Long Term and Seasonal Variations of Pavement Surface Friction

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ABSTRACT

Wet pavement skidding contributes to 13.5% of fatal and up to 25% of all accidents, a substantial part of overall highway toll. Pavement surfaces should have adequate friction to minimize the skid related accidents. Increased temperature/moisture and surface wear/polishing significantly reduce the available friction with increased potential for skid related accidents. Pavement surfaces should therefore also exhibit sufficient friction withstanding the seasonal and long term variation. Several past studies have addressed these aspects with no significant or useful conclusions. The seasonal variation of surface friction was measured monthly for both portland cement concrete (PCC) and asphalt concrete (AC) pavements. For long term friction performance analysis, field data of Long Term Pavement Performance (LTPP) program were obtained for both PCC and AC pavements incorporating all geographic/climatic regions of Canada and United States.

Analysis has shown that seasonal variation of AC and PCC pavements wet surface friction are identical and dependent on ambient or pavement temperature during the testing (driving) and prior weather is insignificant. AC surface friction was shown to increase for up to about eighteen months following the construction and decrease thereafter for about six years. For PCC pavements, friction increases for about 2½ years following the construction and then decreases for about twelve years. Cumulative traffic passes, pavement age, vehicle speed and temperature during the testing, and PCC pavement surface texture types were found to be statistically significant for long term surface friction. AC pavement surface friction was shown to be more sensitive, as compared to PCC, to predominant climatic condition.

INTRODUCTION

According to Transport Canada (*1*), 2,766 people died and another 222,455 injured (17,730 seriously) on Canadian roads in 2003 from a total of 156,904 police reported crashes. Highway crashes costs Canadians about $25 billion annually posing as one of the major barriers to economic prosperity. In the United States, 42,643 fatalities and about 2.9 million injuries were reported from about 6.3 million traffic crashes. Such traffic related incidents significantly affect the US economy with an estimated $230.6 billion loss as of year 2000 in addition to the pain and suffering of the society (*2*). Skidding contributes to 15 to 35 percent of wet weather accidents (*3*). Anon (*4*) mentioned that skidding on wet pavements contributes to 13.5% of fatal and up to 25% of all accidents, a substantial part of the overall highway toll. Provision of adequate friction on pavement surface is a key to minimize the skid related accidents. A number of studies have also revealed that skid related accidents can be reduced by an improvement in pavement surface friction (*5*). For example, the wet/dry pavement accident ratio was shown to increase sharply from a ratio of 0.23 to about 0.7 as the skid number, measured at 64 km/h (SN_{64}), drops below 41, the critical value of SN_{64} (*6*). The wet- weather accidents was shown to reduce by 35% with a net return of 540% after laying anti-skid surfacing at more than 2,000 sites in London, United Kingdom (*7*). Other studies found that an improvement of average friction by 0.1 can reduce the wet-accident rate by 13% (*7*, *8*).

Increased temperature and moisture as well surface wear/polishing significantly reduce the available friction with increased potential for skid related accidents. A study showed that *SN* reduces by about 1.2 points for an increase in temperature by 10°C (*9*). Average difference of skid number measured in winter and summer was shown to be six points (*10*). Pavement friction also changes over time due to environmental and traffic related wear. Therefore, according to the Transportation Association of Canada (*11*), variation of surface friction with time is an important measure of pavement deterioration. For safety as well as economy, the pavement should exhibit sufficient friction over the service life of the surface withstanding the seasonal fluctuations and long term wear and polishing. Only a few researchers have studied the seasonal and long term variations of pavement surface friction but with inadequate and/or inappropriate results/ conclusions and models. This study is aimed to quantify the seasonal and long term variation and determine the influencing factors to aid the highway agencies/practitioners in selecting pavement surfaces with adequate friction.

RELEVANT PAST RESEARCH

A study in Indiana found that skid resistance is the lowest in summer and highest in the spring regardless of the type of asphalt mix (*12*). A Pennsylvania study found that skid resistance (SN_{64}) decreases by 1.7 points for a seven-day period without rain (dry-spell) (*9*). Models were developed for short term changes in friction correlating the dry spell factor (DSF) and/or pavement temperature or a function of rain. For the same DSF and temperature, Pennsylvania model has shown an increase while the North Carolina/Tennessee model has shown a decrease in friction. A significant short term variation in *SN* was found with low skid number after a dry-period and rejuvenating after rainfall (*13*). Models were developed for predicting the low skid resistance during fall from skid resistance measurement at any time during the year hypothesizing that seasonal variations are caused by polishing of microtexture and wear of macrotexture. Others, however, found that seasonal and short-term variations in *SN* occur due to temperature, rainfall and dry spell.

Emery (*14*) developed models for long term skid resistance using three-year data from two highways in Toronto, Ontario. Model for Highway 401 using data of dense graded surface course (HL-1) and dense friction course mixes (Equation 1) shows that a mix with higher stability would exhibit higher skid resistance because of higher capability of the mix in resisting the coarse aggregate immersion in the matrix. The positive sign associated with flow however indicate that higher the flow higher the skid resistance which in contrast to stability.

$$SN_{100} = 0.714\,(MS) + 0.356\,(FLOW) + 1.048\,(VOIDS) + 40.904/\,[EQT\,(\mathrm{F})]^{0.081} - 17.323 \quad (1)$$

Where, SN_{100} = Skid Number at 100 km/h (ASTM E-274), *MS* = Marshall Stability, *FLOW* = Marshall Flow (0.25 mm), *VOIDS* = voids in mix, *EQT* (*F*) = Equivalent Traffic (*F* = commercial vehicle equivalence factor).

Wisconsin Department of Transportation uses the model given by Equation 2 for the prediction of transversely tined concrete pavement surface friction deterioration with time (*15*). The positive sign associated *HV* indicates that friction will increase with an increase in heavy vehicles percentages on the design lane whereas the truth is the opposite. The reason is that the heavy vehicles, with their higher number of tires and/or axle weights and large tires, cause greater wear of the surfaces. The pavement surface would therefore exhibit increased deterioration in friction.

$$\ln (FN) = 3.99 - 0.0419 \ln (LAVP) - 0.00129\, DOL + 0.00474\, HV \quad (2)$$

Where, *FN* = predicted friction number at 60 km/h, *LAVP* = summation of all vehicles expected to pass over design life of the pavements (millions), *DOL* = limestone, dolomite, or ankerite content of coarse aggregate materials (% by weight), *HV* = percent of heavy vehicles in design lane (% lane *ADT*).

