

Surface Runoff: A Rainfall Simulator For Wash-Off Modelling And Road Safety Auditing Under Different Rainfall Intensities

Simone A.
Professor – University of Bologna – DISTART Strade

Vignali V.
Ph.D Student – University of Bologna – DISTART Strade

Bragalli C.
Researcher – University of Bologna – DISTART Costruzioni Idrauliche

Maglionico M.
Researcher – University of Bologna – DISTART Costruzioni Idrauliche

SYNOPSIS

The great traffic and vehicle average speed increase in recent years have improved road pavements performance standards. Road surface must be designed, built and maintained to offer the highest active safety to drivers. This is very important during rainfall events, because the water collected on road pavements produces a drastic decrease of skid resistance and visual distance. So water film depth estimation is one of the most important factor on road safety.

Moreover during rainfall events the rainfall wash pollutants collected on road pavements and dissolve them in urban drainage with an important environmental impact.

In this paper has been studied and modelled the pollutants wash-off on road pavements and the vehicle-road interaction in terms of water film depth. The laboratory equipment consists of an artificial rain system, capable of simulating variable rainfall intensities by different nozzles and by a controlled water discharge system to collect the water flowing from the road surface.

To reproduce different rainfall intensities, three nozzles were used and calibrated according to rainfall intensity, drop dimension distribution and medium drop diameter.

From rated flow calculation it has been investigated:

- the effect of different rainfall intensity regimes on pollutants wash-off and safety;
- the effect of different surface slope on wash-off and safety;
- the effect of water film depth on skid resistance and safety.

The data collected in this way have been submitted to an in-depth analysis, which has provided particularly interesting and significant results regarding design and maintenance of roads according to security and environmental standards.

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INTRODUCTION

The rainfall events on an asphalt surface produce two different effects: the first on the water film, and consequently on road safety, and the other on the road waste runoff, which is directly connected to the environmental impact. In this paper has been studied and modelled the pollutants wash-off on road pavements and the vehicle-road interaction in terms of water film depth.

An understanding of pollutant wash-off characteristics is essential to estimate and to minimise the impacts of pollutants on the environment. Stormwater quality models typically view stormwater pollution as a two stage process, pollutant build-up and pollutant wash-off. Build-up is the accumulation of pollutants on the catchment surface during dry periods and wash-off is the removal of the pollutants by rainfall and runoff (Vaze and Chiew, 2002). The few studies on pollutant build-up, since the detailed experimental pollutant accumulation studies of Sartor and Boyd in 1972, agree that surface pollutant load increase during antecedent dry weather period, but there are doubts on the assumption that the buildup starts from zero after a rain event is realistic. Depending on the rainfall and runoff characteristics, part of the available pollutant is removed from the surface as wash-off, the remainder becomes a part of the fixed load as it attaches itself to the surface. During drying, part of the free load of the build-up process can attach itself to the surface contributing to the fixed load amount. The experimental study on an urban road surface in Melbourne (Vaze and Chiew, 2002) has shown that common storms only remove a small proportion of the total surface pollutant load, also it has suggested that the rainfall and runoff disintegrate and dissolve more surface pollutant that they can actually remove.

The road surface conditions and temperature are very important for the adherence values. In real conditions the road could be contaminated with dust, mud or sand, or covered with water, ice or snow. On the wet roads, when the water thickness is very low and motor vehicle speed in normal range, it could be observed a somewhat decrease of adherence. This fact could be explain due to the diminish value of adhesion friction on lubricated surfaces. The peak and slide values of the longitudinal force coefficient on wet road compared to the values on dry road are presented in figure 1.

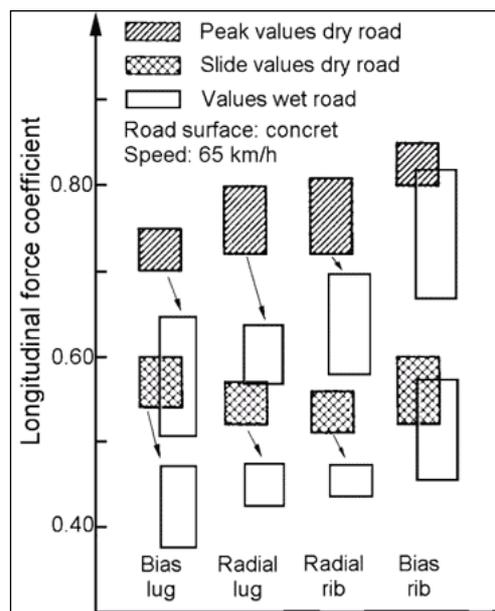


Figure 1: Comparison between dry and wet road adherence conditions [Pauwelussen, 2002]

In addition, the influences of load and vehicles speed are depicted in figure 2.

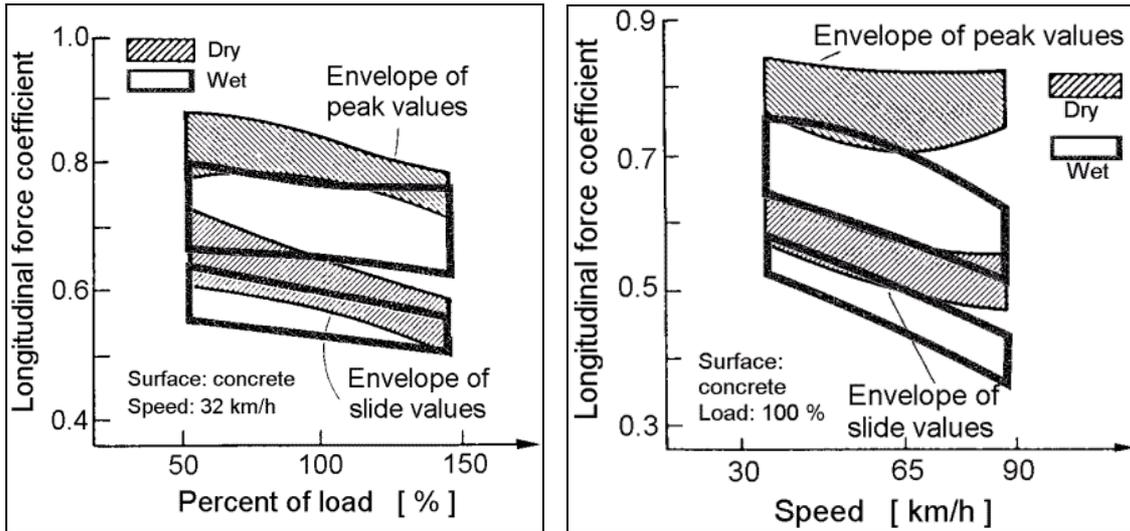


Figure 2: Comparison of load and speed effect on dry and wet roads (radial truck tyre) [Pauwelussen, 2002]

When the water layer thickness and vehicle speed increase the hydroplaning phenomenon appear. So, the tyre is lifting from the road surface due to the pressure created by water under tyre. The magnitude of hydroplaning depends on:

- water conditions (water depth, surface texture and drainage);
- pressure distribution in contact area;
- tyre patterns design (groove capacity on removing water).

The tyre behaviour between the state in which hydroplaning begin and the full (total) hydroplaning state, is commonly described with the "three-zone concept" (Giannini and Noli, 1974). As can be seen in figure 3, zone A (unbroken water film) is in forward region of the contact area where the hydrodynamic pressure lifts and completely separates the tread from the road. In this region the water film remains unbroken and the local coefficient of friction is substantially zero. Zone B (transition zone) is the region where a progressive breakdown of the water is dissipated but where a thin film layer of water still remains. In this region the effective coefficient of friction varies widely. Zone C ("dry" contact) is the region where the lubrication film has been substantially removed and the road frictional forces can be generated. The image of contact area of a heavy truck tyre that rolls on a smooth glass surface covered with water is shown in figure 4. The key objective in order to improve the adherence in this case is to increase the length of zone C through an optimum tread pattern design.

