilient and is highly abrasive resistant. The coal tar/solvent mix has low viscosity and the material is easily absorbed by the bitumen and also by the aggregates on the surface. Coal tar then acts to protect the HMA from moisture and oxidation and also applies additional glue to the HMA surface, reducing FOD potential.

3.3.2 Bitumen emulsion based products

Bitumen emulsion “rejuvenators” such as fog sprays have been used extensively on roads and airports on chip seals but less commonly on hot mix asphalts. These use an emulsion of bitumen and water with the addition of an emulsifier or emulsifying agent to ensure stability. The bitumen emulsion is often further diluted with water. The fog spray is sprayed on the HMA surface to add more bitumen which rebinds any loose and oxidised material. Very soon after spray application, the emulsion breaks, and the water is driven off leaving the residual bitumen in place.

Figure 2 - Shiny wheeltrack, covered aggregate and filled-up voids

Appropriate fog sprays on chip seal surfaces are designed and diluted so that the bitumen settles into (and partially fills) the voids in the surface texture. An emulsion that is too thick may not properly penetrate into the surface voids and will leave behind an excess amount of bitumen on the surface after the emulsion breaks, causing a slippery surface. They are less commonly applied to HMA as the fog spray tends to cover the top of the pavement surface. Some practitioners use sand blinding to provide a grit cover and improve the microtexture. River sand is applied in excess just as the emulsion is breaking. It is rolled with 6 passes before the excess is broomed off. The sand should be graded with a high coefficient of uniformity. Sand further reduces macrotexture and this needs to be considered in assessing the suitability of a surface for a fogspray.

Other surface rejuvenators use a blend of polymer-modified bitumen emulsions, fine filler (material less than 0.075mm in size) and sand (1mm in size and less) to form a seal coat. The materials are pre-blended in large tanks with stirrers, before being applied to the pavement surface by speciality designed truck mounted spray applicators. These materials have been applied to asphalt pavements at rates of between 0.7 l/m^2 to 2.0 l/m^2. At these volumes the material generally sits on the surface of the pavement and deliberately acts as a sacrificial layer, thereby protecting the pavement against further deterioration and reducing oxidation. For this material to be successful it is important that the material be proportioned and designed appropriately. The fine sand/aggregate fraction must be proportioned and graded correctly, and matched to the bitumen volume so that the material is stable in the applied environment and under traffic. It is also necessary that the sand fraction be angular to promote stability of the material.

3.3.3 Chip seals

These are widely used on roads and smaller airfields as surfacings in their own right. They are applications of bituminous materials to a pavement surface with a cover of stones or aggregate (5 mm to 10 mm diameter are used on airfields). These are not considered rejuvenators and lie outside the scope of this paper.

However it should be noted that chip seals can be found on some runways with lighter traffic (chip seals are variously called surface treatment, surface dressing, or chip and spray). A chip seal can usually meet the regulatory requirements in terms of wet weather friction and macrotexture depth; it is a friction treatment in itself. Macrotexture of up to 2.0mm can be found on chip seals, and for this reason, they can be suited to rejuvenation without compromising wet weather friction [17].

4 TECHNOLOGY OF REVERTED RUBBER AQUAPLANING

4.1 Aviation research into reverted rubber aquaplaning

Research into aviation friction in the 1950s and 60s developed dynamic and viscous aquaplaning theory (1960), and reverted rubber aquaplaning theory (1965) [18]. Generation of steam in the tyre footprint was first discussed by Obertorp [19] and offers an explanation for the reverted rubber and the reduced traction that may be developed by tyres at very low speeds. Once reverted rubber is established in the tyre footprint, extremely low friction coefficients develop on wet pavements down to very low ground speeds. Because the friction coefficients that result are as low or even lower, in some cases, than the tyre free-rolling resistance coefficient the tyre has a tendency to remain in the locked wheel condition for long distances on the runway.

