Drainage Issues Related to Porous Pavements

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Synopsis

The paper deals with the issue of the drainage of porous pavements.
This kind of pavements can be divided into two main categories: full depth porous pavements and pavements in which only the friction course is porous. The first is widely used in parking lots and in urban areas where no heavy traffic is expected. For all other purposes, porous friction courses are used: 3 ÷ 5 cm thick in the European practice, about 2 cm in the US practice. The paper focuses drainage issues related to these porous friction courses.
After a brief description of the main features adopted to solve this problem, a model is presented in order to predict the need of sub-drains and their spacing.
This model is the evolution of a previous one, in which some corrections have been introduced taking into account some empirical findings. Originally the model was solved in order to find the maximum level of the water table flowing within the porous friction course. After the introduction of the empirical correction, the model has been further managed in order to find the maximum flow path length before the water starts flowing over the pavement. Thus, it has been solved again using the Runge-Kutta method and several runs have been performed simulating various scenarios of porous friction courses exposed to rainfall. The results of these simulations are reported in tables that provide the maximum flow path length that should not be exceeded to avoid the surface runoff.
These tables can be useful for practitioners to correctly design drain spacing.
For a given road section, the designer simply have to verify that the designed drain spacing does not exceed the maximum flow path length provided by the tables.

Drainage Issues Related to Porous Pavements

Since about fifteen years porous pavements are actually wide spreading. This is due to the great benefits they offer in comparison with traditional hot mix asphalts (HMA) pavements. At reasonable costs, porous pavements offer better acoustical, safety and comfort performance.

Porous pavements can be divided into two main categories: full depth porous pavements and pavements in which only the friction course is porous. The first is mainly used in parking lots and in urban areas where no heavy traffic is expected. For all other purposes, porous friction courses (PFC) are used. Commonly, in the European practice PFC are 3 ÷ 5 cm thick (or more), while in other countries, such as in US, they are about 2 cm thick *(Lefebvre, 1993)*. The different thickness is due to the different aim for which they are laid: in the first case water is expected to drain mainly within the friction course; PFC are therefore designed to eliminate or to reduce as much as possible the water film thickness over the surface. In the second case water is expected to drain through and over the surface *(Roberts et al., 1996)*; the high roughness of road surface helps tires to break the water film so to ensure a good skid resistances even in wet conditions.

As regards water discharge, both of the categories of porous pavements can reduce the negative effects of water on the road surface by: 1) storing the water under the surface and 2) draining it. In full depth pavements both storage and drainage are effective *(Lefebvre, 1993; Goacolou, 1993).* In porous friction courses the second is much more effective because of the reduced thickness of the course. The importance of drain placement is evident for both the categories: in first case they should ensure the drainage of the stored water. In the second they could ensure a more effective drainage. As for full depth porous pavements, many studies have been carried out and drain spacing is an issue well established in the practice. We cannot say the same for the porous friction courses whose practice is relatively young. The need of the placement of draining systems under the porous friction courses is a relevant issue of the practice because of the thickness of layers and the expected runoff behaviour. Even if some interesting studies have been already carried out, in many projects in which sub-drains were provided, their spacing was mostly left to the designers' experience, without the aid of a specific rational method. In the following pages some considerations are given about this issue. The evolution of some studies carried out on drainage capacity of PFC is also presented in order to give some help to the designers in placing draining systems under such a kind of friction courses.

DRAIN SPACING FOR FULL DEPTH POROUS PAVEMENTS

Full depth porous pavements are largely used since 30 years especially for parking lots and for those roads with low traffic volumes. Thus, a large experience was accumulated in designing this kind of projects. From a mathematical point of view their hydraulic behaviour is referable to the behaviour of an aquifer replenished from the top, moving on a impervious horizontal plane. Such a model is commonly studied in hydraulic, irrigation and agricultural sciences so that the experience cumulated in these subjects is loanable for porous pavements practice.

Anyway, in literature a study by T. J. Jackson and M. R. Ragan *(Jackson and Ragan, 1974)* was found to be very interesting. The Authors, starting from some rational studies on full depth porous pavements hydraulic behavior, give a solution to the design problem of such a kind of porous pavements. Referring to the symbols in figure 1, the following equations are given respectively to find the peak discharge Qp (cubic feet per second per feet of pipe) entering each subdrain, the maximum depth Hm (inches) of the saturated zone in the pavement and the time T50 (minutes) required to drain 50% of drainable water after storm:

$$Q_p = \frac{2\sum P}{n_e} e^{[-11.199+0.499\ln(K)]} \quad (1)$$

$$H_m = \frac{\sum P}{n_e} e^{\{-0.459+0.217\ln(BCF1)-0.02[\ln(BCF1)]^2\}} \quad (2)$$

in which BCF1 = $\frac{S^2 n_e^2}{4K}$

$$T_{50} = e^{[4359+0.989\ln(BCF2)]} \quad (3)$$

in which BCF2 = $\frac{S^2 n_e}{4KH_{av}}$ and

$H_{av} = \frac{\sum P}{n_e} e^{\left\{-1.144+0.570 \ln(BCF1)-0.106[\ln(BCF1)]^2+0.007[\ln(BCF1)]^3\right\}}$ is the average depth of saturation zone at the cessation of rainfall.

