# COMBATTING CONCRETE PAVEMENT SLAB PUMPING STATE OF THE ART AND RECOMMENDATIONS

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At the previous International Conference on Concrete Pavement Design and Rehabilitation in Purdue in April 1985 we presented a first synthesis on the subject of the drainage and erodability of concrete pavement foundations based upon the analyses and immediate developments of the International Seminar of 1983 in Paris (Drainage and Erodability at the Concrete Slab-Subbase-Shoulder Interface).

Those in-depth findings were used, enhanced and completed by the Technical Committee on Concrete Roads of the PIARC. A specialized subgroup, in which about 15 people belonging to eight European countries plus the United States were brought together, collected a significant amount of information and favored the exchange of experience, from both the experimental viewpoint as well as from that of operational projects and highway monitoring making it possible to formulate the basis of recommendations for countries more belatedly confronted with these problems.

These exchanges resulted in the publication of a PIARC document entitled "Combatting Concrete Pavement Slab Pumping - State of the Art", first distributed on the occasion of the XVIIIth World Road Congress in Brussels in September of 1987 (Figure 0).

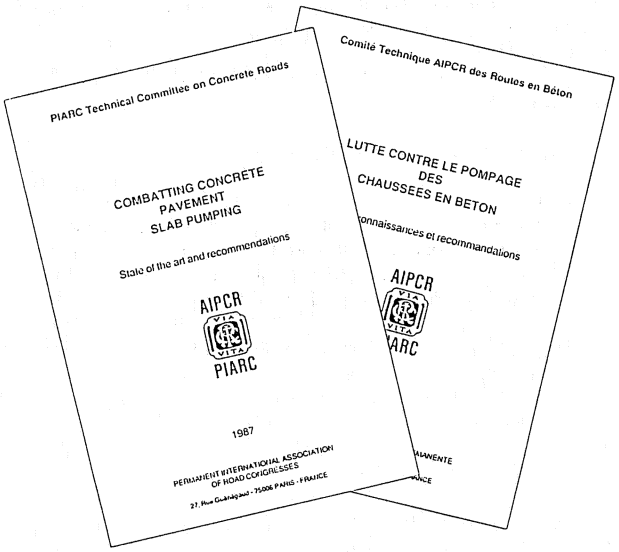



**Figure 0** - Recommendations of PIARC Technical Committee on Concrete Roads.

The present paper has a twofold purpose:

1 - To present the most characteristic aspects of this synthesis based upon the definition of a general framework for recommendations corresponding to a consensus of different researchers and practitioners (trends in the practices of various countries in the past 15 years) accompanied by procedures or methods for adapting these general rules to the specific context of each country or agency.

The practical value of this approach is that it provides designers with a common language based upon classifications established for criteria that have a major impact on the long-term behavior of concrete pavements, namely:

- drainage of infiltration water at slab-subbase-shoulder interface;
- use of low-erodability materials at interfaces;
- optimization of interface drainage, use of low-erodability or non erodable materials and waterproofing of pavements.

2 - To provide a current illustration of slight changes in practices with regard to constructional arrangements able to meet under acceptable economic conditions the general principles laid down to combat pumping.

This is achieved by a certain number of operations allowing the monitoring of projects, the most interesting of which are those handling very heavy traffic. On these roads, the use of appropriate drainage systems and low-erodability materials began about 12 years ago, and much information can be derived from the assessment of the performance achieved. In certain cases, it has been possible to evaluate very objectively the gains in service life obtained with these new constructional arrangements (drainage + low-erodability materials). In other cases, it has been possible to pinpoint areas in which progress remains to be made.

## STATE OF THE ART AND RECOMMENDATIONS REGARDING THE COMBATTING OF CONCRETE PAVEMENT SLAB PUMPING

We shall look successively into the questions of drainage, erodability, optimization between drainage, use of low-erodability materials and waterproofing of pavements. For each subject, the language

or the area covered will be specified, the actual recommendations will be set forth, and we shall see how the principle has been formulated within the framework of a classification of materials and designs.

## DRAINAGE

The main aim with regard to drainage is to reduce as much as possible the time during which water is present at the slab-subbase-shoulder interfaces. The drainage involved is that of rainwater having penetrated into the base of concrete pavements. Drainage also controls infiltration water, water rising and ejection under traffic, as well as internal flows at interfaces.

**General principles** regarding which there is a consensus:

1 - Water is an essential element of the ageing process observed on a certain number of undoweled discontinuous concrete pavements, mainly during the past 20 years.

2 - The use of drainage systems, and especially of longitudinal drains on the slab edge, is current practice in many countries and regarded today as an effective and economical approach in many cases.

