DRAINAGE AND ERODABILITY: INTERNATIONAL SEMINAR SYNTHESIS AND NEW RESEARCH RESULTS RELATED TO FIELD PERFORMANCE

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Engineers from a number of European countries and the United States met in Paris for the Seminar on Drainage and Erodability at the Concrete Slab-Subbase-Shoulder Interface in March 1983. The Seminar's introductory paper described the present state of the art (report of PIARC Concrete Committee for Sydney World Congress). Session areas included: theoretical research, test trucks and measurement innovations, drainage for new and existing pavements, general studies on erodability and faulting, bonding phenomena between concrete slab and subbase, subbase erodability, shoulder erodability and design.

The main technical orientations resulting from the seminar, and which are developed and supplemented by the latest research findings in the paper, are the following:

1. Some proof is emerging that drainage systems for new pavements and, in certain cases, for old pavements, improve significantly the pavement service life. A satisfactory answer has been found for the inadequacies of former concrete pavements (concrete + cement-treated materials without drainage) subjected to heavy traffic.
2. Very positive statistics exist on such questions as the action of water in structures, waterborne fines, drainability through shoulders and sublayers, effectiveness of drainage, laboratory and field studies. These findings are used for experimenting new concepts.
3. The notion of drainage is closely related to that of the erodability of materials. In particular, in most cases, subbase erodability plays a very important role. It has been shown on a significant sampling of French pavements and in other European countries that the subbase erosion phenomenon constitutes, in the final analysis, the main cause of pavement deteriorations. Laboratory studies associated with numerous observations have made it possible to relate the erodability parameter with such other factors as traffic and climate and to propose, with greater accuracy than hitherto possible, appropriate procedures for the use of concrete pavements with undowelled joints.

Background

On March 24-25, 1983 some 80 engineers from 14 countries attended a 2-day seminar on Drainage and Erodability at the Concrete Slab-Subbase-Shoulder Interface in Paris. 30 papers presented the latest research and field results on concrete pavement drainage (USA: 7; France: 12; GFR: 3; Belgium: 2; Spain: 2; USSR: 1; Austria: 1; Italy: 1; Czechoslovakia: 1).

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This paper summarizes the most outstanding aspects of the evolution of new concepts in the area of concrete pavement structures, the development of which was brought out clearly by the seminar. It also looks into some aspects of the research carried out since the Paris seminar, in particular with respect to the erodability of subbase materials for concrete pavements. The authors hope that their work will contribute to the efforts being made to improve the effectiveness of research information exchanges and would like to urge other researchers and engineers to participate more extensively in this respect.

Chapter I. Drainage at Slab-Subbase-Shoulder Interfaces

I.1. General - Review of Former Problems and Results

The general introductory report of the Paris seminar (1) summarized the state of the art in nine points:

1. The consequences of pumping on concrete pavements were found to be relatively serious in a number of countries.
2. Significant water penetration can occur.
3. Inadequate or non-existent vertical or

lateral drainage allows the development of pumping phenomena in the presence of water.

4. The presence of erodable materials under the slabs has considerably accentuated the initiation of pumping phenomena and their extension. The heavier the traffic and the harsher the climatic conditions (rain, frost), the more crucial will these conditions be.

5. Consequently, the possibilities of improving the lateral drainage of the concrete slab-subbase interface on old pavements were tested. For new pavements, a draining support layer was adopted for concrete slabs, though this was not a general rule. These draining support layers can be:

- either draining subbases made of treated materials,
- or untreated materials ("thick slabs" in particular).

6. Various experiments were carried out to analyze the performance of drainage systems (water and fines discharge at outlet of drains, height of water in draining foundations and layers when active, water pressure under slabs upon passage of vehicles, water pressure in pores of an untreated material, and so on).

7. The effect of drainage on the mechanical behavior of road pavement structures is difficult to determine precisely.

8. The behavior of more recent pavements, hence those benefitting from improved drainage designs, is very satisfactory.

9. Drainage improvements on old pavements can pose problems. Two cases would appear to be unfavorable: pavements already significantly deterioated, subbases capable of releasing fines. These two cases are related to the problems of erodability under the action of water. The first case concerns the removal of fines accumulating at the slab-subbase interface (slab faulting will be a sign) or the direct erodability of the subbase material. The second case concerns the internal hydraulic stability of materials making up the road foundation (subgrades). In both cases, there is a problem of the "stability" of these fines with respect to the draining formations. The criteria for filter materials can be used to reduce the "destabilization" of subgrades. The use of geotextiles to limit the risk of "destabilization" at the concrete-subbase interface have not as yet been sufficiently conclusive.

I.2. Drainage - Factors dealt with at the Seminar

The papers presented at the seminar supported and provided further information on a certain number of points regarding these fundamental questions. Before looking into some of the most significant results in greater detail, let us first state that the seminar provided particularly pertinent information on the following subjects:

. Action of water in structures (2); (10); (27).
. Hydraulics of pumping (29); (40).
. Water-borne fines (2); (10); (11); (13); (17); (40).
. Water penetration control (geometry and/or waterproofing) (2); (10); (13); (17); (29).
. Drainability through shoulders (10); (11); (14).
. Maintenance of drainage structures (11); (29).
. Effectiveness of drainage structures on old pavements (17).
. Laboratory and field studies (5); (10); (17).
. New concepts (6); (10); (11); (17); (29).