A model, as given by Equation 3, for the prediction of skid number with normalization for seasonal effects was developed (*10*). The justification of the terms [sin (2π/365)] and I_1 through I_5 in the model is not clear. Furthermore, it is completely impractical that the surface friction on a pavement type will vary with the differences in friction with other pavement types.

$$SN_{64} = 32.28 - 0.14\,(TEMP_5) + 0.031\,(RF_5) - 0.66 \sin [(2\pi/365)\, JD + 13.53\, I_1 - 3.12\, I_2 - 2.78\, I_3 - 9.52\, I_4 + 7.43\, I_5 \quad (3)$$

Where, SN_{64} = skid number at 64 km/h, $TEMP_5$ = average of daily temperatures for five days prior to friction measurement, RF_5 = cumulative rainfall over the 5-day period preceding the measurement, *JD* = Julian calendar day corresponding to the day of measurement, I_1 through I_5 = indicator variables that account for the differences in the mean skid number from one test pavement to another.

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Study in Maryland has shown that friction decreases at a rate of 0.22 *SN* per year on rural roads and 0.26 *SN* per year on urban roads, and 1 *SN* for every 0.56° C (1° F) increase in average daily temperature (*16*). With this trend, the *SN* will drop from 50 (for example) to 23 for an increase in temperature from 20°C to 35°C (27°F change) which seems to be unreasonable. A relationship between the friction (*BPN*) and temperature on intermediately polished surface was developed as given by Equation 4 (*17*). However, no correlation was found when combining all the unpolished to completely laboratory polished asphalt pavement surfaces leaving the data and model questionable. The given correlation also suggests that at 0 °K the *BPN* will be 125 which seemed to be practically unrealistic.

$$BPN_T = 125.2508 - 0.232\, T \quad (4)$$

Where, *T* = temperature in Kelvin, and BPN_T = *BPN* at temperature *T*

Few other related published literature are available but with similar deficiencies. As indicated by Ahammed (*18*), lack of logical interpretation might have resulted in such deficient or conflicting findings and models.

OBJECTIVES

As mentioned in preceding Sections, study on seasonal and long term variations of pavement surface friction are scarce and deficient with inadequate and/or inappropriate results/conclusions or models. This study is aimed to closely evaluate the seasonal variation and long term performance of both AC and PCC pavement surfaces. More specifically the objectives of this paper are: (i) to evaluate the effect of environmental conditions such as ambient and pavement temperatures, rainfall, dry spell, pavement type and mix properties on month to month wet pavement friction variation, (ii) to evaluate the effect of surface age, traffic passes, asphalt and concrete mix properties, annual average temperature and wet days, vehicle speed, climatic region, etc. on long term friction performance, (iii) to develop performance models for seasonal and long term friction variations, and (iv) to provide a brief of the usefulness of results/models to assist highway agencies/practitioners in selecting pavement surfaces with adequate friction..

STUDY SCOPE AND DATA

The seasonal variation of pavement surface friction was measured from February to October 2007 for six PCC and five AC pavement surfaces. The PCC surfaces include smooth surface, burlap, broom and astroturf dragged surfaces, exposed aggregate texture and longitudinally tined surface. Each surface texture configuration consists of three specimens i.e. total eighteen concrete specimens were tested. All the specimens were prepared in the Centre for Pavement and Transportation Technology (CPATT) laboratory at the University of Waterloo, Ontario, from a single ready mix concrete. The selected material is the standard 30 MPa concrete mixture used for various structural applications including the PCC pavements in Ontario. Fifteen AC surface course specimens were obtained from five sections (to avoid traffic closure) those contain aggregates from the same source and constructed by single contractor in one season (same age pavements). They includes HL3 (two sections), Superpave, Stone Mastic Asphalt (SMA) and Polymer Modified Asphalt (PMA) on CPATT test track at Waterloo landfill site. All the specimens were exposed to natural environment at landfill site and surface friction was measured monthly using portable skid resistance tester known as the British Pendulum. The surface texture was measured time to time to determine possible changes in surface macrotexture level. Daily low and high temperatures and rainfall data were obtained from the University of Waterloo weather station in addition to pavement and ambient temperatures during the testing. This enabled to determine the true effect of environment and develop model for seasonal variation correlating statistically significant variables.

For long term friction performance, field data of Long Term Pavement Performance (LTPP) program Release 21 has been obtained for both PCC and AC pavements incorporating all geographic/climatic regions of Canada and United States. The PCC pavements data includes all sections under GPS-3, GPS-4, GPS-5 and GPS-9 consisting of 1,692 friction measurements while AC pavement data includes all sections under GPS-1, GPS-2, GPS-6 and GPS-7 consisting of 2,742 measurements. For each section the information/data obtained include: traffic uses, age, annual wet days, annual average temperature, climatic regions, speed and temperature during the testing, asphalt mix gradation, air voids, voids in mineral aggregates (VMA) and stability, and PCC pavements surface texture types and concrete compressive strength. The effects of all these variables on surface friction were evaluated and long term friction performance models were developed.

DATA PROCESSING

The data of seasonal friction variation were routinely checked during data collection for accuracy and consistency relative to variation in preceding month(s). Measurements were repeated if any doubtful situation occurred. It should be noted that friction measurement were taken on wet surface after thoroughly cleaning to remove any dust or other debris to determine true effect of rainfall, temperature and dry spell.

The friction data in LTPP database consists of measurement taken by several types of friction tester. Therefore, measurements taken by single equipment type that has the maximum number of measurement points were selected to be consistent in the analysis and findings. The selected equipment is ASTM locked wheel skid trailer. Among the locked wheel friction tests, smooth tire was used for couple of sections. These sections were also filtered out to be consistent with respect to the method of friction measurement and equipment used. Only the locked wheel friction test data with ribbed tire were used in the analysis of PCC pavement surface friction. For AC pavements, friction data were further sorted and measurements taken using the ASTM locked wheel skid trailer from a single manufacturer were selected to further reduce the data volume and to be more consistent. The friction data of all sections were then individually checked for accuracy/practicality and consistency such as unusual increase or decrease. All the doubtful data was filtered out to obtain meaningful and useful results/models. As the main objective is to examine the friction resistance performance over long term, sections with at least two friction data in succession of time were used in the analysis, except ranking the PCC surfaces for friction. Finally, data from 238 PCC pavement sections in 38 states/provinces of United Sates and Canada were used in the analysis. For AC pavements, data from 256 sections in 33 states/provinces were used in the analysis.