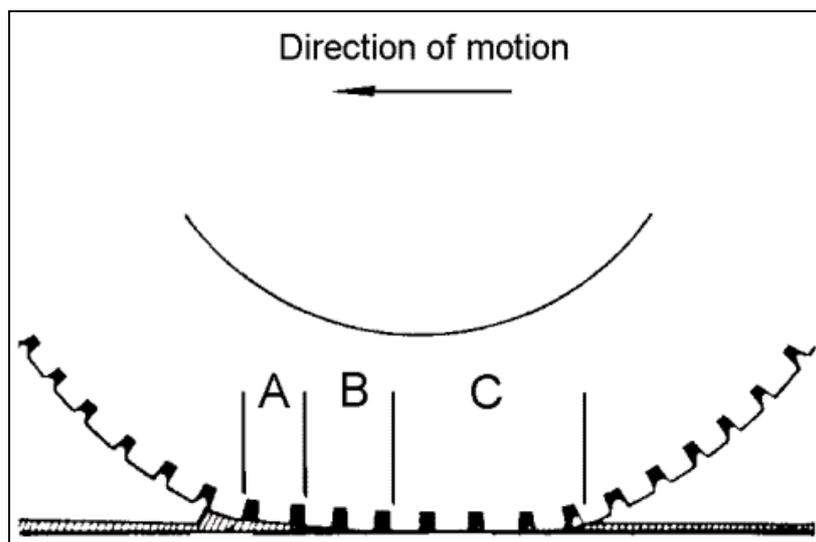


Figure 3: The three-zone concept of contact area [Giannini and Noli, 1974]

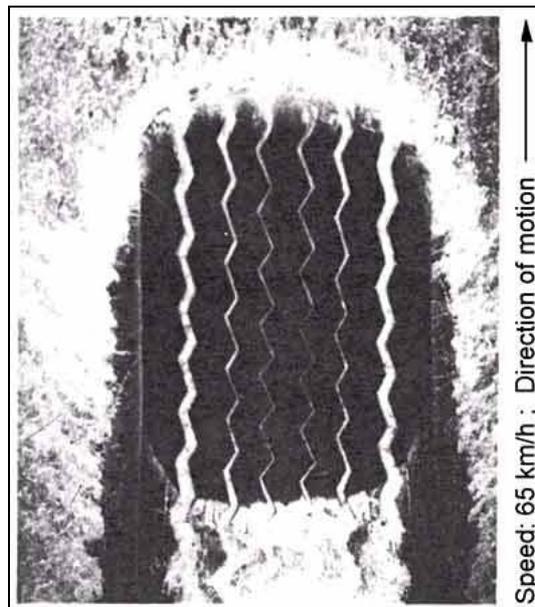


Figure 4: Contact area of a truck tyre rolling through a film of water [Pauwelussen, 2002]

To analyse the pollutant wash-off on road surface and the vehicle-road interaction in term of water film depth, a rainfall simulator has been developed. The rainfall simulation is a very useful method to study the rain water distribution and its effects on a catchment area, as waterproof surfaces (Lorenzini and Becchi, 2000), road pavements (Domenichini and La Torre, 1997), road transitional areas between planimetric curves (Domenichini and Remedina, 1992), soil erosion (Romkens et al, 2001), etc. In this way it's possible to take a lot of measures without waiting for the natural rain and to work with a constant rain intensity without the natural rain intensity variability. So it has been developed the device described in this paper, to aim of understanding the bituminous surfaces runoff and the pollutants wash-off phenomenon.

RAINFALL SIMULATOR

The experimental device is composed from a rainfall simulator, a structure with adjustable inclination on which is placed a bituminous surface, a system to remove external rainfall to the bituminous surface and a collection system of internal rainfall to bituminous surface, set at the final section (figures 5 and 6). The artificial rain system is capable of simulating variable rainfall intensities by different nozzles.

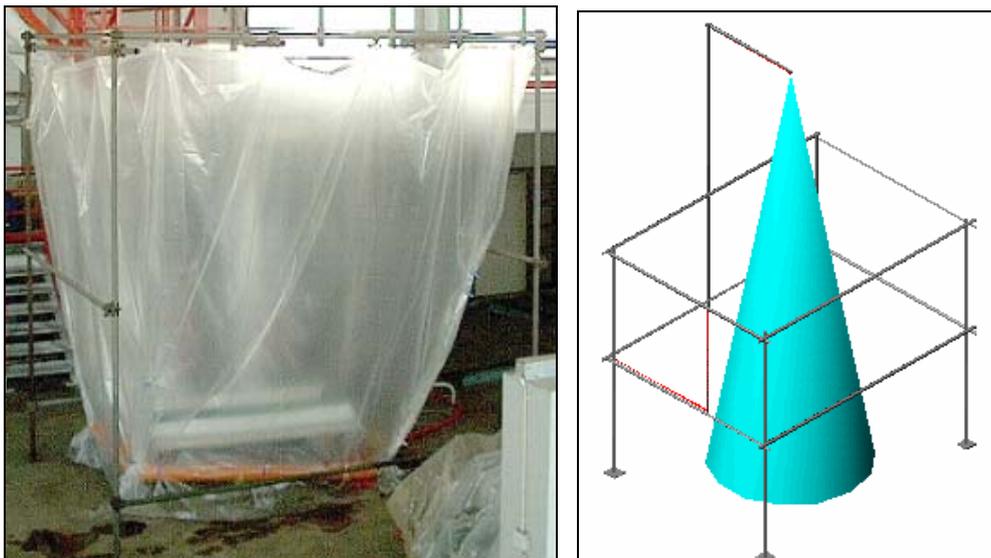


Figure 5: Rainfall simulator

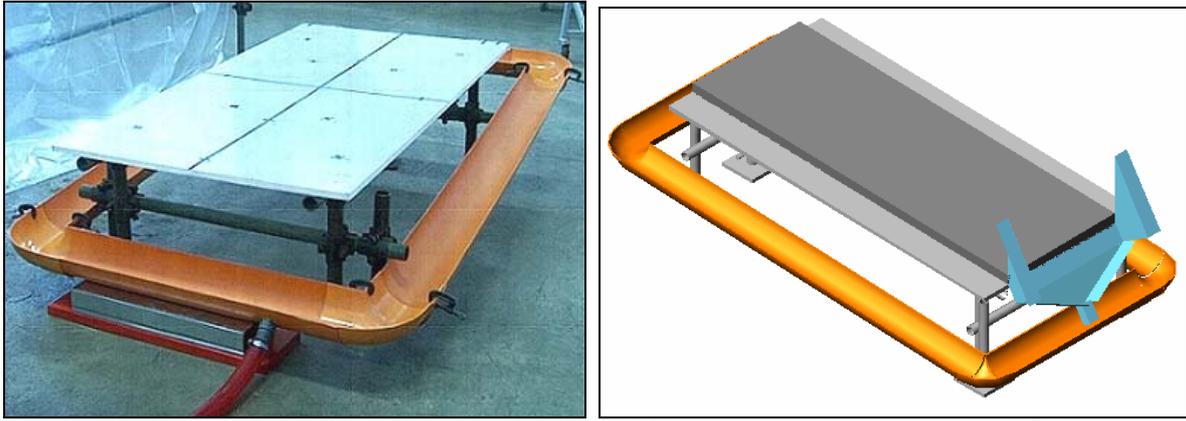


Figure 6: System to remove external rainfall and to collect internal rainfall

Rainfall simulator is made up of a PVC supply system for the nozzle, while control members are composed of a Pressure Reducing Valve (PRV), Spirax Sarco LRV2S model, two manometers at downstream of PRV and before nozzle, and a baffle flow meter.

Lechler Axial Flow Full Cone Nozzles with spread angle of 120°, models 460.728, 460.788, 460.888, have been utilized with a drops fallen height of 6 m (figure 7). The first one has been used for studying pollutants wash-off and the others two to analyse the surface run-off.



Figure 7: Lechler Axial Flow Full Cone Nozzles (460.728, 460.788, 460.888 from left to right)

During the first experimental stage, involving optimization and analysis, we took into consideration a bituminous mixture featuring a specific granulometric grading type curve (figure 8).