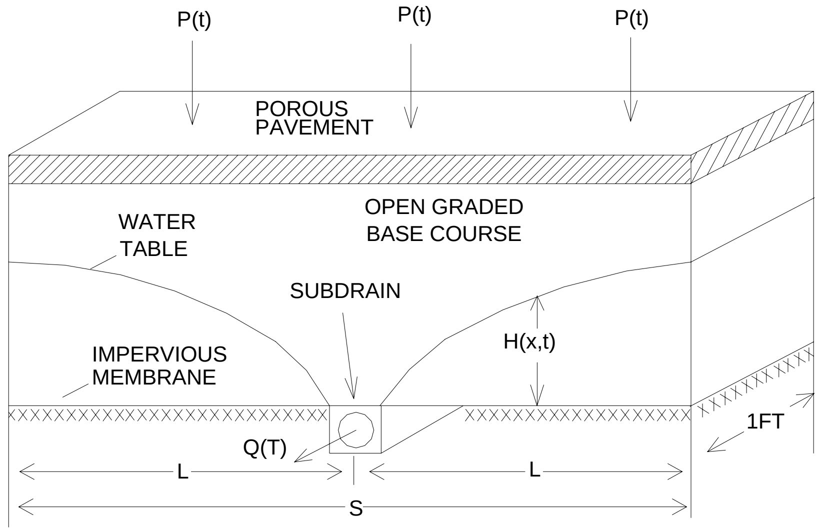

Figure 1: Schematic representation of the porous pavement studied by T.J. Jackson and M.R. Ragan

Equations (1), (2) and (3) are given all as functions of permeability K (inches per minute), effective porosity n_e, sub-drain spacing S (feet) and rainfall ΣP (inches). Given a paving area, they can help the designer to select the right drain spacing or the correct physical properties of the base course in order to achieve a satisfactory drain control.

POROUS FRICTION COURSES

The use of porous pavements also for high volume roads is fairly recent. It is about 15 years that improvements in asphalt cement technologies allowed the production of porous hot mix asphalts capable of considerable mechanical strength. Since that moment porous pavements become largely diffused especially in Europe and North America. There is a substantial difference between American and European practice. In the first case they are usually placed 2 cm thick (the so called Open Graded Friction Courses – OGFC): water is expected to flow over the surface and their main aim is to improve the contact tire/pavement in wet conditions. In the second case they are often placed 3 ÷ 5 cm thick: water is expected to move as much as possible under the surface. The aim is to reduce or completely eliminate the water film over the surface in order to reduce aquaplaning risks, splash & spray and all other risks related to the presence of water over the surface.

The different way of working of the two types of friction courses is due to 1) different gradation and 2) the different thickness of the courses. The reduced thickness of 2 cm PFC makes grains disposing so to present asperities toward the top. In wet conditions it ensures a better tire/pavement contact and, simultaneously, allows a little part of the total amount of water to flow under the surface, trough the grooves between grains. On the other hand, the thicker PFC can store a relatively high amount of water and simultaneously drain it through the layer. But, at the same time, the deep thickness of these PFC makes grains to dispose mostly with the flatter face toward the top. Thus, if water begins to flow over the surface, they offer a reduced contact tire/pavement if compared to OGFC.
But this does not mean that they perform worse than OGFC. In fact because of their storing capacity, for a given rainfall rate, PFC however ensure a thinner water film over the surface than OGFC.
In the same way, if water starts flowing over the surface, PFC don't perform worse than the traditional HMA, even if the great benefits they offer are strongly reduced.

According to what above said, the importance of ensuring a good drainage for porous friction courses is evident. Water should never flow over the surface especially in that roads where vehicles run at high speeds. Drivers could erroneously feel to drive on a rough surface with improved skid resistance, more than how much the pavement is really capable. It is a great safety issue. This is more evident if we think that those roads where speeds are higher are multilane highways in which the flow path of the discharging water is considerable. Here the probability that water could start flowing over the surface is high and, consequently, it is high the risk of accident. In presence of steep longitudinal slopes and/or of transition curves, the risk is further increased. Thus, a PFC project can be considered reliable only if an appropriate draining system is designed. Water film thickness over the porous pavement should be avoided or limited as much as possible. The effectiveness of the draining system is therefore of great importance, especially in these kinds of road sections.

Water drainage systems for porous friction courses

In order to be reliable, the PFC draining system should be studied in all its components. The sound study of drain spacing, permeability and thickness of the layer could be absolutely useless if an effective accommodation of discharging water is not provided at the edge of the pavement. Concerning this issue, fig. 2 shows some typical edge configuration of extra-urban roads taken from the literature *(Lefebvre, 1993)*.

