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Macrotexture modelling and experimental validation for pavement surface treatments

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Abstract. Surface treatments (chip seals, single or double binder application, cape seals, slurry seals, microsurfacing, fog seals, reinforced seals) are widely used in flexible pavements maintenance and rehabilitation because of the reduced costs and the easiness of application. This paper focuses on the evaluation of surface texture of pavement surface treatments. A model was formalised and validated. It allows predicting as-built macrotexture, based on a few input factors (aggregate application rate, emulsion application rate, aggregate gradation). In the pursuit of model validation, an experimental investigation was designed and carried out. Outcomes of this theoretical and experimental study can benefit both practitioners and researchers.

Keywords

Road pavement; surface treatments; model; surface performance; macrotexture; aggregate.

1 Objectives and paper organization

Despite the fact that road safety is an essential performance, the relationship between mixture design and surface properties is still insufficiently known and there is the need for more studies [1, 2]. This paper investigates the surface performance of surface treatments produced with a single surface dressing. In more detail, the main purpose of the study is to analyse the relationship between macrotexture and mix design for surface treatments, where mix design mainly refers to aggregate gradation and asphalt binder quantity. A macrotexture prediction model, based on mix design-related factors, was set up and validated.

To reach this aim (see Figure 1): (A) a detailed analysis of the literature was carried out: (B) a model was then formalized, calibrated and optimized; (C) an experimental plan was designed and carried out in the pursuit of obtaining new observations (data) of the dependent and independent variables; (D) model input-output transformations (input data versus macrotexture prediction) were compared to corresponding input-output transformations for the data derived through the new experiments.

Finally, conclusions were drawn.

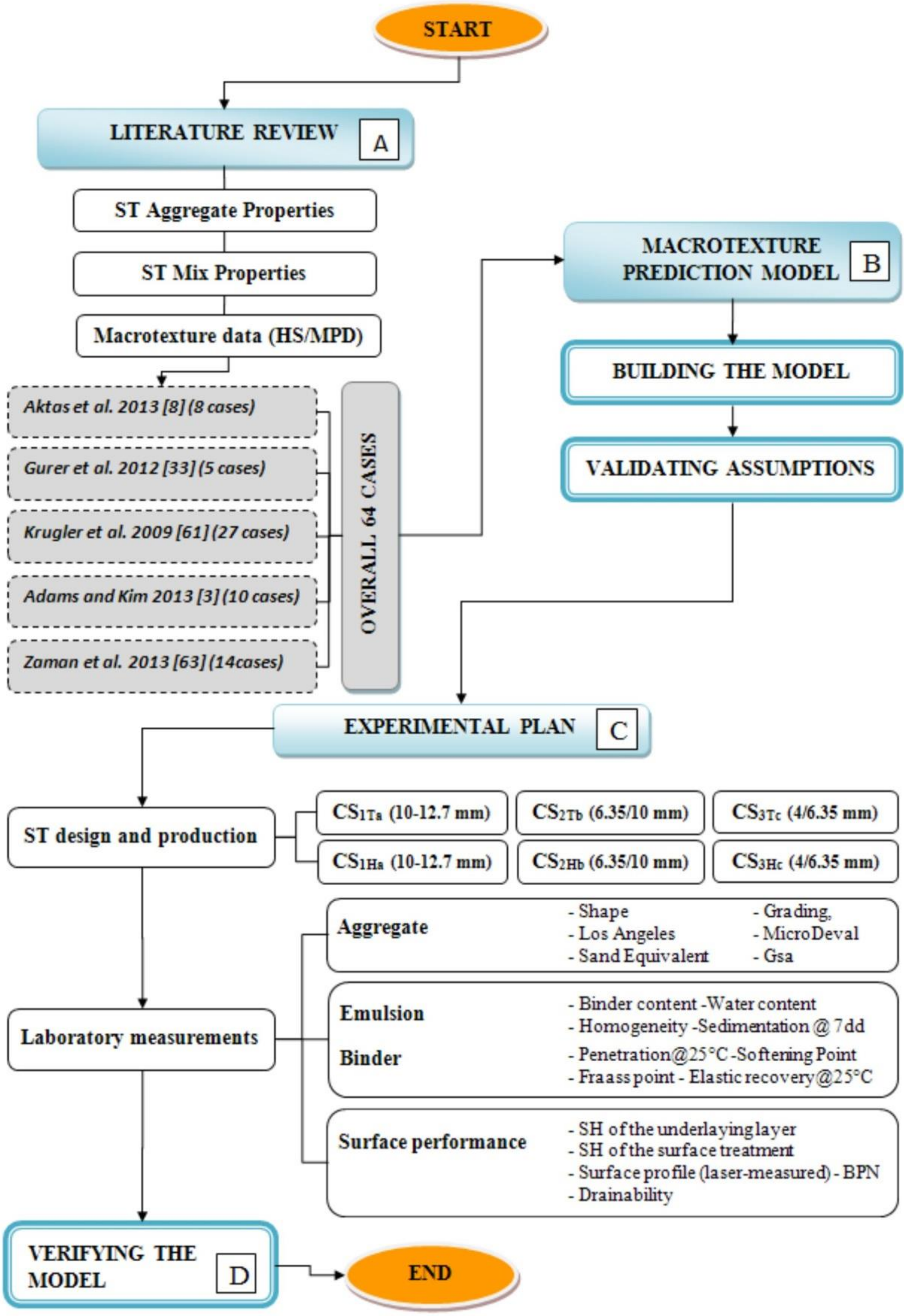


Figure 1. Graphical abstract.
Legend: ST=Surface Treatments; CS=chip seal; SH=Sand Height; BPN=British Pendulum Number; Ti=target bitumen content; Hi= ½ Ti (i=a,b,c)

2 Introduction

Bituminous surface treatments (seal coats, chip seals, etc.) are pavement wearing courses generally made of two major components: asphalt binders and natural mineral chips.

