Experimental evaluation of critical conditions for surface dressings

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Synopsis

The Authors present an original equipment, the Surface Dressing Simulator, designed and realized to reproduce, on small areas, the sequential spread of bituminous emulsion and chipping aggregates, typically required for surface dressing applications.

The prototype has all the characteristics of combined means used for cold treatments (tank, spraybar, chipping spreader) and it is able to simulate critical conditions in terms of longitudinal and transversal slope of the laying surface and, at the same time, to control the longitudinal speed and the materials amount.

The apparatus allowed to calibrate an hydraulic model of theoretical flow for bituminous emulsions on road surfaces with high slope, typical of local roads network, where often the surface dressings fail because an excessive flowing of binder takes place or the laying is not uniform.

The theoretical analysis and the experimental validation suggested practical recommendations in terms of longitudinal speed of tank and optimal setup of spraying nozzles (number, chink extent and height) in critical contexts, not unusual in practice.

Experimental evaluation of critical conditions for surface dressings

The prototype SDS (Surface Dressing Simulator) is a conceptually exact reproduction of modern combined equipments that are able to spread in sequence bituminous emulsion and chipping aggregates for realization of surface dressing applications.
The prototype design and realization have been carried out with the aim to analyze in laboratory the processes of bituminous emulsion flow and mineral chipping spreading. The purpose is to improve the design and quality control of road applications in critical contexts, characterized by high longitudinal and transversal slopes.
The analysis procedure and most significant results of the research, carried out in the Materials and Structures Laboratory of University of Parma, are synthetically explained in this paper. This study allows to comprehend the specificity of flow conditions of a bituminous emulsion that are present on surfaces subjected to dressing.

UNIFORMITY PROBLEMS OF EMULSION APPLICATION RATES

The several design criteria for surface dressing applications, essentially based on volumetric methods, require a careful quantification of binder content to assure the optimum locking of chipping aggregates. The amount of bituminous emulsion usually results from the need of filling the porosity of the surface that has to be roughened (absorption) and, at the same time, to appropriately embed the chipping aggregates for dressing (Canestrari, 2001).
These criteria, considering the limits due to take into account all the possible design variables (size, shape and texture of aggregates, type and setting mechanism of emulsion, temperatures, working conditions and design traffic, Asphalt Institute, 2000) finally suggest an emulsion and chipping aggregate amount, usually expressed in $L \cdot m^{-2}$.
The design recommendation is often difficult into the practical realization where working difficulties are present, especially due to plano-altimetrical configuration of the road, environmental and climatic conditions. Typical examples are associated to the manoeuvrability of emulsion distributor on roads with small radius of curvature and/or high longitudinal and transversal slopes. This fact is very frequent when surface dressing is applied on local roads network.
It is known that the adjustment of the spraybar height above the surface that has to be dressed affects the width of the uniform spraying area, considering the same specific discharge of bituminous emulsion supplied. This rule is based on the geometric study of emulsion jet print produced by nozzles with flat jets and known spraying angles (Figure 1).

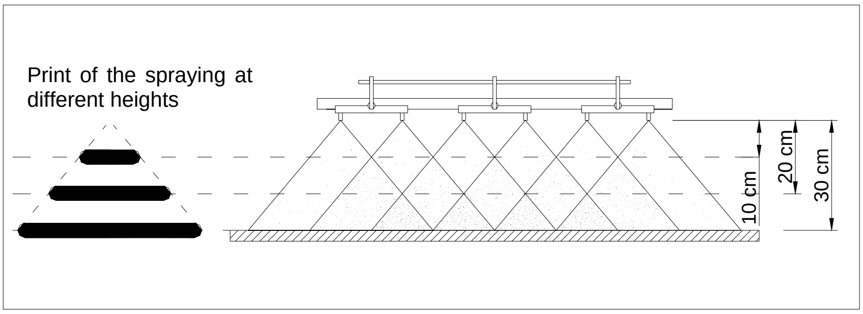

Figure 1: Width of uniform spraying at different spraybar heights.

