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Macroscopic and Microscopic Evaluation of Surface Friction of Airport Pavements

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Abstract: Rubber deposits accumulated on the runway surface pose a distinct threat to the operational safety of aircraft during landings and take-offs in adverse weather. This paper is to evaluate the microscopic and macroscopic effect of rubber deposits on the friction characteristics of runway pavements. A concrete runway at Kaohsiung International Airport was chosen for friction and texture measurements on the pavement surface for analyses. This study comprised field testing and laboratory testing. The surface friction tester, the British Pendulum Test and the grease-patched method were regularly conducted on site for runway pavements over a 24-month period of time. An optical microscope and a scanning electron microscopy (SEM) were used for the microscopic evaluation of rubber deposits taken from runway pavements. Results indicated that runway friction characteristics changed over time primarily due to the buildup of rubber deposits. The accumulation of rubber filled the macrotexture of the pavement surface and caused loss of the skid-resistance of a runway. An increased macrotexture led to a rise in the friction value. The difference between friction values measured in the forward direction and those measured in the backward direction was significant. The directional distribution of rubber deposits as observed by SEM was shown to raise friction level.

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Key words: *Airport pavements; Friction; Pavement texture.*

Introduction

A runway surface needs to be maintained to furnish sufficient skid resistance on the pavement to permit the safe take-offs and landings for all types of aircraft. Pavement texture that creates needed friction can be grouped into two classes: microtexture and macrotexture. Microtexture is the surface texture irregularity of a pavement with characteristic dimensions of wavelength and amplitude less than 0.05 mm, and is known to be mainly a function of aggregate particle mineralogy. Macrotexture is the deviation of a pavement surface with characteristic dimensions of wavelength and amplitude more than 0.05 mm, and is mainly attributed to the size, shape, and distribution of coarse aggregate. Microtexture provides frictional properties for aircraft operating at low speeds and macrotexture provides frictional properties for aircraft operating at high speeds. Together they provide adequate frictional properties for aircraft throughout their landing/take-off speed range. Pavements typically are designed and constructed to provide sufficient texture, both microtexture and macrotexture, to allow for adequate friction when the surface is wet [1-7].

When the wheels of landing aircraft impact a runway pavement, they deposit rubber on the surface texture. Rubber deposits occur in the touchdown areas on runways and can be quite extensive [8]. As deposited rubber accumulates, the available friction between aircraft tires and the runway surface is reduced. This results in hazardous aircraft operating conditions. The different seasons could also lead to the possibility of the runway having contaminants of varying rubber deposits and qualities that contribute significantly to reduced friction capabilities. Measuring the capability of a runway surface to provide aircraft wheel-braking action is critical to airport aviation safety.

One of the main causes of ground-based accidents is a run-off event. Airport agencies and operators often face severe problems related to the poor friction properties of runways. For airfield pavements, friction characteristics are extremely important [9-11]. They provide the spin-up of the wheels, which is required to operate the electronically controlled antiskid braking systems installed in most modern aircraft. Adequate runway surface friction is essential for braking and deceleration operation. A previous study emphasized the role of skid resistance to reduce the accident rate [12]. It was found that lack of skid resistance was the reason of more than a quarter of wet-road vehicle accidents in the United Kingdom [13]. For airport accidents, the National Transportation Safety Board in the U.S. reported that runway condition was a cause or factor in 115 aircraft accidents between 1983 and 1987 [14]. In 1991, a brand new British aircraft skidded more than 1,000 meters into Beagle channel, Chile, during landing. Twenty passengers among 60 tourists on board died in the accident. Thenoux et al. (1996) conducted an investigation to determine why the aircraft skidded off the end of the runway. It was found that the runway had low skid resistance at the time of accident [15]. A more recent accident occurred in Brazil on 17 July, 2007, in which 189 people were dead. The plane touched down in the rain on the airport runway and was not able to stop before the end of the runway. Lack of pavement friction was one of the main factors that led the airline to crash into a nearby fuel station and cargo office.