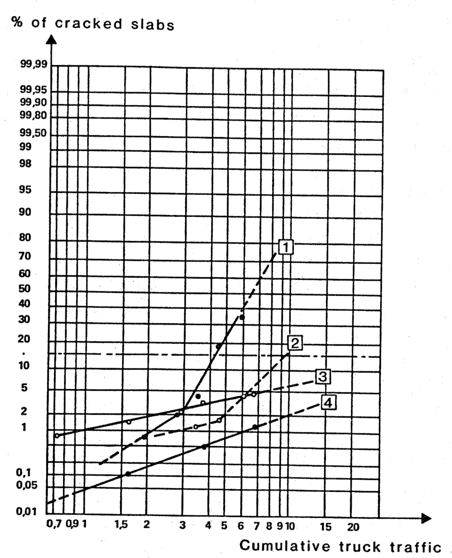
On the other hand, on the whole very vew studies, experiments or completed projects were described on some equally important questions which were also fully related to drainage and erodability; for example:

. Drainage and improved service life (11).
. Draining treated subbases (9).
. Intrinsic properties of materials (including subgrade).
. Design of drainage structures.
. Hydraulic gradients.
. Capillary absorption of water.

In spite of the scarcity of the information dealing with the subjects listed above, the few papers cited were extremely valuable contributions.

For example, J.L. Nissoux (11) presents an overall graph of particular interest on the comparative evolution of cracking rates observed on French pavements of former design, on the one hand, and on pavements of new design with a lean-concrete subbase and lateral drainage, on the other (Figure 1).

Figure 1. Henry's curves of slab cracking rates for different slab structures with and without lateral drainage and with and without lean-concrete subbase, as a function of cumulative truck traffic. On old pavements with cement-treated subbases and without drainage (1 and 2), one observes:
a) a first period of normal and slow progression in the number of cracked slabs;
b) a second period of faster or critical progression corresponding to more or less marked pumping, deflection and faulting effects which accumulate with the actual fatigue of the material.
On pavements with lateral drainage and lean-concrete subbases (3 and 4), the critical progression phase has not yet been reached for the same loading level: 6 x 10^6 trucks.



1- Highly deteriorated old structure
2- Old structure in good condition } with cement-treated subbase
3
4 } New structures with lateral drainage and lean-concrete subbase

These findings, the outgrowth of extensive experimentation (6 x 10^6 cumulative trucks with a legal axle weight of 13 metric tons), demonstrate that the solution of problems relative to water and the surface erodability of materials in contact with the concrete slab can lead to much longer pavement service lives than those of old structures with cement-treated subbases.

I.3. Drainage - Review of Dominating Factors

I.3.1. Water traps in old pavements - Drainage Possibilities and Problems.

The water trap which characterizes old pavements is well-known. F. Verhée and J.F. Griselin (17) described various attemps to control this phenomenon (see Figures 2 and 3).

Figure 2. Review of problem to water trap on old pavements.

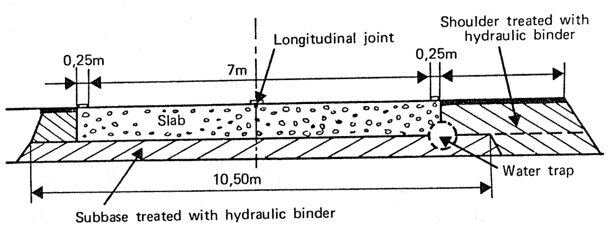
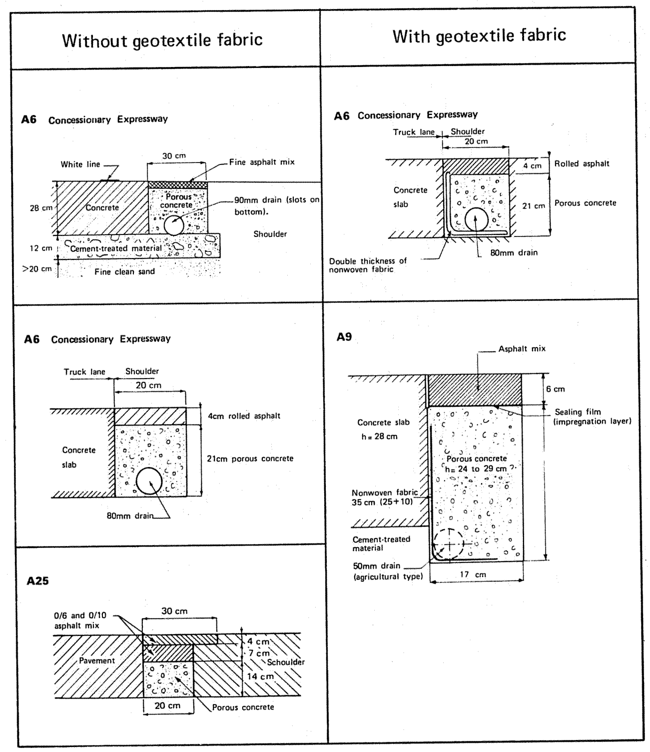


Table 1 above shows that shallow drainage trenches can be valuable provided the pavements are still in good condition and not liable to change (discharge of fines by drainage, especially if subbase erodability may be involved).

If drainage by means of pervious trenches is not possible, it is preferable to reconstruct the shoulder and provide impervious shallow trenches (Figure 4). This solution reduces water penetration, eliminating pumping pit damage and improving motorcycle safety. An allowance of 25 mm x 25 mm (1" by 1") for the placement of a joint product can lead to some damage. It is also possible to provide a sawn and filled joint 8mm (0.32") wide and about 30 mm (1.2") deep.

Figure 3. Solutions to water trap on old pavements: Shallow pervious trenches with and without geotextile fabrics. A6, A25 and A9 Expressways in France.