**Classification of constructional arrangements** (Figure 1)

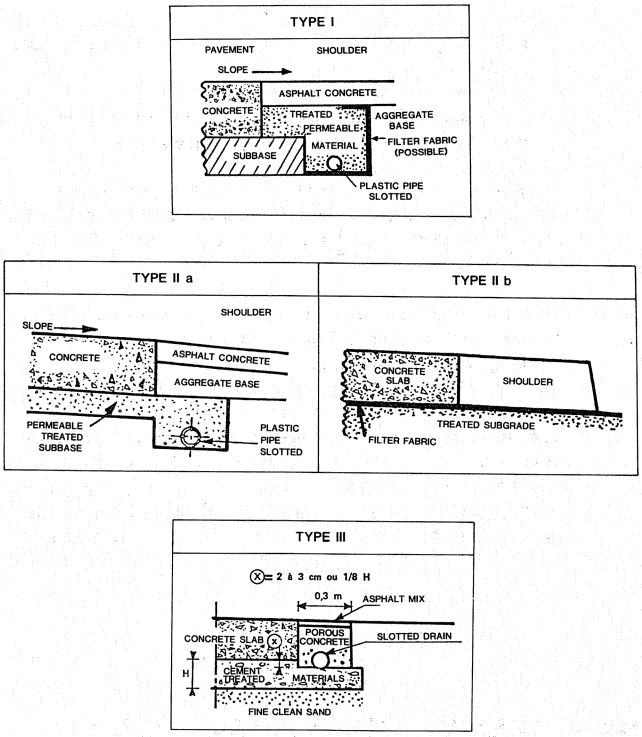



**Figure 1**: Types of slab-subbase-shoulder interface drainage systems.

Design types I, II and III are distinguished.

Type I corresponds to a free-draining edge mass collecting the interface infiltration water.

Type II corresponds to a free-draining layer under the entire area of the concrete pavement. This may consist of a porous granular layer (type IIa) or a prefabricated thin free-draining layer with a special filter fabric (type IIb).

Type III corresponds to the provision of a retrofit shallow longitudinal drainage trench for old pavements.

Designs type I are those for which the greatest perspective and experience exist.

Assessments have demonstrated that particular care was required with regard to drain maintenance possibilities (diameters larger than 150 mm and sufficient radii of curvature), the porosity of the draining material (passing 15 to 20% of communicating voids), uniformity of materials and workman ship, and effective maintenance of outlets. The first projects have demonstrated, in the case of heavy traffic and rainy regions, that the mechanical function of this mass remained satisfactory in the long term but that the hydraulic function had to be improved (clogging of drain and draining material in its "useful" zone).

Type IIa designs provide better hydraulic efficiency. A good compromise has been found for heavy traffic pavements between hydraulic functions (20% voids) and mechanical strength (28-day compressive strength of 15 MPa). Full-width slipform paving allows qualitative monitoring of manufacture and placement suited to the essential functions of this layer. The prefabrication afforded by type IIb designs provide better dependability in terms of hydraulic and mechanical properties, but offer little leeway with respect to possible clogging phenomena.

## ERODABILITY OF MATERIALS AT INTERFACES

. The main goal was to minimize the risk of cavity formation, constituting "pump bodies" under the concrete pavements, by better erosion resistance of subbase and shoulder materials. The erosion involved is mechanical erosion by hammering, rubbing and abrasion by fines under water.

. **General principles** regarding which there is a consensus:

1 - The erodability of subbase and shoulder materials is an essential property that must be taken into account in the design of new pavements and in the diagnosis of existing pavements, because the erosion of materials at interfaces causes pumping and destabilizes the slabs of the concrete pavement.

2 - Simple tests have been developed for characterizing the erodability of materials. they offer the data required for comparing results using a common language understood in all countries.

. **Classification of materials**

The mentioned tests, conducted either in the laboratory or in the field, have shown that it was possible to classify a material in terms of its type and binder content in five erodability classes based upon a decreasing order of erodability resistance (erodability resistance ratio of the order of 5 between each class).

- Class A materials: "Extremely erosion resistant" - Example: lean concrete with 7 or 8% cement; bituminous concrete with at least 6% bitumen -

- Class B materials: "Erosion resistant" - Example: cement-treated granular material with 5% cement treated in the plant -

- Class C materials: "Erosion resistant under certain conditions" - Examples: cement-treated granular material with 3.5% cement treated in the plant; bitumen-treated granular material with 3% bitumen -

- Class D materials: "Fairly erodable" - Examples: granular material treated in place with 2.5% cement; fine soils treated in place; untreated granular materials -

- Class E materials: "Very erodable" - Example: contaminated untreated granular material; untreated fine soils -

This classification is based upon average results observed on pavements. It incorporates the intrinsic properties of mixes reconstituted in an ideal manner in the laboratory and the most current defects encountered as a result of jobsite uncertainties.

## TOWARDS AN OPTIMIZATION OF THE COMBINED EFFECTS OF DRAINAGE, USE OF LOW-ERODABILITY OR NON-ERODABLE MATERIALS AND JOINT SEALING

. **General principles** regarding which there is a consensus.