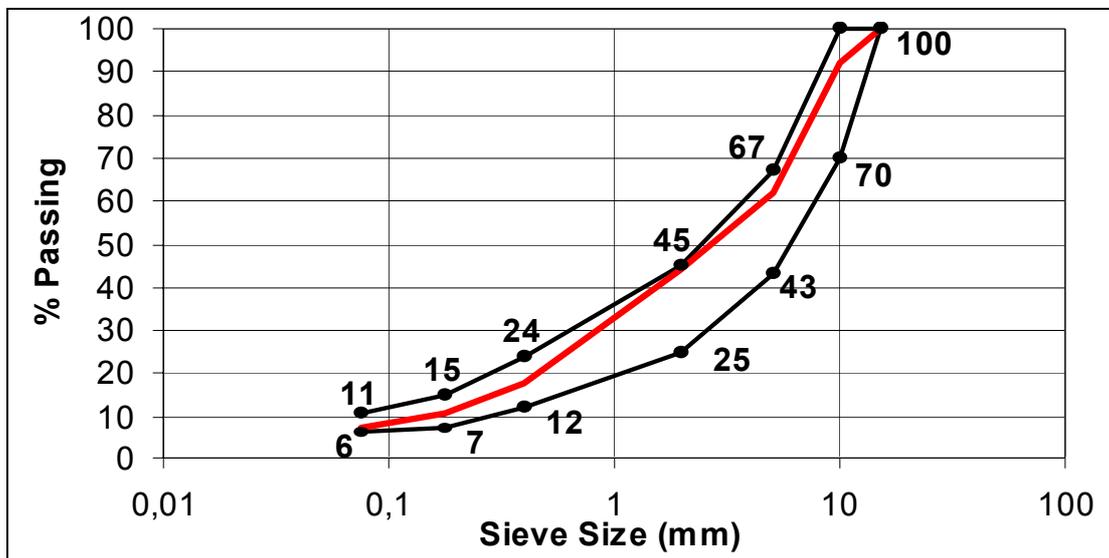


Figure 8: Granulometric range for mixture studied

In order to complete the analysis of the mix, a Marshall optimization study was also performed; the main values deduced from the experimental analysis are shown in Table 1. Therefore, the experimental stretch was used to detect both the macro-texture values with the volumetric technique (*HS*) [CNR, 1983] and the micro-texture with the British Pendulum Tester (*BPN*) [CNR, 1985]. A first analysis of the data shows that *BPN* and average surface macrotexture depth in any case provide values which are more than acceptable.

Table 1: Main features of the mix and surface test experimental results (average values)

<i>Marshall 75+75 blows Void [%]</i>	1.414
<i>Average volume weight [kN/m³]</i>	24.25
<i>Bitumen [%]</i>	5.87
<i>Stability [Kg]</i>	1457
<i>Rigidity [Kg/mm]</i>	530
<i>Average surface macrotexture depth HS [mm]</i>	0.45
<i>BPN</i>	77

The bituminous surface is composed from three sealed plates of 0.70×0.70×0.05 m (figure 9).



Figure 9: Bituminous surface design stages

The study of runoff on road surface appears complex. Laboratory model reproduces the situation with rainfall in absence of wind on a constant inclination surface and runoff with spatial delimitation on three sides and free on downstream size. Even in these simplified conditions are present uncertainty factors.

For thin layers of the water on rough surface, surface tension assumes particular account, the dimension of roughness is comparable with water thickness and the flow of water occurs rather by means a percolation in little rivulets of shape and dimension continuously variable, defined from irregularity surface and from trouble of water drops.

Rainfall simulator has to allow the reproduction of real drops characteristics and for this it has been calibrated verifying intensity, drop dimension distribution by means Flour Pellet Method and fallen velocity estimated with a numerical model that allows to know the trajectory and the temporal variation of the velocity vertical component so to calculate the impact velocity of drops.

On axis and diagonals of experimental surface, several cylindrical pots have been posed to measure the distribution of rain intensity generated from the tested nozzles on a fixed rain time (figure 10).

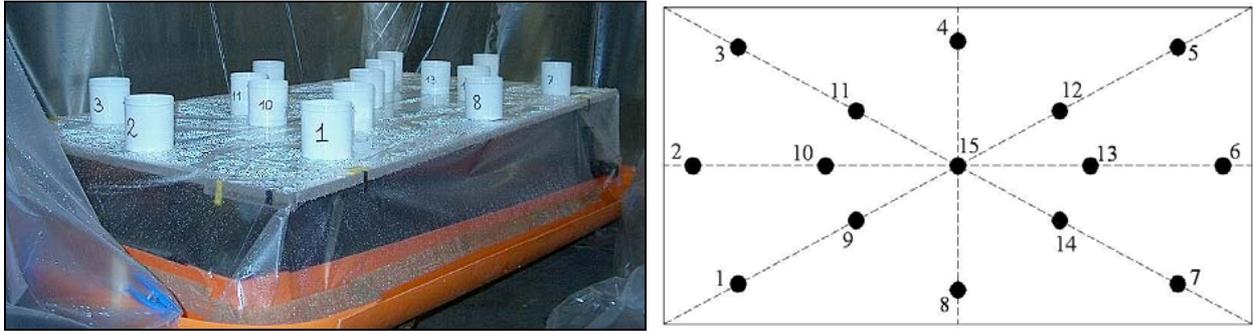


Figure 10: Cylindrical pots distribution on bituminous surface

Repeating on more tests, it is possible to calculate the mean value of the uniformity coefficient of simulated rain UW according to Wilcox and Swailes (table 2):

$$UW\% = 100 \cdot \left(1 - \frac{std}{mean} \right) \quad (1)$$

where std is the mean square deviation.

Table 2: Average rain intensity and uniformity coefficient of simulated rain

Nozzle model	Pressure [bar]	Average Intensity [mm/h]	UW [%]
728	0.3	35	91
788	0.3	21.23	93.27
788	0.5	24.99	94.29
788	0.7	28.80	94.14
888	0.3	64.96	92.76
888	0.5	65.39	96.36
888	0.7	75.43	96.35

These intensity are related to the observations of Giannini and Noli (1974) that assert how to produce critical thickness of water layer on road surface are sufficient rains with intensity of 25-50 mm/h because, if the intensity increase over this limit, the velocity of traffic is inclined to decrease, also in connection with the reduction of visibility.

The evaluation of drop dimension distribution has been made by means Flour Pellet Method described in Laws and Parsons (1943), utilizing the calibration curve obtained from Panini et al. (1993), that allows to take the dimension of median rain drop from the value D_{50} of particle-size distribution of flour pellets. Such determination has been made for central and side positions respect to vertical axis of nozzle.

Table 3: D_{50} of particle-size distribution

Nozzle model	D_{50} central [mm]	D_{50} side [mm]
728	1.32	1.50
788	1.01	1.03
888	1.07	1.19

Introducing experimental results into numerical model, this shows that drops have a velocity comparable with the velocity values determined from Laws (1941) and Gunn e Kinzer (1944).

LABORATORY TEST

Wash-off on experimental surface

The experimental surface has dimensions of 2.10x0.70 m; the sediments, obtained by means a field collection during dry period on the road, have been scattered only on the surface final portion of 1.0x0.7 m. This finds justification in Sartor and Boyd (1974) that point to how about 95% of sediments build up into the first meter of the road adjacent to the sidewalk. The quantity of sediments and their division in particle-size derive from the field experimental study on build-up process.

The duration of rain has been of 15 minutes, with constant intensity about equal to 20 mm/h, with sampling time step of 30 sec. Every sampling has been filtered and the filters have been dried up at 50 °C because to not modify the organic content. After, the quantity of washed sediments in every sampling is obtained, known the initial weight of each filter, by means weighting of dried filters.