The risk of destabilization which may require the provision of drainage on old pavements reached its worst point when deeper drainage structures at the edge of the slabs, cutting through the subbase, were used (Figure 5). W. Gulden (13) showed the particle-size modifications which could be associated with the water-borne fines effect. Not only is it possible to remove fines from the slab-subbase interface, but also under the subbases and in the subgrades (see Table 2).

This ties in with the notions of filter materials and stability criteria with respect to environments

Table 1. Assessment of 6 years of French experience

	Old pavement in good condition (no damage, limited slab deflection and faulting, subbase little or not erodable)	Old damaged pavements (slab deflection, faulting or damage)	
Lateral drainage	Yes: Shallow drainage trench against slab and drain	Subbase	
		Little or not erodable	Erodable
		Possible	No
Reconstruction of shoulder with non-draining trench		Yes if shoulder is damaged: greater slab faulting on shoulder side[a], danger to motorist, pavement already becoming deteriorated	
Deep, distant draining trench	To be used only for particular case of external water penetration (after special study)		

[a]Greater slab deflection on the shoulder side is a sure sign that the fines responsible for this deflection come especially from the shoulder

Table 2. Gradation of drainage stone after three years of service
I-85 Troup County

Percent passing sieve seize	Depth from top of pavement					
	4 inch	7 inch	10 inch	14 inch	17 inch	19 inch
3/4 inch	100	100	100	100	100	100
1/2 inch	89.6	83.3	92.2	94.4	94.4	94.4
3/8 inch	41.3	32.7	44.8	52.9	59.0	68.4
No. 4	8.0	6.5	9.2	9.0	23.0	46.8
No. 10	3.6	4.4	7.5	6.2	21.1	43.3
No. 16	2.5	3.8	6.9	5.8	20.7	41.4
No. 40	1.3	3.1	5.9	5.1	19.5	32.2
No. 60	0.9	2.0	3.9	3.5	13.3	17.7
No. 100	0.5	0.7	1.6	1.9	6.0	5.3

Figure 4. Shallow impervious trench. A6 Expressway in France.

A6 **Concessionary Expressway**

Reconstruction of shoulder edge in nondraining cement concrete with longitudinal «joint reserve» between pavement and shoulder.

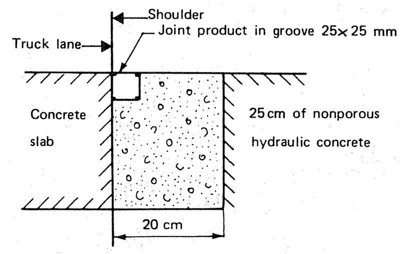
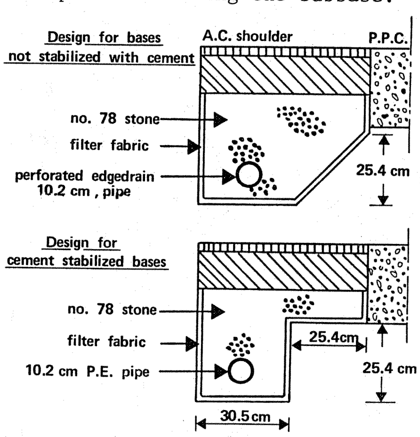
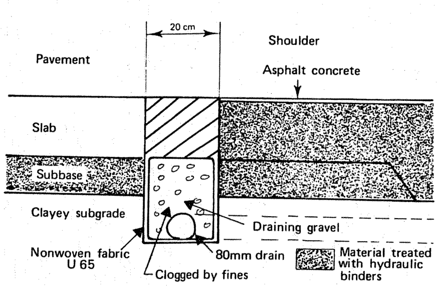


Figure 5. Dangerous drainage structures on old pavements. Deep drain cutting the subbase.



Example 1 studied in USA (Georgia)



Cross section of a drainage trench cutting the subbase and penetrating into a subgrade containing fine elements . Pavement degradation was accelerated by this system which «drained» the fines from the subgrade to the outsi--de of the pavement (A6 Expressway).

Example 2 studied in France

Figure 6. Discharge of fines by drainage structures. Overall results obtained on instrumented sections: I-II Shallow pervious trenches. III Deep pervious trench.

Main results of analysis of recordings made on A6 Expressway
and comparison with old pavement of A1 Expressway

	Without nonwoven filter fabric	With nonwoven filter fabric	On old pavement A1
Amount of water drained/rainfall (%)	47	20	69 (1)
Average response time (min)	14	20	16
Average duration of drainage after rainfall (h)	7	8	3 (2)
Concentrations in suspended matter (mg/l)	220	200	1000 (3)
Fines extracted annually (g/m)	67	26	445
(1) very poor sealing (2) large cavities under slabs favoring water circulation (3) very erodable subbase	I	II	III

(soils to be drained and orifices receiving drainage pipes).

F. Verhée and J.F. Griselin (17) show that, to fully understand the hydraulic phenomena, and in particular the risk of the removal of fines, thorough experiments will be necessary to check the efficiency of the structures (Figure 6). As illustrated by W. Gulden (13) and brought out by these experiments, the use of geotextiles can limit the removal of fines but increases the drainage time. We lack observations on possible clogging caused by ultrafines (80) with time. Such clogging may in fact occur during dry periods or between rains. Let us however note that the pressurizing of water under the slabs should allow dynamic leaching (such is not the case with pure gravity drainage). The experiments already carried out could provide some valuable in-situ verifications.

I.3.2. Drainage of Present and Recent Pavements. Better knowledge of the hydraulics of pumping (18) (40), the diagnosis of problems encountered about 15 years ago, the performance of new structures drained at the concrete-subbase interface are very positive elements for all countries.