The most common solutions for asphalt surface treatments are binder-aggregate seal coating systems (chip seal single or double binder application, cape seal, slurry seal and microsurfacing), asphalt seals (e.g., fog seal), reinforced seals (fiber or geotextile reinforced). These surface treatments are often constructed by spraying the asphalt emulsion onto the existing asphalt pavement or on the basecourse and then dropping the chips into the asphalt emulsion. Afterwards, the surface is rolled to seat the chips for gaining a stronger bond between the aggregate and the binder [3,4]. Multiple layers may be placed and various aggregate and binder types (emulsions, rubber binders) can be used to address specific distress modes or traffic situations [5]. Note that for most of these treatments the following can be stated:

a) They are effective in preventing surface material oxidization, inhibiting raveling, and correcting surface defects. Furthermore, they are often used as a wearing course on low volume roads [6] and they mainly affect skid resistance [7, 8, 9];

b) Construction sequences, number of courses sealed, variation in aggregate nominal size [10], and binder type (asphalt emulsions, cutback, or polymer modified binders) van vary;

c) Fiber-reinforced or geotextile-reinforced solutions are possible [9];

d) Smaller stone chip seals are generally used on residential or other lower traffic volume streets [6, 9, 11-15], while larger chips have been used successfully on roads with heavy truck traffic;

e) The thickness of the constructed chip seal layer is equal to the maximum size of the chips used [16];

f) Typical aggregate spread ranges from 100 to 105% coverage (overlapping aggregates) [16, 17];

g) There is a limit to the stress that this surface dressing can withstand [18];

h) Binder rise should be a minimum of about 35–40% of the height of the aggregate particle after initial rolling and trafficking, increasing to between 50–65% about two years after construction [19];

i) In some locations, sand seals are used when good sources of aggregates for chip seals are not available or too costly [20-27];

i) Variations of macrotexture and surface performance over time, bleeding/flushing, construction-related and traffic-related impacts are common issues [28-38];

k) Asphalt type and film thickness are key factors in mix design for ensuring asphalt mix durability and performance, against stripping, cohesion loss, and premature aging [38-40];

l) As regards seal surface treatments, the phenomenon of bitumen hardening can also occur [41-48];

m) Overall [49-58], the higher the specific surface area of aggregates the lower the asphalt thickness. Furthermore, different methods can be used to derive asphalt film thickness (AFT) and different results can be obtained. Note that the concept of AFT can apply also to surface treatments where the asphalt binder is applied after aggregates. Finally, it may be observed that the main difference among the different methods relies in the relationship between the thickness (T) and the diameter of the grains (D). All the methods state that T is proportional to D but some of them are based on a linear proportionality whereas the French method is based on a power law with an exponent lower than the unity. Additionally, a minimum asphalt film thickness around 6-10 microns is often considered. Note that as for the aggregate embedment depth, different authors suggested values around 30-70% of the nominal maximum aggregate size, being 30% a condition more prone to ravelling and 70% more susceptible of bleeding issues [3, 4, 7, 11, 29, 59-65];

n) As for the shape of aggregate particles, note that it affects the interlocking quality of particles, the stability of the seal, ravelling [11], wearing properties and friction [63-68], mix workability [69]. Upper specification limits for flakiness index (generally FI<25-30%; FI<20% for chip seal on high volume roads) are suggested in the literature [18, 70-73];

o) As for the emulsion rate and bitumen rate, note that a proper mix design characterized by an appropriate balance between the aggregate application rate (AAR) and emulsion application rate (EAR) [3, 4, 74, 75]. A minimum application rate (in L/m2) of 0.1·ALD is often desirable [13], while the design objective is for the residual binder to be about 50% to 65% of the height of the aggregate layer two years after construction [19]. Note that ALD is the average least dimension (in some models about 57% of the average dimension). Reference values for binder application rates in relation to chip seal types are summarized in Alderson [19].

p) Finally note that in the Mechanistic Empirical Pavement Design Guide (MEPDG) chip seal solutions are recommended for improving pavement durability when raveling or shoving phenomena occur [76] and that Guidelines for the Preservation of High-Traffic-Volume Roadways (the second Strategic Highway Research Program, SHRP2, [77]) provide direction to agencies on the selection and use of preservation treatments for high-traffic-volume roadways. Slurry seal usage is limited (<33%) for both ADT>5.000 vpd and ADT>10.000 vpd; chip seals and micro-surfacing use for the same traffic values is moderate (33% to 66% usage). However, whereas a performance-based binder specification (Superpave or performance-graded PG) exists for hot-mix asphalt concrete binders, there is no information about surface treatment binders [78].

Note that in the study conducted by Epps et al. [79] a performance-based specification system for surface treatment binders was developed in order to address some of the deficiencies of the traditional specifications and the inadequacies associated with material selection based on experience. The validity and applicability of the proposed SPG specification were investigated also by Walubita et al. [80].

q) As for costs and durability of surface treatments, note that their cost ranges from 0.2 to 3.5 $/sq.m, while the expected life of the treatment ranges from 1 to 10 years [23-25, 75, 77, 81]. Lower values correspond to fog seals, while higher values correspond to chip seals. Furthermore note that slurry seals tend to cost slightly more initially than chip seal [20-26] and in general, fiber reinforced seals are not as effective as geotextile seals, but they are less costly [9, 15, 27].