The results of some wash-off tests are showed adopted a build up rate of 25 kg/(ha/day). In Table 4 is showed the granulometric distribution and the weight of sediments for the wash-off tests. Test 1 considers a sequence of dry periods: a first dry period of 60 days followed from a rain period (Test 1a) and a second dry period of 14 days followed from another rain period (Test 1b). Test 2 considers a single dry period of 14 days followed by a rain period. For Test 2, the experimental surface has been brought again to initial conditions sucking up the residual sediments.

Table 4: Wash-off tests granulometric distribution

Particle-size classes [μm]	Test 1a [g]	Test 1b [g]	Test 2 [g]
>2000	22.57	5.64	5.64
2000-1190	10.37	2.60	2.60
1190-595	12.34	3.09	3.09
595-297	15.20	3.38	3.38
297-150	13.50	2.50	2.50
150-75	9.98	2.50	2.50
<75	16.04	4.01	4.01

In every test it is possible to observe a pick value of concentration during the first minutes of rain (equal to 14.000 mg/l in Test 1a, 600 mg/l in Test 1b, 1.400 mg/l in Test 2) that precedes the pick of flow, followed from a fast reduction in sediment concentration after 5 minutes of rain, time corresponding to concentration time of the experimental surface. After, the runoff increase stage stops and remain almost constant, round to 0.01 l/s (figures 11 and 12).

The cumulated washed mass is characteristic from particles with size between 38 μm and 297 μm , and his percentage, respect to the initial build up mass, amounts to 5% in Test 1a, 2% in Test 1b and 2% in Test 2 (figure 13).

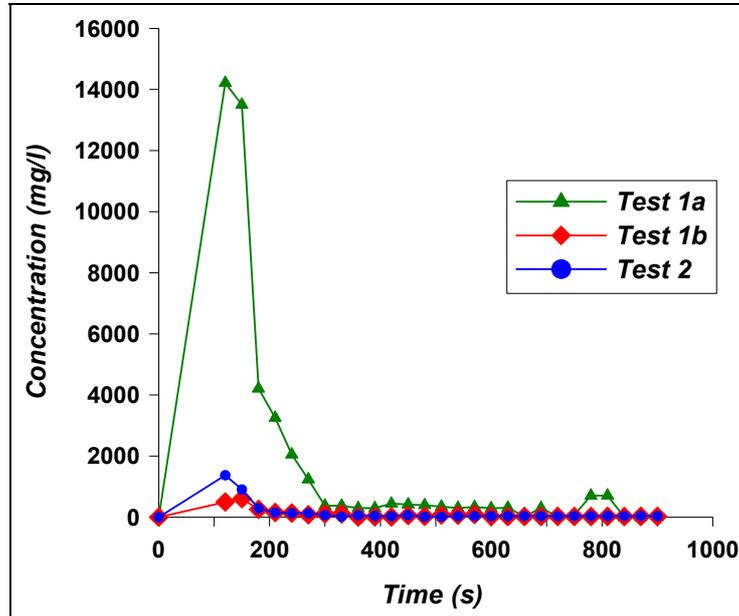


Figure 11: Plot of concentration vs. time curve

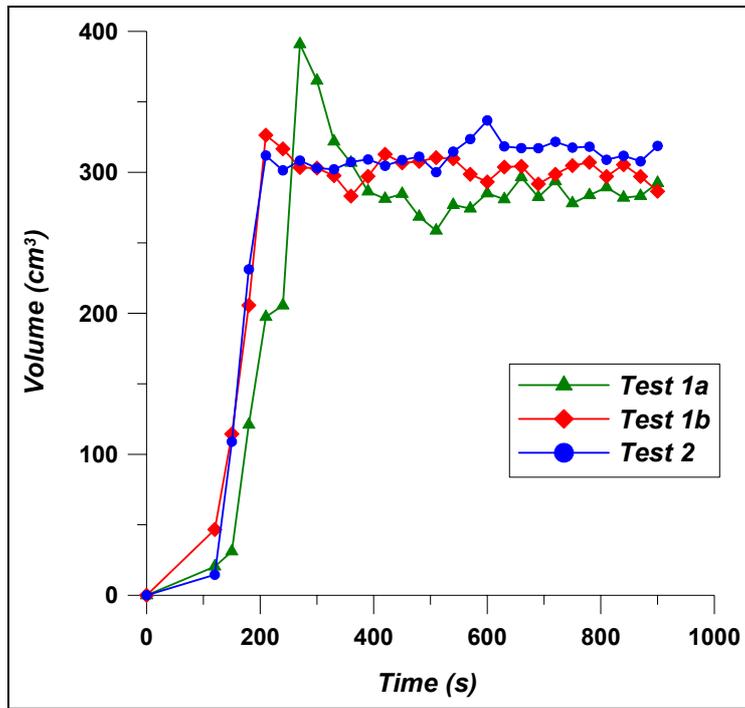


Figure 12: Plot of run-off volume wash vs. time curve

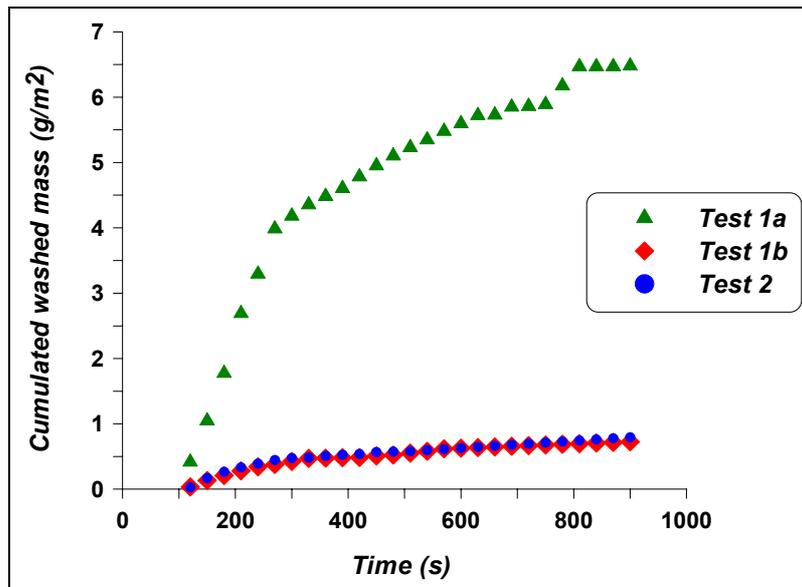


Figure 13: Plot of cumulated washed mass vs. time curve

It has been calculated the wash coefficient $Arra$ with reference to Sartor and Boyd (1974), which describe wash-off by an exponential relationship of the form:

$$Me(t) = Ma(t - Dt) \cdot (1 - e^{-k \cdot t}) \quad (2)$$

where:

$Me(t)$: wash-off mass between the time t and $t+Dt$ [kg];

$Ma(t)$: cumulated mass on the surface at time t [kg];

k : coefficient. It is a function of both particle size and runoff rate:

$$k = Arra \cdot i_p(t) \quad (3)$$

where:

$Arra$: wash coefficient [mm^{-1}];

$i_p(t)$: intensity of rain [mm/h].

Finally:

$$Me(t) = Ma \cdot (t - Dt) \cdot (1 - e^{-Arra \cdot i_p(t) \cdot Dt}) \quad (4)$$

Ammon (1979) proposed values for $Arra$ ranging from 0.22 mm^{-1} and 0.37 mm^{-1} for rain intensities of 5 mm/h and from 0.11 mm^{-1} and 0.16 mm^{-1} for rain intensities of 20 mm/h , but these values were independent from

the particle diameter. On the contrary Sonney (1980) estimates values for *Arra* from transport sediment theory ranging from 0.002 mm^{-1} to 0.26 mm^{-1} , increasing as particle diameter decreases, as rainfall intensity decrease and as catchment area decreases.

The calculated wash coefficient is the average value on simulated rain time of 15 minutes (table 5).