Therefore, in case of applications on low transversal slope surfaces and considering the need of appropriate covering in correspondence of longitudinal joints, the only adjustment of spraybar height allows to control the transversal homogeneity of the spraying. The practical solution that assures the spraying uniformity is surface dressing applications on small radius curves is more complex, even if it is intuitive. In this case it needs to operate on the flow supplied by the spraybar, modifying the working of nozzles of the spraybar (their number and type). The Australian Asphalt Pavement Association suggests a binder amount on curves and an appropriate spraying width with small radius, in function of the planimetric road radius of curvature (AAPA, 2000, Table 1).

Table 1: Indicative binder application rates on curves.

Radius or curves (centre of sprayer) m	Spray width m	Variation in application rate		Examples of binder application rate variation ($L \cdot m^{-2}$)		
		Outside curve	Inside curve	Design	Outside curve	Inside curve
7,5	2	-13	+18	1,5	1,31	1,77
7,5	4	-26	+36	1,5	1,11	2,05
15	2	-6,7	+7,1	1,5	1,40	1,61
15	4	-13	+15	1,5	1,31	1,73
15	8	-26	+36	1,5	1,11	2,05
30	4	-6,7	+7,1	1,5	1,40	1,61
30	8	-13	+15	1,5	1,31	1,73
60	4	-3,3	+3,4	1,5	1,45	1,55
60	8	-6,7	+7,1	1,5	1,40	1,61
120	4	-1,7	+1,7	1,5	1,48	1,52
120	8	-3,3	+3,3	1,5	1,45	1,55

The uniformity of emulsion application, also stated in the recently issued CEN regulation (EN 12272, "*Test methods: rate of spread and accuracy of spread of binder and chippings*") and in Italian reference regulations (CIRS, 2001), is complicated also on roads characterized by high longitudinal slope, where the manoeuvre difficulty of operator is matched with the difficulty to check the flowing phenomena of bituminous emulsion on the inclined plane. These flowing phenomena modify locally the design amount and moreover produce dangerous phenomena of bleeding or fratting-up, that is the total embedment of dressing chipping. Just to be able to study this last aspect, at the Materials and Structures Laboratory of University of Parma, an original prototype (that allows to simulate the most critical working conditions) has been designed and realized.

THE SURFACE DRESSING SIMULATOR (SDS)

The surface dressing simulator reproduces, in reduced scale, a combined machine for realization of surface dressing applications on road pavements. The prototype is formed by a rigid frame that allows by means of a rack the advancing of the machine constituted by a spraybar fed by a tank with bituminous emulsion and by an Archimedean screw chipping spreader (Figure 2).

The auto-braking engine and the complete mechanical and electronic equipment guarantees a safe use. The machine operates on a rectangular area of 250 x 115 cm^2 and it is able to cover a useful surface of 180 x 100 cm^2. Both the external frame and the spraybar can be differently oriented, operating on their respective adjustment systems of height and longitudinal and transversal slope, completely independent.

Several working configurations are possible for the variation of emulsion application amounts (supplied flow, orientation and nozzles number), spraybar height and slope, aggregate size, advancing speed of the machine.

The bituminous emulsion tank capacity is 50 litres, it has a filter and a warming system for setting the optimum spraying temperature.

An hydraulic circuit allows to clean the equipment and the spraybar has a manometer for controlling the supplied pressure.

CALCULATION OF THEORETICAL ADVANCING SPEED OF SPRAYBAR

The road surface with area A subjected to surface dressing application is schematized as a lane long *l* (advancing direction of spraybar) and wide *b*. The plane is inclined as regards to the horizontal of longitudinal slope $i_L = tan\theta \approx sen\theta$ and of transversal slope $i_T = tan\alpha = 0$ (Figure 3).

