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Validation of a Hydraulic Model to Prevent Emulsion Flowing in Chip Sealing

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Abstract: Chip sealing is a pavement surface treatment that consists in the application of an asphalt binder (bitumen or bituminous emulsion) on an existing pavement followed by the spreading of aggregate chips and by the rolling of the surface, in order to embed the aggregate into the binder. This treatment is typically used as preventive maintenance technique of asphalt pavements, in order to seal fine cracks and improve skid-resistance of road surfaces. Moreover, chip sealing is often employed on rural roads, that carry low traffic volumes and are often characterized by critical conditions such as small radius of curvature and/or high longitudinal slopes. In the latter case, the application of the bituminous emulsion becomes a crucial concern as an excessive flowing of the bitumen could take place due to the high pavement slope and its spreading could become not uniform. In order to investigate these aspects, in this study a hydraulic model of the theoretical flow of bituminous emulsions on high longitudinal slope road surfaces was proposed and validated through a laboratory experimental investigation. To this aim, an original laboratory equipment (Chip Seal Laboratory Simulator), that allows the simulation of the most critical conditions during field activities, was properly designed and realized. The theoretical analysis and the experimental validation suggested practical recommendations in terms of longitudinal working speeds in critical contexts, very usual in practice.

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***Key words**: Bituminous emulsion; Chip seal; Hydraulic model.*

Introduction

A chip seal is a paving technique obtained by spraying a proper amount of bituminous emulsion onto the underlying paved surface followed by the spreading of evenly distributed high quality aggregates whose embedment is promoted through adequate compaction [1, 2]. Chip seals are widely used throughout the world for construction and preventive maintenance of asphalt pavements because, when properly designed and constructed, they represent a reliable cost-effective option with respect to other paving solutions [1-5].

The main purpose of chip sealing is to seal the fine cracks in a pavement surface and prevent the harmful infiltration of water in the underlying layers, providing at the same time an improved skid-resistant surface that allows enhanced traffic safety [6-8]. Chip seals are also characterized by cost-effectiveness, energy saving and reduced emissions thanks to lower application temperatures and lower amount of aggregate with respect to traditional Hot Mix Asphalts (HMAs). Moreover, field applications supported by laboratory studies [9] showed that “clear” synthetic emulsions can be successfully used for the construction of clear chip seals in combination with aggregates of different mineralogy in order to satisfy environmental and aesthetical requirements (e.g. pavements for cycle tracks).

Despite the benefits achievable through the use of chips seals, their successful application is strongly dependent on several factors (e.g. existing pavement condition, materials, traffic, construction procedure and climate) that can lead to typical distresses mainly related to chip loss (e.g. ravelling, streaking, delamination, cohesive and adhesive failures) and texture loss (e.g. chip reorientation, flushing, bleeding) [4]. In particular, vehicle damage caused by chip loss is one of the main issues related to the use of chip seals [10-12].

In this regard, factors such as size and shape of the chipping and binder application rates are critical in order to guarantee adequate embedment of aggregate particles, thus ensuring a satisfactory resistance to traffic-related tangential loads. Moreover, suitable particle retention is also associated with a proper aggregate-bitumen adhesion and with the cohesive contribution provided by the asphalt binder as a function of its rheological properties [13-17]. Consequently, the use of polymer-modified binders is often recommended to enhance chip seal performance [10, 18, 19].

As far as chip seal texture loss is concerned, flushing can be considered a widespread problem that leads to slippery and unsafe surfaces, especially in wet conditions [4, 20-22], and thus to shorter service life. Flushing distress can arise when full or partial covering of surface aggregates occurs due to the upward flowing of binder and to an excessive embedment of chipping aggregates into the underlying pavement layer. As other distresses, flushing typically depends on many factors and the understanding of the mechanisms that lead to its occurrence requires both laboratory investigations coupled with in situ validation and field monitoring [22].

Another drawback that could rise during chip seal applications on high longitudinal slope roads is the possible flowing of the bituminous emulsion that implies its not uniform spreading on the

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pavement surface, potentially leading to both texture loss and chip loss distresses.

The objective of this investigation consists in identifying a hydraulic model of the theoretical flowing of bituminous emulsions on high longitudinal slope road surfaces and in the corresponding model validation through an experimental investigation performed with a properly designed equipment: the Chip Seal Laboratory Simulator (CSLS).