Drainage at the concrete-subbase interface is provided either laterally (drainage structure under shoulder) or both laterally and through the subbase itself. The presence of a porous layer can in fact reduce by a factor of 10 the presence of water in the pores of this subbase (34). Figures 7, 8 and 9 illustrate these arrangements. It will be noted that airport pavements have benefitted from these new designs. R. Lorin and E. Michel (9) have pointed out that two factors led to this type of solution (Figure 7).

- Disorders on certain lanes in spite of the

Figure 7. Drainage through porous concrete subbase under airport runway pavement (C. de Gaulle, Roissy, France).

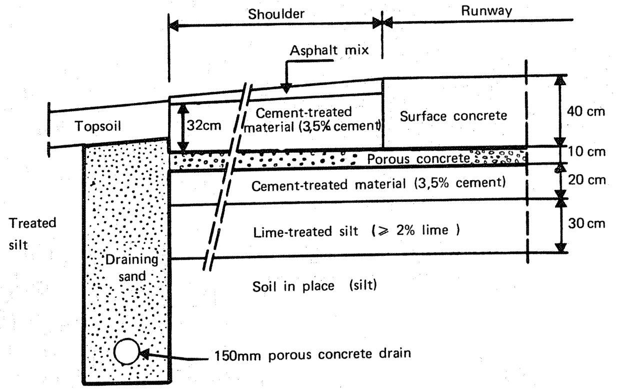


Figure 8. Example of road structure with thick concrete slab. Drainage through pervious gravel. A36 Expressway, France.

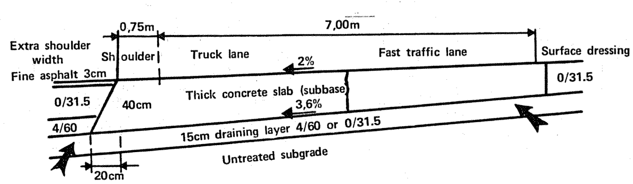
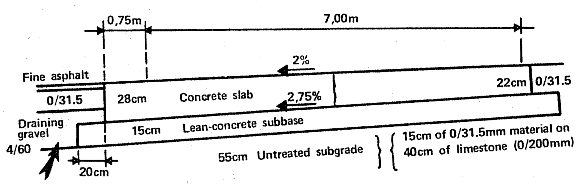


Figure 9. Example of conventional road structure in concrete: slab over lean-concrete subbase. Lateral drainage through pervious gravel.



adaptation of structures to stresses due to increasing loads.

- Need to meet hydrodynamic drainage conditions which former designs did not adequately fulfill.

All these new developments are being followed and it is important to be informed of the slightest deficiencies as early as possible. Thus, different investigations have been carried out or are in progress to verify the proper functioning of hydraulic and mechanical structures. G. Bonnet and J. Poilane have described an experimental thick slab project completed in France in 1978-79 after a first feasibility project completed in 1977 (10). Information on the properties of subbase materials, slab deflection and performance have been indicated (measurements by strain gages). In-situ exmaination by air drilling has brought out two important points:

- The untreated draining layer (4/60) performs correctly.
- Underlying materials appear wetter than under other pavements.

This shows that for slabs over untreated draining materials:

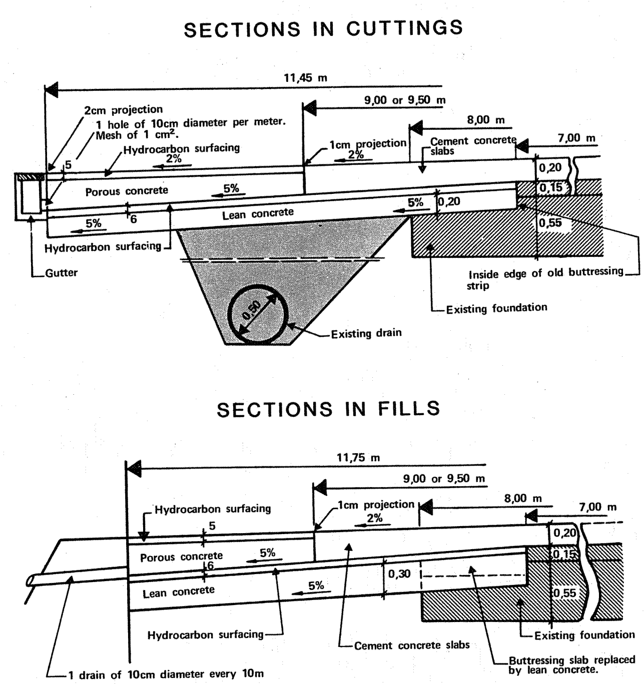
- drainage at the concrete-subbase interface is secured,
- the drainage properties of the subgrade are important (vertical and horizontal drainage),
- it is important to determine the working conditions of such subgrades. A series of measurements on the vertical deformations was recently completed on this experimental project. Other structures of this type over a subgrade in treated materials are being followed in northern France.

J.H. Woodstrom (6) has described the use of a cement-treated draining layer to protect a large-width concrete pavement against the loading of groundwater in a cutting. This under-pavement drainage should take into account interactions between water coming from the surface and groundwater.

The work of H.R. Cedergren, J.A. Arman and K.H. O'Brien can be used in these areas (Development of Guidelines for the Design of Drainage Systems for Highwave Pavement Structural Sections, F.H.W.A., Feb. 1973) and (32). For the thick-slab project we were able to follow in France (10), we evaluated on this basis the drainage requirement of this two-lane roadway structure. A draining layer thickness of 8 cm (3.2") in 4/60 mm (0.16/2.4") untreated materials appeared sufficient. We considered the amount of water capable of entering through the joints on the basis of surface absorption tests. The thickness of 15 cm (6") for this draining layer implicitly takes into account a certain safety factor.