Two theories of reverted rubber aquaplaning developed and are described as follows [20]:

> *In recent years aircraft skidding accidents have taken place under conditions thought to be impossible for conventional tyre hydroplaning. These skidding accidents occurred on smooth, wet or puddle runways and were accompanied by a loss of braking down to speeds of 5-8 knots. Afterward the tyres of the aircraft exhibited a characteristic patch of sticky, soft rubber on the tread. This patch of rubber was called "reverted" rubber because it appeared to have been reverted back to its unvulcanized, uncured state. Because the loss of braking friction occurred down to speeds well below those thought to be minimum for tyre hydroplaning, this loss of friction was*

believed to be connected with the patch or patches of "reverted" rubber. White streaks of clean runway usually resulted from these "reverted" rubber aircraft skids.

Horne et. al. [20] theorized that the soft sticky rubber could form a seal around the edge of the contact patch which would contain high pressure super-heated steam under the contact patch. This steam pressure would tend to lift the tyre away from the pavement surface, and thus reduce traction on wet surfaces. The white streaks would be clean pavement cleared of contaminants by high pressure super-heated steam. A preliminary examination by Horne et al. led them to state this theory, "Thus these initial results based on limited data indicate that reverted rubber may form and possibly provide better sealing around the periphery of the footprint than normal rubber, thus allowing a very thin film of water to be trapped in the footprint, heated up, and to possibly change into steam as predicted by Obertorp."

While the steam theory provides one possible explanation for the skidding accidents which have been observed, it is also possible that liquid films of various types could form in a particularly tenacious way with reverted rubber, in such a fashion as to give a slider bearing effect. The sequence of events leading to aircraft skidding could begin with a momentary locking of brakes, which could cause a sudden surface temperature rise in the sliding contact patch. The rubber in the contact patch would become "reverted," or soft and sticky, due to the heat. Following this, the tyre could then slide over wetted surfaces with very low friction coefficient <u>provided that</u> liquid film pressures were sufficient to distort the now soft and sticky tread rubber in the neighbourhood of asperity tips, so that no asperities actually broke through the liquid film to make direct contact with the rubber. Such a process would be a slider bearing type of motion, where now the slider is flexible and conforming.

These two theories represent fundamentally different ways of looking at the mechanics of reverted rubber skid. All of the laboratory evidence accumulated so far seems to favour the second theory, that of the flexible slider bearing, although on the basis of the limited data available we cannot rule out the presence of heat and steam in the aircraft operating accidents."

4.2 Road research into Bituplaning

Road research found a low dry-friction phenomenon termed Bituplaning [19]. This is a mechanism that could lead to the generation of low levels of surface friction on the road surface, by the action of a locked tyre sliding over a dry binder-rich road surface. It was shown to occur on a number of binder-rich road surfaces in Europe. The phenomenon "Bituplaning" was first identified in literature in 1936 [21]. A motorcycle side force skid tester measured dry friction on a road surface before and immediately after surface sealing.

Investigations into a major UK road accident in 1986 noted "The worst dry skid resistance… in ten years of testing road conditions". The investigation suggested that the low level of dry friction on the road surface was caused by an excessively thick layer of bitumen on the pre-coated chippings used in the hot rolled asphalt. This was rejected by the asphalt surfacing contractors, but this is probably an early manifestation of bituplaning [22]. The 1969 DC-8 accident [9] was very probably a dry "Bituplaning" phenomenon.

5 REVERTED RUBBER AQUAPLANING ON REJUVENATOR

5.1 Processes

It became obvious that various processes took place in the applied top layer of the rejuvenation (fog spray) on George runway 11/29 during the aircraft overrun accident. A theory can be that, bitumen is already close to its softening point during normal service temperature. At wheel-spin up during landing or braking during a rejected take off, the temperature of the bitumen in the contact area rises above softening point i.e. becomes higher than the melting temperature of the bitumen. Bitumen will then deform or melt and will form a slippery surface where sliding can take place.

This would explain the shiny nature of the aircraft tyre tracks observed on the George runway. It could also explain the pattern in the tracks in Figures 3 and 4 as “mirrored anti-skid activity”. It could also explain why long shiny tracks appear on the runway. The theory could be that bitumen, softened or nearly melted are brought to the surface and displaced or smeared by the trafficking braking aircraft. If too much bitumen is ‘brought to the surface’ a planing situation may arise on the bitumen. Unlike aquaplaning which implies presence of water, dry planing occurs on the excess bitumen.