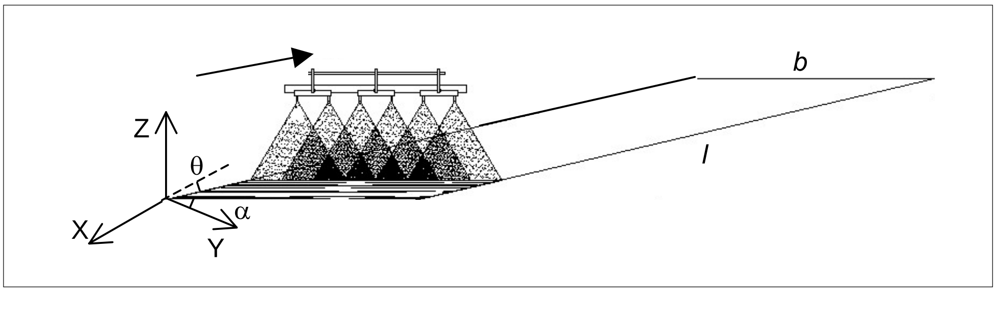

Figure 3: Prototype working system and hydraulic model geometry.

Figure 2: Surface dressing simulator.

A – Complete view.

B – Spraybar.

C – Chipping spreader system on rack.

D – Warmed tank and adjustment systems.

The film thickness δ_{tot} of bituminous emulsion uniformly sprayed by the bar can be considered the sum of δ', equal to the effective useful thickness for aggregate locking and δ_{ass} that is related to the quantity absorbed by the support (micro-cracks and surface porosity). Therefore $\delta_{tot} = \delta' + \delta_{ass}$.

The condition to avoid that the flowing of bituminous emulsion (with specific gravity γ) takes place on the surface subjected to dressing is that the tangential tension is $\tau_c \geq \gamma \cdot \delta' \cdot i$, therefore the maximum thickness of bituminous emulsion film beyond that the flowing phenomenon takes place is:

$$\delta_{\max} = \frac{\tau_c}{\gamma \cdot sen\theta} \quad (1)$$

Supposed $V_{tot} = A \cdot \delta_{tot}$, the volume of the emulsion sprayed by the spraybar, it is possible to write $V_{tot} = V_{ass} + V_{\max} = A \cdot (\delta_{ass} + \delta_{\max})$. Considering the variation during time of applied emulsion thickness, it is possible to write, according to the definition of discharge:

$$\frac{d\delta(t)}{dt} = \frac{d}{dt}\left(\frac{V_{\max}}{A}\right) = \frac{1}{A} \cdot \frac{d}{dt}\left(V_{tot} - V_{ass}\right) = \frac{1}{A} \cdot \left(Q_{tot} - Q_{ass}\right) \quad (2)$$

Integrating equation (2) between the time t_0 and the generic time t, it is obtained:

$$\int_{t_0}^{t} d(\delta(t)) = \int_{t_0}^{t} \frac{1}{A} \cdot \left(Q_{tot} - Q_{ass}\right) dt = \int_{t_0}^{t} \frac{Q_{tot}}{A} dt - \int_{t_0}^{t} \frac{Q_{ass}}{A} dt \quad (3)$$

The first integral decreases during time because when the sprayed quantity increases the superficial pores of the pavement become saturated and the volume of absorbed liquid decreases, until it becomes zero at the generic time t, defined as saturation time t_{sat}.

Supposed $t_0 = 0$ and $t = t_{\lim}$ equation (3) can be written as:

$$\delta(t_{\lim}) - \delta(t_0) = \int_{0}^{t_{\lim}} \frac{Q_{tot}}{A} dt - \int_{0}^{t_{\lim}} \frac{Q_{ass}}{A} dt \quad (4)$$

Q_{tot} represents the sprayed quantity of liquid and, for hypothesis, this value is constant in the time period considered, moreover the values of liquid thickness at time $t_{\lim}$ and t_0 are respectively $\delta_{\max}$ and 0.