I.3.3. Improvements to Old Pavements. J. Warscotte (8) described the case of the widening of a roadway in Assesse in the Belgian province of Namours: use of a porous concrete under the shoulder. Figure 10 shows the design arrangements used:

Figure 10. Overlaying of old pavements with concrete over asphalt. Assesse, Belgiun.



- transverse structural connection (load transfers through lean concrete in subbase),
- use of existing deep drainage structure on edge,
- drainage through shoulder with a porous concrete for the concrete-lean concrete interface,
- differentiation of topography in cuttings and topography in fills.

This approach can be used for concrete road improvements, whether the existing pavement is rigid or flexible.

I.3.4. Water Penetration in Concrete Pavements - Climatic Factors. As regards the evaluation of water penetration through the surface of pavements, A. Brull, G. Raimbault and J.F. Griselin (3) offer very complete proposals in their paper. The Bern Symposium in 1978 on road drainage already provided information on Belgian and French practices in this area. The authors point out that "the suggested evaluations are based upon many simplifying assumptions. This approach makes it possible to set, as a first approximation, the order of magnitude of the sought values".

Difficulties are encountered in developing rational methods. In fact, there are many parameters which vary with respect to both space and time. However, theoretical results compared with field observations show a certain agreement. A relationship between modelling of this type and tests with a permeameter on the surface on pavement joints can be a subject of future investigation of considerable interest.

Calculations have shown that the residence time of water at the concrete-subbase interface was very small with permeable materials. The danger of pumping would be eliminated with very porous materials.

The study suggests that on continuously reinforced concrete the possibilities of water penetration through cracks would be very small owing to the fineness of the cracks. A continuously reinforced concrete with a bituminous surface dressing would consequently allow water penetration only at longitudinal joints or at some large cracks.

While the effects of temperature gradients were not directly brought up in the seminar, A. Sheynin presented information relative to hydraulic gradients (4), the described results having reference to tests on specimens.

These results which relate to newly placed concrete and those up to 3 months old cannot be applied generally, in their present form, to pavements in service. It is conceivable that hydraulic gradients may be involved to the same extent as temperature gradients in slab curling and cambering. In-situ measurements with methods to be developed would constitute a valuable area of investigation.

I.3.5. In-situ Verification of Functioning of Lateral Drains. F. Verhée and J.F. Griselin (17) presented results in which the response time of lateral drainage structures are indicated. A very simple check of such systems can be carried out by allowing water to flow into a transverse joint and examining the outflow. J.L. Nissoux (11) showed (Figure 11) the type of results obtainable. The example relates to a lateral drainage system through a porous concrete. This test, very inexpensive, provides very useful information:

. Response time at outlet for the location at which the inflow Q1 takes place (these locations can be varied).

. The corresponding transit time.

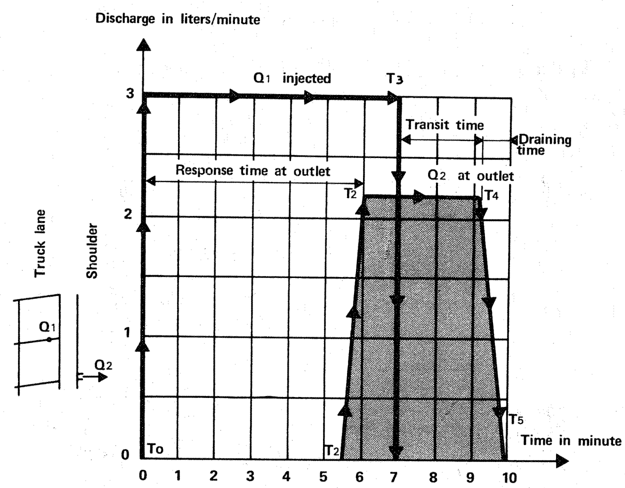
. The draining time.

Figure 11. Response time of a lateral drainage network.

Response time at outlet: T2 (time for constant flow to be reached in drain) minus To (beginning of inflow at Q1).

Transit time: T4 (when constant flow at Q2 begins to decrease) minus T3 (when inflow at Q1 is stopped).

Draining time: Ts (stopping of flow at Q2) minus T4 (start of flow reduction at Q2).



This test can provide data on the retention of water inside the system: by comparing the water inflow and outflow. In addition, it evaluates at a given instant the performance of the designs involved. It is possible to follow any changes occurring with the age and service of the pavement.

G. Grimaldi (5) has, in this spirit, designed and developed a probe-type measurement system making it possible to follow variations in water levels. This system has allowed tests to be carried out under forced conditions (injected water). Tests have thus been carried out under natural precipitations.

I.3.6. Characteristics of Pervious Materials. J. Woodstrom-Caltrans (6), J. Warscotte (8) and G. Michel (9) have investigated the case of treated porous materials. The term porous materials may be considered improper in this respect because pores exist even in a compact material. The use of the term pervious or draining materials is much broader. Tables 3, 4 and 5 give information on the mechanical strength of these materials.

The dimensions of voids and their distribution can differ depending on the types of material (maximum size, percentage of sand, angular crushed materials, alluvial materials, configurations of bonds afforded by the binder).