3 Model and experimental validation

The methodology for building and validating the model is below summarized (in Figure 1 the overall graphical abstract is depicted).

The following main tasks were set out and carried out (see Figure 1):

1) Model building (section 3.1, task B in Figure 1);
2) Model evaluation and training (section 3.2, task B in Figure 1). In task B, data set included data from different sources (as *per* Figure 1), and the size of the training set was 64.
3) Experiments and verification (section 3.3, tasks C and D in Figure 1). In task D (verification) data gathered in task C (experiments) were used. The size of the verification set (sometimes called validation or test set) was 36.

Note that: training and verification were carried out through the use of the equations below introduced and the block diagram in Figure 5 illustrates the procedure which was applied as well equations and variables.

3.1 Model building

Advanced model

Equations are below set up by referring to a variable-shape packing (see Figure 2).

The model here presented can be summarised into three main equations (1-3).

Aggregate particles were modeled as a rotationally symmetric ellipsoids having a polar axis (radius c) shorter than the diameter of the equatorial circle whose plane bisects it (radius a). Such ellipsoids are called oblate spheroids and are contracted along a line (in contrast prolate spheroids are elongated and were considered of negligible interest due to gravity action).

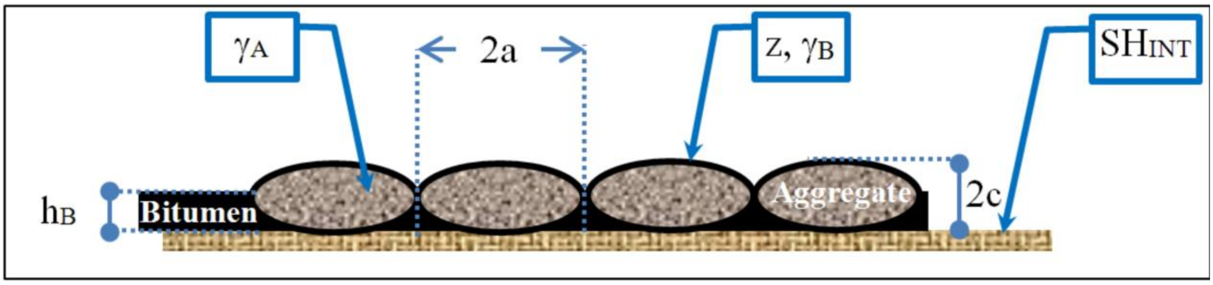


Figure 2. Basics of the model.

Legend. h_B: asphalt film thickness; γ_A: average specific gravity of the single aggregate particle ; z: asphalt film thickness; γ_B: bitumen density ; 2a: equatorial diameter; 2c: polar diameter; SH_{INT}: macrotexture of the underneath layer(sand patch method).

As is well known, aggregate particles are laid upon an underneath layer (of given macrotexture, SH_{INT}, cm, estimated in terms of sand patch method, according to EN 13036-1 [82, 83]). Given the application of a given quantity of emulsified asphalt, a consequent height of bitumen (h_B, cm) and macrotexture are derived.

The first equation refers to the bitumen volume V_B (cm^3), derived from emulsion application rate: the quantity of bitumen spread on the aggregate (member on the left side of equation 1) is used: i) to fill the voids among the aggregate particles (first two expressions of the member on the right side of expression); ii) to have a given asphalt film thickness (z) over the bitumen height (third term, member on the right side of expression); iii) to fill the macrotexture of the underneath layer (SH_{INT}, last term).

In particular, Q_B refers to bitumen application rate (g/cm^2) while γ_B is bitumen density (g/cm^3) and z (cm) is the bituminous film thickness in the upper part of grains (if existing).

The equation which was set up is below reported (1):

$$
\begin{aligned}
VB &= \frac{Q_B}{\gamma_B}\cdot a^2\cdot 4\alpha = a^2\cdot 4\alpha\cdot h_B - \frac{\pi\cdot c^2\cdot {h_B}^2}{3a^2}\cdot(3c-h_B)+\\
&+\frac{\operatorname{sign}\left(\frac{h_B}{2\cdot c}-0.5\right)\cdot\left[\left(\frac{h_B}{2\cdot c}-0.5\right)\cdot 2\right]^2+1}{2}\cdot 2\cdot\pi\cdot a^2\cdot\beta\cdot z\cdot\left[1+\left(\frac{1-\left(1-\frac{c^2}{a^2}\right)}{\sqrt{1-\frac{c^2}{a^2}}}\right)\cdot \operatorname{arctanh}\sqrt{1-\frac{c^2}{a^2}}\right]+\\
&+a^2\cdot 4\cdot\alpha\cdot SH_{INT}
\end{aligned}
\qquad (1)
$$

The second equation refers to aggregate application rate (AAR, g/cm^2). Note that: i) VA refers to the (osculatory) volume of the single aggregate particle; γ_A (g/cm^3) refers to the average specific gravity of the single aggregate particle and it is different from G_{mb}, because γ_A derives from the same weight compared to a higher (osculatory) volume.

A_{SH} (cm^2) is the surface of the elementary area. The overall area derives from the replication of many elementary areas.