Runway rubber deposits pose a distinct threat to the operational safety of aircraft during landings and take-offs in adverse weather. Because the operational window for aircraft movement can change quite rapidly on a heavily rubber-accumulated surface during the

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rainy season, research is warranted for the evaluation of rubber deposits for airport pavements. It is imperative that pavement surfaces provide adequate friction and drainage ability to minimize the number of accidents that might occur as a result of rubber deposits. However, there is relatively little information available for characterizing the fundamental properties of rubber deposits and their effect on runway friction. The objectives of this study are as follows:

- Analyze the microstructure of rubber deposits,
- Evaluate the effect of rubber deposits on runway surface friction,
- Conduct a field study on the effect of rubber deposits on macrotexture, and
- Assess the potential for macrotexture changes to affect friction.

Experimental Plan

Runway Location and Friction Measurement

The test runway is located at the Kaohsiung International Airport (KIA) as shown in Fig. 1. KIA possesses one concrete runway 09L/27R with 3,150 m long and 60 m wide. The runway can be divided into three parts: 09L touchdown zone, midpoint zone and 27R touchdown zone. Because of the wind blow direction, 95% of aircraft land in the 09L direction. The most slippery runway segments were located in aircraft touchdown areas that were covered with heavy rubber deposits at the 09L touchdown zone. As shown in Fig. 1, the centerline on the runway 09L was fully covered by rubber deposits while the centerlines in the other two parts were still visible. The Saab Surface Friction Tester (SFT) used at KIA is a continuous friction measurement device that applies a fifth wheel at a constant slip ratio to measure the surface coefficient of friction. A water tank in the SFT can be used to spray a water film, equivalent to a depth of about 0.5 mm, on the runway surface in front of the fifth wheel. The SFT is used primarily to check the runway surface condition to identify the point at which runway maintenance (rubber deposit removal and/or re-surfacing) needs to take place. All SFT runs were conducted at the test speed of 95 km/h using an ASTM E1551 test tire. The SFT was run sequentially in the runway 09L direction about 3 m north of the centerline, and then back in the runway 27R direction about 3 m south of the centerline. The test loop was then repeated from the other direction. The friction readings, expressed as a friction coefficient between 0 and 1, are plotted for each 100 m interval over the length of the test section. A higher friction value represents better surface frictional resistance.

British Pendulum Testing

The British pendulum consists of a hard rubber pad attached on a free-swinging arm that is set to contact a fixed length of pavement at each test location as described in ASTM E 303. Test was conducted by sliding a rubber shoe on the runway surface. A recording arm marks the result on a dial, the British pendulum number (BPN). The greater the friction between the slider and the test surface, the more the swing is retarded and the larger the BPN reading. The resulting BPN is used to evaluate the friction characteristics of runway surface in the field besides the SFT. Tests were performed along and adjacent to the landing strip on runway 09L at ten different locations starting from station 5+50. The distance between any two successive locations was 30 m and the offset started from runway centerline was 1 m. A set of twelve field BPN measurements was transversely conducted for each station on runway 09L. The average field temperature was 25°C when the BPN measurements were taken. Because the slip speed of the British pendulum tester is very slow, BPN is mainly dependent on microtexture. BPN provides useful information because direct measurement of microtexture is difficult.

Macrotexture Measurement

The grease-patched method was used to determine the macrotexture of the pavement surface by measuring the average distance between the peaks and valleys in the pavement texture. The grease was spread on the pavement in a rectangular shape with a spreading tool. The lines of masking tape were placed on the pavement surface 10 cm apart. The distance along the lines of masking tape was then measured and the area that was covered by the grease was

Fig. 1. Rubber Deposits at the Kaohsiung International Airport (KIA).

computed. The area of the roughly rectangular patch of grease was calculated by using the average of four equally spaced widths. The grease volume divided by the covered area is reported as the mean texture depth (MTD). MTD is a macrotexture characteristic that is determined using the above volumetric method.