5.2 Combined aquaplaning and bitu-planing

At George, the accident aircraft experienced rubber reversion aquaplaning. This was very clear from the state of the aircraft tyres after the accident [11]. There are two fundamentally different theories of looking at rubber reversion skids: a dry slider bearing theory, and a wet steam theory. Combing these two theories for slippery runways after rejuvenation, the following possible scenario can be described.

- At wheel spin-up there is generated a temperature high enough to soften or melt the bitumen.
- Excess bitumen (or surface treatment) can cause the wheel to have a reduced wheel spin-up resulting in skidding. Frictional heat from the skidding can cause even a very thin layer of water (such as on a damp pavement) to become steam and super heated steam.
- With superheated steam present the temperature is far above the softening point of the bitumen, and could even be above the melting temperature of bitumen.
- The bitumen being displaced, moves and builds on top of bitumen adjacent to it in the direction of travel, and thus acts as a seal contributing to establishing and maintaining the steam cushion in the steam theory.
- Now there is a lubrication layer of steam and melting (or melted bitumen) which prevents the wheel spinning up. A rubber reversion aquaplaning situation is created on top of a bitu-planing situation. From observations of the runway at George more than three months after the accident, it was obvious that displacement of bitumen took place. By repeated displacement, a smoothening effect takes place that creates surfaces with less macrotexture. The bitumen being smeared by the braking aircraft causes the bitumen to in-fill the HMA voids leading to the creation of a bitumen-rich slippery surface. This can be seen in the shiny tracks on runway 11/29 (Figure 4).

5.3 Limitations of friction measurement after rejuvenation

ICAO recommends that the friction of a paved runway should be measured to assess periodically the slipperiness of paved runways when wet [6; ATT A-6, 7.1]. It recommends the use of a self wetting continuous friction measuring device (CMFE). This has been done successfully throughout the world for many years. Yet the experiences here show that CMFE cannot be relied on to detect reverted rubber skidding on slippery runways with poorly performing rejuvenation. Such runways can in fact show adequate CMFE results and be slippery to aircraft when wet, as was seen in the investigation of the accident at George.

Figure 3 – shiny wheeltracks on George 11/29 runway

Figure 4 – close up detail of shiny wheeltracks on George 11/29 runway

The problem was also seen with the USA T-33 accident (reasonable friction using a pendulum type decelerometer), Chile accident (British Pendulum Test inconclusive, but a CMFE later showed poor friction), and the Norway accident (CMFE not able to detect slippery conditions). It is confounded by the limitations of CMFE in measuring friction on a runway with ruts and depressions, where water ponding from natural rainfall can be much deeper than the 1mm depth of water during the self-wet CMFE test method.

In 2003 the US Army investigated the comparative field performance of various proprietary rejuvenators and seal coat materials over a period more than 1 year [12]. The field performance was evaluated through their effect on skid resistance, texture and changes on visual appearance. Texture was measured by using the Sand Patch method. Skid resistance was measured by using the British Pendulum, and two versions of CFME's, one light trailer version and one heavier integrated version. The results of the surface texture testing showed that the addition of material to the pavement surface reduced the surface texture. The results of the British Pendulum testing could not, except for general trends, readily determine the effect of an individual material on the skid resistance. For the two CFME's average readings varying from three to seven values were used in statistical comparison. No direct correlation with the results obtained was found between the two types of CFME's, however; they indicated similar trends regarding low and high values of skid resistance.

So why is CMFE unreliable in detecting reverted rubber skidding? The full-scale test at George using a Boeing 737-400 showed up the propensity for reverted rubber skidding and the slippery runway, but the CMFE did not. It is now hypothesized that the weight and speed of the aircraft (10 tonnes weight per main gear tyre, 180 kph speed) raised the temperature of the bitumen sufficiently for it to melt, and the geometry of the tyre (tyre contact area of 800 cm^2) was such that the melted bitumen could then act as a seal to trap the steam and super-heated steam beneath the tyre. This is in stark contrast to the conditions under the measuring tyre of a typical CMFE machine (0.02 tonnes weight on tyre, 65 and 95 kph speed, 14 cm^2 contact area), and probably why the CMFE is unreliable in detecting the problem.