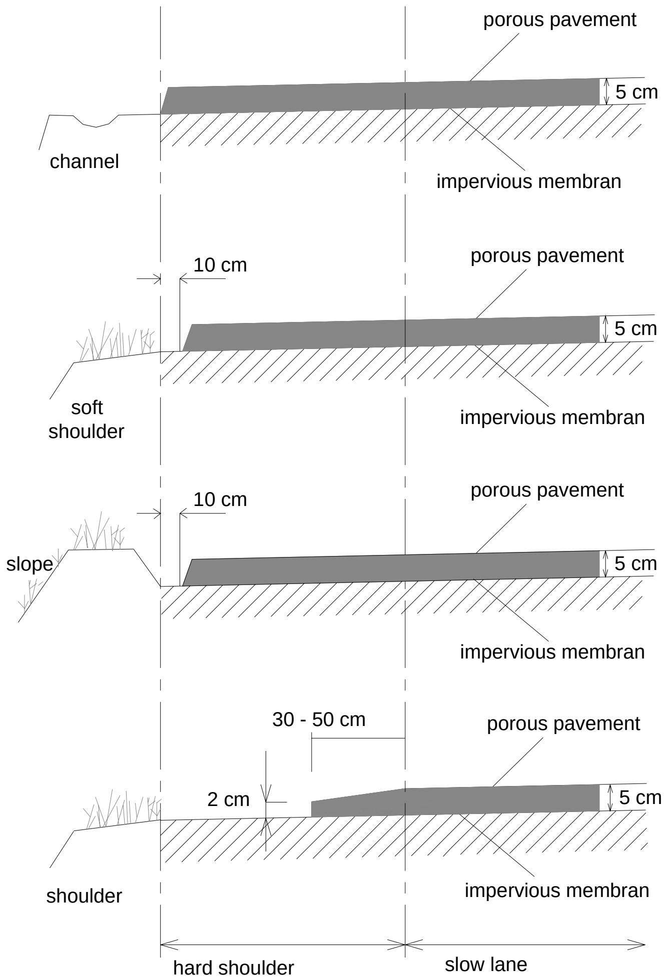

Figure 2: Typical examples of PFC surfacing

Beyond the PFC water should not find any obstacle to its free flowing. Thus, channels must be provided to favorite the water flow. They should be large enough to ensure the flow also in presence of dirt. The third example in the figure reports a typical settlement of many projects on Italian motorways. The PFC is extended over the hard shoulder and a channel 10 cm wide is left in order to ensure the free water discharge beyond the porous layer. In other countries the PFC is extend only on a 40-50 cm of the hard shoulder so that a larger cross section of the hard shoulder is left free for the water flowing. In this way an improved protection against dirt clogging is ensured as well as savings. On the other hand, the presence of a 4-5 cm step at the edge of the slow lane could be very dangerous. For this reason the extension of the paved area over the shoulder should have a beveled profile going from 4 – 5 cm to 2 cm. This beveling profile should never be obtained by over compacting the edge. It causes the loss of porosity and subsequently the failure of the drainage system.

After the design of edge configuration, the need of sub-drains should be investigated. In many road sections, slopes are such that some help is needed to ensure a good drainage.

In urban areas it happens mostly when the cross fall of the street has not a sufficient slope. In extra urban roads, it happens in transition curves, where the cross fall is necessary small, and in all that cases in which the combination between cross and longitudinal slopes make the runoff path too long. Moreover, in multilane highways, even if there is a good cross fall and no steep longitudinal slope, the carriageway width is too large to prevent the surface runoff. In all these cases sub-drains should be provided. As mentioned in previous paragraphs, the prevention of the surface runoff on PFC is very important from safety point of view, especially for multilane highways. The correct placing and spacing of sub-drains is therefore an important issue.

DRAINS PLACING AND SPACING IN POROUS PAVEMENTS

About this issue, many different cases can be found in the practice literature. According to some Authors the flow path length of water within the PFC should never exceed 20 m *(Palazzi et al. 1991)*. Others report reduced distances between drains till the example of the Portuguese project reported by A.S. Luis *(Luis, 1997)* in which sub-drains where placed 6/8 m spaced.
In all the cases it seems that in the practice drain spacing is often left to the skill of the designer more than to the use of an univocal rational design method.

From a physical point of view, drain spacing depends on 4 fundamental variables: the PFC permeability (k), the amount of flowing water (q), the geodetic inclination of the road section (i), and the thickness (T) of the PFC. Taking into account these variables a mathematical model was studied in order to understand the behaviour of water running off from a PFC. The fundamental equation of the model is:

$$\frac{d}{dx}\left(Hk\frac{dh}{dx}\right) = -I \qquad (4)$$

where x is the abscissa on the horizontal plane of the seepage path counted from the bottom of the system, h is the piezometric head referred to the horizontal plane at the abscissa x, H is the piezometric head referred to the inclined plane at the abscissa x, I is the constant rate of replenishment from the top (rainfall intensity), and k is the permeability of the PFC.
Equation (4) was solved given the boundary conditions of impermeability at the top edge of the road cross section (because of symmetry or the physical presence of impervious materials - $\frac{dh}{dx}=0$), and the presence of the channel at the bottom edge of the PFC ($H = H_0$):

$$\frac{dH}{dx} = \left[\frac{I\cdot(L-x)}{H\cdot k}\right] - i$$

Its solutions are:

$$\left[\left|A-\frac{i+\sqrt{\Delta}}{2}\right|^{\frac{1}{2}\left(\frac{i}{\sqrt{\Delta}}-1\right)}\right]\cdot\left[\left|A-\frac{i-\sqrt{\Delta}}{2}\right|^{-\frac{1}{2}\left(\frac{i}{\sqrt{\Delta}}+1\right)}\right] = c\cdot(L-x) \qquad \text{for } \Delta > 0 \qquad (5)$$

and

$$log\left[\left(\frac{I}{k}\right)^2\cdot(x-L)^2\cdot\left(A^2-iA+\frac{I}{k}\right)\right] - \frac{2i}{\sqrt{-\Delta}}\,arctg\left(\frac{2A-i}{\sqrt{-\Delta}}\right) = c \qquad \text{for } \Delta < 0 \qquad (6)$$

where:
$\Delta = i^2 - 4\frac{I}{k}$;
$A = \frac{h-iL}{x-L}$;
L is the length of the flow path and
c is the constant of integration.

The model was tested in laboratory. The predicted free water surfaces were found to fit very well the actual surfaces if the following correction were made to the permeability:

$$k = \{[-0{,}013(\ln(I/k_D))^2 - 0{,}226\ln(I/k_D) - 0{,}96] \cdot i + 63.19 \cdot (I/k_D)^{0,6}\} \cdot k_D \quad (7)$$

where:
i is the geodetic inclination of the road section expressed in percent,
k is the actual permeability of the PFC, and
k_D is the Darcy's permeability of the PFC, as measured in laboratory.