Finally the following equation is obtained:

$$\delta_{\max} = \frac{Q_{tot}}{A} \cdot t_{\lim} - \int_{0}^{t_{\lim}} \frac{Q_{ass}}{A} dt \quad (5)$$

Combining equations (1) and (5) and taking into account that $t_{\lim} > t_{sat}$ and at the generic time $t > t_{sat}$ the value of discharge Q_{ass} is zero, it is possible to write:

$$\frac{\tau_c}{\gamma \cdot sen\theta} = \frac{Q_{tot}}{A} \cdot t_{\lim} - \int_{0}^{t_{\lim}} \frac{Q_{ass}}{A} dt \; = \; = \frac{Q_{tot}}{A} \cdot t_{\lim} - \int_{0}^{t_{sat}} \frac{Q_{ass}}{A} dt \quad (6)$$

The discharge Q_{ass} can be defined as the derivative with respect to time of the voids volume (V_{voids}) constituted by micro-cracks and permeable pores that the bituminous emulsion fills during spraying.

The voids volume can be written as the ideal total volume (V) of the layer to be dressed, multiplied by the surface porosity (*e*), obtaining:

$$Q_{ass} = \frac{dV_{voids}}{dt} = \frac{d(e(t) \cdot V)}{dt} = V \cdot \frac{d(e(t))}{dt} \quad (7)$$

From equation (7):

$$\int_{t_0}^{t} d(e(t)) = \int_{t_0}^{t} \frac{Q_{ass}}{V} dt \quad (8)$$

$$e(t) - e(t_0) = \frac{Q_{ass}}{V} \cdot t \quad (9)$$

Supposed $t = t_{sat}$ and $t_0 = 0$, remembering that $e(t_{sat}) = 0$, it results:

$$-e(0) = \frac{Q_{ass}}{V} \cdot t_{sat} \quad (10)$$

Deriving equation (10) with respect to time, it is obtained:

$$-\frac{d(e(t))}{dt}=\frac{Q_{ass}}{V} \quad (11)$$

in other words, multiplying both members by V/A:

$$-\frac{V}{A}\cdot\frac{d(e(t))}{dt}=\frac{Q_{ass}}{A} \quad (12)$$

inserting equation (12) in equation (6) it is obtained:

$$\frac{\tau_c}{\gamma\cdot sen\theta}=\frac{Q_{tot}}{A}\cdot t_{\lim}-\int_0^{t_{sat}}\left(-\frac{V}{A}d(e(t))\right)=\frac{Q_{tot}}{A}\cdot t_{\lim}+\frac{V}{A}\cdot(e(t_{sat})-e(0))=\frac{Q_{tot}}{A}\cdot t_{\lim}-\frac{V}{A}\cdot e(0) \quad (13)$$

Deducing $t_{\lim}$ it is obtained:

$$t_{\lim}=\frac{A}{Q_{tot}}\cdot\left(\frac{\tau_c}{\gamma\cdot sen\theta}\right)+\frac{V}{A}\cdot e(0)\cdot\frac{A}{Q_{tot}} \quad (14)$$

The condition in which the spraybar advancing speed (v_{av}) supplies emulsion for a time that does not allow flowing phenomena is that $t_{\lim} \geq t_{av} = l/v_a$ where t_{av} is the spraybar advancing time and *l* is the length of application area. In the limit situation it is:

$$t_{\lim}=t_{av}=\frac{l}{v_{av}}=\frac{l\cdot b}{Q_{tot}}\cdot\left(\frac{\tau_c}{\gamma\cdot sen\theta}\right)+\frac{V}{A}\cdot e(0)\cdot\frac{l\cdot b}{Q_{tot}} \quad (15)$$

from which:

$$v_{av}=\frac{Q_{tot}}{b}\cdot\left(\frac{1}{\left(\frac{\tau_c}{\gamma\cdot sen\theta}\right)+\frac{V}{A}\cdot e(0)}\right)\cong\frac{Q_{tot}}{b}\cdot\left(\frac{1}{\left(\frac{\tau_c}{\gamma\cdot sen\theta}\right)+HS}\right) \quad (16)$$