Another study undertaken by the US Oklahoma Department of Transport [23], found that the application of a penetrating rejuvenation treatment reduced the surface friction of a functionally stable pavement for an initial 3 months period, until such time the material had worn away exposing the original surface, at which time surface levels friction increased to pre-treatment levels. In this study surface texture measurements found that the macro texture remained essentially unchanged.

Friction values reported by the Australian Airforce for a RWY pavement [24], identified that the friction measured at 65km/hr was variable after the application of a rejuvenation treatment, suggesting that the micro texture on lower values of the macro texture had been altered by the treatment. Measurements taken at 95km/hr remained relatively consistent before and after the treatment, suggesting that the macro texture had not been significantly affected. The variables identified in these few examples demonstrate how important it is to account for macro and micro texture together with geometry and drainage when reviewing results generated from CMFE. This is not always completed as it is assumed that RWY pavements are maintained to a high functional condition.

It should be noted that CMFE has proved to be useful elsewhere in detecting poor friction characteristics leading to viscous aquaplaning. However one aircraft accident due to reverted rubber skidding is one too many, and rejuvenation of hot-mix asphalt runways appears to be poor engineering practice.

6 TREATMENT OF SLIPPERY RUNWAYS AFTER REJUVENATION

6.1 Distinguishing between poor and good performing rejuvenation treatments

It is necessary to distinguish between poor and good performing rejuvenation treatments, as clearly some rejuvenation treatments have resulted in no problems. The performance of these can be attributed as much to surface engineering (whether it be planned or unplanned) as to the operational environment, including runway length, aircraft operation, and climate.

The difficulty lies in detecting a poor performing rejuvenation leading to a slippery runway, before an incident occurs. Poorly performing rejuvenation is apparent upon visual inspection by highly experienced airport engineers, but experience is that it is not necessarily evident to inexperienced engineers or operations staff.

The experience shows that CMFE cannot be relied upon to detect slippery runways and reverted rubber skidding mode due to poorly performing rejuvenation. Thus, in applying CMFE testing, it is fundamentally important to also consider the functional characteristics of the pavement. Testing of pavements with good shape resulting in good drainage will generally provide results which can be related to the operation of aircraft in wet weather. However pavement surfaces with poor functional characteristics such as localised depressions, surface ruts, cracking, poor shape, and surface shoving or slippage could result in water pooling in wet weather. CMFE testing in self-wet mode does not account for these surface defects which attract deeper water films. Such runway surfaces can in fact have good CMFE results during testing, and still be slippery to aircraft when wet. The full scale aircraft test at George was able to detect the poor performing rejuvenation treatment, but such testing is expensive and difficult to arrange. Anecdotal comments made at the George test suggest it was rather more hazardous than expected.

The ICAO provisions, taken all together, may often detect the problem. Geometry, shape and drainage are important. Rejuvenation of HMA generally makes the surface fail the macrotexture requirement, which is an obvious indicator. Unfortunately, this is not always reliable because if the runway is grooved and the grooves are in good condition, then they will provide enough macrotexture. The final determinant therefore is to include a visual inspection of microtexture (Figure 5). This, with the ICAO provisions, addresses the four legs of good wet weather friction being macrotexture, microtexture, geometry and drainage. Again, it must be stated that friction testing alone is not to be relied on to detect slippery runways after rejuvenation with the propensity for reverted rubber skidding.

It should be noted that the slipperiness can change over time, and the problem may occur months after rejuvenation. One runway investigated had a surface treatment rejuvenator, which apparently performed reasonably for six months and then became slippery. The rejuvenator incorporated sand, and this had presumably been abraded away or otherwise lost by trafficking over 6 months since application.

The best result can be had by not rejuvenating runways at all, but by overlaying or replacing the hotmix asphalt when it is aged. This also allows correction of the ruts and depressions that could lead to dynamic aquaplaning.