Fundamental Properties of Rubber Deposits

Rubber deposits on runway 09L were taken for close observation in the laboratory. An approximate 2cm x 2cm x 0.5cm sample was chipped out of areas where rubber deposits were accumulated on runway 09L, as illustrated in Fig. 1. A total of sixty rubber deposit samples were periodically taken to examine the increase in accumulation thickness. Both optical microscope and scanning electron microscopy (SEM) were used to facilitate the direct examination of rubber deposits. The samples of rubber deposits were put on a filter paper and were metalized and then observed with a Hitachi Model S-3000N Model. A Motic Digital Microscope DM143 Model was employed to magnify images of samples of rubber deposits through visible light and a system of lenses.

Results and Discussion

Analyses of Rubber Deposits

Rubber deposits were accumulated at the touch down zone on the runway 09L surface. An average landing leaves approximately 700 g of rubber in a thin layer on the runway (Gransberg 2008). The heat generated during the interaction causes a chemical reaction called polymerization that changes the rubber deposits into a stiff, smooth material. They are no longer rubber like that on the tires of the airplane. The rubber of the tires is relatively soft and flexible and designed to absorb some of the shock of the landing aircraft. The aircraft tires are stationary just before they touch the ground. At the moment they touch, the rubber meets the runway for about 300 to 500 meters. During that time, the tires are under tremendous pressure between the tire and the runway surface. Right at the interface, these contact points cause considerable friction and heat. The heat created results in a polymerization of the rubber, turning it into a very hard material that is spread on the runway surface in a thin layer.

Rubber deposits as shown in Fig. 2 are located on painted areas of runway pavement surfaces. With repeated landings of aircraft, this hardened rubber fills the texture of the pavement giving it a smooth, almost glass like surface that can make landing the aircraft and stopping difficult, particularly when the pavement is wet. Glass beads, while used primarily to increase conspicuity of markings, are also used to increase friction levels on painted areas. It is important to keep the skid-resistance properties of painted surfaces as close to that of unpainted surfaces as possible. The odd number on the left side of Fig. 2 indicates the rubber deposits in black, and the even number is related to the pavement markings in white. The most persistent contaminant problem at KIA is deposit of rubber from tires of landing jet aircraft. The average thickness of rubber deposits is 0.38, 0.21, 0.01, and 0.17 mm for layers 1, 3, 5, and 7, respectively. The painted areas were remained for aircraft operation. Layers 1, 3, 5, and 7 were 11, 7, 4 and 7 weeks old, respectively.

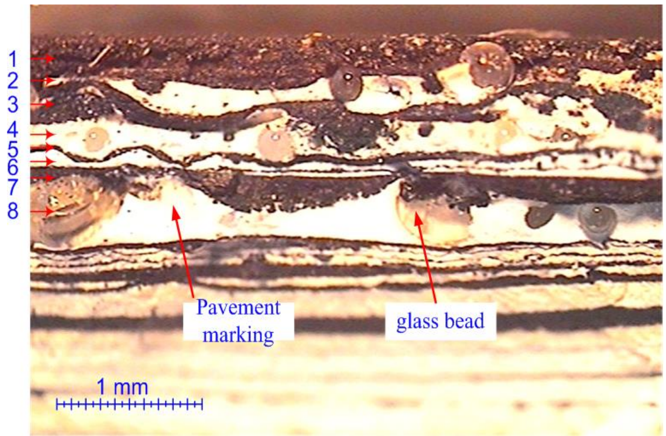

Fig. 2. Accumulation of Rubber Deposits.

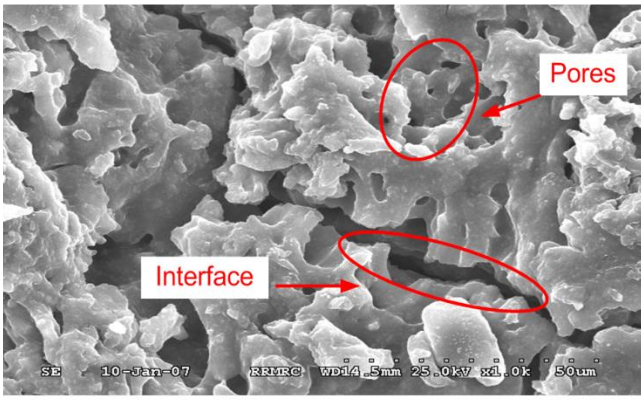

Fig. 3. Microstructure of Rubber Deposits.