Table 3. Aggregates for bituminous draining materials

Sieve sizes	Percentage passing	
	3/4" Max.	1/2" Max
1"	100	--
3/4"	50-100	100
1/2"	--	50-100
3/8"	15-85	15-100
No.4	0-5	0-5

Table 4. Example of draining concrete and effect on the degree of compacting on mechanical strength (28-day compressive strength)

	COMPOSITIONS			
	First Composition (with sand)		Second Composition (without sand)	
	7/20mm 1,400 kg/m3		7/20mm 1,130 kg/m3	
	Sand 300 kg/m3		2/7mm 565 kg/m3	
	Cement 150 kg/m3 (waterproof even with aggressive water)		Cement 200 kg/m3	
	Water 70 liters		Water 86 liters	
	MECHANICAL STRENGTH			
	Compressive Strength N/mm2	Bulk Density kg/m3	Compressive Strength N/mm2	Bulk Density kg/m3
Upper part	24.0	2271	22.9	2142
Middle	16.1	2179	17.7	1999
Lower part	8.5	2021	11.2	1963
Average	16.2	2157	17.1	2048
Standard Deviation	7.6	120	7.5	120

1 mm = 0,04 in

1 Kg/m^3 = 0,06 lb/ft^3

1 N/mm^2 = 4520 pdl/in^2

Table 5. Bending strength estimated from tensile strength given by splitting test.

	Phase 1 (Voegele)	Phase 2 (Guntert)	Phase 3 (CMI)
Measured splitting test TS	1.56 MPa	1.98 MPa	1.8 MPa
Estimated 28-day bending strength[a]	2.6 MPa	3.3 MPa	3 MPa
Density	1.86	1.93	1.94
Porosity	25.4%	22%	21.6%
Vertical permeability on cores (1/m2/S)	18.7 18.7	12.1 12.1	12.4 12.4
Evaluation of conductivity K	1.4 cm/s	0.9 cm/s	0.9 cm/s

[a]Estimated from tensile strength given by splitting test: $BS = \frac{TS}{0.6}$

1 MPa = 10,4 short ton/ft^2

1 cm/s = 0,39 in/s

The percentage of voids sought for porous concrete can be 10 to 15 percent (8). This too calls for a clarification. If we refer to reference values for compactness, we are considering the percentage of total voids. But, some of these voids may not be in communication. For pervious materials, it would be preferable to speak of percentage of communicating voids.

B.J. Dempsey (2) shows, in connection with an experimental system (Figure 12), that with untreated materials containing mobile fines (fine sands and silts more particularly) pumping phenomena are liable to occur and will be related to erodability (Figure 13). The maximum pumping effects involve the longitudinal edges of the slabs. The combined action of slopes, longitudinal profiles and cross-falls as well as the effects of the progressive concentration of water in ramps, can create local risks of saturation

Figure 12. Cross section of experimental laboratory system showing the location of pore pressure sensors.

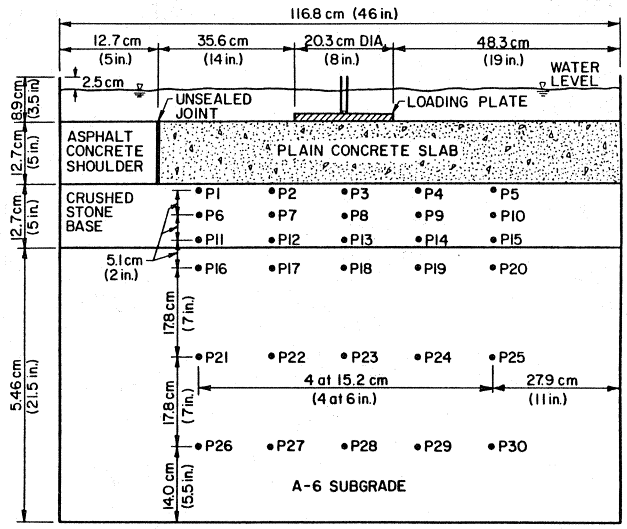
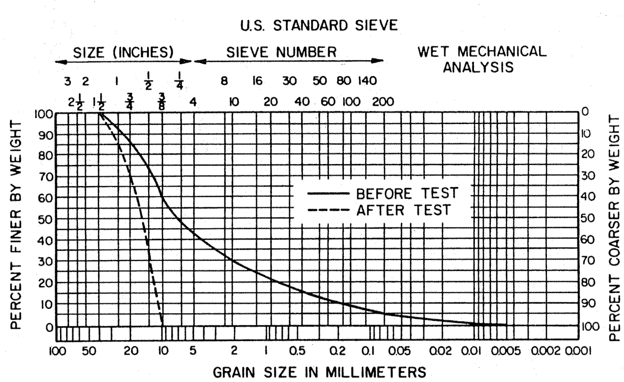


Figure 13. Example of result obtained with the experimental system of B.J. Dempsey on a typical CA6 material (conductivity 2.10^{-4} cm/sec). A considerable loss of material is observed at the slab-subbase interface and in particularly a loss of all fine elements.

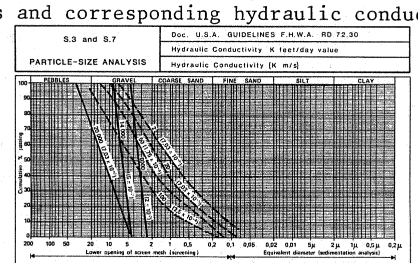


in the materials. J.L. Nissou (11) raises the question of the requirements to be applied for medium and light traffic: "in the case of medium traffic, it should be possible to use lower-performance subbase materials while conserving the lateral drainage structure. However, it is difficult, for want of sufficient observations, to adjust the quality of the subbase and the simplicity of the drainage structure. Since no doubt should exist in this regard, solutions must be proposed which one feels represent an over-design. Fortunately, such is not the case with light and very light traffic levels. An untreated subbase offering modest drainage is easy to obtain in many cases" (area of slabs without treated subbase used extensively for agricultural roads and for roadways in housing developments).

