Pavement Surface Performances Evolution: an Experimental Application

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Abstract

Pavement surface performances have a great influence on road functionality and can affect user’s safety, vehicle operational costs, environmental sustainability. The assessment of evolution of pavement surface performance plays a fundamental role in road pavement management and is useful in order to allocation of maintenance resources. In the light of the above, Authors introduced the first results carried out from a two-year monitoring of an experimental road section. Four different dense graded wearing courses were designed with different aggregates: limestone, basalt and expanded clay. Several surface performances were measured by different devices (Skid Tester, Sand Patch Test, Laser Profilometer).

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1. Introduction

As is well known, surface texture plays a key role in tyre-road interaction phenomena and greatly affects road safety. Surface texture, defined by the ISO Standards 13473-1 as “the deviation of a pavement surface from a true planar surface”, can be seen as the superposition of many elementary harmonics, each one corresponding to a specific domain associated with a wavelength range: microtexture, macrotexture, megatexture and roughness. These classes of texture are related to several phenomena that fulfil on the boundary surface between the vehicle and the pavement, where tangential contact forces are transmitted as reported by [1]. In more detail, both micro and macrotexture contribute to improve road surface performance, affecting the following issues: i) Skid resistance; ii) Splash & spray and visibility; iii) Tyre-road noise; iv) Rolling resistance and tyre wear.

The adherence mechanism can be ascribed to three main causes: friction, adhesion and hysteresis. The adhesion phenomenon takes effect at the smallest texture scales (microtexture); it is due to the molecular interaction forces which grow between the tyre and the surface. The adhesion friction is dominant until critical slip occurs. At higher speeds the hysteresis mechanism arises: the tire repeatedly deforms, enveloping surface

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texture asperities. Macrotexture determines the hysteretic deformation of the rubber and the consequent
development of horizontal forces which are opposed to the slipping of wheels \cite{2–3}. Surface texture has a great
influence on skid resistance especially in wet surface conditions (presence of water, ice, oil, etc.). Depending on
the water film thickness, it is possible to distinguish between three different events, classified as follows: 1) hydroplaning or aquaplaning (film thickness higher than 0.5 mm); 2) viscoplaning (thickness range between 0.5mm and 0.10 mm); 3) damp (thickness lower than 0.10 mm). The aquaplaning speed depends on several
parameters such as: spin down, tire inflation pressure, tread depth, water depth and mean texture depth; this speed
increases when the texture depth increases according to \cite{4}. As a matter of fact, accident ratio depends both on
texture and friction. Several previous works show that the crash rate decreases with an increase in both
macrotexture depth and skid resistance \cite{5–6–7}.

The aerodynamic phenomena of splash and spray on wet pavement surfaces are essentially connected to the
water drainage through the interconnected voids of the asphalt mix. Splash and spray leads to poor visibility
conditions for drivers, thus influencing road users safety. Splash is due to the action of forcing water out of the
tyre path; water drops are greater than 1 mm and describe a parabolic trajectory. The formation of smaller drops
diameter about 0.5mm) and their nebulisation during the vehicle motion on the surface determine the production
of clouds of spray, very dangerous especially for smaller vehicles travelling nearby heavy trucks. Also in this
case, pavement surface characteristics play a key role in the generation of these phenomena as reported by \cite{8}.

Several studies show that open graded friction courses (OGFC) or stone mastic asphalt (SMA), characterized by a
high macrotexture (Mean Profile Depth values higher than 1.0) provide surface drainage and can reduce water
nebulisation in wet weather conditions \cite{9–10}. Visibility loss increases at a rate of 1.4 times higher for the dense
graded friction courses than for SMA and OGFC. The splash and spray contributes to 10% of the wet weather
accidents determined by a poor visibility \cite{8–11–12–13}.