Details about the model and its experimental validation are in *(Ranieri, 1998 and Ranieri, 2002).*

As consequence of these studies, a design nomogram useful for runoff control in PFCs was presented (see figure 3). For every inclination (i) of the pavement, the nomogram provides the value of the non-dimensional ratio H_{max}/L between the maximum depth (H_{max}) of the water table flowing through the porous layer and the length (L) of the seepage path, in function of the non-dimensional ratio 4I/k between the rainfall intensity (I) and the permeability (k). Thus, given both the geometric characteristics of the road section and the permeability of the porous asphalt, the maximum level of the water flowing through the PFC is known for a given rainfall intensity.

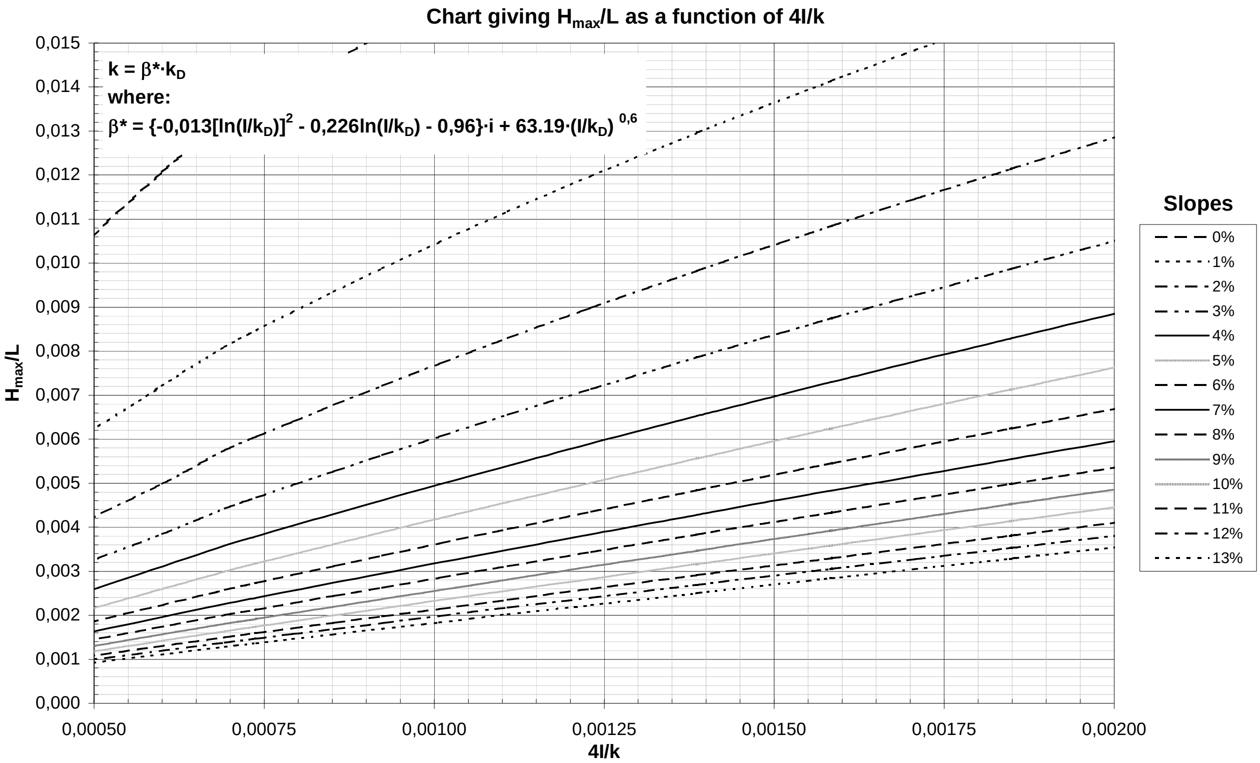

Figure 3: Chart giving the values of H_{max}/L (non-dimensional) as a function of the non-dimensional ratio 4·(I/k); k_D is the Darcy's permeability, which is the permeability usually measured with common laboratory permeameters. The slope (i) is expressed in percent

After this first result, the model has been managed by introducing the empirical equation (7) in equation (4). Thus, the model has been solved in a numerical way by using the IV order Runge-Kutta method.
Given the boundary conditions above and the incremental step Δx, the following system of linear equations has been written:

$$H_j = H_{j-1} + \frac{\Delta x}{6}\left(W_1 + 2W_2 + 2W_3. + W_4\right) \quad (8)$$

where: j = 1, 2, ..., n;
$n = L/\Delta x$;

$$W_1 = \frac{I \cdot \left(L - x_{j-1}\right)}{H_{j-1} \cdot \beta \cdot k_D} - i;$$
$$W_2 = \frac{I \cdot \left[L - \left(x_{j-1} + \frac{\Delta x}{2}\right)\right]}{\left(H_{j-1} + \frac{\Delta x}{2} \cdot W_1\right) \cdot \beta \cdot k_D} - i;$$
$$W_3 = \frac{I \cdot \left[L - \left(x_{j-1} + \frac{\Delta x}{2}\right)\right]}{\left(H_{j-1} + \frac{\Delta x}{2} \cdot W_2\right) \cdot \beta \cdot k_D} - i;$$
$$W_4 = \frac{I \cdot \left[L - \left(x_{j-1} + \Delta x\right)\right]}{\left(H_{j-1} + \Delta x \cdot W_3\right) \cdot \beta \cdot k_D} - i;$$

and

$\beta = [-0,013(\ln(I/k_D))^2 - 0,226\ln(I/k_D) - 0,96] \cdot i + 63.19 \cdot (I/k_D)^{0,6}$.