Application of Bituminous Emulsions in Critical Conditions

The design criteria for chip seal applications are essentially based on volumetric methods and require a careful quantification of binder content to assure the optimum locking of chipping aggregates. The amount of bituminous emulsion residue usually results from the needs of saturating the porosity of the pavement surface and ensuring appropriate embedment of the chipping aggregates [1-4]. These criteria consider all the possible design variables (size, shape and texture of aggregates, type and setting mechanism of emulsion, temperatures, working conditions and design traffic) and lead to the design values of the optimum emulsion and chipping aggregate application rates. However, design specifications are often difficult to be fulfilled during the construction phases due to working drawbacks, especially in terms of plano-altimetrical road geometry and 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, often encountered when chip seals are applied on local roads.

It is well known [1, 2, 4] that, for a given discharge of bituminous emulsion supplied, the spray-bar height above the pavement surface affects the width of the uniform spraying area (Fig. 1). Therefore, in case of applications on surfaces with low transversal slope, the only adjustment of the spray-bar height allows the transversal homogeneity of the spraying to be controlled. On the contrary, chip seal applications on small radius curves require a more complex practical solution in order to obtain spraying uniformity. In fact, in this case it needs to operate on the flow supplied by the spray-bar acting on the nozzles (e.g. number, type, spacing and orientation). The Australian Asphalt Pavement Association [23] suggests a corrected binder application rate and an appropriate spraying width as a function of the curve radius.

The uniformity of emulsion application is also critical on roads characterized by high longitudinal slope due to the possible flowing phenomena of bituminous emulsion, that could lead to undesired distresses related to texture loss and chip loss.

Hydraulic Model for the Analysis of Bituminous Emulsion Flowing

The road surface subjected to chip sealing can be schematized as an area A having a length l in the advancing direction of the spray-bar and a width b in the transversal direction. This area A has a longitudinal slope $i_L = \tan\theta \approx \sin\theta$ with respect to a horizontal plane (Fig. 2).

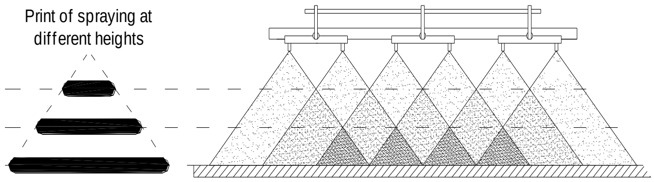

Fig. 1. Width of Uniform Spraying at Different Spray-bar Heights.

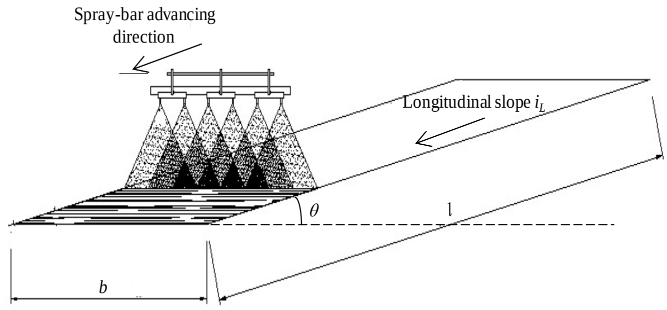

Fig. 2. Prototype Working System And Hydraulic Model Geometry.

The film thickness δ_{tot} of the bituminous emulsion uniformly sprayed by the bar can be considered as the sum of two contributions, according to Eq. (1):

$$\delta_{tot} = \delta' + \delta_{abs} \tag{1}$$

here δ' is the emulsion thickness necessary for the aggregate locking (effective thickness) and δ_{abs} is related to the quantity absorbed by the texture, the micro-cracks and the porosity of the pavement surface (absorbed thickness).

The condition to avoid the flowing of bituminous emulsion on the inclined road surface is given, for an unitary surface area, by the equilibrium between the internal cohesion τ_c of the emulsion and the tangential component of the effective emulsion weight associated with δ' as follow:

$$\tau_c \geq \gamma \times \delta' \times \sin\theta \tag{2}$$

where γ represents the emulsion specific weight.