In-situ observations in the spirit of the tests conducted by B.J. Dempsey (2) will thus be indispensable. As illustrated in Figure 14, it is already possible, based upon the particle-size distributions of untreated materials, to have a good idea of available permeabilities. The factors which should be examined more closely in the field are the following:

- Conservation of permeability values with time (effects of adaptations, percolation of fines, mixture and origin of these fines in connection with the condition of joint products).
- Possibility of saturation according to joint product condition, geometrical data and environments.
- Pressure and speed of water ejection at interface between slab and untreated subbase and in the material of this subbase.
- Possible effect of type and properties of improved or natural subgrades for light traffic.

Figure 14. Example of grading of untreated pervious materials and corresponding hydraulic conductivity.



I.3.7. Maintenance of Drainage Structures - Age of Structures. This subject was not directly addressed at the seminar. The conservation of the effectiveness of drainage structures (or surface water and particularly for internal water) is quite obviously an essential requirement implicitly acknowledged by all the papers.

Consequently, the basic requirements to be considered will be:

- proper design of drainage structures;
- verification of operation (see Paragraph 1.3.5.) and performance (more observations would appear to be necessary in the field);
- the conservation of system operation and performance levels throughout the service life of the pavement.

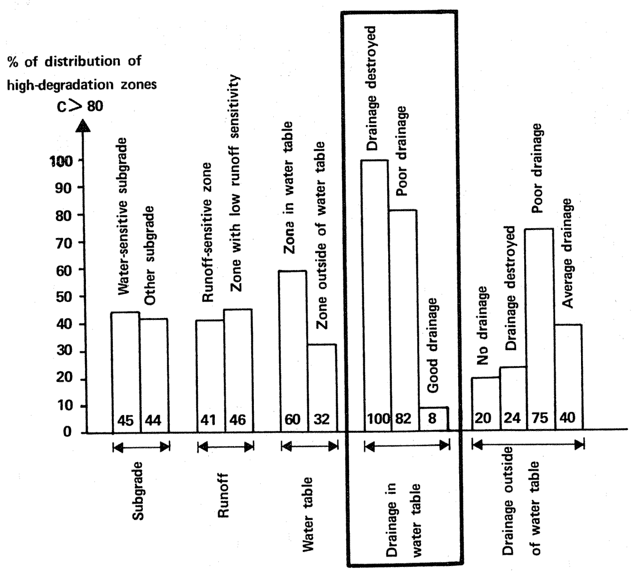
What will be required is monitoring of pavements, implementation of maintenance techniques and solutions to the shortcomings encountered. Proceeding otherwise would mean taking risks and counting in the long term only on the performance of structures (as concerns control of erodability risks and control of risks related to inadequate waterproofing).

The implications of such a procedure were brought out again during a very recent study conducted in France in connection with the demolition and reconstruction of the heavy-traffic lane of the A6 Expressway in 1983. J.C. Grisoni and M. Thomachot were able to evaluate qualitatively and quantitatively the role and the condition of the drainage system in the sublayers of an old concrete pavement from observations carried out on the 7.2 km (4.32 miles) of the project mentioned, and looked for relationships between:

- risk zones (subgrade, runoff, water table);
- condition of drainage system and its effectiveness,
- damage observed on the old pavement.

Figure 15 provides a synthesis of the different correlations obtained. While in the present case there are no significant correlations between the subgrade or runoff or drainage outside of the water table and the damage which occurs, there is however

Figure 15. Synthesis of observations made during demolition and reconstruction of A6 Expressway in Essonne region of France in 1983.
Table data: In zones designed with drainage in water table, the plot is affected at 80% by significant degradation (degradation coefficient 80).
Degradation coefficient: C = 3x + 2(y + z) + u + v
x: % of fractured slabs (2 cracks or more)
y: % of slabs cracked transversely
z: % of slabs cracked longitudinally
u: % of slabs cracked obliquely
v: % of slabs with small corner breaks



an altogether opposite tendancy between the presence of a water table, drainage in the water table and the observed damage. This latter comparison is particularly meaningful because:

- the line with destroyed damage is affected 100 percent by significant degradations (degradation coefficient higher than 80),
- the line with poor drainage is affected 82 percent by significant degradations,
- the line with good drainage is only affected 8 percent by significant deteriorations.

As regards the relationship between significant degradations and the presence of the water table, it is observed that 60% of the line concerned by a water table is graded. A detailed study has shown that 90 percent of the zones for which one observes significant degradations, at least 300 meters (100 ft) long, are located within the water table.

By thus eliminating specific cases of degradation which may correspond to very localized irregularities of various origins, it is possible to show the very good correspondence between high levels of deterioration and groundwater areas.

Chapter II. Erodability at Interfaces between Concrete Slabs, Subbase and Shoulder

This chapter deals with the most recent findings reported in our 12 papers within the subject area of "Erodability under the Concrete Slab" of the program of the Paris seminar.

The theoretical and experimental studies, pavement observation and exchange of information during recent years have yielded three types of results:

1. Working out of new design methods introducing the notion of erodability.
2. Classification of pavement materials utilizable in the subbase and shoulders based upon erodability resistance, providing a guide for areas of utilisation.
3. Recommendations and exchanges of experiments on the most effective design arrangements for improving the service life of pavements within an acceptable economic context.

II.1. Development in Structural Design Methods

The most complete work in this area is that presented by R.G. Packard and S.D. Tayabji (19) reporting on a revision of the Portland Cement Association's structural design method of 1966.

An important aspect of this revision is the introduction of a subbase erodability criterion which is added to the more traditional criterion of the maximum fatigue strength of the concrete.