Table 5: Coefficient *Arra* values

<i>Test</i>	<i>Ma (t)</i> [g]	<i>Me (t)</i> [g]	<i>i_p (t)</i> [mm/h]	<i>Arra</i> [mm ⁻¹]
1a	100	4.54	19	0.0097
1b	25+ residual sediments of Test 1a	0.51	21	0.0040
2	25	0.56	21	0.0042

The experimental values are agree with Sonney results. The wash coefficient *Arra* related to the same quantity of scattered sediments is the same for Test 1b and Test 2 even if the conditions of the experimental surface are different because the presence of residual sediments after Test 1a. It is possible to suppose that during Test 1b, the sediments not removed from rain during Test 1a are not more available from rain with the same intensity because trapped into interstices of the bituminous surface and represent the fixed load. The removed sediments are mainly related to the build up sediments on the surface during the following simulated dry period. This means that the wash coefficients *Arra* calculated for the showed tests seems independent from the fixed load on the experimental surface.

Runoff on experimental surface

The mainly sizes characterizing the runoff process on inclined surface are the intensity and duration of rain, the nature, slope and dimension of surface, the initial saturation condition of surface, that influence the increase, stationeries and decrease time of flow and the kept volumes from surface.

The experimentation has been developed in two phases:

- at first it has been investigated the influence on runoff process of surface slope with different rain intensity and experimental surfaces, in particular a perfect waterproof surface in PVC and a classic bituminous surface. The objective is the observation of the different entity of "reservoir effect" produced from surface during the three phases of runoff curve. Indeed, it is possible to distinguish between a superficial flow that, for intensity of 25-50 mm/h, develops mainly in rivulets and an internal flow into the bituminous surface, characterised from a different velocity.
- in the second phase, departing from the flow rates flowing out the final section of the bituminous surface, it has been calculated the water film depth as the mean value of water depth respect the surface.

In every test it is possible to observe the three phases of runoff curve: after a very brief initial period (equal to 30 s), it can be seen a fast flow rate growth during the initial seconds of rainfall event, followed from a stationary phase in which the flow rate remains almost constant until the end of rain (time = 900 s), and from a fast reduction since to the complete road drying. This third phase of runoff curve depends on the reservoir effect (figures 14, 15 and 16). The runoff on bituminous surface shows in all tests a decrease of regime discharge thus the maximum flow, and a decrease of the growth line steep of runoff curve with the reduction of surface slope.

It is possible to observe that the maximum flow with the PVC surface is greater respect to the maximum flow with bituminous surface and the growth line of runoff curve appears more steep for PVC surface respect to those with bituminous surface (figures 17, 18 and 19).

The descendant line of runoff curve on PVC surface and bituminous surface are connected within rain time (1470 s). For road paving, the growth phase of runoff curve results of short duration, between 2-5 minutes (Giannini and Noli, 1974), comparable with the laboratory tests obtained.

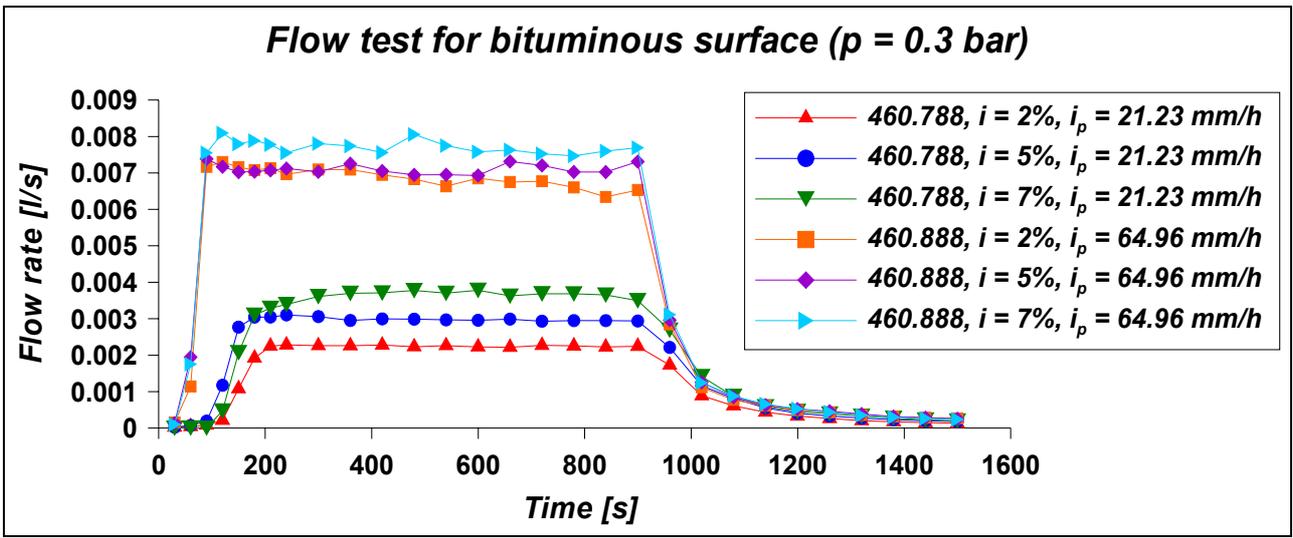


Figure 14: Plot of flow rate vs. time curve for bituminous surface at pressure of 0.3 bar

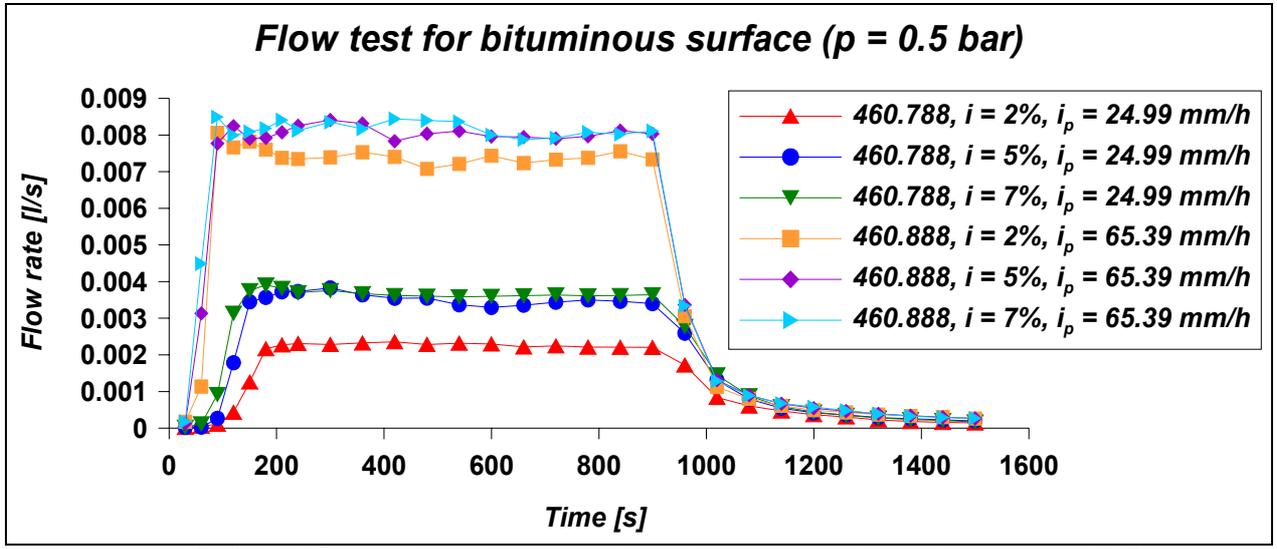


Figure 15: Plot of flow rate vs. time curve for bituminous surface at pressure of 0.5 bar