Optimization should lead to a coherent set of choices concerning:

- type of load transfer;
- subbase and shoulder material erodability class;
- drainage system;
- sealing or non-sealing of joints.

For very heavy traffic and severe climates, the tendency is to use doweled slabs with sealed joints or continuously reinforced concrete over a highly erosion resistant subbase, either with longitudinal drainage of the subbase or a complete shoulder in cement concrete. Precautions are to be taken as concerns the design, construction and maintenance in order to ensure satisfactory long-term hydraulic functions. The option of an entirely free-draining subbase layer is gaining favor and offers good possibilities when careful working conditions are applied.

When climate and traffic are less severe, there are alternative or intermediate approaches: permeable subbase; normal erosion resistance.

For pavements handling less truck traffic, the drainage of the subbase is generally not required, and erodable materials may be adequate.

. **Classification of designs**

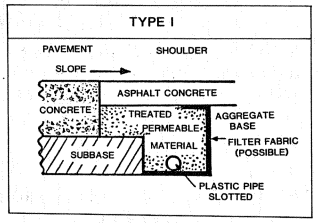
Table I indicates the constructional arrangements adopted, reflecting the evolution of practices in various countries in the past 15 years for undoweled pavements without traffic-supporting shoulders. Depending on the extent of truck traffic and climatic conditions related to the dimension of the time water is present on the surface, the table indicates the constructional arrangements recommended for drainage, subbase materials and also joint sealing which is an all too often neglected constituent of the infiltration water cycle in discontinuous concrete pavements.

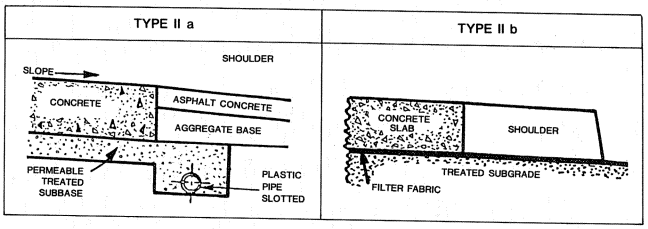
| TRUCK TRAFFIC | HIGH | | | MEDIUM | | | LOW | | |
|---|---|---|---|---|---|---|---|---|---|
| SURFACE WATER EXPOSURE TIME / CONSTRUCTIONAL ARRANGEMENTS | High | Medium | Low | High | Medium | Low | High | Medium | Low |
| INTERFACE DRAINAGE (TYPE) | I or IIa | I or IIa | I or* IIb | I or IIa or IIb | I or* IIb | OPTIONAL | | | |
| SUBBASE AND SHOULDER EDGE MATERIAL (ERODABILITY CLASS) | A | A or B | B | B | B or C | C | C or D | C or D | D or E |
| JOINT SEALING | yes | yes | yes | yes | Optional with B yes with C | OPTIONAL | | | |

* Subject to checking of stresses in concrete with filter layer actually used.

- Legend :

1 - Drainage




2 - Significant materials of erodability classes (examples)

A : lean concrete with 8 % cement ; bituminous concrete with 6 % bitumen
B : cement-treated material with 5 % cement produced in the plant
C : cement-treated material with 3.5 % produced in the plant ; bitument-treated material with 3 % bitume
D : material treated in place with 2.5 % cement, treated soils
E : untreated, unprocessed material

**Table I**: Constructional arrangements proposed for combatting concrete pavement pumping

## PRACTICAL APPLICATION OF GENERAL RECOMMENDATIONS FOR A CONTRACTING AGENCY

The general aspects of the recommendations for combatting concrete pavement slab pumping based upon the classification and hierarchy described above must be considered in terms of acquired knowledge and experience on the local level. In any case, data available internationally must be regarded as complementary to local knowledge and experience.

Concretely, each country or agency must set its own references based upon the performance of pavements within their own context in order to assign specific values to each classification. The procedure proposed for this purpose has four phases:

1 - Definition of quantification criteria for traffic indicators - water exposure time - erodability of materials, compatible with available facilities for the collection of data and instrumentation.

2 - Observations and tests on a sufficient number of pavements in services made up of structures and materials usually encountered in the country considered or in representative similar contexts.

3 - Deriving an assessment scale combining the interpretations furnished by the general recommendations and the results of observations and tests on pavements in service.

4 - Establishing a three-dimensional graph of traffic, water factor, erodability, and plotting the situation of pavements in service along with their performance diagnosis.

For geographical areas in which little experience has been acquired with concrete pavements, several countries may be effectively associated in this type of study. The exchange of experience makes it possible to cover a broader range of situations in terms of loading and climatic conditions, which is favorable to the definition of rules with a good degree of reliability.