The tyre-road noise derives from various and simultaneous generation mechanisms that occur at different
degrees, depending on surface and tyre conditions. About 60-80% of this noise is due to vibrations, characterized
by a frequency of emission lower than 1000 Hz. This phenomenon is primarily determined by texture
wavelengths in the range of 10mm-500mm. The rate of noise related to the air pumping mechanism is around 10-
30% and it is due to aerodynamic effects: some of the air inside the voids is squeezed out, and some is trapped
and compressed; when the tire loses contact with the pavement, the trapped air is forced out or sucked back in
again. The air pumping mechanism is governed by texture wavelengths lower than 10mm. A lower percentage of
noise can be attributed to the aerodynamic flow and to the stick and slip process. Other mechanisms (horn effect,
Helmholtz resonance, pipe resonance, sidewall vibrations and cavity resonance) cause the amplification of the
generated noise, increasing the sound level heard \cite{4–14–15}.

Rolling resistance needs to be analyzed associated with other parameters such as fuel consumption, tyre wear,
gas emissions. This phenomenon occurs when a wheel is rolling on a surface and determines the tyre energy loss
because of three main mechanisms: 1) bending deformations of the tyre sidewalls (macro deformations); 2) micro
deformations in the contact area between tyre and pavement surface; 3) slippage friction in the contact area.
Rolling resistance represents about the 14% of the total energy consumed by the vehicle. It depends both on the
unevenness and megatexture classes at low speeds; otherwise also the macrotexture wavelength range seems to
have effects on the rolling resistance generation at higher speeds. Several studies show that the tyre wear is
strictly affected by pavement surface characteristics in terms of both skid resistance and texture; the same works
provide also some equations for the estimation of the tyre sculptures wear \cite{15–16–17–18}.

2. Deterioration models of surface performance: a literature review

Pavement surface characteristics change over time. These variations are principally due to traffic actions
(long-term variations), but they can also be identified as “short term variations” due to weather, rainfall and other
environmental conditions (such as temperature variability), according to \cite{19}. Furthermore, other factors related
to asphalt mix composition, primarily the aggregates, the binder and their combination, have a great effect on micro and macrotexture evolution. Identifying the causes of deterioration and predicting the evolution of surface performance are fundamental operations to ensure proper planning and management methodologies. Several previous studies investigated on these issues and some empirical models were carried out from experimental measurements in order to predict the progression of road surface performance.

Generally, the evolution of skid resistance is characterized by an initial increase in friction coefficient that occurs in the months immediately after the laying of the road surface because of the actions due to vehicular traffic: the bitumen film is gradually removed from the aggregates surface. Each aggregate is more exposed to the contact with the tire and, consequently microtexture increases. This first phase is known as the “early life skid resistance”. Once the binder has been completely removed, the skid resistance evolution curve reaches a maximum. Afterwards (after 2 million of vehicle passes or 2 years of pavement service life) this higher exposure causes a decrease in skid resistance due to the smoothing and polishing actions under traffic loads [20–21].

Also macrotexture evolution shows a progressive decrease over time because of the occlusion of the voids due to both the migration phenomenon of the binder and the dust and oil accumulation. In addition, under the effect of prolonged post-compaction action due to the traffic, the aggregates are embedded in the asphalt matrix with a further reduction of the average texture depth, as reported by [22].

On the basis of the international literature, Table 1 offers a summary of many microtexture and macrotexture progression models.

Also seasonal variations have a considerable effect on pavement micro and macrotexture evolution. In particular, many seasonal factors such as temperature, precipitations and dry days before the test affect tire-pavement friction measurements. The general trend shows higher skid resistance values in the fall and winter and lower measurements during the spring and summer; the tendency follows a cyclical sinusoidal pattern throughout the year [23]. The most common hypothesis that can explain this phenomenon is that during the summer dust is often interposed between the wheel and the surface and becomes more abrasive determining a smoothing effect; on the contrary, in winter the rainwater flushes out the finer particles responsible for polishing and reacts with the aggregate surface. This results in a higher micro and macrotexture. The extent of skid variability throughout the year can reach around 30% with respect to the average value. However, there is not general agreement on the magnitude of this effects [19–24].