Average skid number of multiple measurements on each section was used as the friction of each section and at each age. The time (age) between successive friction measurements and cumulative age for each section was calculated. The temperature during the testing, vehicle speed and all other data were converted to metric units. Mean Annual Average Daily Traffic (AADT) and percentage of trucks on LTPP lanes were calculated from traffic data during the years of friction measurements. Cumulative traffic on LTPP lanes was then calculated. Mean annual wet days (% of number of days in each year) and annual average mean temperatures were calculated from weather data of year 1986 to 2005 (twenty years). For PCC surfaces, average 28-day compressive strength was calculated for each section with appropriate correction for test at different ages. For AC surfaces, mean Marshall Stability, flow, voids and VMA were calculated. The % coarse aggregate as well as maximum aggregate size in the mix was also obtained for each surface. Table 1 shows the summary statistics of the data used in the analysis. The data covers four climatic regions: dry freeze, wet freeze, dry no freeze and wet no freeze.

As shown in Table 1, the average ages for both PCC and AC surfaces are small compared to time needed to produce significant deterioration of surface texture and friction. Further, pavement friction usually increases at early age until the construction debris and loose materials on surface are cleaned up by traffic movement and environmental actions (e.g. rain). The full benefit of aggregate microtexture is available once the bitumen or cement coating from surface aggregate is completely removed. The friction then start to decrease and continue to decrease until pavement surface distresses (e.g. ravelling, cracks, etc.) cause the friction to increase. A data set comprising two opposite trends likely to compensate each other in all analysis and modeling the effect of contributing factors. Therefore, the processed data was divided into two groups: the first group consists of increase in friction during the early age while the second group consists of decrease in friction after the early age increase. This allowed analyzing and developing models for both early age and long term friction performance of the pavement surfaces.

ANALYSIS AND RESULT

Seasonal Variation of Pavement Surface Friction

Figure 1 shows the month to month variation of average wet surface friction for both AC and PCC surfaces from February to October, 2008. As shown in the figure, the variation of skid resistance for both AC and PCC surfaces are almost identical with some fluctuation from time to time. The PCC wet surface friction was shown to vary by up to 10 *BPN* while variation of AC wet surface friction was up to 13 *BPN* depending of pavement or ambient temperatures during the test rather than month or day of the month. This finding agrees closely with that by Jayawickrama (*10*) in regards seasonal variation between winter and summer, taking *SN* value as 60% to 70% of *BPN*. Statistical tests between AC and PCC surfaces and among various AC surfaces showed that neither pavement types nor pavement mix types are statically significant at 5% significance level for monthly variations in wet surface friction.

Figure 2 shows the effect of pavement surface and ambient temperatures on friction variation. As shown in the figure, trends for the air and surface temperatures are identical and overlapping each other. This indicates that seasonal variation of surface friction can be estimated from either of these although ambient temperature has shown slightly higher correlation with friction with correlation coefficient (*r*) value of 0.88. The developed correlation between friction and temperature is given by Equation 5. The model is statistically significant at 5% level of significance. The developed correlation shows that for 1°C increase in temperature the wet surface friction will decrease by 0.35 *BPN*. Wambold (*19*) recommended a minimum SN_{64} of 35 or British Pendulum Number (*BPN*) of 55 as the acceptable friction. With this estimate a *BPN* of 0.35 would mean a SN_{64} of 0.22 i.e. for each 1°C increase in temperature the skid number will decrease by 0.22. This estimate resembles finding by Hill (*9*) in regard to temperature effect.

$$BPN_T = 75.181 - 0.35 * T \qquad (5)$$

Where, BPN_T = *BPN* at temperature *T* and *T* = ambient temperature (°C)

Attempts had been made to correlate seasonal friction variation with the mean texture depth (*MTD*), mean 1-day, 3-day, 5-day and 7-day low as well high temperatures and rainfalls, and number of dry days (dry spell) preceding test day. None of these variables were statistically significant at 5% significance level. All these observations indicate that the seasonal variation of surface friction can not be predicted in advance unless the temperature of that particular time and date are known and prior environmental conditions are also insignificant. It should be noted though that short term variation due to oil spillage, debris/dust on surface and washing out of contaminants can be significant depending on the extent of contamination.

PCC Pavements Long Term Surface Friction

Effect of PCC Texturization Methods

For determining the contribution of different texturization methods on skid resistance, skid number at single speed of 64 km/h (40 mph) i.e. SN_{64} was chosen. The variation of average SN_{64} and the ranks of different texturizations on concrete surface, where rank 1 represents the surface with the highest skid number and descending *SN* value as the rank decreases, are shown in Figure 3. Burlap drag plus transverse groove was shown to exhibit the highest skid resistance while astroturf dragged surface was shown to exhibit the lowest friction among the concrete surfaces.

Effect of Temperature on Friction Performance

To examine the effect of ambient temperature during the testing and the annual average temperature on long term skid resistance, the SN_{64} was plotted as shown in Figure 4. As shown in the figure, both trends are fairly constant indicating that neither ambient temperature nor the annual average temperature has noticeable effect on long term skid resistance of the concrete pavement surface.

Friction Variation with Age of PCC Surfaces

Figure 5 shows that PCC pavement surface friction increases for about 2½ years during the early age. Friction starts to decrease after this initial period of increase. The trend in the figure shows that friction increases by about 4 points (*SN*) on average from initial *SN*. The trend for changes in friction after an initial (early life) increase is shown in Figure 6. Figure 6 shows that friction decreases for a period of about 12 years with an average reduction by 9 *SN*. The friction then shows an increasing trend probably due to pavement surface distresses. The variation of skid resistance with cumulative traffic passes is shown in Figure 7. As shown in the figure, PCC surfaces friction decrease linearly with increase in traffic exposure.

AC Pavements Long Term Surface Friction

Effect of Temperature on Friction Performance

The variation of AC friction with ambient temperature during testing has shown a slightly sharper trend as compared to PCC surfaces with decrease in friction with an increase in temperature. The annual average temperature was statistically insignificant that showed a flat line with no noticeable change in friction with temperature further indicating that prior temperature has no significant effect on long term friction.

Friction Variation with Age of AC Pavement Surfaces

The variation of AC surface friction during the early age is shown in Figure 8. As shown in the figure, AC pavement surface friction increases for a shorter period than PCC surfaces and full friction is attained after about 18 months on an average and then friction starts to decrease. On an average the early life friction increases is about 5 points (*SN*). In Figure 9 the trend for changes in friction after an early life increase is shown where a reduction in friction by 7 *SN* is observed in a period of about 6 years. The AC surface thereafter shows an increasing trend probably due to pavement surface distresses. The skid resistance variation on AC surfaces with cumulative traffic passes is shown in Figure 10. As shown in the figure, AC surface friction decreases for traffic exposure up to 20 million, and thereafter surface friction increases as most pavements experience surface distress after such traffic exposures.