Then, the need of sub-drains has been investigated. Given the thickness of the PFC, the maximum flow path length (MFPL) that should not be exceeded to avoid the surface runoff was observed at different values of the inclination of the road section (i), the rainfall intensity (I), and the permeability (k_D).

Table 1 reports preliminary results obtained running the model with typical data of a PFC project: thickness of the layer T = 4 cm, k_D = 1.0 cm/s, rainfall rates ranging from 10 mm/h to 25 mm/h, and the geodetic inclination of the road section ranging from 1% to 13 %.

Tab 1: Maximum flow path length (MFPL) to avoid the surface runoff for various inclinations of the road section and rainfall rates. The thickness of the porous pavement is 4 cm and its Darcy's permeability is 1.0 cm/s

Rainfall rates (mm/h)	Path length (m)												
	i=1%	i=2%	i=3%	i=4%	i=5%	i=6%	i=7%	i=8%	i=9%	i=10%	i=11%	i=12%	i=13%
10	2,18	2,74	3,32	3,91	4,52	5,13	5,75	6,38	7,01	7,65	8,29	8,93	9,58
15	1,97	2,44	2,93	3,44	3,95	4,46	4,99	5,52	6,05	6,58	7,12	7,67	8,21
20	1,83	2,25	2,69	3,14	3,59	4,05	4,51	4,98	5,45	5,93	6,40	6,88	7,37
25	1,73	2,12	2,52	2,92	3,33	3,75	4,18	4,60	5,03	5,46	5,90	6,34	6,77

As shown, the MFPL ranges from 1.73 m for I = 25 mm/h and i = 1%, to 9.58 m for I = 10 mm/h and i = 13 %. Thus, the length of 20 m above mentioned seems to be inappropriate as also in the extreme cases (i > 10 ÷13%, I = 10 mm/h) the maximum flow path length before water starts to run over the pavement is about 8-10 m. For the lowest values of slopes, the MFPL is very short.

As the slope increases the MFPL increases too, with a quasi - constant rate. On the contrary, given the slope, the increasing of the rainfall rate gives a fall of the MFPL. The rate of this fall tends to decrease with the increasing of the rainfall intensity. It appears that as the amount of water flowing increases, the velocity of the water increases with a rate less than proportional. What above said is evident in figure 4 that shows the curve giving the MFPL as a function of the slope for different rainfall rates. The angular coefficient (m) of the functions MFPL vs i decreases showing a knee at the rate of about 16 mm/h.

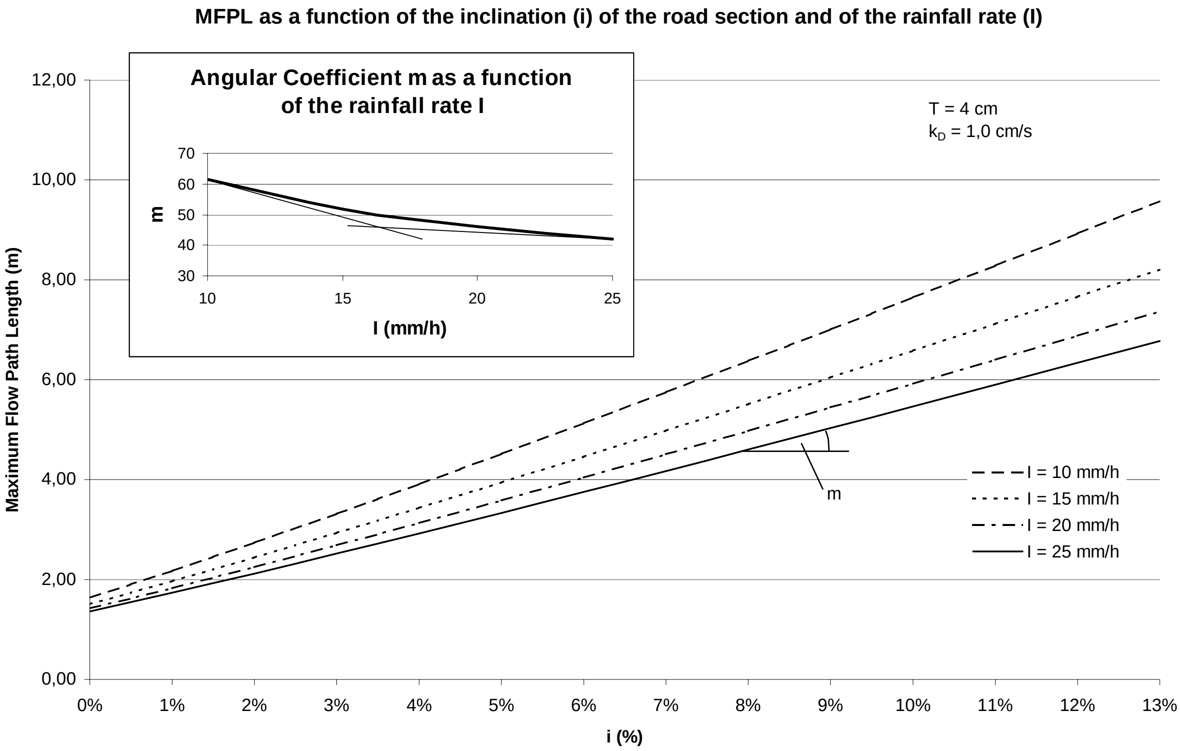

Figure 4: Maximum flow path length as a function of the slope (i) and the rainfall intensity (I)

So, when a PFC is placed, steep slopes are needed. In absence, subdrains are strongly recommended. Paradoxically, according to what above said, steep slopes are less effective in presence of low rainfall rates. Sub drains should not be provided only in a case of level road sections.