Therefore the maximum thickness δ_{max} of the bituminous emulsion film to prevent the flowing phenomenon is:

$$\delta_{\max} = \frac{\tau_c}{\gamma \times \sin\theta} \tag{3}$$

Defining V_{tot} as the volume of the emulsion sprayed by the spray-bar, it is possible to write:

$$V_{tot} = A \times \delta_{tot} = A \times (\delta_{max} + \delta_{abs}) = V_{max} + V_{abs} \tag{4}$$

where V_{abs} is the volume absorbed by the pavement surface and V_{max} is the maximum effective volume that prevents emulsion flowing.

Considering the variation during time of the effective emulsion thickness and reminding the definition of discharge Q, it is possible to write:

$$\frac{d\delta(t)}{dt} = \frac{d}{dt}\left(\frac{V_{\max}}{A}\right) = \frac{1}{A} \times \frac{d}{dt}\left(V_{tot} - V_{abs}\right) = \frac{1}{A} \times \left(Q_{tot} - Q_{abs}\right) \tag{5}$$

The integration of Eq. (5) from the time t_0 to the generic time t provides:

$$\int_{t_0}^{t} d\delta(t) = \int_{t_0}^{t} \frac{1}{A} \times (Q_{tot} - Q_{abs}) dt = \int_{t_0}^{t} \frac{Q_{tot}}{A} dt - \int_{t_0}^{t} \frac{Q_{abs}}{A} dt \tag{6}$$

Supposed $t_0 = 0$ and $t = t_{lim}$, corresponding to the limit condition before the emulsion flowing, Eq. (6) can be written as:

$$\delta(t_{\lim}) - \delta(t_0) = \int_{0}^{t_{\lim}} \frac{Q_{tot}}{A} dt - \int_{0}^{t_{\lim}} \frac{Q_{abs}}{A} dt \tag{7}$$

where Q_{tot} is the total quantity of sprayed emulsion that is, for hypothesis, constant in the time interval considered. Moreover the values of emulsion thickness at time t_{lim} and t_0 are respectively δ_{max} and 0, allowing the following equation to be obtained:

$$\delta_{\max} = \frac{Q_{tot}}{A} \times t_{\lim} - \int_{0}^{t_{\lim}} \frac{Q_{abs}}{A} dt \tag{8}$$

Combining Eq. (3) and Eq. (8), it follows:

$$\frac{\tau_c}{\gamma \times \sin\theta} = \frac{Q_{tot}}{A} \times t_{\lim} - \int_{0}^{t_{\lim}} \frac{Q_{abs}}{A} dt \tag{9}$$

The integral in Eq. (9) decreases during time because when the sprayed quantity of emulsion 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}.

Taking into account that $t_{lim} > t_{sat}$ and the discharge Q_{abs} is zero at the generic time $t > t_{sat}$, it is possible to write:

$$\frac{\tau_c}{\gamma \times \sin\theta} = \frac{Q_{tot}}{A} \times t_{\lim} - \int_{0}^{t_{sat}} \frac{Q_{abs}}{A} dt \tag{10}$$

Defining V_v as the volume of voids (consisting of texture, micro-cracks and permeable pores) of the road pavement, the derivative of V_v with respect to time is the speed of variation of these voids during emulsion spraying. Thus, the discharge Q_{abs} can be defined as the opposite of this derivative:

$$Q_{abs} = -\frac{dV_v}{dt} \tag{11}$$

Since the voids volume V_v is obtained as the ideal total volume V of the layer to be chip sealed multiplied by the surface porosity (e), Eq. (11) can be rewritten as follows:

$$Q_{abs} = -\frac{d(e(t) \times V)}{dt} = -V \times \frac{de(t)}{dt} \tag{12}$$

From Eq. (12), it is possible to obtain:

$$-\frac{de(t)}{dt} = \frac{Q_{abs}}{V} \tag{13}$$

Then, multiplying both members by V/A:

$$-\frac{V}{A} \times \frac{de(t)}{dt} = \frac{Q_{abs}}{A} \tag{14}$$

Inserting Eq. (14) in Eq. (10) it is obtained:

$$\begin{aligned} \frac{\tau_c}{\gamma \times \sin\theta} &= \frac{Q_{tot}}{A} \times t_{\lim} - \int_{0}^{t_{sat}} \left(-\frac{V}{A} d(e(t)) \right) \\ &= \frac{Q_{tot}}{A} \times t_{\lim} + \frac{V}{A} \times [e(t_{sat}) - e(0)] = \frac{Q_{tot}}{A} \times t_{\lim} - \frac{V}{A} \times e(0) \end{aligned} \tag{15}$$

as e (t_{sat}) = 0 for definition. Solving Eq. (15) with respect to t_{lim}, it is obtained:

$$t_{\lim} = \frac{A}{Q_{tot}} \times \left(\frac{\tau_c}{\gamma \times \sin\theta} \right) + \frac{V}{A} \times e(0) \times \frac{A}{Q_{tot}} \tag{16}$$