PERFORMANCE MODELS

Multiple regression analysis in statistical analysis software SPSS 15.0 was used for developing long term friction performance models. The available variables were entered in the model and statistically significant variables were selected through proper examination of the models. This resulted in several iterations of the "Enter" and "Stepwise" regression modules. The predictor variables those were statistically significant at a 5% level of significance, make practical sense and improve the prediction power of the models were selected for building the final models. The dependent variable (*DV*) for these models is average skid number. The predictor (independent) variables included in the modeling attempts for both PCC and AC pavements are: surface age, cumulative vehicle passes, percentage of trucks, vehicle speed, ambient temperature during the testing, annual average temperature, annual average wet days, and code for climatic regions (dry versus wet and freeze versus no freeze). For AC pavements, additional predictor variables were: maximum aggregate size, coarse aggregate percentage, voids (%) and VMA (%) in the asphalt mix, and Marshall Stability and flow. For PCC pavements additional variables include: concrete compressive strength and a texture rank type code that accounts for the difference in surface texture type.

The best correlation of each independent variable with the dependent variable was selected using the curve estimation module in SPSS. The attempted trends include: linear, quadratic, inverse, logarithm, exponential and power. The trend that showed greater correlation coefficient (r) and make logical sense was selected for transformation of each individual variable (IV) if not linear. In all modeling attempts, the normality was checked based on distribution of standardized residual. Observation points with standardized residual absolute values exceeding 2.0 were filtered out as outliers based on guidance in statistical analysis text (*20*). The process was repeated until normality condition is met. The multicollinearity was checked based on variance inflation factor (VIF) where a VIF value of less than 4 to 5 indicates no multicollinearity problem (*20*).

PCC Surfaces Long Term Friction Model

The long term friction modelling attempts showed that annual average temperature, annual average wet days and different climatic regions that distinguish between dry (dry freeze and dry no freeze) and wet (wet freeze and wet no freeze) weathers as well as between freeze (dry freeze and wet freeze) and no freeze (dry no freeze and wet no freeze) were statistically insignificant and/or meaningless. This indicates that the PCC pavement friction performance is less sensitive to environmental condition. The percentage of trucks was also shown to be statistically insignificant at 5% significance level but the cumulative traffic passes was significant. Concrete compressive strength was also statistically insignificant. Pavement age and cumulative traffic were statistically significant in separate model. Two sets of model therefore were developed. The summary of these two models are presented in Table 2 and given by Equation 6 (Model A) and Equation 7 (Model B).

$$SN_s = 21.767 - 0.717\ Y + 40.345\ R - 0.198\ S \quad (6)$$

$$SN_s = 35.840 - 0.240\ V + 35.486\ R - 0.308\ S - 0.131\ T \quad (7)$$

Where, SN_s = Skid Number at speed *S*, *S* = vehicle speed in km/h, *Y* = pavement age in years after an early age increase in friction (age since construction minus 2½ years), *V* = cumulative traffic passes in million after an early age increase in friction (total traffic since construction minus traffic passes in 2½ years), *T* = friction test temperature in °C, *R* = Rank for different textures of PCC pavements relative to average friction number exhibited by all surface textures. The surface texture that exhibited above average skid resistance based on the network has got a rank above 1.0 and vice versa. The ranks for various surface textures are: astroturf drag = 0.87, burlap drag = 0.92, broom drag = 0.93, diamond ground = 0.96, astroturf drag & tining = 0.98, grooved float = 0.99, tining = 1.04 and burlap drag & transverse groove = 1.08.

As shown in Table 2, both models are statistically significant at 5% significance level with all the predictor variables (*p*-values less than 0.05). The coefficient of determination (R^2 value) is 0.592 for Model A and 0.701 for Model B. The low R^2 value does not indicate any problem if each regression coefficient is statistically significant at a pre-selected significance level, make logical sense and regression diagnostic does not show any problem. The regression coefficients associated with age indicate that PCC surface friction reduces @ 0.717 *SN* per year or 0.240 *SN* per million vehicle movements, increases with improved texture rank, and decrease with speed as well temperature during testing (driving). All these make practical sense. Regression diagnostic has shown that *VIF*s are 1.01 to 1.08 which are lower than the acceptable maximum value of 4 to 5 that leaves no doubt about the model. The errors were shown to be normally distributed about the mean and the scatter plot of errors has shown no particular pattern further proving the adequacy of the model. The models therefore can be used to predict the PCC pavements surface friction after about 2½ years of construction. For example, if surface friction after 10 years is to be predicted, the *Y* variable in Equation 6 would be 7½ years. For pavement management, it is recommended to apply both models and use the lowest friction value obtained from these two models for preventive action.

AC Surfaces Long Term Friction Model

For AC pavement long term friction, the annual average temperature and annual average wet days were statistically insignificant resembling PCC pavements. However, the codes defining different climatic regions were statistically significant. The correlations of friction with asphalt mix properties such as voids and VMA were impractical with very high correlation coefficient making all other IVs insignificant. A close study by the authors also found that neither voids nor VMA has statistically significant and meaningful correlation with friction because both voids and VMA are internal properties of the mix while the surface friction is an external property of the pavement surface. The coarse aggregate percentage and maximum aggregate size were also statistically insignificant for long term surface friction. Pavement age and cumulative traffic were statistically significant in separate model resembling PCC pavement surfaces and two sets of model therefore were developed. The summary of these two models are presented in Table 3 and given by Equation 8 (Model C) and Equation 9 (Model D).

$$SN_s = 63.079 - 1.208\,Y + 5.321\,DW + 2.697\,FNF - 0.179\,S - 0.242\,T \tag{8}$$

$$SN_s = 59.644 - 0.265\,V + 5.901\,DW + 3.691\,FNF - 0.133\,S - 0.293\,T \tag{9}$$

Where, SN_s = Skid Number at speed *S*, *S* = vehicle speed in km/h, *Y* = pavement age in years after an early age increase in friction, *V* = cumulative traffic passes in million after an early age increase in friction, *T* = friction test temperature in °C, *DW* = dry versus wet weather code (dry weather = 1 and wet weather = 0), and *FNF* = freeze versus no freeze weather code (no freeze = 1 and freeze = 0).

The coefficient of determinations (R^2 values) for models C and D (Equation 8 and 9) are 0.484 and 0.412, respectively. However, as shown in Table 3, all the predictor variables for both models are statistically significant at 5% significance level with *p*-values less than 0.05. Equation 8 and Equation 9 also show that the coefficients associated with the IVs are logical. Regression diagnostic also showed that errors are normally distributed and the scatter plot of errors showed that errors are randomly distributed about a line with mean equal to zero and with no particular trend. The VIFs are from 1.03 to 1.16 indicating no multicollinearity problem. The significance of *DW* and *FNF* indicate that AC pavements surface performance is more affected by the environmental condition as compared to PCC surfaces. More susceptibility of asphaltic concrete to environmental changes probably justifies such variation.