It follows (equation 2):

$$
AAR = \frac{V_A\cdot\gamma_A}{A_{SH}} = \pi\frac{c\ \cdot\gamma_A\cdot\beta}{3\cdot\alpha} \qquad (2)
$$

α is defined in the range ($3^{0.5}$/4, 1), while β is defined in the range (0.5, 1).

The third equation involves the “sand” volume (V_{SH}) and the consequent sand height (SH, as *per* EN 13036-1). This latter is usually the unknown variable.
As for the calculation of the sand patch value (SH), the following equation (3) can be derived:

$$
\begin{aligned}
SH = {} & 2 \cdot c - \pi \frac{\beta \cdot c}{3\alpha} - h_B - \frac{\pi \cdot c^2 \cdot {h_B}^2}{12 a^4 \cdot \alpha} \cdot (3c - h_B) + \\
& - \frac{\operatorname{sign}\left(\frac{h_B}{2 \cdot c} - 0.5\right) \cdot \left[\left(\frac{h_B}{2 \cdot c} - 0.5\right) \cdot 2\right]^2 + 1}{4 \cdot \alpha} \cdot \pi \cdot \beta \cdot z \cdot \left[1 + \left(\frac{1 - \left(1 - \frac{c^2}{a^2}\right)}{\sqrt{1 - \frac{c^2}{a^2}}} \right) \cdot \operatorname{arc\,tanh} \sqrt{1 - \frac{c^2}{a^2}} \right] + \\
& - SH_{INT}
\end{aligned}
\tag{3}
$$

<u>Simplified model</u>

A simplified model was set up (see equations 4-6) by modelling aggregate particles as quasi-spherical grains of given radius (*r*, cm).
In this case, the first equation that refers to bitumen volume, V_B (cm^3) can be derived as follows (4):

$$
\begin{aligned}
VB = {} & \frac{Q_B}{\gamma_B} \cdot r^2 \cdot 4\alpha = r^2 \cdot 4\alpha \cdot h_B - \pi \frac{h_B \cdot \beta}{3} \cdot \left(3 \cdot h_B \cdot r - {h_B}^2\right) + \\
& + 2\pi \cdot \beta \cdot r \cdot (2r - h_B) \cdot z + r^2 \cdot 4 \cdot \alpha \cdot SH_{INT}
\end{aligned}
\tag{4}
$$

Also in this case the quantity of bitumen spread on the aggregate is used to fill the voids among the aggregate particles, to have a given asphalt film thickness over the bitumen height (depending on treatment type) and to fill the macrotexture of the underneath layer
The second equation for the AAR calculation becomes (equation 5):

$$
AAR = \frac{V_A \cdot \gamma_A}{A_{SH}} = \pi \frac{r \ \ \cdot \gamma_A \cdot \beta}{3 \cdot \alpha}
\tag{5}
$$

As for the equation 5, note that A_{SH} is the surface of the elementary area and that the overall area derives from the replication of many elementary areas.
The third equation for the Sand Height calculation can be derived as follows (6):

$$
\begin{aligned}
SH = {} & \frac{V_{SH}}{A_{SH}} = \\
= {} & \frac{8r^3 \cdot \alpha - \pi \frac{4\beta r^3}{3} - 4r^2 \cdot \alpha \cdot h_B + \pi \frac{h_B \cdot \beta}{3} \cdot \left(3 \cdot h_B \cdot r - {h_B}^2\right) - 2\beta \cdot \pi \cdot r \cdot (2r - h_B) \cdot z - r^2 \cdot 4 \cdot \alpha \cdot SH_{INT}}{r^2 \cdot 4 \cdot \alpha}
\end{aligned}
\tag{6}
$$

Note that in analysing and solving the three equations in both cases (quasi spherical grains/rotationally symmetric ellipsoids), the following sets of parameters can be listed:

- Main inputs: AAR aggregate application rate; EAR: emulsion application rate or QB bitumen application rate; Aggregate gradation, r.
- Minor inputs: z, film thickness in the upper part of grains; SH_{INT}: sand height of the underneath surface;
- Major outputs: height of the bitumen (embedment depth, hB) and sand height.

3.2 Model evaluation and training

As mentioned, the above model relies also on several parameters (mainly related to sphere packing). In order to check whether the model fits experimental measurements or other empirical data, these latter were split into two disjoint subsets: training data (see Figure 1) and verification data (see the section Experiments and verification). The training data were used to estimate the model parameters and to test for model reasonableness. The verification data even were derived from an experimental plan, ad hoc designed and carried out. The verification data were used: a) to assess model accurateness (cross-validation and extrapolation); b) to investigate the relationship between other relevant technological issues (surface properties). As for the metric to measure the distances between observed and predicted data (especially in model training), a loss function was chosen (linear least squares). The following procedure was used during calibration:

- Input a given height of bitumen (cm) over the interface. Other minor inputs: sand height of the underneath layer, α and β coefficients (dimensionless, sphere packing).
- derive the volume of bitumen, by using the first equation;
- derive the consequent error (in the estimate of the volume of bitumen);
- derive the AAR (aggregates, g/cm2), through the second equation;
- derive the consequent error (in the estimate of the AAR);
- derive the SH, through the third equation;
- derive the associated error (in the estimation of the SH);
- minimise the sum of errors, by changing the height of bitumen;
- from gradation, α and β, height of bitumen, asphalt binder thickness, SH_{int}, through the third equation the SH is derived.

Figure 3 summarizes the results obtained in terms of observed versus estimated values of bitumen quantity (cm). Note that observed values are well replicated by the model.