Let us point out that this was done a few years ago within the climatic context of oceanic Europe and that the values obtained are the following (for undoweled pavements and a legal axle of 10 metric tons):

Traffic:

| | |
|---|---|
| High traffic level | : more than 2,000 trucks per day on most heavily trafficked lane |
| Medium traffic level | : from 400 to 2,000 trucks per day |
| Low traffic level | : less than 400 trucks per day |

Water exposure time:

| | |
|---|---|
| . High exposure | : more than 150 days of rainfall annually |
| . Medium exposure | : 50 to 150 days of rainfall annually |
| . Low exposure | : less than 50 days of rainfall annually |

Application examples:

*Context*: Freeway handling a high level of truck traffic (legal axle of 13 metric tons)
High water exposure (180 days of rainfall annually

*General constructional arrangements*: Table II

| Heavy traffic | >150 Trucks/day | | | 150 à 750T/day | | | <150T/day | | |
|---|---|---|---|---|---|---|---|---|---|
| Days of rainfall /year / Constructional arrangements | >150 d | 50 to 150 d | <50d | >150d | 50 to 150 d | <50 d | >150 | 50 to 150 d | <50d |
| Interface drainage (type) | I Or II a | I Or II a | I Or II b | I Or II a Or II b | I Or II b | Optional | | | – |
| Subbase and shoulder materials (erodability class) | A | A Or B | B | B | B Or C | C | C Or D | C Or D | D Or E |
| Joint sealing | Yes | Yes | Yes | Yes | Opti. onal B Yes C | Optional | | | |

**Table II**: Constructional arrangements: French context

*Construction*: typical cross-section: Figure 2.

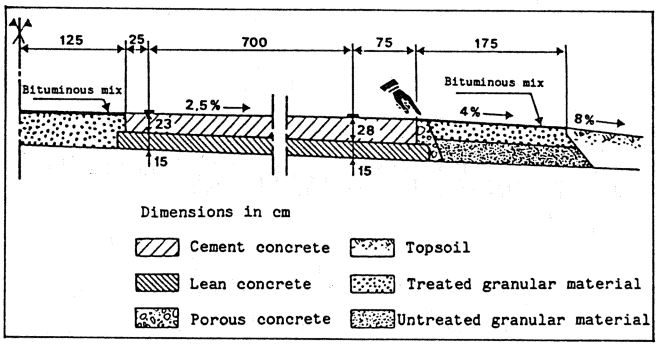



**Figure 2**: Schematic representation of structure and surroundings.

The cross-section of Figure 2 shows the chosen options:

- interface drainage type I without drain option
- subbase materials in lean concrete, hence of erodability Class A ("Extremely erosion resistant")
- joint sealing.

## VARIATIONS IN CONSTRUCTIONAL ARRANGEMENTS IN ACCORDANCE WITH THESE RECOMMENDATIONS

Theoretical studies and performance evaluations on discontinuous concrete pavements of former design, along with the examination of entire routes exhibiting varying situations in terms of structure, age and constructional arrangements and the monitoring of their evolution sometimes for over 10 years, have amply demonstrated the validity of the elements of the present recommendation.

What is required is constant observation of the operating mode of these new constructional arrangements (mechanical and hydraulic efficiency) and, what is of greater interest on the whole to us, the long-term behavior of these structures.

Several avenues of action have been initiated to deal with these questions:

- In general, the use of models of the COPES (Portland Cement Concrete Pavement Evaluation System) type of the University of Illinois appears to be particularly promising because it makes it possible to work on the basis of a common language and to compare reliably and effectively the performance of pavements and the lessons derivable therefrom. This program offers a real opportunity for international cooperation, and such cooperation is already under way between Europe and the United States. There are many benefits to be achieved through such cooperative efforts; the following may be cited:

- The COPES product is a high-performance tool for improving the design, construction and maintenance of concrete pavements (cf. the many existing explanatory models, calling for extension and validation for other contexts)

- There are areas of innovation and contexts specific to Europe as concerns design and loading situations making it possible to broaden the knowledge base of the COPES. In return, there is the benefit of an evaluation of each of our constructional arrangements in accordance with the COPES multidimensional analysis system. Among these specific areas may be mentioned:

  . the volume of truck traffic on strategic routes and the effect of the legal axle weights of certain countries (13 T);
  . the trapezoidal cross-sections and extra pavement widths used;
  . thick slabs;
  . nonerodable bases;
  . longitudinal drainage of interface water or free-draining bases;
  . short slabs with variable joint spacing.

- COPES is a consistent system geared to major highway research programs of the next decade (example: Long Term Pavement Performance of Strategic Highway Research Program) while remaining primarily pragmatic and modular. It is a preparatory procedure which is simpler and, consequently, more accessible to a large number of countries wishing to cooperate with limited facilities in international research programs.

Tangibly, the PIARC Concrete Road Committee has created a subcommit-tee on a "Tool for evaluating long-term performance of concrete pavements to ensure the consistency and the monitoring of this action".