The flow path length (L) and its inclination (i) depend on the combination of the carriageway width (L_c), its longitudinal gradient (i_l) and its cross slope (i_c) through the following equations:

$$L = L_c \left[1 + \left(\frac{i_l}{i_c}\right)^2\right]^{1/2} \quad (9)$$

$$i = \left(i_c^2 + i_l^2\right)^{1/2} \quad (10)$$

It's therefore evident how easy is that water can flow over the surface in presence of steep longitudinal grades, especially for multilane carriageways. Figure 5 shows a typical case of the failure of a project in Italy. It can be easily observed how the water comes out from the PFC at the beginning of the slow lane, yet.

Figure 5: Typical example of the failure of a project

Subdrains are therefore needed in presence of low slopes and/or of large road cross sections. Moreover, to avoid the failure of the project, subdrains should be designed and placed accurately, with regard to all the variables affecting the problem (L_c, i_l, i_c, k_D, T and I). They should be placed, across the section using U shaped metal profile or by digging a little trench (see figure 6).

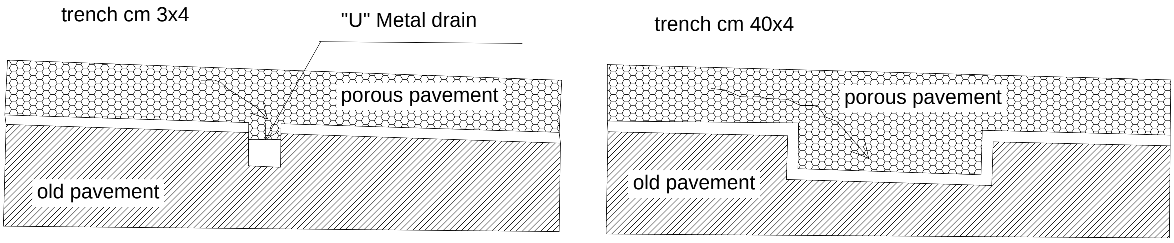

Figure 6: Examples of subdrain placing in a multilane carriageways

As for the calculation of the spacing, table 2, 3 and 4 report the MFPL obtained running the model above mentioned for different values of Darcy's permeability, rainfall rates and PFC thickness.
For each combination of the variables (i, k_D, T and I), the tables provide for the correct values of the MFPL that should not be exceeded.

Thus, for a given road section, the designer can easily compare the MFPL values provided by the tables with the actual flow path length calculated with equations (9) and (10). If MFPL is exceeded, he should provide subdrains that shall be placed spaced no longer than the MFPL.

Tab 2: Maximum flow path length (MFPL) to avoid the surface runoff for various inclinations of the road section (i), permeability (k_D) and rainfall rates (I). The thickness of the PFC is 5 cm

k_D (cm/s)	I (mm/h)	Maximum flow path length (m) i= 0%	i= 1%	i= 2%	i= 3%	i= 4%	i= 5%	i= 6%	i= 7%	i = 8%	i = 9%	i= 10%	i= 11%	i= 12%	i= 13%
	10	1,78	2,29	2,82	3,36	3,92	4,48	5,06	5,64	6,22	6,81	7,41	8,00	8,60	9,21
	15	1,64	2,07	2,52	2,98	3,45	3,93	4,41	4,90	5,40	5,89	6,39	6,90	7,40	7,91
	20	1,55	1,93	2,33	2,74	3,16	3,58	4,01	4,44	4,88	5,32	5,77	6,21	6,66	7,11
0,5	25	1,48	1,83	2,20	2,57	2,95	3,33	3,73	4,12	4,52	4,92	5,32	5,73	6,14	6,55
	30	1,43	1,76	2,09	2,44	2,79	3,15	3,51	3,88	4,25	4,62	4,99	5,37	5,75	6,13
	40	1,35	1,64	1,94	2,25	2,56	2,88	3,20	3,52	3,85	4,18	4,51	4,85	5,18	5,52
	50	1,29	1,56	1,83	2,11	2,39	2,68	2,98	3,27	3,57	3,87	4,17	4,48	4,78	5,09
	10	2,04	2,72	3,42	4,15	4,89	5,65	6,42	7,19	7,98	8,76	9,56	10,36	11,17	11,97
	15	1,89	2,46	3,05	3,67	4,29	4,93	5,58	6,23	6,89	7,56	8,23	8,90	9,58	10,26
	20	1,78	2,29	2,82	3,36	3,92	4,48	5,06	5,64	6,22	6,81	7,41	8,00	8,60	9,21
1,0	25	1,70	2,17	2,65	3,15	3,65	4,17	4,69	5,22	5,75	6,29	6,83	7,37	7,92	8,47
	30	1,64	2,07	2,52	2,98	3,45	3,93	4,41	4,90	5,40	5,89	6,39	6,90	7,40	7,91
	40	1,55	1,93	2,33	2,74	3,16	3,58	4,01	4,44	4,88	5,32	5,77	6,21	6,66	7,11
	50	1,48	1,83	2,20	2,57	2,95	3,33	3,73	4,12	4,52	4,92	5,32	5,73	6,14	6,55
	10	2,22	3,01	3,85	4,70	5,58	6,48	7,39	8,31	9,24	10,17	11,12	12,07	13,02	13,98
	15	2,04	2,72	3,42	4,15	4,89	5,65	6,42	7,19	7,98	8,77	9,56	10,36	11,17	11,97
	20	1,93	2,53	3,16	3,80	4,46	5,13	5,81	6,50	7,19	7,89	8,60	9,30	10,02	10,73
1,5	25	1,85	2,39	2,96	3,55	4,15	4,76	5,38	6,01	6,64	7,28	7,92	8,56	9,21	9,86
	30	1,78	2,29	2,82	3,36	3,92	4,48	5,06	5,64	6,22	6,81	7,41	8,00	8,60	9,21
	40	1,68	2,13	2,60	3,09	3,58	4,08	4,59	5,10	5,62	6,15	6,67	7,20	7,73	8,27
	50	1,61	2,02	2,45	2,89	3,34	3,80	4,26	4,73	5,20	5,68	6,16	6,64	7,12	7,61
	10	2,35	3,24	4,18	5,15	6,14	7,15	8,17	9,21	10,26	11,31	12,38	13,45	14,52	15,61
	15	2,17	2,92	3,72	4,54	5,37	6,23	7,09	7,97	8,85	9,74	10,64	11,54	12,45	13,36
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2,0	25	1,96	2,57	3,21	3,88	4,55	5,24	5,94	6,65	7,36	8,08	8,80	9,53	10,26	11,00
	30	1,89	2,46	3,05	3,67	4,29	4,93	5,58	6,23	6,89	7,56	8,23	8,90	9,58	10,26
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Tab 3: Maximum flow path length (MFPL) to avoid the surface runoff for various inclinations of the road section (i), permeability (k_D) and rainfall rates (I). The thickness of the PFC is 4 cm