Defining v_{adv} as the advancing speed of the spray-bar and l and b, respectively, as the length and the width of the emulsion application area, t_{adv} is the spray-bar advancing time and is equal to:

$$t_{adv} = \frac{l}{v_{adv}} \tag{17}$$

The condition that assures the absence of flowing phenomena is:

$$t_{\lim} \geq t_{adv} \tag{18}$$

In order to obtain the maximum advancing speed $v_{adv\text{-}max}$ of the spray-bar able to guarantee the absence of emulsion flowing, the limit condition must be considered:

$$t_{\lim} = t_{adv-\max} = \frac{l}{v_{adv-\max}} = \frac{l \times b}{Q_{tot}} \times \left(\frac{\tau_c}{\gamma \times \sin\theta} \right) + \frac{V}{A} \times e(0) \times \frac{l \times b}{Q_{tot}} \tag{19}$$

from which:

$$v_{adv-\max} = \frac{Q_{tot}}{b} \times \left(\frac{1}{\left(\frac{\tau_c}{\gamma \times \sin\theta} \right) + \frac{V}{A} \times e(0)} \right) \tag{20}$$

Eq. (20) allows the determination of the maximum theoretical advancing speed of the spray-bar in order to avoid emulsion flowing and not uniform emulsion spreading on roads with high slopes.

This advancing speed is a function of several factors:

- bituminous emulsion characteristics (τ_c and γ) that depend on the product formulation and on the laying temperature;
- road geometry (b and $\sin\theta$);
- supplied discharge (Q_{tot});
- conditions of the surface to be chip sealed $\left(\frac{V}{A} \times e(0) \right)$.

The last parameter can be approximately evaluated through the measurement of the macro-roughness, that can be assessed with a volumetric patch technique (EN 13036-1), allowing the Mean Texture Depth (*MTD*) to be obtained. In order to take into account the micro-cracks and porosity that could characterize existing pavement surfaces, the *MTD* parameter is multiplied by a factor $\alpha \geq 1$. Thus, the maximum theoretical advancing speed of the spray-bar $v_{adv\text{-}max}$ can be obtained by the following equation:

$$v_{adv-\max} \cong \frac{Q_{tot}}{b} \times \left(\frac{1}{\left(\frac{\tau_c}{\gamma \times \sin\theta} \right) + \alpha \times MTD} \right) \tag{21}$$

Laboratory Study for the Validation of the Hydraulic Model

Chip Seal Laboratory Simulator (CSLS)

Chip seal applications were simulated through an original laboratory equipment, expressly designed and realized for this purpose: the Chip Seal Laboratory Simulator (CSLS). The equipment reproduces, in a laboratory scale, a combined lorry facility (Fig. 3) used to spread in sequence bituminous emulsion and chipping aggregates during chip sealing applications.

The CSLS is composed by a rigid frame where a heated tank containing bituminous emulsion, a spray-bar with six nozzles and a chipping spreader (Fig. 4) are assembled. The bituminous emulsion tank has a capacity of 50 L and is constituted by a filter and a heating system for setting the optimum spraying temperature. A hydraulic circuit allows the equipment cleaning and a manometer controls the pressure supplied by the spray-bar.

This equipment is able to simulate bituminous emulsion applications on critical conditions, such as high longitudinal and transversal slope of road surfaces and, at the same time, to set the longitudinal spreading speed and the material amount applied.

The CSLS operates on a rectangular area of 2.50×1.15 m^2 and is able to cover an effective surface of 1.80×1.00 m^2. In order to obtain pre-selected longitudinal and transversal slopes, both the external frame and the spray-bar can be independently oriented operating on their respective height adjustment systems.

Several working conditions are possible in order to modify the emulsion application amounts (discharge supplied, orientation and number of nozzles), the spray-bar height and slope, the aggregate spreading rate and the advancing speed of the equipment.

Experimental Program and Testing Procedures

According to the following experimental program, several conditions of material application were considered and the corresponding flowing speed on the inclined pavement surface was measured. In this study, the CSLS was used only for bituminous emulsion spraying, without applying chipping aggregates.