- From a specific viewpoint, detailed monitoring and instrumentation provide information which is particularly valuable inasmuch as there is greater perspective and there is the possibility, within the context in which they have been carried out, of faster application to local practices. We are presenting below two examples which appear to us to be particularly interesting, resulting from observations conducted on the heavy-traffic freeways of the Paris region, namely the Autoroutes A1 and A6. In both cases, what is involved is the partial reconstruction of pavements (truck lanes and sometimes the middle lane of freeways with 2 x 3 lanes) and parts of nonconcessionary freeways.

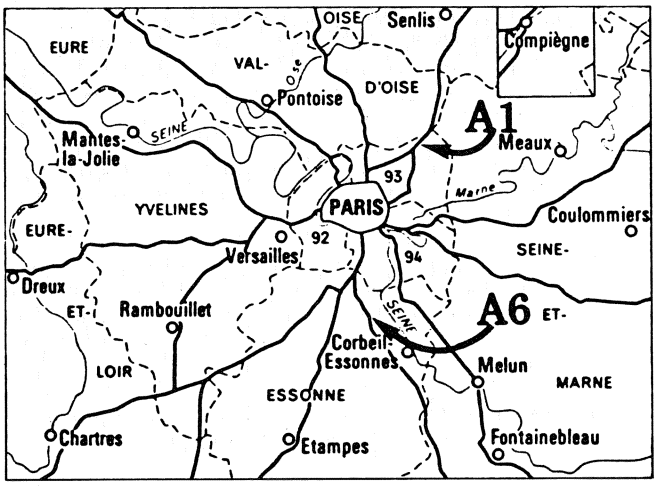



**Figure 3**: Location of sections of A1 and A6 observed.

*Case of Autoroute A1* (Province to Paris direction)

* First observation *

The old pavement, consisting of undoweled concrete slabs without interface drainage and with a base ranging from Class C (erosion resistant under certain conditions) to Class D (fairly erodable), had to be reconstructed in the truck and middle lanes in 1976 after 12 years of service handling cumulative truck traffic of 17 million vehicles of over 5 T useful load on the most heavily loaded lane.

The new pavement, built in 1976 using many of the principles of the recommendation (see typical section in Figure 4), had by mid-1988 handled some 35 million trucks on the most heavily loaded lane in the part which was the most interesting from the observation viewpoint.

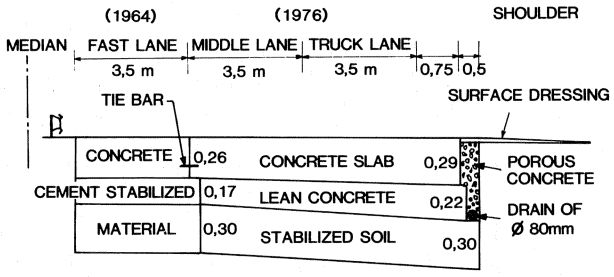



**Figure 4**: A1 - Province to Paris direction - KM 18.800 to 10.300
Schematic section of structure

It can already by stated that the use of a nonerodable base and edge drainage have made it possible to multiply the service capacity of the pavement by at least two. The present condition of the pavement and its rate of evolution suggests that this multiplying coefficient may be three by the end of its service life if proper maintenance is provided.

* Second observation *

The hydraulic function deteriorates faster than the mechanical function.

For the hydraulic function, the situation is summarized as follows:

- The year the facility was opened to traffic, 75% of the outlets were functioning during rain, 13% exhibited a zero flow and 12% were out of service.
- After 7 years, only one case of pumping was observed, in a zone in which a modification had been made (elimination of outlet).
- After 11 years, the drainage system, which practically never received any maintenance, became almost inoperative. The outlets of the fill sections do not discharge, and the inspection grids are buried under vegetation in the cut sections.

The pumping phenomenon has extended gradually (fine-laden water discharge). It represents almost 70% of the length.

After 12 years, the construction of a fourth lane over a distance of 2.5 km corresponding to one of the most heavily trafficked sections, provided the opportunity for cutting the drainage trench and the slab edge. It was thus possible to confirm that the drainage system was not working, in neither the fill or cut sections: the 80-mm diameter PVC longitudinal drain is most often clogged up to 50 to 100% of its capacity (Figure 5). The porous concrete around the drain is also clogged as depicted in Figure 6.

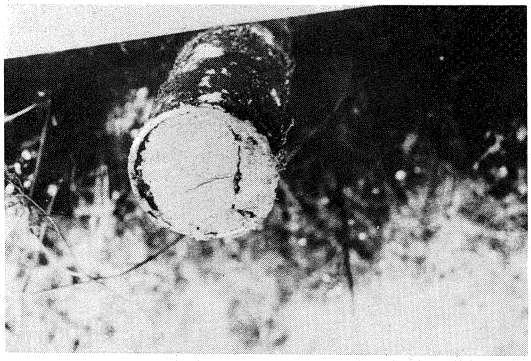


**Figure 5** : Significant condition of longitudinal drain clogged up to 100 % on certain sections of A1 (observations after 12 years)