In its expression equation (16) allows to establish the optimum theoretical advancing speed of the spraybar. This speed is such as to not set up unwanted flowing or irregular amounts on roads with significant slopes. This advancing speed is in function of bituminous emulsion characteristics (τ_c and γ) depending on product formulation and laying temperature, of road geometry (*b* and *sen*θ), of supplied discharge (Q_{tot}) and of conditions of surface to be dressed, referable, in first approximation, to a macro-roughness measurement (sand height method, HS).

EXPERIMENTAL STUDY OF FLOWING CONDITIONS

The theoretical expression, in the simplicity of its final form, however highlights the complexity of factors that affect the choice of optimum advancing speed of spraybar in applications. Through the SDS simulator have been reproduced several applicatory conditions, characterized by high longitudinal slope, with the aim to analyze and quantify the emulsion flow on the inclined plane. The study of flowing conditions have made use of sophisticated techniques of photogrammetrical survey and images analysis necessary to evaluate the flow advancing of a bituminous emulsion (cationic modified type C70 BP/3, prEN 13808) with the advancing of spraying front.

Experimental preparation

The surface dressing applications have been carried out on supports formed by a layer of bituminous mixture manufactured inside appropriate vats assembled with supports that can be adjusted in height (Figure 4-A/B). The vat is long enough to allow the advancing of spraying front of bituminous emulsion and control the amount and the speed of the flow. To limit the number of variables that have to been considered in the flow speed study, the supports have been realized substantially identical, previously wet and with an extreme smooth surface (HS<0,26 mm). The afterwards spraybar flow monitoring caused several difficulties and alternative techniques for measurement of flow pattern and finally the velocity profile have been necessarily required. Some techniques have been based on the employment of high resolution camera (1300x1300 pixel at 12Hz, Figure 6-A/B), experimented for following the advancing front through the use of light tracers (spherules of polystyrene, Figure 5) subsequently associated with vectors. The polystyrene spherules were excellent in the first flowing tests on bituminous layer carried out only with water. But the modified bituminous emulsion has been employed, due to its viscosity, it did not allow an univocally determined reading of tracer movement (expanded polystyrene). Therefore a professional camera has been employed, by means of that the advancing of emulsion flow has been evaluated for each single frame (average of 6 points of measure) using a polychrome reference grid (Figure 7-A). Another camera, set at the side of the investigation area, allowed to register the spraybar advancing and the supply regularity (Figure 7-B).