The substance at the bottom of Fig. 2 is the residue from previous rubber removal operation. Rubber deposits also fill the macrostructure of the pavement surface, which might diminish the ability of grooves to adequately drain the water during a rain event, increasing the likelihood of hydroplaning.

Fig. 3 shows the microstructure of rubber deposits at the 09L touch-down zone. Rubber deposits are made of polymer particles, air and dust depending on pavement conditions, aircraft types and the surrounding environment. Free spaces within the particles are shown as pores. A discontinued interface is also present between two different layers of rubber accumulation. These are created during the aircraft landing with morphological processes inducing changes in the densities. A rubber cover in an airport pavement area could be mechanically compacted due to aircraft movements. The compaction processes in rubber are similar to high-temperature sintering processes used in the field of ceramics and powder metallurgy. Making rubber deposits is like making hot isostatically pressed superalloys used in hot sections of aeroengines. Rubber deposits are formed in the atmosphere by complex joining processes of polymer molecules. These polymer particles encompass a large variety of morphological habits and sizes. After the deposition of rubber on the runway pavements, a process known as metamorphism modifies the geometrical features of the particles. Rubber accumulation is dependent on the type and frequency of aircraft landing operations; e.g., weight of aircraft, the number of wheels that touchdown on the surface, climate, runway length, and runway composition.

Friction Characteristics of Runway Pavements

Presented in Fig. 4 are the friction test results measured over one year period of time for runway 09L. Friction measurements vary across the runway centerline and along the length of the test section due to differences in runway texture and rubber contamination. Standard deviations are calculated for each of the friction tests at the target speed. The standard deviation ranges from 0.01 to 0.04. These results are similar to those reported by Anderson et al. (2001) [16]. SFT is one of the friction measurement devices listed in the recommended practices by the International Civil Aviation Organization (ICAO 2002) [17]. According to the requirement of ICAO, when the SFT wet pavement surface friction value μ is less than 0.34, the surface condition of the runway is considered "poor." In Taiwan, the current decision procedure for activating rubber removal operation is dependent on the magnitudes of areas that have μ values below 0.34, which is the minimum acceptable friction value. The activation procedure is prepared based on average friction values for 100-m-long segments of the runway. An average friction value of 0.47 is adopted as a maintenance planning friction level. This maintenance planning friction level represents a level at or below which a rubber removal operation should be initiated.

The presence of a rubber coating gradually deteriorates the skid resistance over the full range of runway pavements tested, as shown in Fig. 4. The friction variations over time can be divided into three parts. The first part starts about at station 2+00, and ends at 11+00. In Part 1, the friction tends to decrease mainly due to rubber deposits. The heavy rubber deposits began at approximate station 2+00 and covered about 35% of the pavement 3.5 m on either side of the centerline. From stations 4+00 to 11+00, the rubber deposits became thick and covered almost 100% of the pavement 7.0 m on either side of the centerline. This suggests that the inferred friction decrease was primarily caused by the presence of the rubber deposits. These rubber deposits brought the friction value below the minimum friction level approximately three months after rubber removal. For some runway surfaces, they exhibited friction increase due to the clearance of the rubber deposits on the surface.

Part 2 is located between 12+00 and 24+00. It is shown that it is not necessary for the friction to decrease over time in this part. If the coarse aggregates have sound friction characteristics, the pavement surface friction usually fluctuates due to the aircraft applications. There is a slight decrease in the SFT friction value near station 20+00 because of the adjacent taxiway. Part 3 belongs to runway 27R where few aircraft land or take off because of the wind blow direction. In this part, pavement surface friction may reduce due to the loss of surface integrity. The friction characteristics of Parts 2 and 3 are usually above the maintenance planning friction level, which is 0.47.