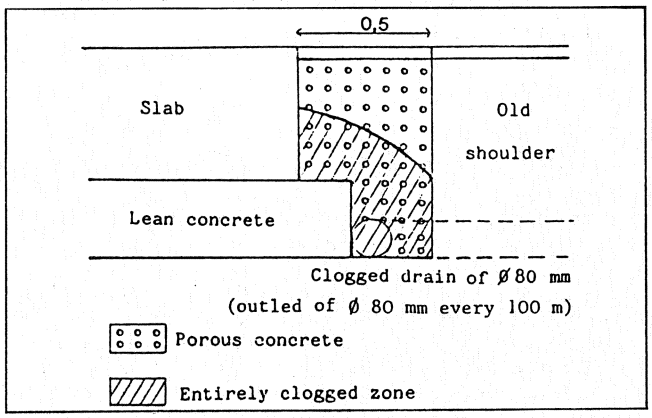



**Figure 6** : Location of clogged zone around drain in drainage

The clogging fines are being analyzed. They range from very wet, sticky and grey (ultra-fine materials which appear to correspond to latency attrition fines) to a more granular and blackish appearance. The observation of these fines appears to rule out the theory that they come from the treated sand of the subgrade, as no rising of fines has been observed through the subbase cracks. Two other origins are in fact indicated:

1 - Normal attrition at the interface between two hard materials subjected to intensive hammering

2 - Surface contaminations by traffic, which are significant owing to the level and typology of the traffic involved, and which are collected by the runoff water penetrating into the pavement structure; joints have never been resealed since construction.

For the mechanical function, the response of the pavement has hitherto been satisfactory. There is of course some discharging of water and fines at the slab-shoulder interface related to the malfunctioning of the drainage system, but it is to be noted that:

- the slab-drainage trench contact zone performs correctly; no local subsidence is observed, even at the location of the water discharges, unlike in the old structure in which subsidence on the slab edge could jeopardize the safety of users;
- zones without original cracking evolved only slowly: after 12 years, the transverse cracking rate is less than 3%;
- surface properties are still excellent after the work carried out in 1978 (longitudinal grooving, now prohibited in France) and 1983 (transverse grooving by sawing): average texture depth of 1.6 mm with the sand patch test, and sideways force coefficient of 0.63, representing values significantly better than those recorded on bituminous pavements (repaving) on adjacent sections.

* Third observation *

In spite of a service life shorter than expected (about 10 years), though the absence of maintenance on this pavement played a large part, the effectiveness of the draining masses was nevertheless significant. In the direction opposite the section examined up to the present time, some sections have not been drained owing to project or site constraints. This appeared clearly, while this absence of drainage led to the discharge of water and fines, as of the second year in an unfavorable situation (low point) and the fifth year in a current situation. For Autoroute A1, it is possible to evaluate the time elapsing between the appearance of pumping on undrained and drained sections at about 4 years. Considering the evaluation curves for the deterioration of drained and undrained pavements, this leads to at least the doubling of the service capacity (cf. comparison between new and old pavement of A1).

*Case of A6*

What is involved here is the reconstruction of the heavy traffic lanes on a roadway having two times three lanes in cement concrete, based upon an annual program of 10 to 15 km carried out in a few weeks during the summer because of extremely severe operating constraints along this route (radial freeway from Paris to Lyons).

The typical section is shown schematically in Figure 7:

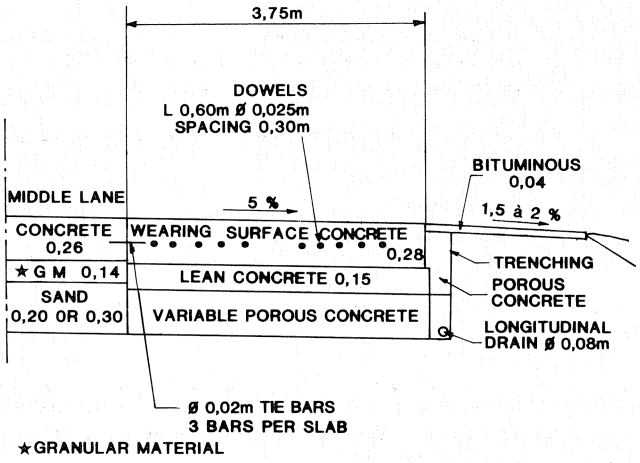



Figure 7: A6 Essonne Region - Reconstruction of heavy traffic lane with dowelled concrete slabs Schematic diagram of structure

Investigations on the hydraulic functioning of this structure were conducted during a period of 6 months (second semester of 1986) on a sector of about 100 meters integrated in the rehabilitation program of 1985. The experimental system made it possible to isolate the considered zone and to simultaneously measure, for each significant rainfall, the volume of rain (Vp), the runoff volume recovered on the surface by a concrete gutter (Vr) and the effective drained volume coming out of the longitudinal drain (Vd) (Figure 8).