k_D (cm/s)	I (mm/h)	Maximum flow path length (m)													
		i = 0%	i= 1%	i= 2%	i= 3%	i= 4%	i= 5%	i= 6%	i= 7%	i = 8%	i = 9%	i= 10%	i= 11%	i= 12%	i= 13%
0,5	10	1,42	1,83	2,25	2,69	3,14	3,59	4,05	4,51	4,98	5,45	5,93	6,40	6,88	7,37
	15	1,31	1,66	2,02	2,39	2,76	3,14	3,53	3,92	4,32	4,71	5,11	5,52	5,92	6,33
	20	1,24	1,55	1,87	2,19	2,53	2,86	3,21	3,55	3,90	4,26	4,61	4,97	5,33	5,69
	25	1,19	1,47	1,76	2,06	2,36	2,67	2,98	3,30	3,62	3,94	4,26	4,59	4,91	5,24
	30	1,14	1,40	1,67	1,95	2,23	2,52	2,81	3,10	3,40	3,69	3,99	4,29	4,60	4,90
	40	1,08	1,31	1,55	1,80	2,05	2,30	2,56	2,82	3,08	3,34	3,61	3,88	4,15	4,41
	50	1,03	1,24	1,46	1,69	1,91	2,15	2,38	2,62	2,86	3,10	3,34	3,58	3,83	4,07
1,0	10	1,64	2,18	2,74	3,32	3,91	4,52	5,13	5,75	6,38	7,01	7,65	8,29	8,93	9,58
	15	1,51	1,97	2,44	2,93	3,44	3,95	4,46	4,99	5,52	6,05	6,58	7,12	7,67	8,21
	20	1,42	1,83	2,25	2,69	3,14	3,59	4,05	4,51	4,98	5,45	5,93	6,40	6,88	7,37
	25	1,36	1,73	2,12	2,52	2,92	3,33	3,75	4,18	4,60	5,03	5,46	5,90	6,34	6,77
	30	1,31	1,66	2,02	2,39	2,76	3,14	3,53	3,92	4,32	4,71	5,11	5,52	5,92	6,33
	40	1,24	1,55	1,87	2,19	2,53	2,86	3,21	3,55	3,90	4,26	4,61	4,97	5,33	5,69
	50	1,19	1,47	1,76	2,05	2,36	2,67	2,98	3,30	3,62	3,94	4,26	4,58	4,91	5,24
1,5	10	1,77	2,41	3,08	3,76	4,47	5,18	5,91	6,65	7,39	8,14	8,89	9,65	10,42	11,18
	15	1,64	2,18	2,74	3,32	3,91	4,52	5,13	5,75	6,38	7,01	7,65	8,29	8,93	9,58
	20	1,54	2,02	2,52	3,04	3,57	4,10	4,65	5,20	5,75	6,31	6,88	7,44	8,01	8,59
	25	1,48	1,92	2,37	2,84	3,32	3,81	4,31	4,81	5,31	5,82	6,33	6,85	7,37	7,89
	30	1,42	1,83	2,25	2,69	3,14	3,59	4,05	4,51	4,98	5,45	5,93	6,40	6,88	7,37
	40	1,34	1,71	2,08	2,47	2,86	3,27	3,67	4,08	4,50	4,92	5,34	5,76	6,19	6,61
	50	1,29	1,62	1,96	2,31	2,67	3,04	3,41	3,78	4,16	4,54	4,92	5,31	5,70	6,09
2,0	10	1,88	2,59	3,34	4,12	4,91	5,72	6,54	7,37	8,21	9,05	9,90	10,76	11,62	12,48
	15	1,73	2,34	2,97	3,63	4,30	4,98	5,67	6,37	7,08	7,79	8,51	9,23	9,96	10,69
	20	1,64	2,18	2,74	3,32	3,91	4,52	5,13	5,75	6,38	7,01	7,65	8,29	8,93	9,58
	25	1,56	2,06	2,57	3,10	3,64	4,19	4,75	5,32	5,89	6,46	7,04	7,62	8,21	8,80
	30	1,51	1,97	2,44	2,93	3,44	3,95	4,46	4,99	5,52	6,05	6,58	7,12	7,67	8,21
	40	1,42	1,83	2,25	2,69	3,14	3,59	4,05	4,51	4,98	5,45	5,93	6,40	6,88	7,37
	50	1,36	1,73	2,12	2,52	2,92	3,33	3,75	4,17	4,60	5,03	5,46	5,90	6,34	6,77