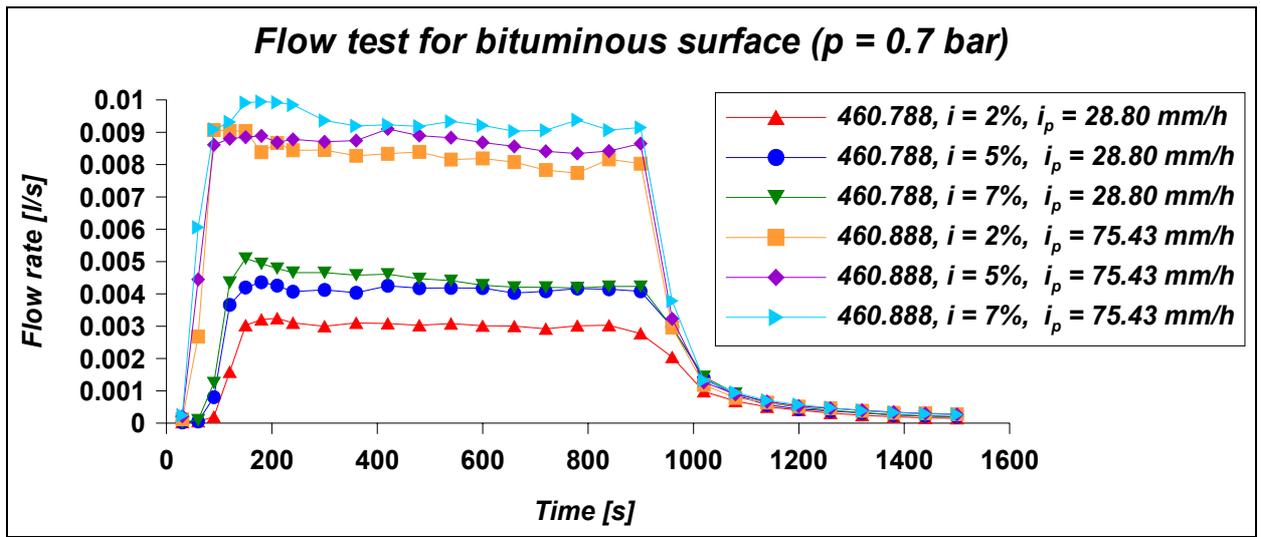


Figure 16: Plot of flow rate vs. time curve for bituminous surface at pressure of 0.7 bar

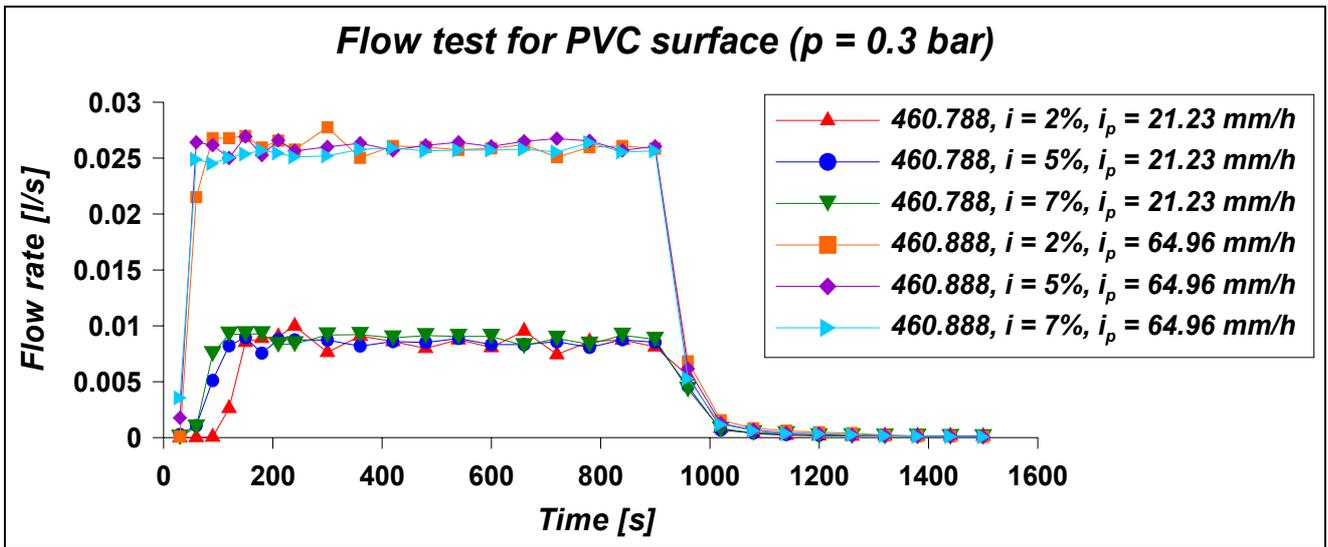


Figure 17: Plot of flow rate vs. time curve for PVC surface at pressure of 0.3 bar

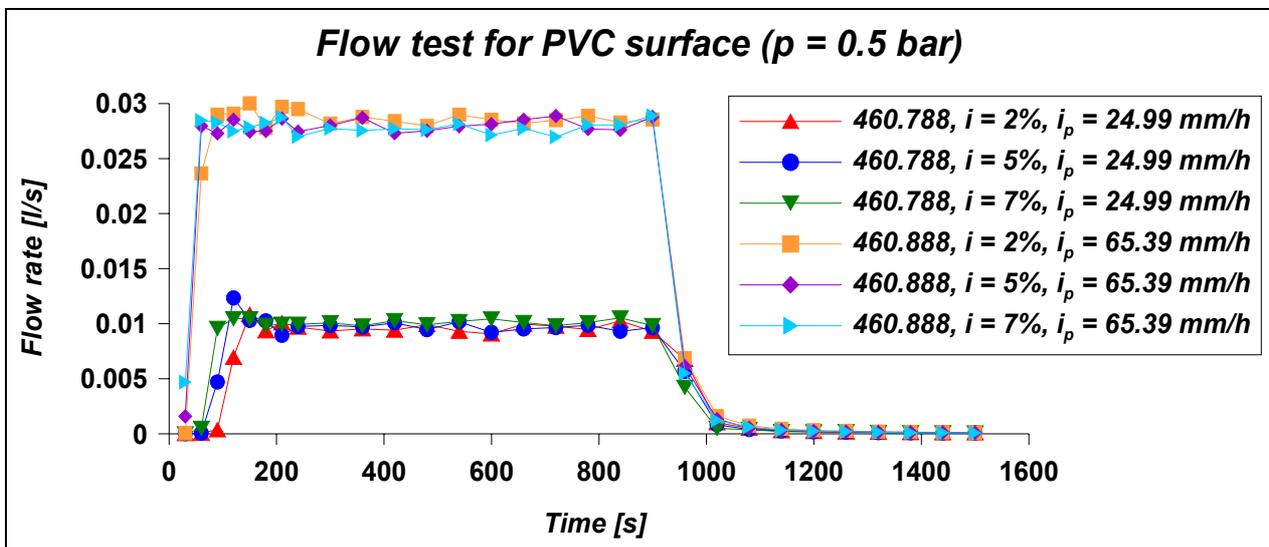


Figure 18: Plot of flow rate vs. time curve for PVC surface at pressure of 0.5 bar

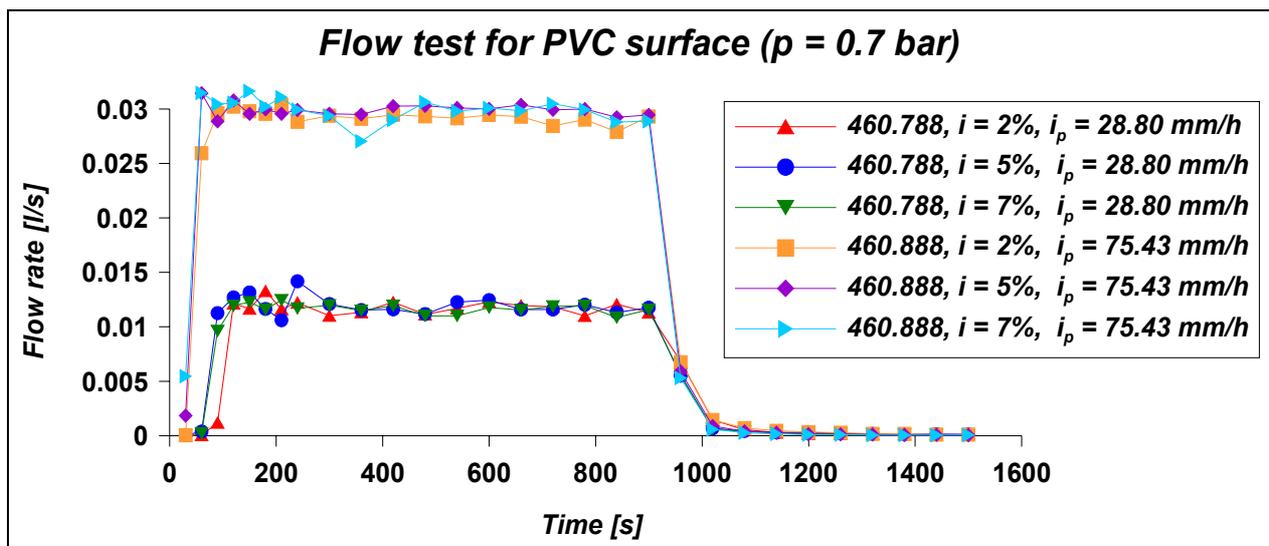


Figure 19: Plot of flow rate vs. time curve for PVC surface at pressure of 0.7 bar