Two other parameters of interest are the length of time between successive rubber removal operations, and the total number of aircraft passes that has taken place during the time period. Fig. 4 shows that the rubber removal operation is usually performed within four months of the previous operation. It is apparent that time factor along would not be adequate to identify the need for rubber removal. All the cases have complete aircraft data. It is found that traffic passes and rubber deposits are positively correlated, with a coefficient of determination value of 0.98. In other words, 98% of

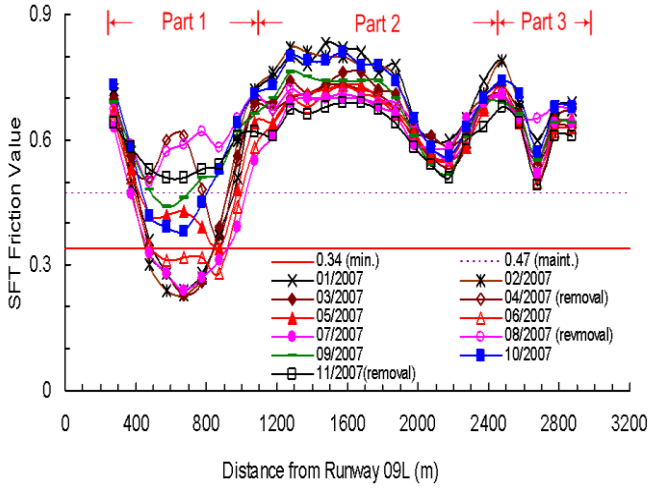

Fig. 4. SFT friction Value Changes at KIA.

the variation in rubber accumulation can be explained by the number of aircraft landing. The characteristics of rubber deposits and the use of SFT allow the airport operator to develop a schedule for rubber removal frequency specific to each runway.

KIA uses shotblasting for rubber removal and pavement retexturing on runway pavements. Shotblasting propels abrasive particles onto the runway surface, which blasts the contaminants from the surface. The shotblaster can be adjusted to produce the desired surface texture, and is environmentally clean since the entire operation is self-contained. It collects the abrasive particles, loose contaminants and dusts from the runway surface, and then recycles the steel shot for reuse. The abrading process left exposed sand-sized particles that would provide good macrotexture and microtexture with beneficial friction characteristics. Equipment is truck-mounted and can easily be relocated from the runway in case of an emergency landing. At least two SFT friction test runs were conducted after a rubber removal operation to ensure that a predetermined desirable friction level is restored. Fig. 4 shows that runway rubber removal operations restored the SFT friction value to be about 0.6 for the areas between stations 5+00 and 9+00. The SFT friction value increased by about 0.3 after rubber removal operations were carried out.

Effect of Rubber Deposits on Friction Characteristics

Fig. 5 is plotted for the average SFT friction of two runs made on the north side of the runway centerline, while the other set of data is plotted for the average of two runs made on the south side of the runway centerline. Each point represents the average of five consecutive 100m at the touchdown zone. The data for the north side of the runway centerline show more variance, about ± 0.07 units, than those for the south side of the runway. The average SFT friction varies along the length of the test section from a low of 0.30 to a high of 0.64.

The SFT friction values of the backward direction are shown to be higher than those of the forward direction. Because of the wind blow direction, 95% of the total aircraft land on and take off from runway 09L at KIA. The forward direction follows the aircraft landing direction while the backward direction travels against the

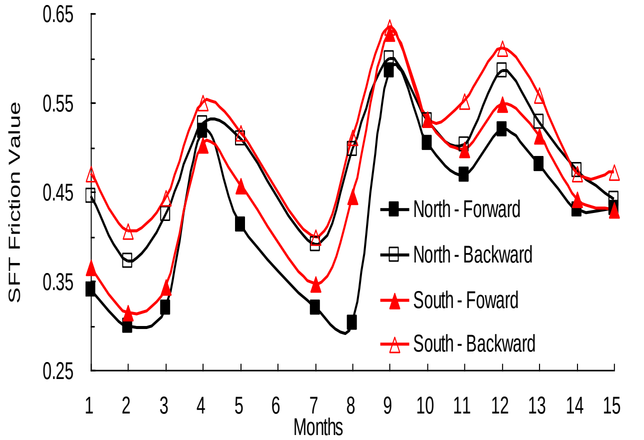

Fig. 5. Directional Changes in SFT Friction Value at Runway 09L.