Tab 4: Maximum flow path length (MFPL) to avoid the surface runoff for various inclinations of the road section (i), permeability (k_D) and rainfall rates (I). The thickness of the PFC is 3 cm

k_D (cm/s)	I (mm/h)	Maximum flow path length (m) i = 0%	i= 1%	i= 2%	i= 3%	i= 4%	i= 5%	i= 6%	i= 7%	i = 8%	i = 9%	i= 10%	i= 11%	i= 12%	i= 13%
	10	1,07	1,37	1,69	2,02	2,35	2,69	3,03	3,38	3,73	4,09	4,44	4,80	5,16	5,52
	15	0,98	1,24	1,51	1,79	2,07	2,36	2,65	2,94	3,24	3,54	3,84	4,14	4,44	4,75
	20	0,93	1,16	1,40	1,64	1,89	2,15	2,41	2,67	2,93	3,19	3,46	3,73	4,00	4,27
0,5	25	0,89	1,10	1,32	1,54	1,77	2,00	2,24	2,47	2,71	2,95	3,19	3,44	3,68	3,93
	30	0,86	1,05	1,26	1,46	1,67	1,89	2,11	2,33	2,55	2,77	3,00	3,22	3,45	3,68
	40	0,81	0,98	1,16	1,35	1,53	1,73	1,92	2,11	2,31	2,51	2,71	2,91	3,11	3,31
	50	0,77	0,93	1,10	1,27	1,44	1,61	1,79	1,96	2,14	2,32	2,50	2,69	2,87	3,05
	10	1,23	1,63	2,05	2,49	2,94	3,39	3,85	4,31	4,79	5,26	5,74	6,22	6,70	7,18
	15	1,13	1,47	1,83	2,20	2,58	2,96	3,35	3,74	4,14	4,54	4,94	5,34	5,75	6,16
	20	1,07	1,37	1,69	2,02	2,35	2,69	3,03	3,38	3,73	4,09	4,44	4,80	5,16	5,52
1,0	25	1,02	1,30	1,59	1,89	2,19	2,50	2,81	3,13	3,45	3,77	4,10	4,42	4,75	5,08
	30	0,98	1,24	1,51	1,79	2,07	2,36	2,65	2,94	3,24	3,54	3,84	4,14	4,44	4,75
	40	0,93	1,16	1,40	1,64	1,89	2,15	2,41	2,67	2,93	3,19	3,46	3,73	4,00	4,27
	50	0,89	1,10	1,32	1,54	1,77	2,00	2,24	2,47	2,71	2,95	3,19	3,44	3,68	3,93
	10	1,33	1,81	2,31	2,82	3,35	3,89	4,43	4,99	5,54	6,10	6,67	7,24	7,81	8,39
	15	1,23	1,63	2,05	2,49	2,94	3,39	3,85	4,32	4,79	5,26	5,74	6,22	6,70	7,18
	20	1,16	1,52	1,89	2,28	2,68	3,08	3,49	3,90	4,31	4,73	5,16	5,58	6,01	6,44
1,5	25	1,11	1,44	1,78	2,13	2,49	2,86	3,23	3,60	3,98	4,37	4,75	5,14	5,53	5,92
	30	1,07	1,37	1,69	2,02	2,35	2,69	3,03	3,38	3,73	4,09	4,44	4,80	5,16	5,52
	40	1,01	1,28	1,56	1,85	2,15	2,45	2,75	3,06	3,37	3,69	4,00	4,32	4,64	4,96
	50	0,96	1,21	1,47	1,73	2,00	2,28	2,56	2,84	3,12	3,41	3,69	3,98	4,27	4,56
	10	1,41	1,95	2,51	3,09	3,68	4,29	4,90	5,53	6,16	6,79	7,43	8,07	8,71	9,36
	15	1,30	1,75	2,23	2,72	3,22	3,74	4,25	4,78	5,31	5,85	6,38	6,93	7,47	8,02
	20	1,23	1,63	2,05	2,49	2,94	3,39	3,85	4,31	4,79	5,26	5,74	6,22	6,70	7,18
2,0	25	1,17	1,54	1,93	2,33	2,73	3,14	3,56	3,99	4,42	4,85	5,28	5,72	6,16	6,60
	30	1,13	1,47	1,83	2,20	2,58	2,96	3,35	3,74	4,14	4,54	4,94	5,34	5,75	6,16
	40	1,07	1,37	1,69	2,02	2,35	2,69	3,03	3,38	3,73	4,09	4,44	4,80	5,16	5,52
	50	1,02	1,30	1,59	1,89	2,19	2,50	2,81	3,13	3,45	3,77	4,10	4,42	4,75	5,08

CONCLUSION

After some general considerations on drainage issues related to porous pavements, the paper reports a study about the need of sub-drains in porous friction courses (PFC).
This issue was investigated by setting a quasi rationale model. It was run with different boundary conditions, typical of PFC projects. The discussion of the results confirmed that drains are necessary especially in presence of low slopes and/or of large road cross sections.

As for drain spacing, some tables are presented. They were obtained by running the model for different rainfall rates and in different conditions of thickness, permeability and inclination of the PFC. The tables provide the values of the maximum flow path length that should not be exceeded to avoid the surface runoff. These tables can be useful for practitioners to correctly design drain spacing. For a given road section, they simply have to verify that the designed drain spacing does not exceed the maximum flow path length provided by the tables.

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