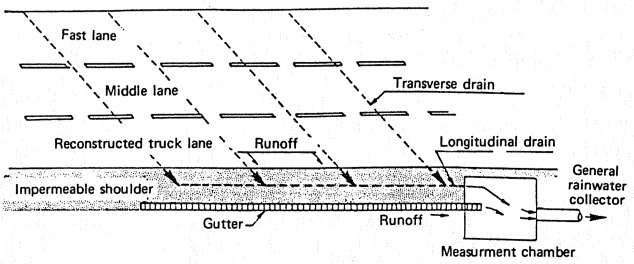



Figure 8: General diagram of instrumented zone on A6 in Essonne region.

The measurement chamber is equipped with two triangular-overflow gage tanks for the respective measurement of runoff and drained water heights (Figures 9 and 10). Water levels are themselves measured with a bubble-type water level gage (Figure 11). The rainfall volume is measured by means of a tipping bucket rain gage with an accuracy of 1/10 mm.

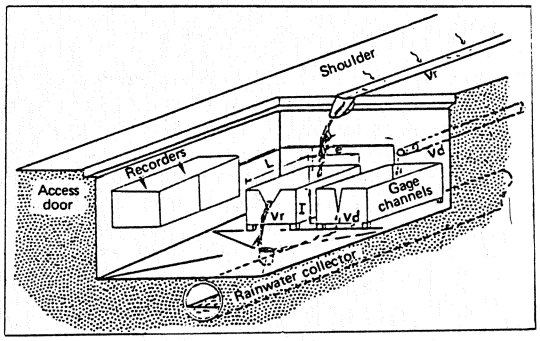



Figure 9 : Schematic diagram of measurement chamber.

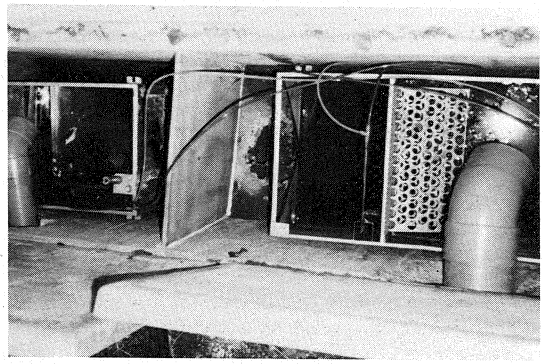


Figure 10 : Gage channels for runoff (on left) and drainage (on right).

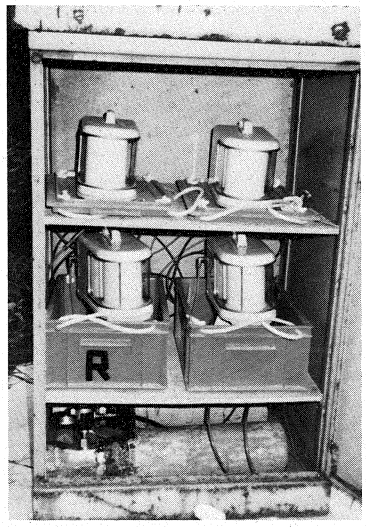


Figure 11: Runoff water level gage (0-30 cm full scale with its full-scale (0-1 m) duplicate.
Drainage water level gage (0-16 cm full scale with its 0-30 cm duplicate).

The following observations were made:

1 - The 11 rainfalls investigated have average intensities of the

order of a few millimeters per hour (1 to 3 mm; maximum at 7.8 m). They are thus altogether significant of the usual conditions of the presence of water in the Paris region.

2 - Confining ourselves to the 0-3 mm intensity range, it is observed that the ratio of the runoff volume to rainfall volume is low: lower than 0.5 in both cases. Theoretically, half of the precipitation water thus penetrates into the pavement structure through the longitudinal and transverse joints of the fast and middle lanes essentially. Even if we take into account such phenomena as evaporation, wetting and especially the removal of water by traffic projection, particularly intense in this area, it is evident that the pavement is not waterproof.

3 - Draining efficiency, evaluated in terms of the ratio of drained water volume to the theoretical entering water volume, is excellent during the first period of observations for the current range of rainfall intensities (0-3 mm). The first four values between June and September 1986 are respectively 0.91, 0.92, 0.91 and 0.83. These values then drop rapidly: 0.54 and 0.44 in October, and then 0.36 and 0.32 in November. It is likely that clogging at the drain resulted in a fast effect, as suggested by the large quantities of fines observed during each maintenance operation in the gage channels.

In addition to examinations in the drainage system, other investigations of this type would be necessary to verify that we have properly covered a first critical period in the evolution of drainage efficiency in this very special type of configuration in which the porous concrete draining layer placed directly on the untreated soil acts as a subgrade into which the fines from this soil can migrate.