The developed models show that AC surface friction reduces @ 1.208 *SN* per year or 0.265 *SN* per million vehicle passes which is relatively higher than PCC surfaces. AC pavement will exhibit 5 to 6 point greater skid resistance if weather is predominantly dry (dry no freeze and dry freeze) as compared to wet weather (wet freeze and wet no freeze). If the weather is predominantly freezing (dry freeze and wet freeze) the AC pavement will exhibit 3 to 4 points lower skid resistance as compared to no freeze weather (dry no freeze and wet no freeze).

CONCLUSIONS

This paper evaluated the seasonal and long term variations of both AC and PCC pavements surface friction using the field data. The seasonal variations of both AC and PCC pavements wet surface friction were shown to be similar. The wet surface friction was shown to vary with ambient or surface temperature during the testing or driving probably due to changes in tire hardness. Prior weather such as rainfall or temperature preceding test days was not statistically significant for seasonal friction variation. The seasonal variation analyzed in this paper however did not account for the short term variation due to surface contamination such as dust/debris or oil or rubber deposit. The friction was shown to vary @ 0.35 *BPN* for one degree Celsius variation in temperature.

Full surface friction is attained after about 1½ (AC) to 2½ (PCC) years, on average, following the construction. The surface friction decreases thereafter for about six (AC) to twelve (PC) years. The surface friction is stable or decrease thereafter at insignificant rate but start to increase once the pavement surface start to deteriorate (e.g. raveling). AC surface friction is more affected by predominant weather conditions as compared to PCC surfaces. Four alternative models were successfully developed for the prediction of long term friction. In practice, both models should be utilized and lower friction value should be used for pavement management or investigation purposes.

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Table 1. Descriptive statistics of the LTPP data

Statistics	Count	Min.	Max.	Mean	Stand. Dev.
PCC Pavements					
SN	743	22.0	65.5	46.6	6.86
Age, years	743	0	15.95	2.85	3.22
AADT	277	462	13,637	4,757	3,153
Cumulative traffic, million	277	0	42.02	5.85	7.82
Truck %	277	2.9	68.5	18.1	12.6
Speed, mph	743	41.8	88.5	65.3	4.64
Air temp., °C	655	0	41.7	22.3	8.25
Compressive strength, MPa	677	20.64	56.67	37.2	7.60
Annual avg. temp., °C	743	2.8	22.9	13.4	4.25
Annual avg. wet days, %	743	9.2	51.8	34.6	8.16
AC Pavements					
SN	1,229	23.0	68.5	44.8	8.01
Age, years	1,229	0	12.05	2.12	2.26
AADT	474	407	16,700	3,723	3,387
Cumulative traffic, million	474	0	37.3	3.6	4.98
Truck %	474	3.8	44.9	15.5	9.85
Speed, mph	1,229	57.9	88.5	67.5	7.86
Air temp., °C	1,164	0	42.8	22.5	8.22
Marshall Stability, N	218	3,526	19,907	8,336	2,927
Annual avg. temp., °C	1,079	2.7	25.1	12.7	4.23
Annual avg. wet days, %	1,079	6.5	56.6	35.0	9.59
Max. aggregate size, mm	484	9.5	38	16.9	4.1
Coarse aggregate, %	515	2	69	39.4	11.33
VMA, %	266	11.8	29.2	17.5	3.11
Voids, %	432	1.7	17	5.8	2.57

Table 2. Summary of friction performance models for PCC pavements

Parameters	*N*	Coefficients	*t*-value	*p*-value	*VIF*	R^2
Model A (Equation 6)						
Intercept	153	21.767	3.69	0.000		0.592
Age, year	153	-0.717	-10.80	0.000	1.07	
Relative Rank	153	40.345	7.02	0.000	1.04	
Speed (km/h)	153	-0.198	-6.28	0.000	1.08	
Model B (Equation 7)						
Intercept	127	35.840	6.70	0.000		0.701
Cum. Traffic (Million)	127	-0.240	-9.61	0.000	1.02	
Relative Rank	127	35.486	6.84	0.000	1.03	
Speed (km/h)	127	-0.308	-11.30	0.000	1.03	
Test Temp. (°C)	127	-0.131	-4.89	0.000	1.01	

Note: N = Number of observation points, VIF = Variance Inflation Factor.

Table 3. Summary of friction performance models for AC pavements

Parameters	*N*	Coefficients	*t*-value	*p*-value	*VIF*	R^2
Model C (Equation 8)						
Intercept	468	63.079	29.394	0.000		0.484
Age, year	468	-1.208	-10.00	0.000	1.03	
Dry-Wet Code (*DW*)	468	5.321	10.17	0.000	1.04	
Freeze Code (*FNF*)	468	2.697	5.34	0.000	1.13	
Speed (km/h)	468	-0.179	-5.72	0.000	1.14	
Test Temp. (°C)	468	-0.242	-8.74	0.000	1.08	
Model D (Equation 9)						
Intercept	467	59.644	26.20	0.000		0.412
Cum. Traffic (Million)	467	-0.265	-3.57	0.000	1.04	
Dry-Wet Code (*DW*)	467	5.901	10.78	0.000	1.03	
Freeze Code (*FNF*)	467	3.691	6.96	0.000	1.12	
Speed (km/h)	467	-0.133	-4.03	0.000	1.16	
Test Temp. (°C)	467	-0.293	-10.16	0.00	1.09	

Note: N = Number of observation points, VIF = Variance Inflation Factor.

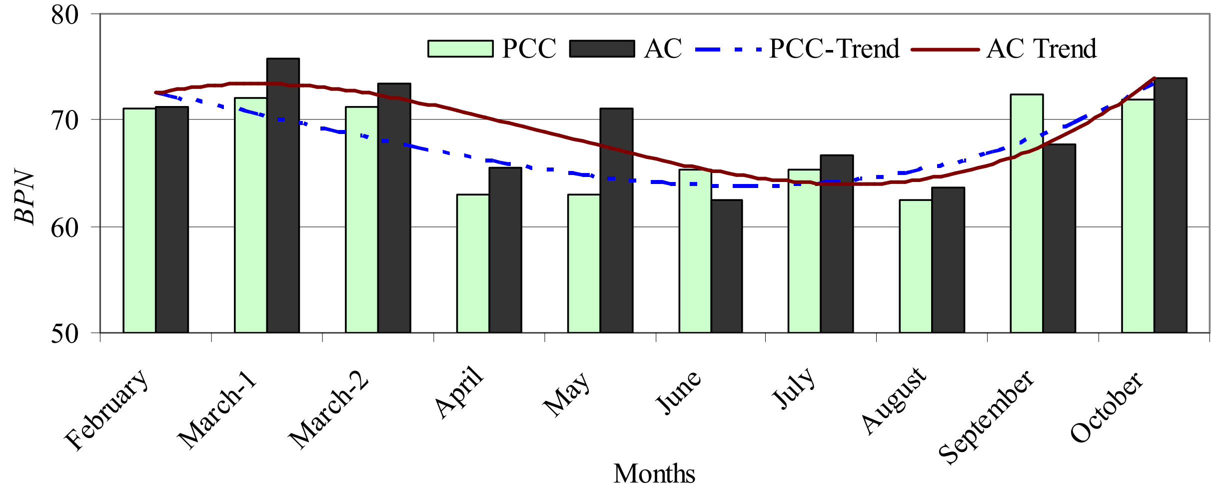

Figure 1. Month to month variation of pavement surface friction.