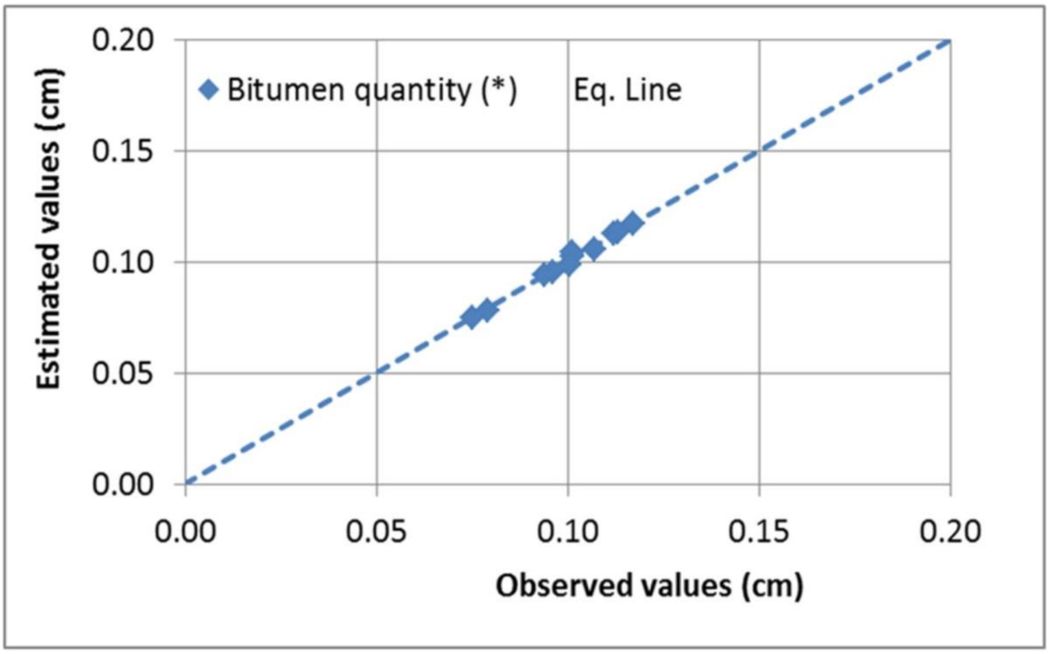


Figure 3. Observed (x-axis) versus estimated values of bitumen quantity (cm).
Note. Bitumen Quantity(*):Q_B/γ_B. γ_B= 1.03 g/cm^3; α=0.99; β=0.99; SH_{INT}= 0.010 cm. Simplified model.

3.3 Experiments and Verification

An experimental plan was designed and carried out in the pursuit of obtaining new observations (data) of the dependent and independent variables. Model input-output transformations (input data versus macrotexture prediction) were compared to corresponding input-output transformations for the data derived through the new experiments, herein carried out. In order to assess how aggregate dimension can affect chip seals surface performance, slabs with three different aggregate sizes (CS_1:10/12.7mm, CS_2: 6.35/10mm, CS_3:4/6.35mm) and three target emulsion application rates (T_a=0.18 g/cm^2; T_b=0.14 g/cm^2; T_c=0.15 g/cm^2, respectively) were designed and produced. Furthermore, with the aim of evaluating the effect of binder content on surface texture variation, slabs with the same aggregate gradations (10/12.7mm, 6.35/10mm, 4/6.35mm) and other three emulsion application rates (halved with respect to the target ones) were also designed and produced (H_a=0.09; H_b=0.07; H_c=0.075, respectively). The chip-sealed layer was placed on a support layer (a hot mix asphalt slab) with a thickness of about 5 cm. The support layer was also characterized in terms of dimensional bulk specific gravity of compacted samples (according to [84] and surface texture by means of the sand patch test [83].

The chip seal layer was constructed by spraying the binder emulsion on the support slab and then dropping the aggregates on the surface that was previously quartered in order to simulate the distribution process of the chip spreaders in the field. Before compaction, a 1 cm-thick rubber sheath, internally reinforced by a network of canvas, was laid on the surface in order to avoid the crushing of the aggregate, thus reproducing the function of a rubber-wheeled compactor that is generally used for surface treatments compaction on site.

Three slabs for each aggregate dimension were compacted using the Unical Slab Roller Compactor (USRC) that was constructed in the Laboratory of Road Material at the University of Calabria. It is a mechanical, self-propelled smooth steel roller with forward-reverse control, designed according to the UNI EN 12697-33 standard [84]. The binder used for the chip seal layer was a fast breaking emulsion of a SBS polymer modified binder, that is commonly used for surface treatments (both single and double layer). The emulsion was stored in the oven and then sprayed at a temperature of 69°C±2°C on the surface of the support slabs. Tables 1-7 summarise the main features of the experimental investigation and its results in terms of model verification. Table 1 and 2 summarize the main features of the bitumen emulsion and the residual binder.

Table 1. Main features of bitumen emulsion and residual asphalt binder

EMULSION PROPERTIES	VALUES	STANDARD VALUES	REFERENCES
Water content	31.0%	31 ± 2%	EN 1428 [83]
Binder content	69.0%	>68%	EN 1431 [86]
Homogeneity	0.08%	max 0.2%	EN 1429 [87]
Sedimentation @ 7dd	6%	max 10%	EN 12847 [88]
pH (acidity)	2.8	2 ÷ 6	EN 12850 [89]

Table 2. Main features of bitumen emulsion and residual asphalt binder

RESIDUAL BINDER PROPERTIES	VALUES	STANDARD VALUES	REFERENCES
Penetration@25°C, 100 g / 5”	60 dmm	50 ÷ 70 dmm	EN 1426 [90]
Softening Point (Ring & Ball)	80.0 °C	> 75°C	EN 1427 [91]
Fraass point	-21°C	≤ - 18°C	EN 12593 [92]
Elastic recovery@ 25°C	82%	> 75%	EN 13398 [93]

The values of EAR and AAR used for the production of the chip seal layers are listed in Table 3.