**Practical consequences - New orientations for projects**

Findings at our disposal relative to hydraulic functioning patterns of constructional arrangements of the type with a drainage trench on the slab edge do not call into question the achievements of the past, further enriched on this occasion (cf. case of A1) with respect to the need for interface drainage to increase by at least twice the service capacity of doweled or undoweled discontinuous concrete slabs. They however show that it is possible to do much more, with good expectations, as indicated by the first tangible results obtained, which would appear to show that, for a modest improvement in the drainage system (modest in terms of efficiency and/or durability), a much more significant improvement is observed in the mechanical behavior of the structure. There are many ways of achieving such progress, among which may be mentioned:

1 - Reaffirm the common sense principles inherent in highway engineering theory:

. It is necessary to prevent the massive inflow of water into the pavement structure. In the case of pavements handling heavy traffic under a severe environment, period resealing of joints is essential (cf. clogging by pollution fines on A1; rainwater penetration rate on A6);

. It is also essential to maintain the draining systems just as one maintains the roadway. This calls for maintainable structures (diameters of 150 mm instead of 80 mm, connection with adequate radii of curvature);

. Promote workmanship at all levels of the highway construction chain. Among the cases examined above, there were problems of uniformity of porous materials, inverted slopes on drains, and so forth. Drainage trenches are often regarded as accessory structures and, as such, are not and sometimes cannot be treated with the same care given to pavement materials spread over the full width. For projects which are difficult from the standpoint of completion time, preference must be given to designs which minimize the extent of these accessory works (full-width draining layers are to be preferred to drainage trenches, for example).

2 - Larger dimensioning of the parts of the structure related directly to the hydraulic function. For example:

. design draining materials with 20% voids instead of the 12 to 15% of former designs, while providing the same mechanical strength; ensure uniformity of material in place;

. increase the capacity of longitudinal drains (150 mm instead of 80 mm)

. provide better water removal through outlets every 50 meters instead of 100 meters.

Such arrangements will be provided on the project to be carried out between 1988 and 1990 on Autoroute A1 to widen that facility to four lanes.

This is the procudure adopted by Aéroport de Paris in 1980 for the construction of a runway at Charles-de -Gaulle Airport. As an indication, let us mention the mix designs of the porous concrete used and the performance obtained (Table III).

**Table III** - Mix designs and properties of porous concrete used in the subbase of major airport runways and road pavements.

| Mix design formula | Charles de Gaulle 1980 | Al Seine St Denis 1988 |
|---|---|---|
| CPJ45 cement<br>0/4 alluvial sand<br>6/20 gravel<br>Water | 200 kg<br>250 kg<br>1350 kg (limestone)<br>85 litres | 200 kg<br>220 kg<br>1380 kg (silico-limestone)<br>50 litres |
| 28-days bending strength (MPa) | 2.5 | 2.4 |
| Porosity (%) | 22 % | 20 % |
| Flow ($l/m^3/s$) | 191 | - |

3 - Use the full range of structural maintenance methods available further upstream: reconstruction of edge drainage trench, tie bars to improve load transfers, careful sealing of joints and cracks, creation of short slabs by sawing original slabs in two, etc. Properly coordinated with operations relative to surface properties, and properly executed, these techniques should make it possible to improve considerably the service capacity of concrete pavements.

## CONCLUSIONS

The action being taken to combat concrete pavement slab pumping is not over and considerable progress is still required in order to better combine and complement the hydraulic and mechanical functions of each component of the concrete pavement as a whole.

The PIARC document dealing with the state of the art and recommendations for combatting concrete pavement slab pumping represents a significant initial phase in this endeavor. It outlines a general framework of goals and actions prioritized around clear decisions with respect to drainage systems, use of low-erodability materials and the

optimization of drainage, erodability and waterproofing. A methodology is proposed so that potential users (countries, groups of countries, agencies) may adopt the optimization thresholds specific to their technical, economic and environmental context.

Within the European context, the first results of the recommended constructional arrangements show, in the case of very heavy traffic and severe climates in the presence of water, that the service capacity of the pavements is multiplied by at least two compared with traditional designs but that better results are still possible by improved design and/or construction and maintenance on the hydraulic function for the removal of water at interfaces. Full-width draining layers on the concrete pavement, with a high percentage of voids (about 20%), and longitudinal drains of 150-mm diameter with outlets every 50 meters, appear to be a good alternative for difficult sites handling heavy traffic.

Exchanges of experience must be favored. Experimentation is becoming increasingly complex and costly: in addition to conventional pavement surveying requirements there is the need to understand the hydraulic functioning of structures. The movement and migration of fines in the pavement structure and free-draining materials is by itself an extremely vast research area of primary importance for achieving progress in the design of new structures and new materials. The same applies to the role of filter fabrics within this hydraulic function. Coordinated research programs between several countries are increasingly becoming mandatory for advancing with the thoroughness, reliability and short lead times often required by agencies from research organizations and contractors. The international cooperation initiated in connection with the COPES system should contribute to better awareness as to the value of comparing experience and experimental data using a common language.

All the players in this undertaking will collectively benefit from explanatory models enhanced by a much broader observation base, and also supported by very detailed spotlights on the most pertinent sites.