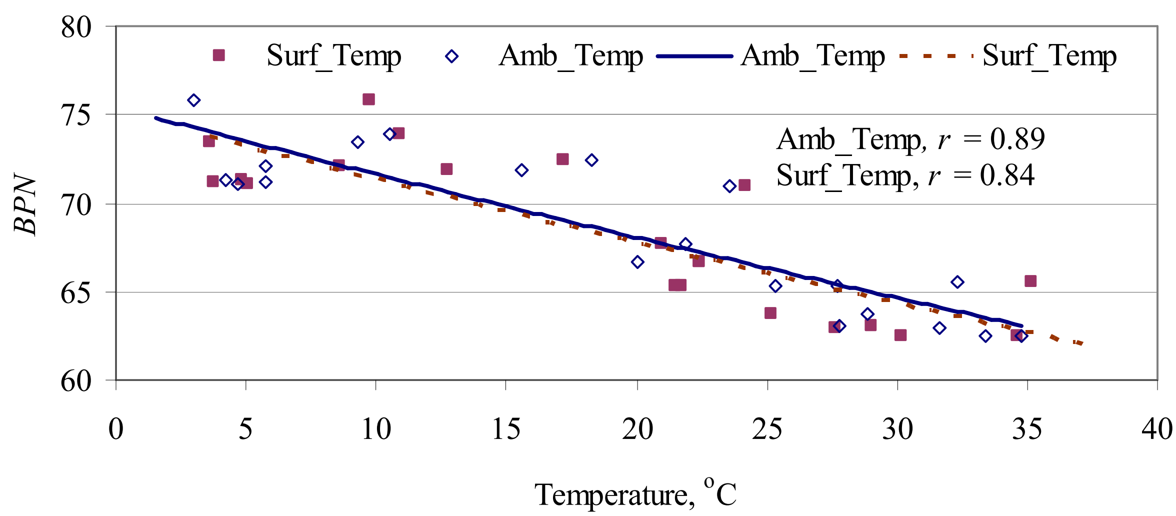

Figure 2. Effect of pavement surface and ambient temperatures on monthly friction variation.

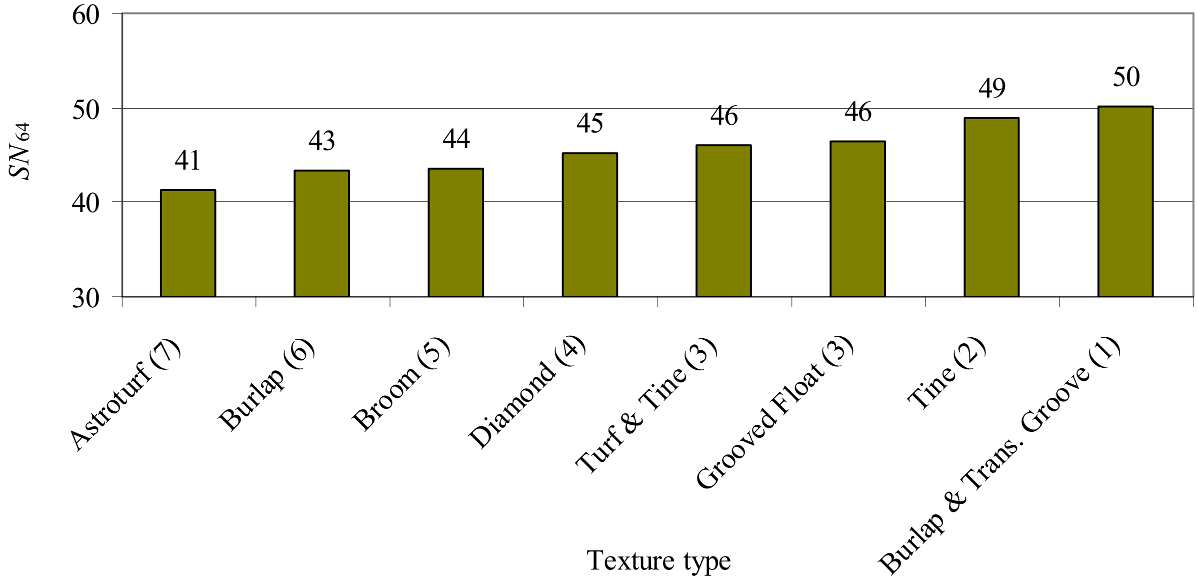

Figure 3. Average friction at 64 km/h & ranks for different texturization methods of PCC.