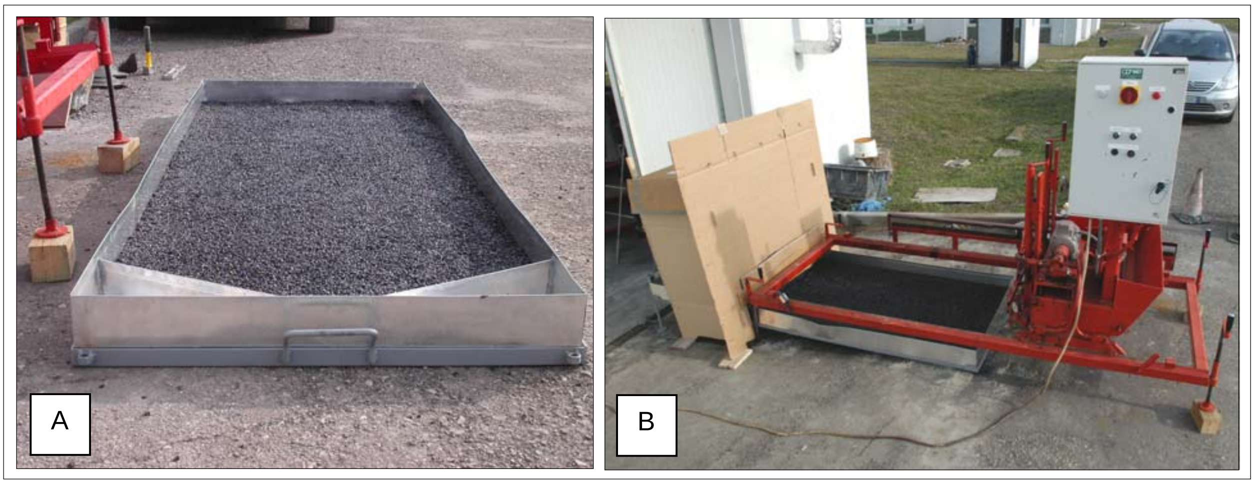

Figure 4: Installation trial preparation (A) and test configuration of SDS (B).

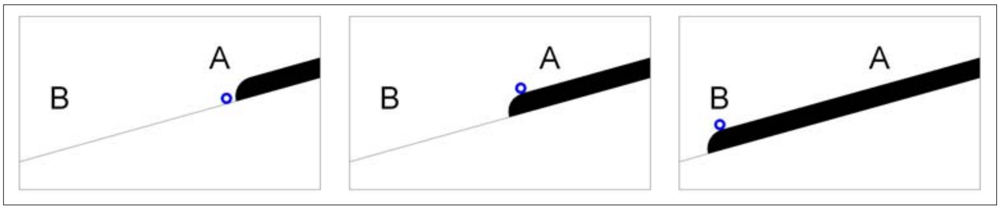

Figure 5: Employ of a light tracer (expanded polystyrene) for flowing speed study.

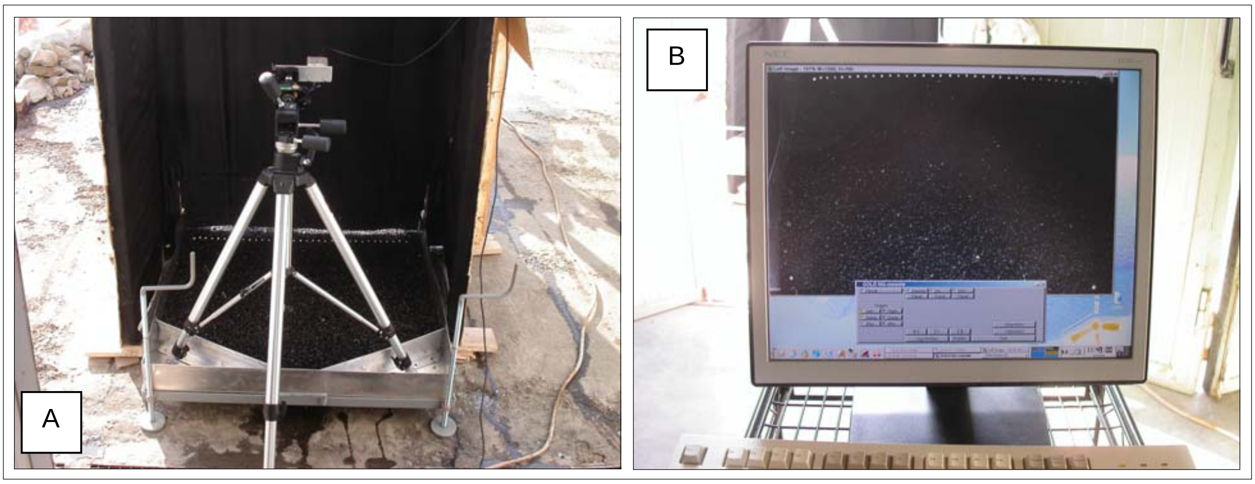

Figure 6: Setting and equipment for emulsion flowing study.