Texture deterioration rate is difficult to be estimated because it is affected by many factors, including aggregate properties, binder properties and aggregate-binder combination, road geometry and traffic, as discussed below.

The ability of an aggregate to resist the polishing action of traffic depends on several parameters: hardness, mineralogical composition, crystalline structure, shape, angularity, resistance to abrasion, resistance to polishing, petrographic nature. It is a common practice to assume that aggregates with lower Los Angeles abrasion loss, lower sulfate soundness loss, lower freeze-thaw loss, lower absorption, and higher specific gravity have better resistance to polishing.

Moreover, synthetic aggregates (slag or expanded clay), can also improve pavement frictional resistance; rocks consisting of minerals with nearly the same hardness wear uniformly, thus having a low resistance to polishing.

Aggregates composed of a hard mineral and a weak mineral behave differently: the softer mineral mass wears quickly, exposing the hard grains to the traffic loads, keeping good frictional properties for extended periods of time [2–19–22].
Table 1. Micro and macrotexture evolution: mathematical models by a literature review

<table>
<thead>
<tr>
<th>Reference</th>
<th>Models</th>
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| [25]      | \( S_{N100} = 0.174M_S + 0.356(FLOWS) + 0.904[EQT(F)]^{0.081} - 17.323 \)  
\( S_{N80} = 0.196M_S + 5.472(VOIDS) + 3.6320[EQT \cdot 4]^{0.65} - 40.32 \)  
Where \( S_{N100} \): Skid Number at 100Km/h; \( S_{N80} \): Skid Number at 80Km/h; \( M_S \): Marshall Stability; \( FLOWS \): Marshall Flow; \( VOIDS \): Air Voids in mix; \( EQT(F) \): Equivalent traffic; \( F \): commercial vehicle equivalent factor. |
| [26]      | \( FN = 41.4 - 0.00075D^2 - 1.45 \ln(LAVP) + 0.245\text{LAWEAR} \)  
Where \( FN \): Friction Number at 40 mph; \( D \): % dolomite in the mix; \( LAVP \): Lane Accumulated Vehicle Passes; \( \text{LAWEAR} \): Los Angeles Aggregate Wear |
| [27]      | \( M_{SCC} = 0.024 - 0.0000663 \cdot CVD + 0.010 \cdot PSV \)  
Where \( M_{SCC} \): Mean Summer SCRIM coefficient; \( CVD \): commercial vehicles per lane per day; \( PSV \): Polished Stone Value |
| [28]      | \( MSSC_{ave} = 0.0013 \cdot PSV + 0.10 \cdot e^{-CHCV} - 0.07 \cdot ALD + 0.44 \)  
Where \( MSSC \): average MSSC; \( PSV \): Polished Stone Value; \( CHCV \): cumulative heavy vehicle traffic per lane in millions; \( ALD \): average least dimension of the sealing chip (mm) |
| [29]      | \( F_N = -1.576(X_1) - 0.00022(X_2) + 0.41014(X_3) + 105.38 \)  
Where \( F_N \): Friction Number (ribbed tire); \( X_1 \): speed, mph; \( X_2 \): Annual Average Daily Traffic; \( X_3 \): years since last maintenance of the pavement. |
| [30]      | \( \mu = c \cdot (t + 1)^b \)  
Where \( \mu \): skid resistance; \( c \): initial skid resistance; \( t \): time, years; \( b \): value for the development |
| [31]      | \( F_{(n_{eq}, BEF)} = (a \cdot BEF + b) \cdot e^{n_{eq}} + d \cdot BEF + e \)  
Where \( n_{eq} \): equivalent number of standard light vehicle passes; \( BEF \): Basalt Exposure Factor; \( a, b, c, d, e \): experimentally derived model coefficients |
| i) [32]   | ii) [33]   |
| i) \( CAT_{att} = CAT_{init} - \alpha \cdot T^\beta \)  
ii) \( CAT_{att} = 115.30 - 11.21 \log(TCV_P) \)  
Where \( CAT_{att} \): transversal adherence coefficient; \( CAT_{init} \): initial transversal adherence coefficient; \( \alpha, \beta \): experimental coefficients; \( T \): equivalent number of standard light vehicle passes; \( TCV_P \): cumulative heavy traffic |
| iii) [34] | \( \Delta CAT_{50i} = -0.663 \cdot 10^{-6} \cdot K_{cat} \cdot MAX[0; \Delta QCVi] \)  
Where \( \Delta CAT_{50i} \): transversal adherence coefficient at 50 Km/h variation during the \( i \) year; \( \Delta QCVi \): heavy daily traffic during the \( i \) year; \( K_{cat} \): calibration factor |
| [35]      | \( \Delta H_{S_{att}} = K_{tx} \cdot \left( H_{S_{0}} - H_{S_{i-1}} - \alpha \cdot H_{S_{0}} \cdot \left( 10^{(H_{S_{i-1}}-H_{S_{0}})/(\alpha \cdot H_{S_{0}})} + \Delta NELV \right) \right) \)  
Where \( \Delta H_{S_{i}} \): macrotexture variation during the \( i \) year (Sand Patch Test); \( K_{tx} \): calibration factor; \( H_{S_{0}} \): macrotexture initial value; \( H_{S_{i-1}} \): macrotexture value in the \( i-1 \) year; \( \Delta NELV \): number of equivalent vehicles during the \( i \) year; \( \alpha \): experimental coefficient |
The aggregate-bitumen combination should be influenced by additional heavy trafficking or high levels of stressing that can accelerate the removal of the bitumen film. This phenomenon seems to be strictly associated to the binder type used in the asphalt mix. Several studies show that using polymer modified binders in asphalt mixtures results in a surface in which aggregate remain coated for a longer period of time when compared to an unmodified binder during the early life of surfacing [21–41–42]. Experimental studies on asphalt mixes produced with modified binders, confirm that aggregate with a lower PSV strips quickly; for this reason, in the phase of early life skid resistance, they may perform similarly, and in some cases better, than a much higher PSV aggregate according to [41].