A polymer modified bituminous emulsion, classified as C70BP3 (according to EN 13808) was employed during the whole investigation.

Three lengths of the sprayed zone (0.5, 1.0 and 1.5 m) were considered in order to study the influence of the total mass of emulsion on the flowing speed and the corresponding transient regime effects were analyzed.

Fig. 3. Combined Lorry Facility for Spreading Bituminous Emulsion and Chipping Aggregates.

Fig. 4. Chip Seal Laboratory Simulator.

Fig. 5. Adjustable Metallic Container for the Pavement Surface Preparation.

Seven different longitudinal slopes of the pavement surface (4, 5, 6, 7, 8, 9 and 10%) were considered in order to examine the influence of this parameter on the flowing speed. These slopes were achieved through specifically prepared metallic containers ($2.50 \times 0.95 \times 0.12$ m^3), assembled with supports that can be adjusted in height (Fig. 5).

The pavement surface to be chip sealed was realized by compacting, on each container, an asphalt concrete (AC 8) layer with a thickness of 28 mm and an average MTD value of 0.25 mm.

During the tests, the spray-bar advancing speed was equal to 0.133 m/s and the nozzles pressure was 25 kPa. In these conditions, the total emulsion discharge Q_{tot} sprayed on the pavement surface was 1.67×10^{-4} m^3/s at a temperature of about 50°C.

The flowing speed of the bituminous emulsion was evaluated through an optical system characterized by two professional cameras (Fig. 6), placed in two different positions with respect to the emulsion flowing direction. A CANON XM-1 camera was located frontally whereas a SONY DC TRV-15E camera was set sideways, allowing the recording of the spray-bar advancing and the checking of the spreading regularity. However, the latter parameter showed very scattered results that did not allow to obtain useful information on the regularity of the emulsion spreading.

Experimental Results and Model Validation

The flowing speeds of the bituminous emulsion as a function of the road longitudinal slope are reported in Fig. 7. As expected, results show that the lower the sprayed zone length the lower the flowing speed, as the total mass of emulsion slightly influences the latter parameter. However, for longitudinal slopes lower than 9%, spraying lengths of 1.0 and 1.5 m provided very similar flowing speeds allowing assuming that the transient regime effects are concluded and after 1.00 m of spraying the conditions of uniform flowing speed begin.

It is worth noting that emulsion flowing begins when the longitudinal slope exceed 4%. In fact, the tests performed with this slope showed that the emulsion-advancing front corresponded to the spray-bar position. Moreover, results provided an emulsion flowing speed (Fig. 7) very close to the advancing speed of the spray-bar (0.133 m/s).

The latter result can be used to check the validity of the theoretical hydraulic model previously described. In fact, Eq. (21) allows the evaluation of the maximum advancing speed of the spray-bar able to avoid bituminous emulsion flowing $v_{adv\text{-}max}$, as a function of the longitudinal slope of the road surface to be chip sealed. This theoretical calculation requires the knowledge of the values assumed by several parameters:

- $Q_{tot} = 1.67\times10^{-4}$ m^3/s;
- $b = 0.95$ m (width of the container);
- $\gamma = 9.996$ kN/m^3;
- $\alpha = 1$ (a new pavement is considered);
- $MTD = 0.25\times10^{-3}$ m.
- $\tau_c = 0.4$ N/m^2.

The parameter τ_c can be calculated, in first approximation, through Eq. (2) where the equal sign is considered and sin θ is replaced with the slope i_{max} that represents the maximum slope after which emulsion flowing begins:

$$\tau_c = \gamma \bullet \delta' \bullet i_{max} \quad (22)$$

In this study, the value of i_{max} was estimated experimentally by measuring the conditions that determine the flowing of the modified bituminous emulsion on a smooth metallic reference slab of known dimensions, whereas the effective thickness δ' was obtained as "wet" height calculated by considering that the emulsion total volume applied by the equipment can be spread on an area that includes also the portion subjected to superficial flowing. For the tested emulsion, i_{max} was found to be about 5% (0.053) and δ' to be about 0.8 mm.

The introduction of these values on Eq. (21) permits the theoretical calculation of $v_{adv\text{-}max}$ for different longitudinal slopes, as reported in Table 1, that allows appreciating the good agreement between the theoretical evaluation and the experimental results.