Experimental results

Afterwards the values of flowing speed are reported. They have been measured varying the longitudinal slope of sprayed strip in two conditions: water spraying (Figure 8) and modified bituminous emulsion spraying (Figure 9) without chipping aggregates spreading.

The results refer to an experiment carried out with spraybar advancing speed equal to 13,3 $cm \cdot s^{-1}$, and with a nozzles pressure equal to 0,25 bar.

Altogether the spraybar uniformly lays 1,4 $kg \cdot m^{2}$ of liquid at the temperature of 50°C. The flowing speed measurements have been executed with the variation of the length of the sprayed zone behind the grid for measures (1,5, 1,0 and 0,5 metres).

The grid for measures allowed to quantify the instantaneous speed of flow in 6 advancing points, on 45 cm length afterwards the spraybar. As expected, the flowing speed values result significantly different considering water or emulsion, even if both of them, after 1 metre of spraying, show that conditions of uniform flowing speed begin (values corresponding to 1 m and 1,5 m of spraying length almost superimposed), for slopes until 8%.

It has been noticed that the flowing begins when the slope exceed 4%; until this value the emulsion advancing front corresponds to the spraybar position.
The theoretical calculation of spraybar advancing optimum speed, in conditions referable to the ones of this experience (Table 2), accords with the directly observed phenomenon.

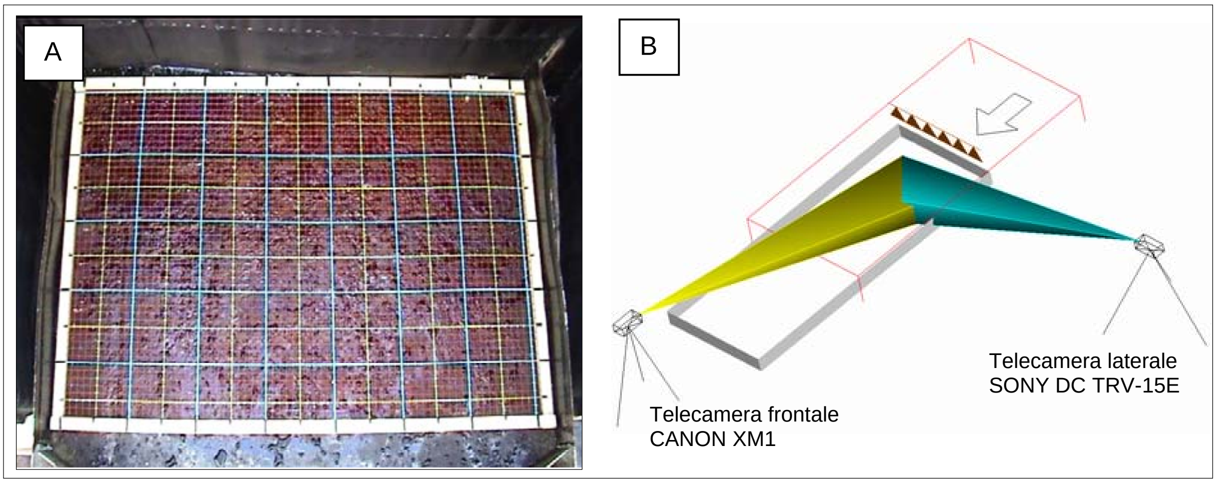

Figure 7: Grid for flow advancing survey (A); scheme of shot (B).