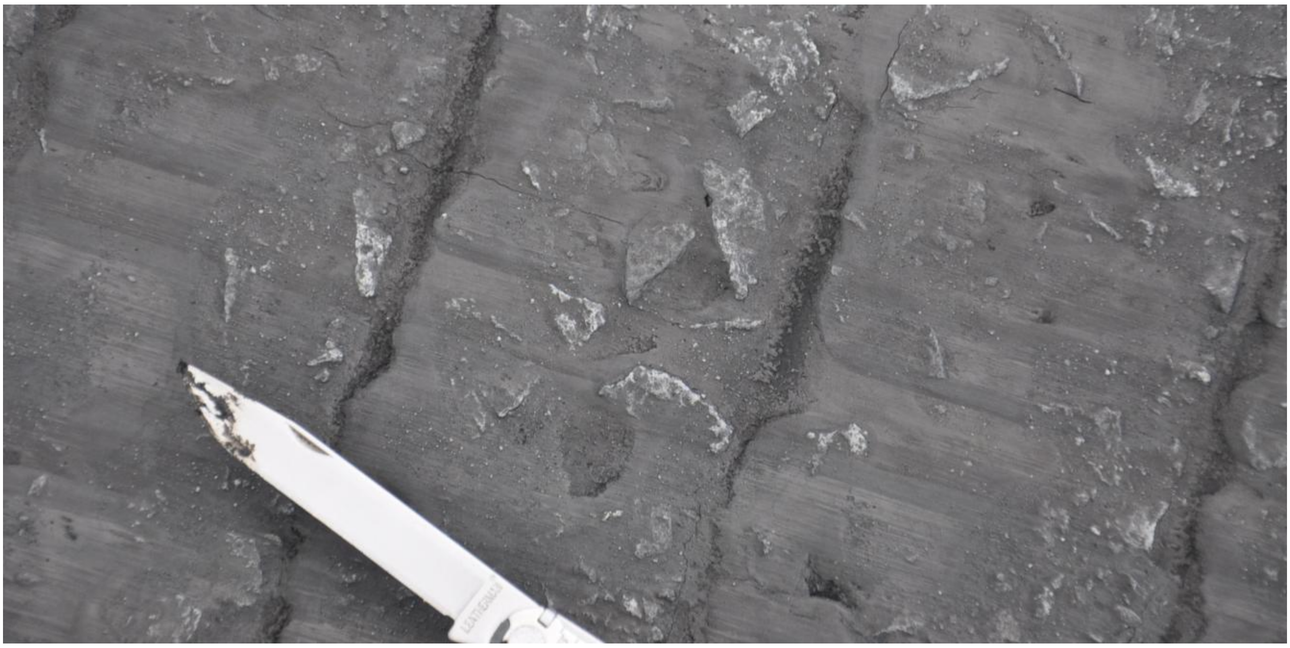

Figure 5 – close up of surface treatment rejuvenation with poor microtexture and worn inadequate grooves

6.2 Removal of rejuvenation

Excess rejuvenation surface treatment should be considered as a contaminant causing hazardous conditions for aircraft operations and should be removed. In the interim, operational restrictions need to be urgently applied; or the runway closed. The removal of mis-applied rejuvenation is neither easy nor quick. The options are to cover the rejuvenation with a new surfacing or to remove it. The surfacings that could reasonably cover it are hot-mix asphalt, a friction treatment (porous asphalt or an ultra-thin friction course) or a chip seal (possibly with polymer modified bitumen and with careful attention to design to avoid loose stone [17]). A slurry seal is rarely suitable because it does not meet the macrotexture recommendation of a minimum of 1mm. The use of hot-mix asphalt will usually require a friction treatment on top such as grooving for the same reason.

Expensive options for the removal of rejuvenation treatments include milling off the top of the HMA (also termed planning or profiling) and laying a new surfacing, or the less expensive high pressure water blasting of the surface or aggressive brushing of the runway with rotating steel-brushes. The aim of the water blasting technique is not to totally remove the rejuvenator from the surface but to remove only a portion of the material so as to restore frictional capability to the runway surface. Water blasting requires trials in which the machine speed and water pressure are varied to achieve the desired result. Too much water pressure may also make things worse, by the action of "polishing" the aggregate which is the process of making the surface of the aggregate smooth. Too much pressure, or too-aggressive brooming, may also destroy surface integrity resulting in widespread ravelling.