Table 3. Emulsion and aggregate application rates for chip seals

CHIP SEAL TYPE	EAR (g/cm^2)	AAR (kg/m^2)
CS_1 (10/12.7mm)	0.09-0.18	1.5
CS_2 (6.35/10mm)	0.07-0.14	1.25
CS_3 (4/6.35mm)	0.075-0.15	0.85

As for aggregate properties, limestone aggregate was used for chip seal layers; the main aggregate properties are listed in Table 4.

Table 4. Main aggregate properties

AGGREGATE PROPERTIES	VALUES	REFERENCES
Los Angeles Abrasion [%]	20.7	EN 1097-2 [94]
Aggregate Specific Gravity [g/cm^3]	2.87	EN 15326 [95]
Polished Stone Value	0.39	EN 1097-8 [96]
Sand Equivalent [%]	89	EN 933-8 [976]
Resistance to wear (Micro-Deval) [%]	6.9	EN 1097-1 [98]

In order to gather information on particles shape and spacing (which can affect chips embedment in the binder layer), aggregates were firstly characterized in terms of shape index, flakiness index and elongation index. These parameters were estimated as the mean values for a representative sample of 100 chips for each aggregate dimension class (Table 5).

Table 5. Shape factors for the three aggregate dimension classes

AGGREGATE PROPERTIES	CS_1	CS_2	CS_3	REFERENCES
Shape Index [%]	2	15	13	EN 933-4 [99]
Flakiness coefficient (D/S)*	1.39	1.55	1.41	CNR B.U.95/84 [100]
Elongation coefficient (L/D)*	1.50	1.51	1.62	CNR B.U.95/84 [100]

Notes. L: longest dimension; D: intermediated dimension; S: shortest dimension. The shape index is calculated as the ratio between the mass of non-cubical particles and the total mass of particles tested; note that non cubical particles are those where the thickness (S) is less than 1/3 of the length (L). Flakiness index (according to Italian Standard Specifications [101]) is defined as the ratio between the average aggregate size and the smallest size of aggregate (D/S).

Each aggregate dimension class was also characterized in terms of average least dimension (see Table 6).

Table 6. ALD calculation for each aggregate dimension class

	CS_1	CS_2	CS_3
AVERAGE LEAST DIMENSION [mm]	7.5	5.6	4.0

Note. ALD= 0.568×CS-0.142 [59]

A road bitumen type 50-70 was used. On average, its application rate was about 1kg/m^2 (see Tables 1-4). As for aggregates (see Tables 3-6), Los Angeles value (LA=21), polished stone value (PSV=39) complied with the corresponding lower/upper specification limits (LA: USL=30; PSV: LSL=31, see [4]). Average least dimension ranged from 4 to 7.5 mm and these values were used to control that the aggregate chips were not submerged in asphalt binder (compliance with aggregate spread rate and emulsion spray rate, see [4]).

In the experiments which were carried out, both aggregate and wavenumber-related descriptors were determined to survey slabs surface texture (ISO Standards 13473-1, [102-103]). A Laser Profilometer (see Figure 4) based on conoscopic holography was used and texture indicators were evaluated according to the standard ISO 13473-3 [104].

Figure 4. Sand height (left) and laser profilometer measurements (right)

Profiles were surveyed in terms of (x,z) coordinates, where z represents profile depths. Device characteristics are summarized in Table 7.

Table 7. Main profilometer characteristics

PROFILOMETER CHARACTERISTIC	VALUE
Mobility	Stationary, Slow
Texture wavelength range, Range covered BD class	0.20÷50mm
Pavement contact	Contactless devices
Principle of operation	Laser profilometer
Objective Focal Length	100mm
Max Vertical measuring range	35mm
Vertical resolution for class	0.003÷0.03 mm: 0.012mm
Stand-off distance:	90mm
Minimum horizontal resolution Δx (sampling interval) BD for class	0.05÷1 mm
Angle coverage	170°

A first evaluation of surface profiles surveyed in terms of (x,z) coordinates together with a qualitative analysis of images of slabs surfaces showed: i) a great variation in terms of surface profile amplitudes and wavelengths among the slabs produced by using aggregate of different dimensions; ii) that higher values of aggregate Average Least Dimension (ALD) corresponded to higher values of the maximum wavelength of surface profiles (see also: [105, 106]). Slabs surface macrotexture was also characterized in terms of Sand Height, SH (mm), according to the EN 13036-1 [83], as shown in Figure 4.

Table 8 summarizes the range of variability of sand height values and Mean Profile Depth (MPD) values for all slab produced.

Table 8. SH and MPD variation in relation to chip seal type

CHIP SEAL TYPE	EAR (g/cm^2)	SH (mm)	MPD(mm)
CS_{1H} - CS_{1T}	0.09-0.18	5.3-4.7	3.4-3.1
CS_{2H} - CS_{2T}	0.07-0.14	4.5-4.0	3.0-2.8
CS_{3H} - CS_{3T}	0.075-0.15	2.7-2.3	2.2-2.0

Legend. EAR: Emulsion application rate; CS_{1H}: Chip seal type CS_1 (10/12.7mm) with the lowest EAR. CS_{1T}: Chip seal type CS_1 (10/12.7mm) with the highest EAR. SH: sand height (EN 13036-1); MPD: mean profile depth.