The variation of micro and macrotexture in the longitudinal direction is also due to the road geometry: driving through a curve or approaching an intersection require a greater friction effort because the stresses transmitted from the vehicle to the road surface become greater and, consequently, the degradation phenomenon is faster in these areas. One of the factors that determine the arising of a shear stress on the contact surface is the variability in loads distribution due to the fact that the wheel track changes from a straight motion to a different direction in curve. In particular, the centrifugal force determines a load transfer from the inner wheels toward the outer ones of about 10-20%, for French studies, and of more than 60% for Belgian and Australian researchers. The study carried out by Hamlat [43] shows the effect of tangential forces on the aggregate in the asphalt mix and how this efforts can determine the progressive deterioration of surface texture.

Several parameters related to vehicle types and traffic flow have a great effect on surface texture evolution. The cumulative damage due to the passage of a certain number of vehicles in a time unit determines the actual state of evolution of the road surface. The most common method used to aggregate the effects of a non-homogeneous traffic requires that loads are expressed in terms of Equivalent Standard Axles (ESA). Other factors related to load configuration, such as axle and wheel configuration, tyre features, tyre inflation pressure, load transverse distribution factors play a key role in surface texture deterioration [44–45–46].

3. The Experimental Plan

This paper discusses the experimental data of surface performance of asphalt pavements carried out from a two-year monitoring of an experimental road section. This work is part of a wider Research Project designed and realized by the Road Materials Research Laboratory of University of Calabria in partnership with the Road Network Division of Provincial Administration of Cosenza (Italy), with the final aim of conducting a technical and economic study on the definition of the allowance thresholds in the road management and maintenance contracts [47–48–49].