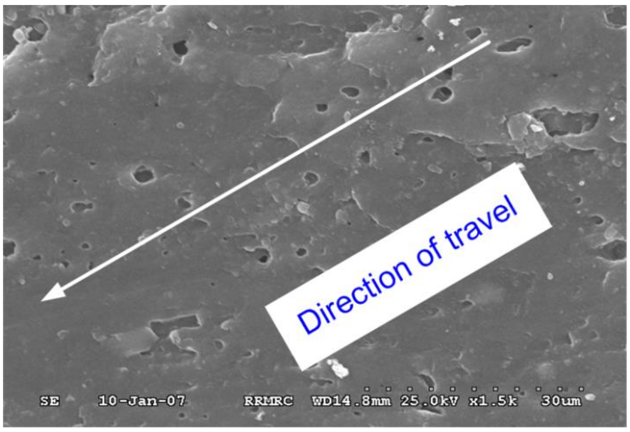

Fig. 6. Rubber Deposits Corresponding to Travel Direction.

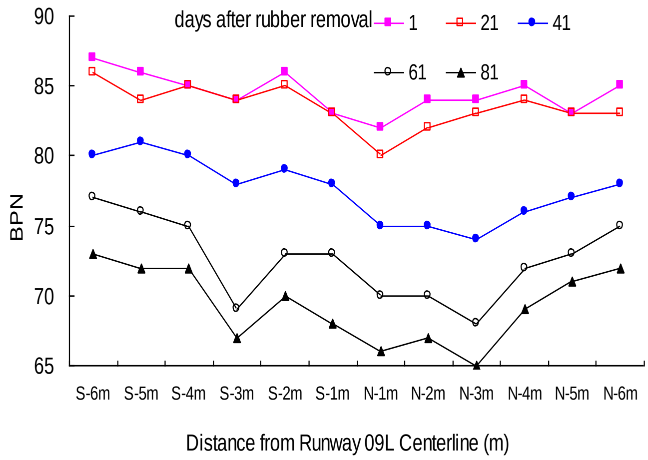

Fig. 7. BPN Values Changing with Time Duration.

landing direction.

With the data measured in south and north of the runway centerline, two paired difference t-tests are performed to determine if the differences between friction values in the forward direction and friction values in the backward direction are significant or not. The results show that the differences between friction values measured in the forward and backward directions are significant as indicated by p-values, which range between 0.012 and 8.9×10^{-6}.

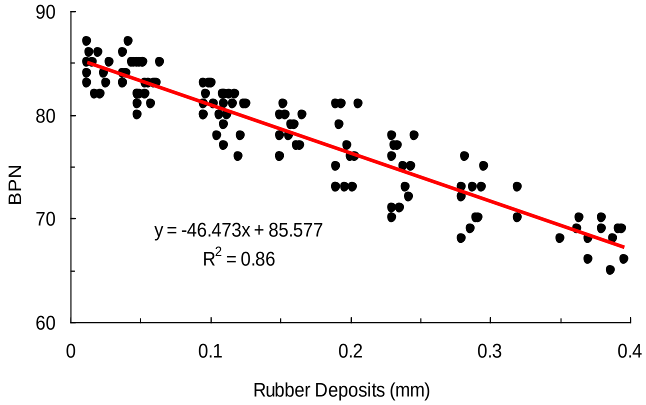

Fig. 8. Effect of Rubber Deposits on BPN.

The difference is considered significant if the two-tailed p-value is less than the significant level (α) of 0.05.

Fig. 6 demonstrates that the buildup of rubber deposits follows the direction of the landing tire of aircraft. Layer upon layer of rubber deposits accumulates on each other, and forms a directional distribution like fish scales. The directional distribution of rubber deposits appears to be the reason why the SFT friction values measured in the backward direction are higher than those in the forward direction.