As for model verification, Figure 5 summarizes the verification process.

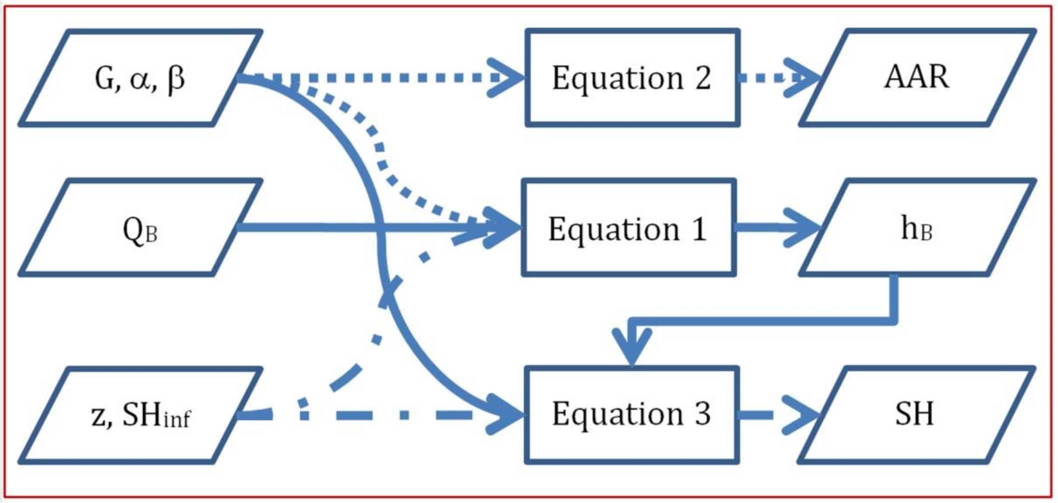


Figure 5. Use of the closed-form equations to design a bituminous surface treatment based on surface properties

Finally, Figures 6 and 7 summarize model verification. Note that the mixes produced in the laboratory were used. In more detail, Figure 7 illustrates that data well fit the statistical model, which is very important from a safety standpoint due to the fact that SH greatly affects roads safety. In summarising, as abovementioned, given the above inputs (e.g., AAR, EAR): i) the method provides h_B and SH; ii) these latter parameters are checked by pavement designer for functional and safety purposes. To this end it is noted that according to layer specifications, a minimum value of SH must be in place (the lower specification limit ranges from 0.4 to 0.8mm, based on layer type, road importance and traffic level).

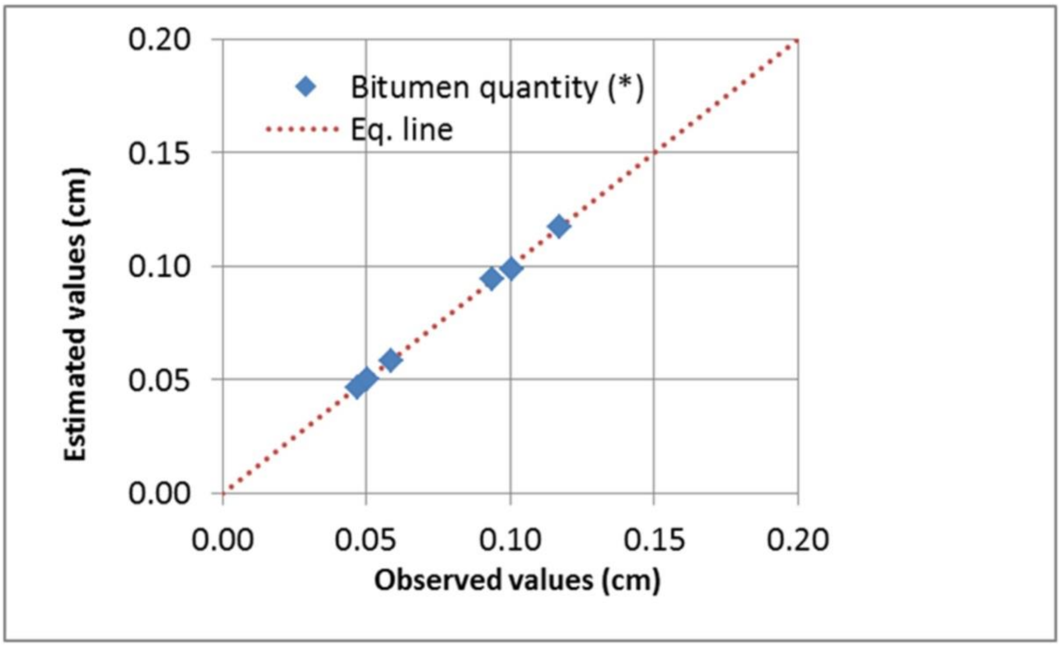


Figure 6. Asphalt binder height (observed vs. estimated values)-model mixes produced in the lab