It has been calculated the area subtended by the descending branch of the flow rate plots (time > 900 s) with different rain intensities and different surface slopes. From comparison between bituminous surface and

PVC surface results it has been valued the water volume kept by asphalt, known also as "reservoir effect" (figures 20, 21 and 22).

The results show a decrease of reservoir effect with the reduction of rain intensity and with the increase of surface slope.

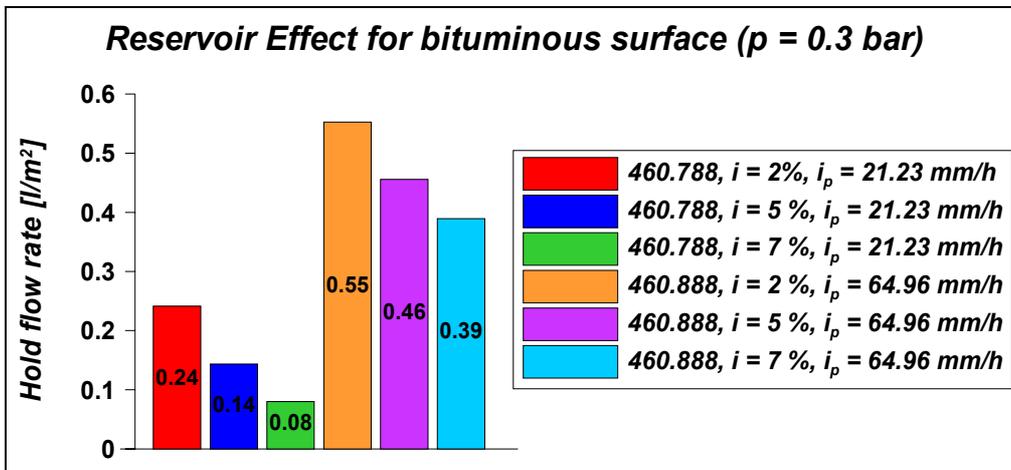


Figure 20: Plot of reservoir effect of bituminous surface at pressure of 0.3 bar

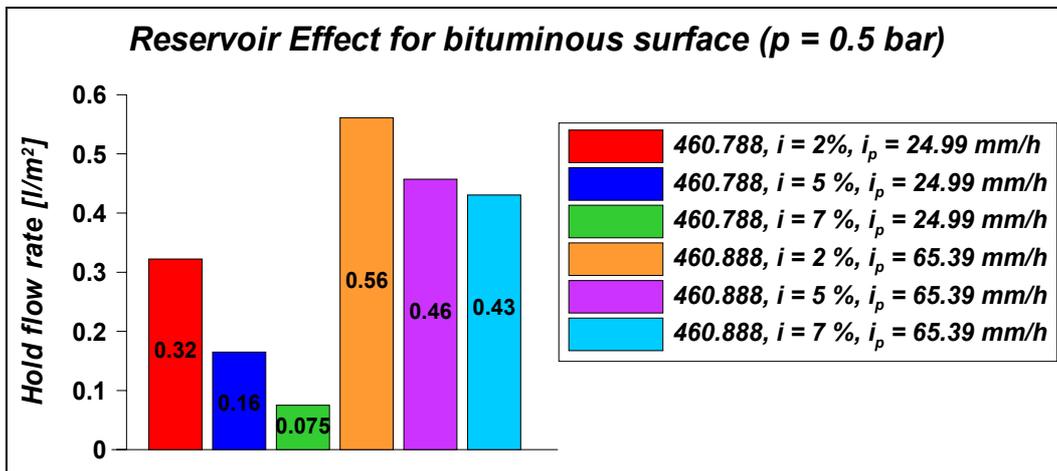


Figure 21: Plot of reservoir effect of bituminous surface at pressure of 0.5 bar

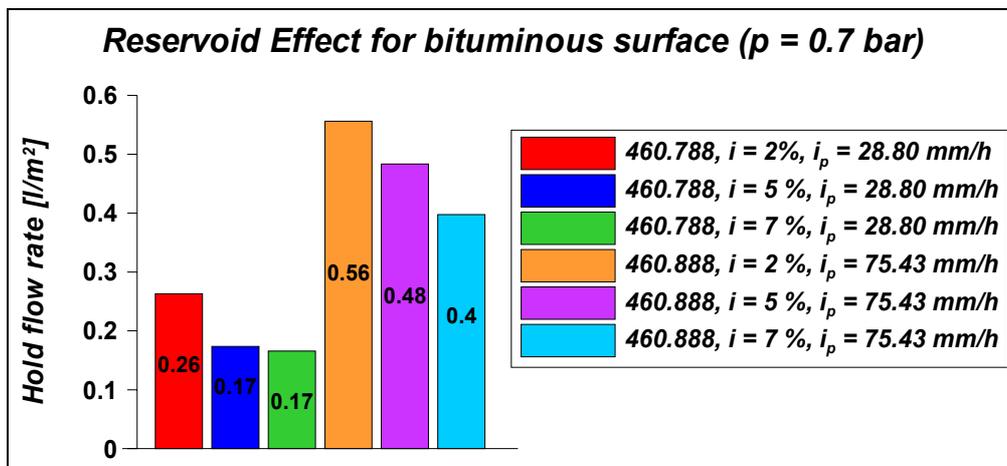


Figure 22: Plot of reservoir effect of bituminous surface at pressure of 0.7 bar

From flow rates flowing out the final section of the bituminous surface it has been calculated the water film depth through the "reservoir model" (Artina et al, 1997), because it is agree with runoff lengths similar to the

real roadways widths. It assimilates the catchment to a linear reservoir and it supposes that the flood volume depends only on the flow height in the final section. Its hydrograph is:

$$0 < t < T: q(t) = q_0 \cdot \left(1 - e^{-\frac{t}{k}}\right) \quad (5)$$

$$t > T: q(t) = q_{\max} \cdot e^{-\frac{t-T}{k}} \quad (6)$$

where:

q_0 : initial flow rate [m^3/h];

k : linear reservoir constant [h];

q_{\max} : maximum flow rate [m^3/h];

T : concentration time [h].

The initial flow rate is:

$$p(t) = \varphi \cdot i_p \cdot A \quad (7)$$

where:

φ : runoff coefficient;

i_p : rainfall intensity [m/h];

A : catchment area [m^2].

The concentration time T of bituminous and PVC surface has been calculated by flow rate experimental data. The results show an increase of T with the reduction of surface slope and of manifold pressure. The PVC surface values are smaller than bituminous surface values (table 6).