6.3 Temporary operational measures for contaminated runways

Excessive application of rejuvenation surface treatments should be considered as a contaminant causing hazardous conditions for aircraft operations and just like other contaminants should be removed. This process takes time – usually several months – because it has to be investigated (and even trialled), designed, specified, contracts let, contractor mobilised and the work done. In the interim before removal, operational restrictions will need to be urgently applied or the runway closed.

The commercial realities are that closing the runway is a major issue. The airport will try and remain open, and airlines will try and remain operating there. The immediate need, within hours of discovering a problem, is to issue a NOTAM stating that the runway is slippery when wet. A contaminated runway presenting a high risk, being short in length with serious consequences for aircraft running off and in a wet climate, may need to be closed. At George, a NOTAM was issued restricting the use of runway 11/29 by large transport aircraft (>5700kg) when the runway was wet [11]. This caused substantial disruption to airline services.

As well as NOTAMs, airlines or the regulator generally impose their own operational limitations for operations other than DRY in the interim, and these have included:

- No tankering fuel (carrying in tonnes of extra fuel to avoid local expensive fuel; this increases the landing weight and speed).
- Thrust reversers are required, must be working, and must be used.
- The possible reduction in braking action is to be briefed and discussed as a 'Threat' during the pre-departure briefing.
- Wet performance data and TOGA thrust for takeoff (no FLEX or de-rate; this is effectively maximum thrust).
- No takeoff during heavy rain, and takeoff is to be delayed until rain stops and excess water drains off the runway surface.
- Tailwind component for landing of 5 knots maximum.
- Use of full flap for landing.
- Medium autobrake (which is effectively the highest autobrake setting available for landing).
- Captain to conduct the landing.

7 CONCLUSIONS

Aged hot-mix asphalt on a runway at the end of its functional life is usually overlaid or replaced. However the time of overlay can be extended for several years by applying a rejuvenator, such as a bitumen emulsion or a coal tar based product. This has been used successfully on roads, carparks, taxiways and aprons, but runways are different. A number of accidents and incidents are discussed where slippery conditions occurred after the application of rejuvenation treatments on runways.

Detailed investigation of one accident found that combined reverted rubber aquaplaning and bitu-planing had occurred. Friction testing after that accident did not show a problem, and the same was seen in some of the earlier accidents on rejuvenated runways. It is concluded that CMFE <u>cannot</u> be relied upon to detect slippery runways where reverted rubber skidding occurs due to poorly performing rejuvenation. Furthermore pavement surfaces with poor functional characteristics such as localised depressions and surface ruts can result in water pooling in wet weather. CMFE testing in self-wet mode may not adequately account for these surface defects which attract deeper water films. Thus in assessing slippery runways, it is fundamentally important to consider all four legs of good wet weather friction management, being macrotexture, microtexture, geometry and drainage. CMFE testing alone is not adequate.

Excess rejuvenation surface treatment should be considered as a contaminant causing hazardous conditions for aircraft operations and should be removed. In the interim before removal, operational restrictions will need to be urgently applied or the runway closed. Rejuvenation of hot-mix asphalt runways appears to be poor engineering practice. The best result can be had by not rejuvenating flexible runways at all, but by overlaying or replacing the hotmix asphalt when it is aged or functionally inadequate. This also allows correction of ruts and depressions that could lead to dynamic aquaplaning.