3.1. Test Site

The test site is located in the district of Cosenza (namely SP 243, Rive Destra Crati). Four different dense graded friction courses were designed and laid on four road sections, characterized by a two-way single carriageway layout with both a straight stretch and a curve of radius less than 100m (see Figure 1a).

The estimate of equivalent hourly flow rate for the peak 15 min ranged between 400 and 500 veh/h per lane for each section. The analysis of traffic flows data showed that the percentage of heavy vehicles on the road fluctuates between 11% and about 16% per day.

Wheel tracks alignments were identified by means of a study of vehicles trajectories (see Figure1b); measuring points were marked on the wheel tracks: on these points all type of experimental measurements were carried out.
3.2. Asphalt Mixes

Asphalt mixes variability is due to the use of aggregate of different petrographic nature: limestone, basalt and expanded clay. The same aggregate gradation was used for all mixtures (Figure 2).

The bituminous mixtures are characterized as follows (the percentages are expressed on the total weight of the mix):
- M0 Mix: 100% limestone aggregate;
- M1 Mix: 85% limestone aggregate, 15% basaltic aggregate (aggregate size d> 5mm UNI);
- M2 Mix: 70% limestone aggregate, 30% basaltic aggregate (aggregate size d> 5mm UNI);
- M3 Mix: 82% limestone aggregate, 8% expanded clay (aggregate size 3-11mm UNI).

The binder content was about 5.5% on the weight of the asphalt mix, with the exception of M3 Mix in which the binder content reaches a value of 8%.

3.3. Surface Performance Measurement Devices

Micro and macrotexture measurements were carried out by means of the following devices and techniques: British Pendulum Tester (BPT- CNR B.U. n°105/85), Sand Patch Test (SPT-CNR B.U. n°94/83) and Laser Profilometer (LP- ISO 13473-3) (Figure 3). Both extrinsic and intrinsic indicators were determined. The experimental road pavements were monitored every 6 months since they were laid (August 2009). Overall 4 monitoring campaigns were done. Five measurement points for each wheel track were selected, for a total of 40 points for each section (20 in straight and 20 in curve).

Fig. 3. Measurement devices and measurement points distribution on a road section

Measurements were carried out on all trial sections in both directions along the wheel tracks; the sand patch test was done on intermediate points (“dry”) between two consecutive “wet” measurement points on which the other tests were done. Figure 4 shows the distribution of measurement points on the surface; the same scheme was used for both straight and curve sections.

Fig.4. Measurement points distribution on the road surface
4. Results and discussion

Collected data were averaged along the wheel tracks for each direction, distinguishing between measurements points in straight and in curve, for each trial section.

4.1. Microtexture data

Microtexture results, expressed in terms of BPN (British Pendulum Number), show some differences in the evolution trends, especially in the phase of early life skid resistance; this variability is probably due to the composition parameters (aggregates and binder type) of the mixtures.

M0 Mix is characterized by an initial increase in BPN, whereas for the other three mixes microtexture decreases six months after the pavements were laid. The different behavior can be due to the different nature of aggregate; limestone, having a lower PSV than basalt and expanded clay, has a lower resistance to the stripping phenomenon: the modified binder is easily removed and the aggregate becomes immediately more exposed [21–41–42]. In the other mixes, in which the aggregate mixture is more resistant to the stripping, the binder coatings quickly become smoothed; this can explain the low values of friction registered after 6 month for M1, M2 and M3 mixes.

Figure 5 shows the evolution of microtexture in terms of $\Delta$BPN, calculated as the percentage difference between the measured BPN and a terminal value of BPN equal to 35 (established by current Italian Standards) for both straight and curve sections. For all the mixtures monitored, the maximum value of BPN is reached after 13 months, that corresponds to the period in which the bitumen film is removed and the aggregates are completely exposed to the traffic actions; these same actions determine the next decrease (see Figure 5). M2 and M3 mixes have always the highest microtexture values; Figure 5 shows that M1 and M2 mixes have the same trend throughout the monitoring time, although the values of $\Delta$BPN for M2 mix are always higher than those measured for M1 mix, emphasizing the effect due to the presence of a double proportion of basalt in M2 with respect to M1; the mix produced with 100% of limestone aggregate shows a BPN decrease of about 10-15% from 13 to 18 months.