Effect of Rubber Deposits on British Pendulum Number

The pendulum values were measured at an interval of one meter up to six meters away from the runway centerline. With approximate one thousand data points all together, plotting marks for every experiment point would clog the figure and confuse readers. For the reason of clarity, the daily data are omitted. Five typical sets of BPN data from runway 09L are shown in Fig. 7. S-1m denotes 1 m south of the runway centerline and N-1m is 1 m north of the centerline. As expected, the BPN value decreases with increasing time duration of rubber deposits. The BPN values close to centerline are lower than ones away from center line. The average BPN value obtained with the pendulum at 81 days after rubber removal was 69.5. While there is no specific recommendation for airport, the BPN of 55 to 65 is considered to be sufficient and safe for special runway sections such as braking section.

As is demonstrated in Fig. 8, a reduction in BPN is associated with an increase in rubber deposits. The magnitude of the reduction can be predicted with an R^2 value of 0.86. The information obtained represents a broad collection of data on the friction characteristics of runways at airports that have turbojet aircraft operations. Field observations of the runway pavement surface conditions and analyses of the friction test data could identify those areas on the runway pavement which are below the minimum acceptable friction level. Test data and surface condition information obtained during this study were given to airport owners so that they could take proper corrective measures to eliminate runway frictional deficiencies.

BPN results are compared with the SFT friction values for the sections on runway 09L as shown in Fig. 9. There is a higher variability among the BPN measurements than the SFT values. The

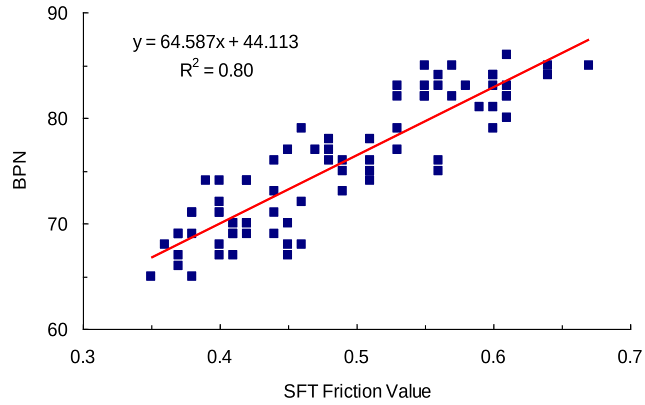

Fig. 9. Comparison of BPN with SFT Friction Value.

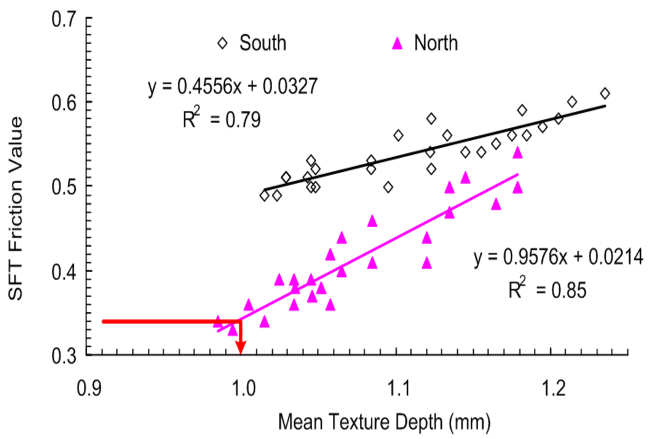

Fig. 10. Mean Texture Depth Changing with SFT Friction Value.