Table 6: Concentration time values

Nozzle model	Pressure [bar]	Surface slope [%]	T bituminous surface [s]	T PVC surface [s]
788	0.3	2	202	168
788	0.3	5	174	143
788	0.3	7	168	114
788	0.5	2	200	150
788	0.5	5	165	142
788	0.5	7	148	114
788	0.7	2	173	141
788	0.7	5	148	128
788	0.7	7	143	112
888	0.3	2	137	89
888	0.3	5	126	88
888	0.3	7	114	60
888	0.5	2	136	88
888	0.5	5	116	59
888	0.5	7	85	48
888	0.7	2	121	88
888	0.7	5	114	57
888	0.7	7	85	57

The model has been calibrated through the parameter k . By exponential regression it has been found a function between the reservoir constant (k) and the rain intensity (i_p), able to coincide the theoretical data with experimental values ($R^2 = 0.96$):

$$k = 0.0013 \cdot i_p^{-0.7663} \quad (8)$$

From the maximum flow rate (q_{\max}), the surface area (A) and the reservoir constant (k), it has been calculated the water film thickness for bituminous surface (the thickness over the pavement texture) (w) and for PVC surface (w_{PVC}):

$$w = \frac{k \cdot q_{\max}}{A} \quad (9)$$

where:

w : water film thickness [m];

k : reservoir constant [h];

q : maximum flow rate [m^3/h];

A : catchment area [m^2].

These values have been compared with results obtained from the following analytical formulas (table 7):

- Ross and Russam [32]: $w_1 = 0.015 \cdot (c \cdot l \cdot i_p)^{0.5} \cdot i^{-0.2}$ (10)

where:

w_1 : water film thickness [cm];
 c: runoff coefficient;
 l: length of runoff path [m];
 i_p : rainfall intensity [cm/h];
 i: slope of runoff path.

- Strickler [28]: $w_2 = \left(\frac{q}{k_s \cdot i^{0.5}}\right)^{0.54}$ (11)

where:

w_2 : water film thickness [m];
 q: maximum flow rate [$m^3 \cdot m/h$];
 k_s : roughness coefficient [$m^{-1/3}/s$];
 i: slope of runoff path.

- Artina et al. [3]: $w_3 = \left(\frac{q}{0.78 \cdot n \cdot A \cdot (\phi \cdot a)^{1/n}}\right)^{\frac{n}{n-1}}$ (12)

where:

w_3 : water film thickness [m];
 q: maximum flow rate [m^3/h];
 n: exponent of the depth-duration curve;
 A: catchment area [m^2];
 ϕ : runoff coefficient;
 a: coefficient of the depth-duration curve.

For the town of Bologna has been assumed n equal to 0.62 considering short duration rainfalls.

- Macchione and Veltri [2]: $w_4 = 0.0474(l_p \cdot i_p)^{0.5} \cdot i^{-0.2}$ (13)

where:

w_4 : water film thickness [mm];
 l_p : water stream way length [m];
 i_p : rainfall intensity [mm/h];
 i: slope of runoff path.

Table 7: Water film depth value for bituminous and PVC surface

Nozzle model	Pressure [bar]	Surface slope [%]	Bituminous surface					PVC surface
			w (9) [mm]	w_1 (10) [mm]	w_2 (11) [mm]	w_3 (12) [mm]	w_4 (13) [mm]	w_{PVC} (9) [mm]
788	0.3	2	0.14	0.43	0.29	0.13	0.28	0,61
788	0.3	5	0.19	0.34	0.34	0.16	0.15	0,54
788	0.3	7	0.23	0.33	0.38	0.25	0.22	0,56
788	0.5	2	0.13	0.46	0.29	0.12	0.31	0,58
788	0.5	5	0.21	0.39	0.38	0.17	0.26	0,66
788	0.5	7	0.21	0.36	0.38	0.37	0.24	0,56
788	0.7	2	0.16	0.50	0.35	0.11	0.33	0,64
788	0.7	5	0.21	0.41	0.41	0.14	0.27	0,68
788	0.7	7	0.25	0.39	0.44	0.27	0.26	0,60
888	0.3	2	0.19	0.65	0.54	0.15	0.49	0,71
888	0.3	5	0.19	0.54	0.54	0.15	0.41	0,69
888	0.3	7	0.21	0.51	0.57	0.17	0.38	0,68
888	0.5	2	0.21	0.65	0.57	0.26	0.50	0,76
888	0.5	5	0.21	0.55	0.58	0.33	0.41	0,74
888	0.5	7	0.22	0.51	0.58	0.34	0.39	0,74
888	0.7	2	0.20	0.70	0.61	0.47	0.53	0,70
888	0.7	5	0.21	0.59	0.61	0.75	0.44	0,72
888	0.7	7	0.23	0.55	0.64	0.76	0.41	0,73

The results show that the experimental values are agree with w_3 results (Artina et al, 1997) especially for low and medium rain intensity, and with w_4 results (Macchione and Veltri, 1988) especially for low rain intensities and medium and high surface slopes. For high rain intensities the experimental data don't confirm the analytical ones. This fact could be explain due to the increase of reservoir effect, which causes the growth of

water enclosed inside the road pavement and consequently the reduction of water film thickness. This is confirmed by the comparison between the water film depth for bituminous and PVC surface (table 7). The water film depth (w) increases to growth of manifold pressure and of surface slope. This fact could be explain due to the decrease of reservoir effect to the increase of the surface slope, because the water doesn't remain trapped inside the asphalt and so it flows on the road pavements.

From comparison between PVC and bituminous surface results it has been calculated the reservoir effect of the bituminous surface (table 8). The results confirm flow rate tests data (figures 21, 22 and 23), especially for medium and high rain intensities.

Table 8: Experimental reservoir effect values

Nozzle model	Pressure [bar]	Surface slope [%]	$W_{\text{bituminous surface}}$ [mm]	$W_{\text{PVC surface}}$ [mm]	Reservoir effect [l/m ²]
788	0.3	2	0,14	0,61	0,19
788	0.3	5	0,19	0,54	0,14
788	0.3	7	0,23	0,56	0,13
788	0.5	2	0,13	0,58	0,21
788	0.5	5	0,21	0,66	0,20
788	0.5	7	0,21	0,56	0,16
788	0.7	2	0,16	0,64	0,24
788	0.7	5	0,21	0,68	0,23
788	0.7	7	0,25	0,60	0,18
888	0.3	2	0,19	0,71	0,50
888	0.3	5	0,19	0,69	0,48
888	0.3	7	0,21	0,68	0,45
888	0.5	2	0,21	0,76	0,53
888	0.5	5	0,21	0,74	0,50
888	0.5	7	0,22	0,74	0,49
888	0.7	2	0,20	0,70	0,53
888	0.7	5	0,21	0,72	0,52
888	0.7	7	0,23	0,73	0,51

The results show that for time and rain intensity according to the experimental ones, frequent for Bologna, the experimental HS value, typical for traditional wearing course, is not enough to avoid the water film on the road surface. To drain water on a road pavement are preferable porous asphalt or stone mastic asphalt, which eliminate hydroplaning and spray phenomenon.

CONCLUSIONS

To study the pollutants wash-off on road pavements and the effect of water film depth on skid resistance and safety, it has been builded an experimental device composed from a rainfall simulator, a structure with adjustable inclination on which is placed a bituminous surface, a system to remove external rainfall to the bituminous surface and a collection system of internal rainfall to bituminous surface, set at the final section. The artificial rain system is capable of simulating variable rainfall intensities by different nozzles.

The experimental tests have shown that part of the available pollutant is removed from the surface as wash-off; the remainder becomes a part of the fixed load as it attaches itself to the surface. The removed sediments are mainly related to the build up sediments on the surface during the following dry period. This means that the calculated wash coefficients $Arra$ seems independent from the fixed load on the experimental surface.

From flow rates flowing out the final section of the plate, it has been studied the reservoir effect of the bituminous surface. The results show its decrease with the reduction of rain intensity and with the growth of surface slope. Through the "reservoir model", adjusted to the experimental data, it has been calculated the water film depth with different surface slope. It increases to growth of manifold pressure and of surface slope. So it is possible to design the "reservoir effect" of the bituminous surface in order to provide a minimum level of wet skid resistance. The experimental device described in the paper could be considered as an useful tool to decide upon the most suitable means of water removal. The aim of the apparatus should be to improve the understanding of the runoff on bituminous surfaces and to develop new predictive techniques to determine the water film depth value and to design bituminous surfacing materials that will result in safer roads in the future.

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