![Fig. 5. BPN evolution trends for straight and curve sections](image)

4.2. Macrotexture data

Figure 6 plots the progression of macrotexture, measured with the Sand Patch Test, for both straight and curve sections. The parameter $\Delta$HS is estimated as the percentage difference between the measured value at each step of monitoring and the initial values (immediately after the pavements were laid), for all mixes.
As it is possible to see there is an early life decrease (after 6 months) that may be explained by smearing or migration of the binder together with a post-compaction action due to traffic loads that have the effect of reducing texture depth. This initial decrease is followed by a small but significant increase (after 13 months) corresponding to the phase in which the migrated bitumen was removed by trafficking, with the exception of M3 mix for which this phase is shifted forward in time probably due to the higher binder content of the mix [42]. The latest monitoring step (18 months after the pavements were laid) is characterized by an increase in texture depth for M1, M2 and M3 mixes that can be explained by a further migrated binder removing phenomenon; for M0 mix texture depth remains quite constant.

Texture data carried out by means of a Laser Profilometer were also analyzed in order to calculate macrotexture aggregate indicators. The Mean Profile Depth (MPD_{iso}) was determined by means of a profilometric analysis according to the ISO 13473-1. MPD_{iso} values are compared with HS values obtained with the Sand Patch Test. The results are plotted in Figure 7 and exhibit linear relationships quite similar to that reported in the ISO 13473-1 for both the straight and the curve sections. Data are referred to all mixes and to the 4 monitoring steps. The coefficient of determination (R^2) is lower than 0.5 in both cases probably because of the small range of variation of macrotexture values.

**5. Conclusions**

The assessment of pavement surface performance evolution plays a key role in road pavement management and maintenance operations. Based on the abovementioned facts, this study focused on the analysis of the most
important factors that affect texture deterioration such as aggregate and binder properties, road geometry and traffic. Several microtexture and macrotexture prediction models were also listed. Surface performance data were carried out from a two-year monitoring of an experimental road section where four different dense graded friction courses, produced with aggregate of different petrographic nature, were laid. Traditional tests to measure in-situ micro and macrotexture were carried out; overall 4 monitoring campaigns were done. It is noted that this project was run in partnership with the Road Network Division of Provincial Administration of Cosenza (Italy).

Microtexture results show some differences in the deterioration behavior of the 4 mixes, probably related to the petrographic nature of aggregate and to the binder type, confirming how the combination of aggregate and bitumen has a significant effect on skid resistance, especially during pavement early life. In particular, aggregates with lower PSV values (limestone) have a lower resistance to the stripping phenomenon, becoming immediately more exposed to traffic actions. In the case of mixes with aggregates characterized by higher values of PSV, few months after the surface laying (around 6 months), the binder coatings are smoothed but not removed from the aggregate, determining a lower early life skid resistance. Macrotexture evolution was also investigated; the data analysis shows that the general trend in terms of texture depth is an early life decrease followed by increase and then either gradual decrease or increase, depending on the mix type. The initial decrease is due to the migration phenomenon of the bitumen inside the voids of the mix; after some months (around 6) the migrated bitumen is removed by trafficking and the texture depth begins to increase again. This trend is different for M3 friction course, probably because this mix is characterized by a higher percentage of binder content that contributes to clog the voids for a longer time. In this case, texture depth begins to increase around 13 months after the pavement was laid.

The relationship between macrotexture data measured by means of two different devices (Sand Patch Test and Laser Profilometer) was also investigated. A further analysis of the surface profile data will be carried out in order to determine also texture disaggregate indicators.

Future research will concern a better understanding of the investigated evolution trends based on other experimental measurements, with the final aim of predicting surface performance progression through a mathematical model.

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