Note. Bitumen quantity(*): Q_B/γ_B

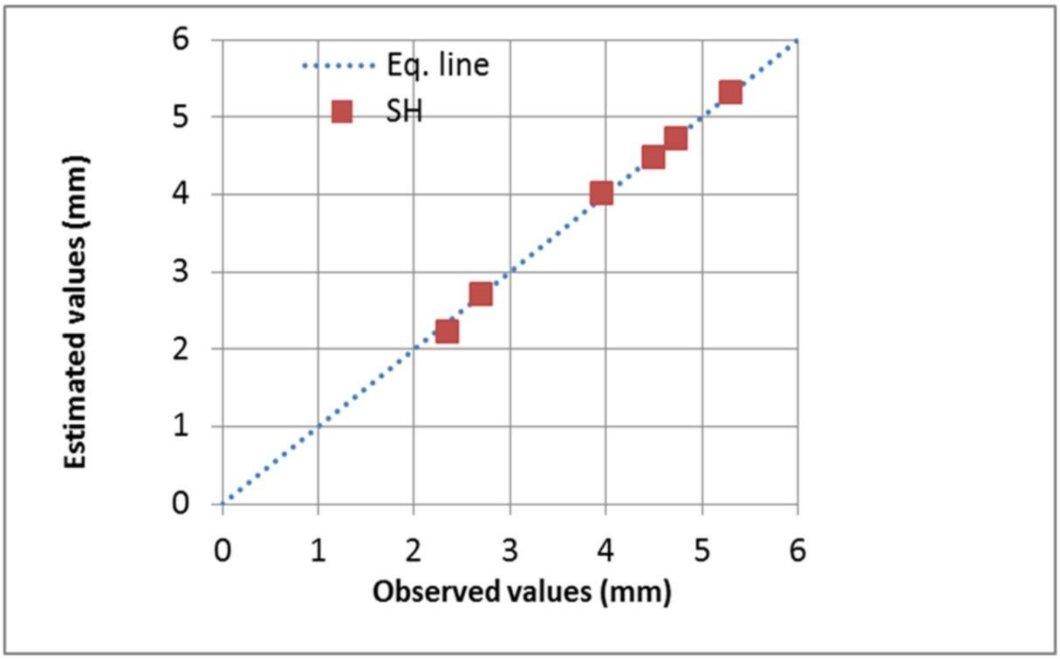


Figure 7. Sand height (observed vs. estimated values)-model mixes produced in the lab

4. Conclusions

As is well known, surface texture of wearing courses and treatments affects overall performance over time, overall costs and safety of a transportation infrastructure.

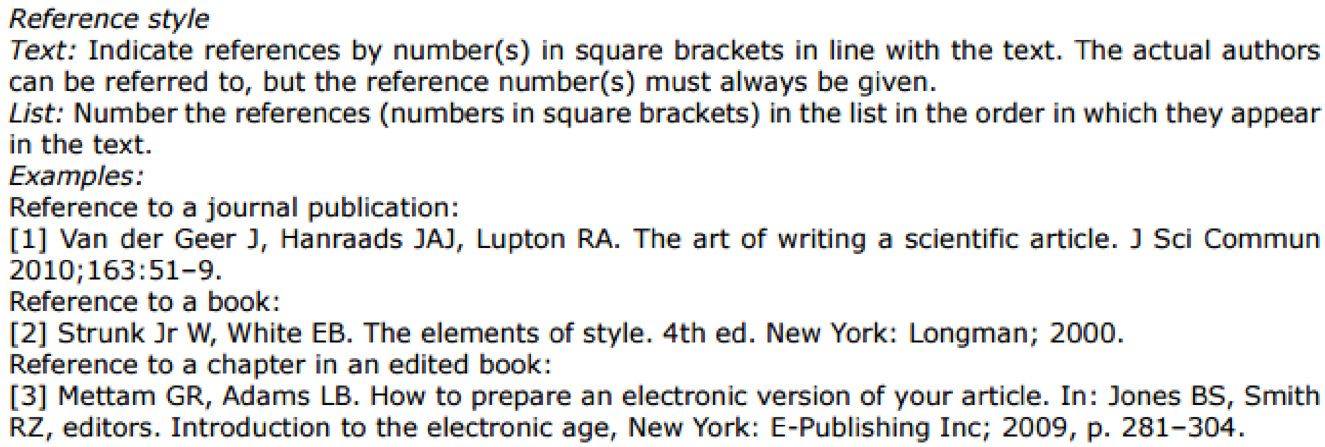
Despite the fact that road safety is a vital performance, the relationship between mixture design and surface properties is still mainly unknown and there is the need for either empirical or fundamental predictive models.

Consequently, a macrotexture prediction model, based on mix design-related factors, was set up and validated.

The model provides a system of three equations in which, given several main technological inputs (e.g., aggregate application rate; emulsion application rate, aggregate gradation), the macrotexture can be predicted (SH value).

Importantly, supplementary factors, such as asphalt film thickness (upper part of grains), and the macrotexture of the underneath surface are considered in the model.

The system of three equations can be easily solved and outcomes can benefit both practitioners and researchers. Future research will address the dependence of supplementary factors (shape factors) as well as the variation of the macrotexture over time, depending on aggregate distribution, spatial location and mineralogical properties.



Reference style

Text: Indicate references by number(s) in square brackets in line with the text. The actual authors can be referred to, but the reference number(s) must always be given.

List: Number the references (numbers in square brackets) in the list in the order in which they appear in the text.

Examples:

Reference to a journal publication:

[1] Van der Geer J, Hanraads JAJ, Lupton RA. The art of writing a scientific article. J Sci Commun 2010;163:51–9.

Reference to a book:

[2] Strunk Jr W, White EB. The elements of style. 4th ed. New York: Longman; 2000.

Reference to a chapter in an edited book:

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