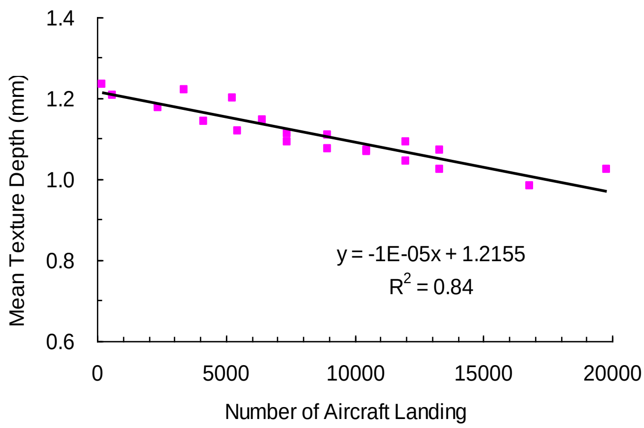

Fig. 11. Mean Texture Depth Changing with Number of Aircraft Landing.

increase in SFT friction value from 0.35 to 0.65 is accompanied with an increase in BPN from 65 to 85. These two methods are statistically related with an R^2 value of 0.80. The results of BPN appear to correlate well with the surface friction tester.

Effect of Macrotexture on Skid Resistance

Fig. 10 shows the effect of mean texture depth (MTD) on the SFT friction value. The friction coefficient increases when the mean texture depth increases, which can be explained by the fact that the increase in macrotexture improves drainage, thus increasing friction coefficient at the test speed of 95 km/h. This is quite understandable; it illustrates the importance of the harshness of macrotexture. Expectedly, macrotexture depths are higher for the southern sections, ranging from 1.01 to 1.24 mm. This trend corresponds with the directional distribution of rubber deposits.

For a minimum SFT friction value of 0.34, the corresponding MTD is 1.0 mm in order to provide adequate surface friction. Surface macrotexture is a predominant contributor to wet-pavement safety as illustrated in Fig. 10. The safety of a pavement surface is related to both the surface friction and texture of the pavement. The average MTD value was 0.99 mm six meters away from north of the runway centerline 81 days after rubber removal. At that time the landing strip along the centerline of the runway did not seem to possess enough macrotexture.

The mean texture depth decreases as the number of aircraft increases as shown in Fig. 11. The MTD was 1.23 mm, and then fell to 1.02 mm after three months of traffic with about 220 aircraft per day. The statistical linear regression technique is adopted for developing the predictive model because of its simple operation and wide availability. The independent variable is the total number of aircraft passes since the last rubber removal. Beside the rubber accumulation, the effect of air traffic is to wear and polish the runway pavement surface. This is due to the horizontal forces exerted by the vehicle tires on the pavement surface. Under these forces, the protruding aggregates are worn, polished or removed, thus reducing surface microtexture and macrotexture. Fig. 11 indicates that the pavement wear can be represented through an overall decline of pavement texture as well as the accumulation of rubber deposits.

Conclusions

This paper examined the effect of rubber deposits on the friction characteristics of the runway pavement surface. Based on the results and analyses, the following conclusions were drawn. Runway pavement friction measurements experienced variations primarily due to changes in rubber deposits and pavement surface macrotexture. The buildup of rubber deposits filled the macrostructure of the pavement surface, and deteriorated the skid resistance. Heavy rubber deposits could completely cover the pavement surface texture, thereby causing reduction in friction measurements. The optical observation of rubber deposits showed the presence of multiple layers of polymer scale compacted by aircraft landing. The scanning electron microscopy indicated the microstructure of rubber deposits consisting of air voids and interfaces. There existed a linear relationship between the British Pendulum Number and the SFT friction value. The characteristics of rubber deposits and the use of friction measurements allowed the airport agency to develop a schedule for rubber removal frequency specific to each runway. The macrotexture depths for the north of the runway centerline were different from those for south of the runway center, because of the wind blow direction affecting aircraft landing. In addition, the changes in friction values measured forward and backward were significant at the touchdown zone. The frictional deficiencies on runway pavements could be represented through an overall decline of mean texture depth as well as rubber accumulation. The SFT friction value increased by about 0.3 after rubber removal operations were carried out. An increase in the mean texture depth could lead to an increase in skid resistance. Macrotexture allowed for the rapid drainage of water from underneath the tire and consequently increased the contact between pavement surface and the tires, thus enhancing pavement friction characteristics.

Acknowledgements

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