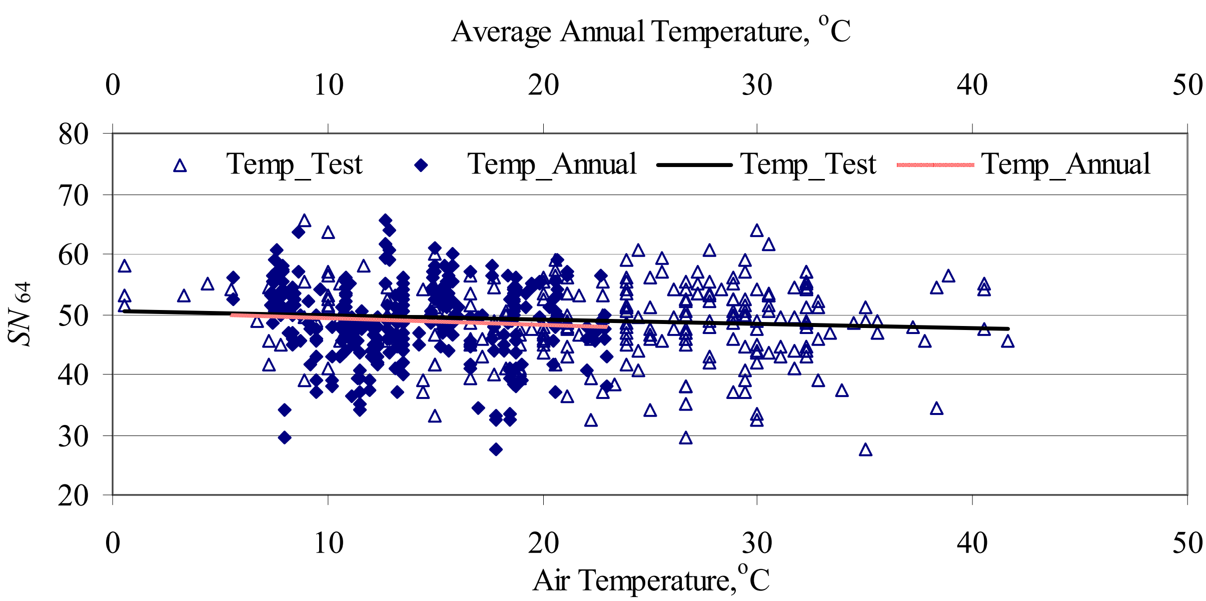

Figure 4. Effect of air temperature on friction of PCC pavements measured at 64 km/h

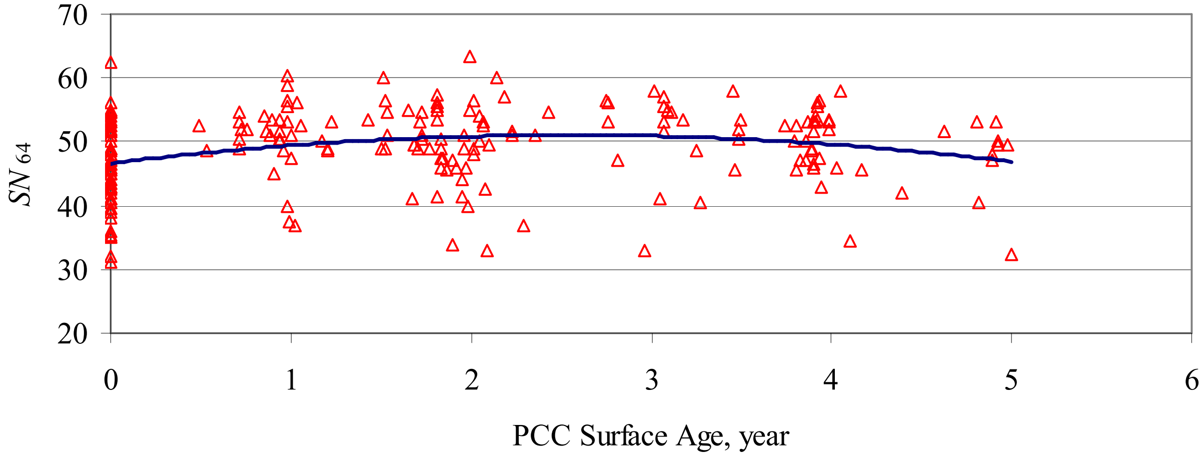

Figure 5. Early life skid resistance changes on PCC pavement surface.

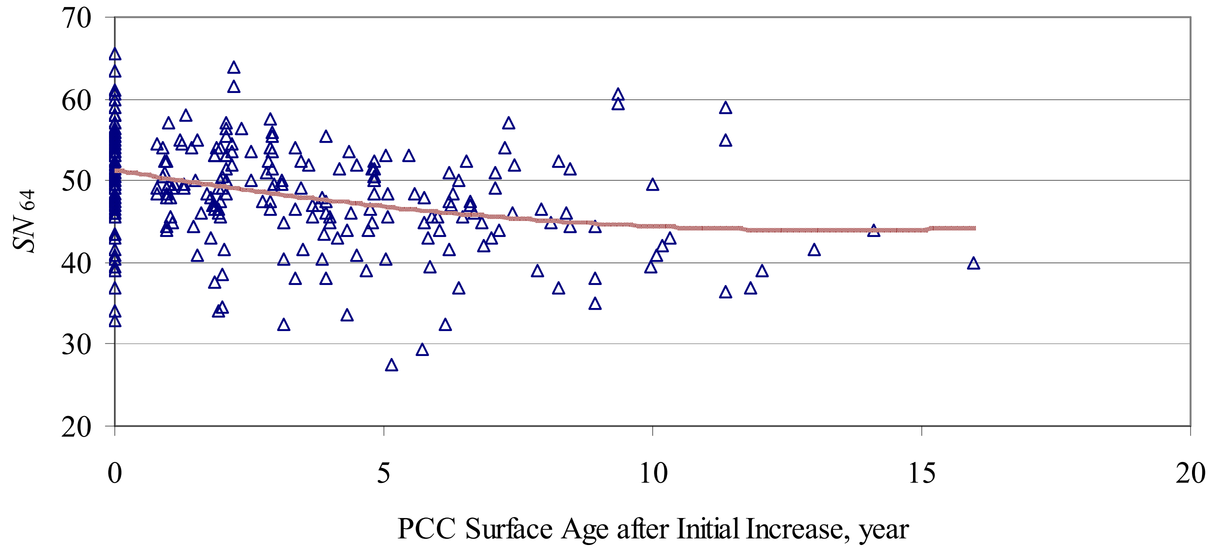

Figure 6. Changes in skid resistance of PCC surface with time after an initial increase.

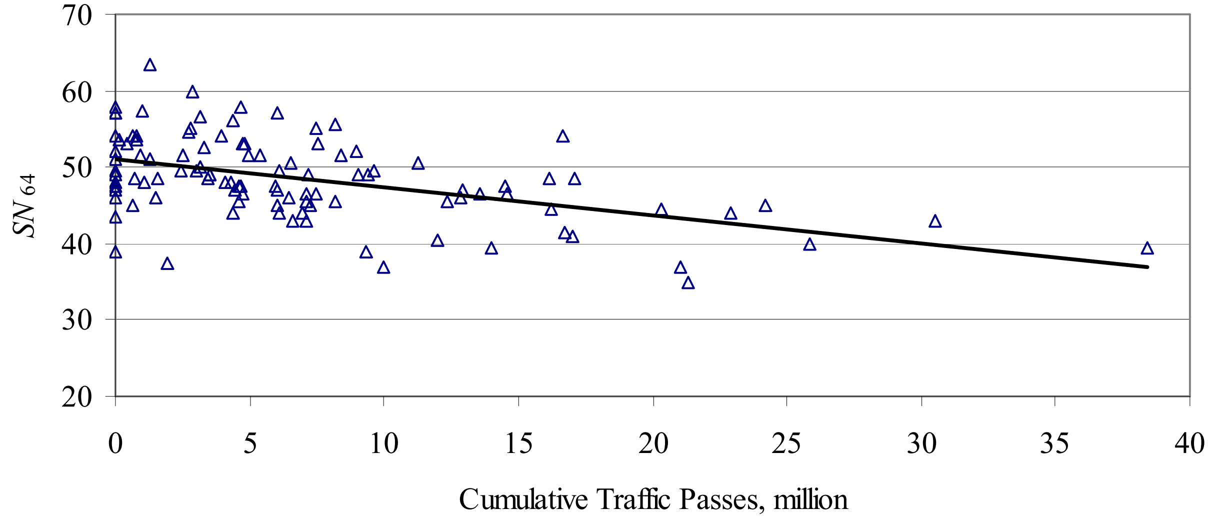

Figure 7. Changes in PCC skid resistance with traffic uses after an early life increase.