In fact, for a longitudinal slope of 4% the parameter $v_{adv\text{-}max}$ is equal to about 0.136 m/s (Table 1), meaning that bituminous emulsion flowing does not occur when the spray-bar advances with this speed on this slope. Analogously, the experimental investigation, performed with a spray-bar advancing speed of 0.133 m/s showed that emulsion flowing begins when the longitudinal slope exceed 4% (Fig. 7).

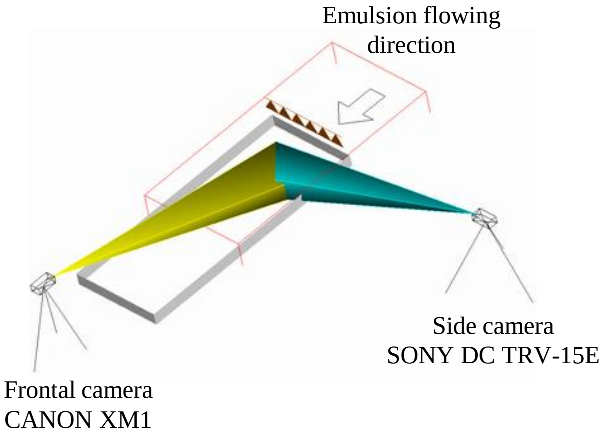

Fig. 6. Emulsion Flowing Evaluation.

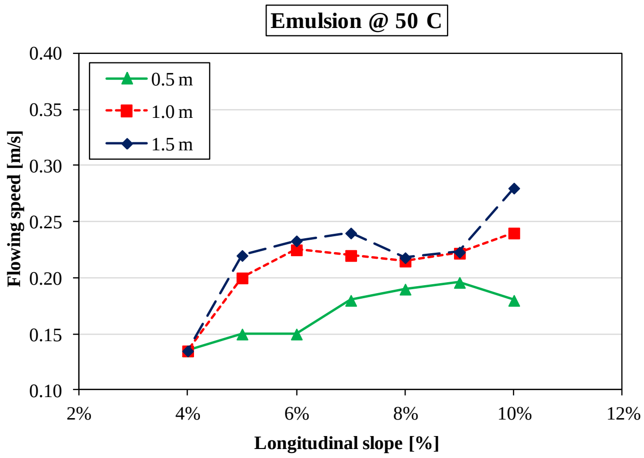

Fig. 7. Flowing Speeds of the Bituminous Emulsion.

Table 1. Theoretical Values of the Maximum Advancing Speed $v_{adv\text{-}max}$.

Longitudinal Slope θ [%]	Maximum Advancing Speed $v_{adv\text{-}max}$ [m/s]
3	0.107
4	0.136
5	0.162
6	0.186
7	0.208
8	0.228
9	0.247
10	0.264

Conclusions

The investigation presented in this paper analyzed the influence of the pavement longitudinal slope on the emulsion flowing during chip sealing applications.

In the first part of the study, a hydraulic model of the theoretical flow of bituminous emulsions was proposed. It allowed the determination of the maximum advancing speed of the spray-bar in order to avoid emulsion flowing on high longitudinal slope road surfaces. This parameter was found depending on several factors: bituminous emulsion properties (internal cohesion and specific weight), road geometry (width and slope), emulsion discharge supplied, characteristics of the surface to be chip sealed (presence of micro-cracks, Mean Texture Depth).

In the second part of the study, the theoretical model proposed was validated through a laboratory experimental investigation. To this aim, an original laboratory equipment, the Chip Seal Laboratory Simulator (CSLS), was properly designed and realized. It reproduces, in a laboratory scale, a combined lorry facility used in situ and allows deducing in laboratory precious information about effectiveness and practical aspect of chip sealing applications. The experimental investigation showed that, for the spray-bar advancing speed analyzed (0.133 m/s) and for longitudinal slopes lower than 9%, after 1.00 m of emulsion spraying the conditions of uniform flowing speed begin, so that the transient regime of bituminous emulsion flowing can be considered concluded. Moreover, experimental results showed a good agreement with the theoretical model as, for the spray-bar advancing speed considered, the emulsion flowing began when longitudinal slope exceed 4%, accordingly to the model previsions.

Finally, this study allows concluding that the hydraulic model proposed can be used to control bituminous emulsion flowing through the appropriate adjustment of the spray-bar advancing speed.

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