REFERENCES

1. ATSB (2009) Runway excursions Part 1: A worldwide review of commercial jet aircraft runway excursions. Aviation Research and Analysis Report, AR-2008-018(1). Australian Transport Safety Bureau, Canberra.
2. ATSB (2001) Boeing 747-438 VH-OJH, Bangkok, Thailand, 23 September 1999. Aviation Safety Investigation Report 199904538. Australian Transport Safety Bureau, Canberra.
3. Moyer, R. A. (1934) Skidding Characteristics of Road Surfaces. Highway Research Board Proceedings, Vol 13, Part I, pp123–168.
4. Shupe, J. W. (1958) A laboratory investigation of factors affecting the slipperiness of bituminous paving mixtures. Joint Highway Research Project: FHWA/IN/JHRP-58/07; Project C-36-53D, Washington.
5. Giles, C. G. and R., (1948) Non-Skid Roads. Proc. Public Health and Municipal Engineering Congress, London.
6. ICAO (2004) Annex 14 Aerodromes. Vol.1. Aerodrome design and operations. 4th ed. International Civil Aviation Organisation, Montreal.
7. Schumacher, P. W. J. (undated). The James Brake Decelerometer records the story of runway slickness. Unpublished.
8. Tomita, H. (1970). Tire-pavement friction coefficients. Naval Civil Engineering Laboratory, Technical Report R-672, Port Hueneme, California.
9. Reed, J. H., Laurel, O. M., McAdams, F. H., Thayer, L. M and Burgess, I. A. (1970). Aircraft accident report. Seaboard World Airines, Inc. Douglas DC-8-63F, N8634. Stockton Metropolitan Airport, Stockton, California. October 16, 1969. NTSB-AAR-70-24, National Transportation Safety Board, Washington D.C.
10. Rushing, J. F. and Falls, A. J. (2010) Long-term performance evaluation of asphalt surface treatments: Product placement. ERDC/GSL SR-10-1, U.S. Army Engineer Research and Development Centre, Geotechnical and Structures Laboratory. Vicksburg, Mississippi.
11. CAA (2010) Interim Report Number 2 in respect of the Investigation into the cause(s) of an accident involving an Embraer 135-LR aircraft, ZS-SJW during landing at George Airport on 7 December 2009. Accident and Incident Investigation Division (AIID), South African Civil Aviation Authority, Midrand, South Africa.
12. Shoenberger, J. E. (2003). Rejuvenators, Rejuvenator/Sealers, and Seal Coats for Airfield Pavements. ERDC/GSL TR-03-1, U.S. Army Engineer Research and Development Center, Geotechnical and Structures Laboratory. Vicksburg, Mississippi.
13. Prapaitrakul, N, Freeman, T and Glover, CJ (2005) Analyze existing fog seal asphalts and additives: literature review. Report FHWA/TX-06/0-5091-1. Texas Department of Transportation, Austin.
14. Brown, E. R. (1988). Preventive Maintenance of Asphalt Concrete Pavements. National Center for Asphalt Technology, NCAT, Auburn.
15. Anon. (1988). Standard practice for pavement recycling. Joint Departments of the Army and air Force, USA, TM 5-822-10/AFM 88-6, Chapter 6.
16. Neubert, T (2010) Friction: Science or Fiction. FAA Worldwide Airport Technology Transfer Conference, April 20-22, Atlantic City, USA.
17. Emery, S (2008) Seals for Heavy Duty Airport Pavements. 1st International Sprayed Sealing Conference. Adelaide, 27-28 July 2008.
18. Horne, W. B. (1975) Wet runways, NASA TM X-72650. Langley Research Centre, Virginia.
19. Obertorp, D. H. F. (1962) Decrease of skid properties of wet road surfaces at high speeds. Symposium on skid resistance. Spec. Tech. Publ. No. 326, American Society for Testing and Materials.
20. Horne, W. B., Yager, T. J. and Taylor, G. R. (1968) Review of causes and alleviation of low tire traction on wet runways. NASA, Langley Research Centre, Virginia.
21. Bullas, J. C. (2007) Bituplaning: A Low Dry Friction Phenomenon of New Bituminous Road Surfaces. Thesis, University of Southampton, Faculty of Engineering, Science and Mathematics, School of Civil Engineering and the Environment.
22. Bullas, J.C. and Hounsell, N.B. (2006) "Slippery when dry?" - low dry friction and binder-rich road surfaces. Journal of the Institute of Traffic Accident Investigators, 15, (3), 67-81.

23. Riemer, C. Gransberg D.D., Zaman, M., and Pittenger, D., (2010) Comparative Field Testing if Asphalt and Concrete Pavement Preservation Treatments in Oklahoma. First International Conference on Pavement Preservation, Newport California US, pp 447 – 460.
24. Dardano J, (2004), Report – Runway/Tyre Friction Testing – Richmond Airport June 2004, Sydney Airport Corporation Ltd.