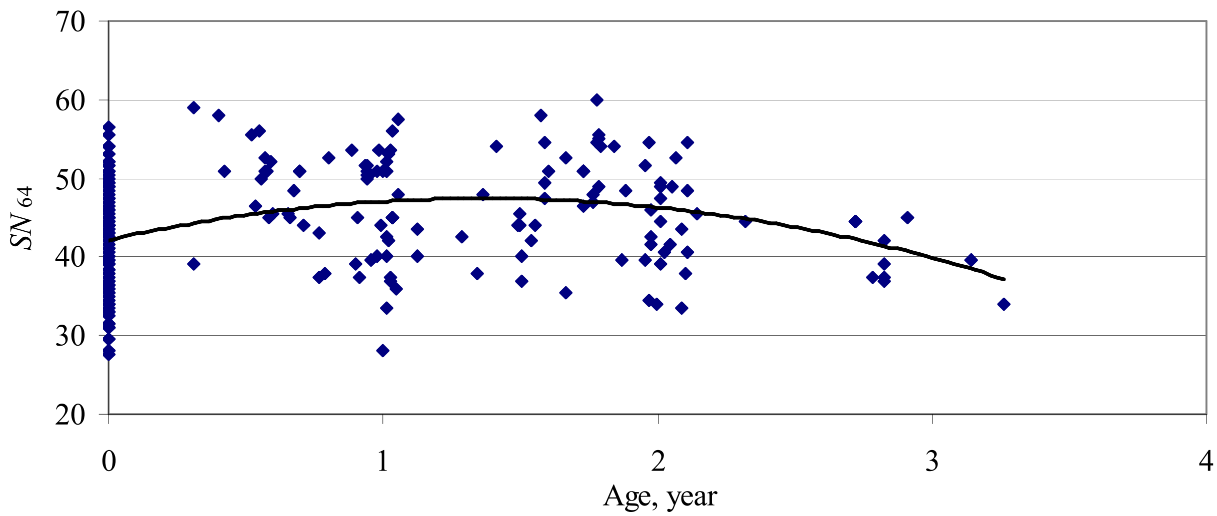

Figure 8. Early age AC surface friction changes.

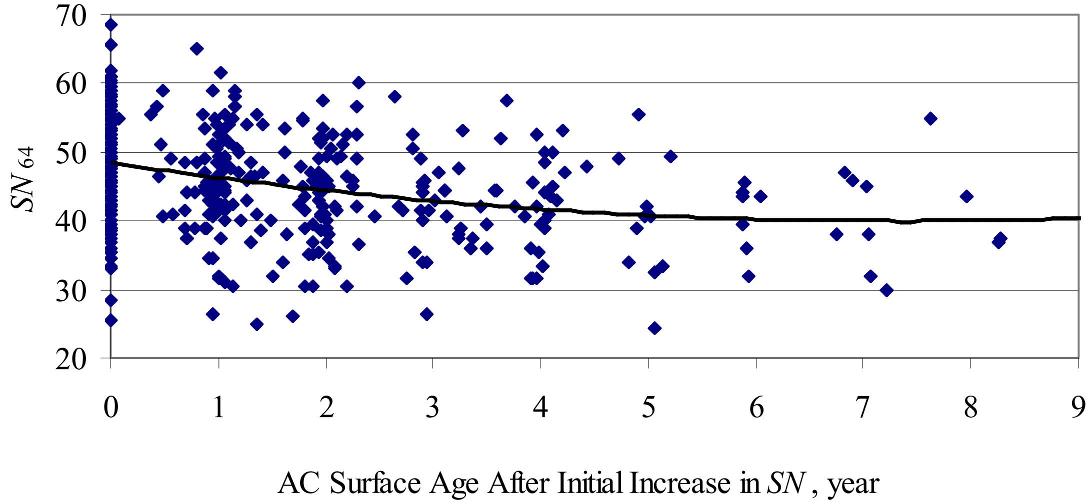

Figure 9. Changes in AC pavements skid resistance with age after an early life increase.

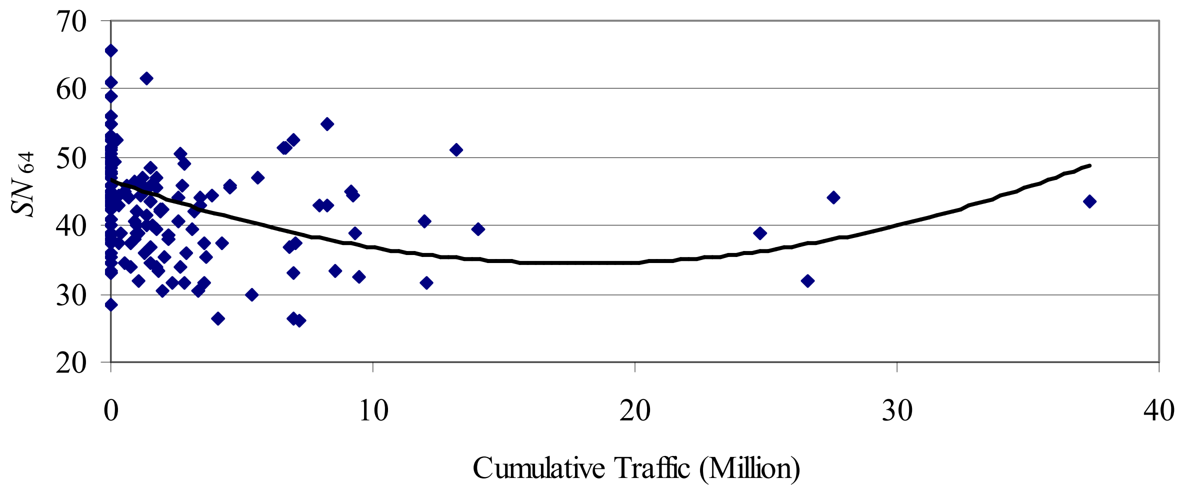

Figure 10. Changes in AC skid resistance with traffic uses after an early life increase.