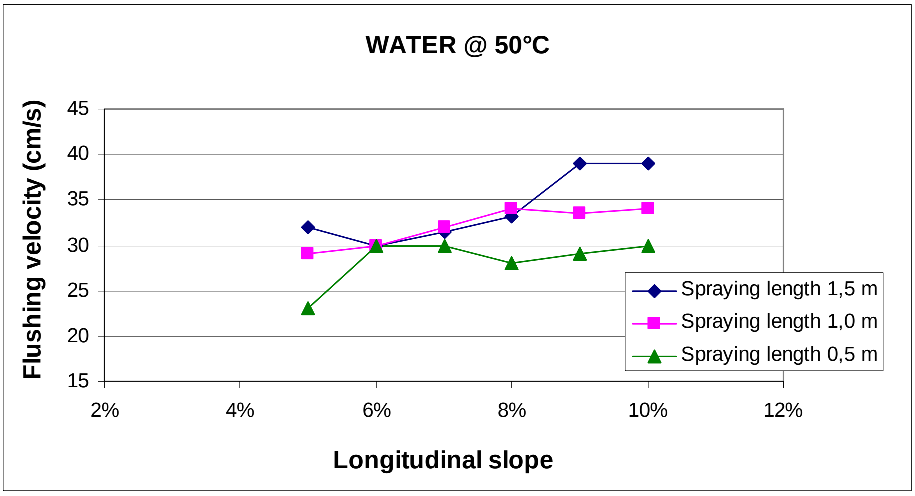

Figure 8: Measure of water flowing speed.

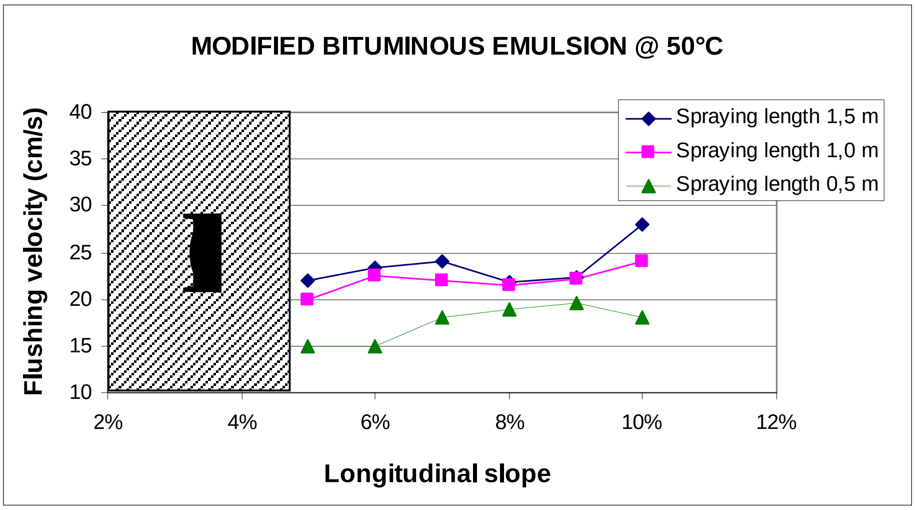

Figure 9: Measure of bituminous emulsion flowing speed.

Table 2: Theoretical values of optimum advancing speed.

Longitudinal slope %	Optimum advancing speed cm·s^{-1}
3	10,70
4	**13,59**
5	16,21
6	18,60
7	20,79
8	22,80
9	24,66
10	26,37

CONCLUSIONS

The Surface Dressing Simulator system allows to deduce in laboratory precious information about effectiveness and final aspect of surface dressing applications that can be used in design and realization of machines. By means of SDS it is possible to easily realize surface dressing applications on small areas that are exactly alike the ones realized by the real combined machine. In the case of surface dressing application on roads characterized by high longitudinal slope, working problems arise connected to the beginning of emulsion flowing phenomena afterwards.

The experiment carried out employing modified bituminous emulsion has highlighted that the phenomenon begins when longitudinal slope exceed 4% and it can be avoided or controlled through the appropriate adjustment of spraybar advancing speed.

The explained theoretical model, that allows the calculation of the optimum advancing speed, is congruent with the direct measures of flowing speed executed in test areas.

The chipping aggregate spread, that has not been introduced in the explained experience, can limit the flowing phenomenon when combined machine emulsion/chipping aggregate are employed in real applications.

ACKNOWLEDGMENT

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