A distinction is thus made between the two major components in pavement damage:

- the erodability component which synthesizes the pavement failure mode by excessive pumping and the formation of cavities in the subbase,
- the fatigue component which synthesizes the failure phenomena by excessive loading.

These two criteria are evaluated by indicators for deflections and stresses at the different sensitive points of the slab by means of a finite-element program: the JSLAB program.

Specifically, the authors of the method have arrived at relationships associating, on the one hand, the energy transmitted by loading (p x w; pressure at slab-subbase interface x deflection on slab corner), the thickness of the slab and the modulus of subgrade reaction and, on the other, the number of loading cycles corresponding to the service life of the pavement.

The method makes it possible to calculate the damage accumulated by erosion (in percentage) which is the sum of the elementary damages accumulated for each loading. This damage is added to the conventional fatigue damage established according to Miner's laws.

Graphs have been plotted which indicate the number of loading cycles as a function of the erodability factor, and of the vehicle profile, for different subbase and shoulder configurations (Figure 16).

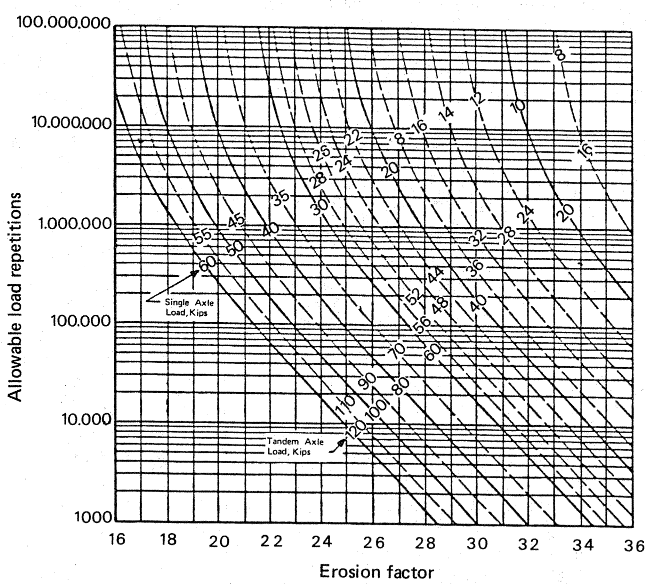
The authors suggest the initial use of this criterion as an indicator providing guidelines. Modifications may be made subsequently to take into account the climate, drainage, local factors, and so on. More numerous observations will help to determine the required adjustments and refinements.

This tool has moreover made it possible to conduct trend studies from which it has been found, for example:

- that "erodability" damage is generally what determines the structural design of medium and heavy traffic pavements using undowelled joints, and very heavy traffic pavements using dowelled joints;
- that in terms of equivalent concrete thickness, the amount added would be equivalent to between 2 and 5 cm (0.75" and 2") for a cement-treated subbase, and between 4 and 7.5 cm (1.5" and 3") for a lean concrete.

Other equivalences of this type are mentioned by

Figure 16. Graph obtained with new PCA design method introducing an erosion factor; after R.G. Packard and S.D. Tayabji.



one of the authors (28) who reports on methods developed by Sawan and Darter taking into account the erodability of materials in connection with the design of concrete shoulders and the effect of this on the structural design of the slab itself.

II.2. Classification of Pavement Materials from the Viewpoint of Erodability for Use in Subbases and Shoulders of Concrete Pavements

The most striking studies were conducted in France (18) (27) and in the United States (22).

In France, the theoretical and experimental studies conducted by Nguyen Cong Phu and M. Ray were intended primarily to allow the modelling of the pumping phenomenon.

It was thus demonstrated that the expulsion of water under the concrete slabs entailed a threshold phenomenon in which the initial depth of the cavity played an important role, as shown by the information given in Table 6.

With the thresholds derived from the theoretical study, this reference was used to establish the widest possible range of materials used in subbases or shoulders. What was sought was numerical values characterizing the erodability of the materials and determining the variations of this erodability as a function of defects in the materials and loading conditions.

Test apparatus were designed by the French Road Research Laboratory (Laboratoire Central des Ponts et Chaussées), among which the most effective were:

- the rotary brushing apparatus (Figure 17),
- an apparatus mounted on a vibrating table (Figure 18),
- an apparatus for measuring the critical speed by means of a water jet (Figure 19).

The latter apparatus showed that an untreated granular material offered very poor resistance to the dynamic action of a water expulsion speed of 5 meters (16.5 ft.) per second, i.e. a speed lower than that likely to be encountered in mode 2. This

Table 6. Thresholds defined by the study of hydraulics of pumping and meaning for concrete pavements.

MODE	CAVITY DEPTH	WATER DISCHARGE RATE	SLAB/SHOULDER INTERFACE CONDITION	STAGE OF PAVEMENT SERVICE LIFE
1	0.5 mm (0.02") subbase surface with very little erosion	Low 4 m/s	Initially, small cavities due mostly to negative gradients	Latency period
2	0.5 to 1 mm (0.02-0.04")	Transient low 4 to 8 m/s Critical stage of water expulsion	Small cavities at weakest points capable of enlarging owing to very high speeds	Acceleration period
3	1 mm Highly eroded subbase surface	6 m/s to a few m/s (settling according to depth of cavity)	Possibility of stabilization of minimum cavity depth but there is slab fatigue and failure	Period of damage occurence

1 mm = 0,04 in

1 m/s = 3,28 ft/s

Figure 17. Rotary brushing device. No-load rotating speed of 850 rpm. Steel brush diameter of 100 mm. Simple and reproducible test (but may not simulate under-slab erosion exactly in the case of treated sands, for example).

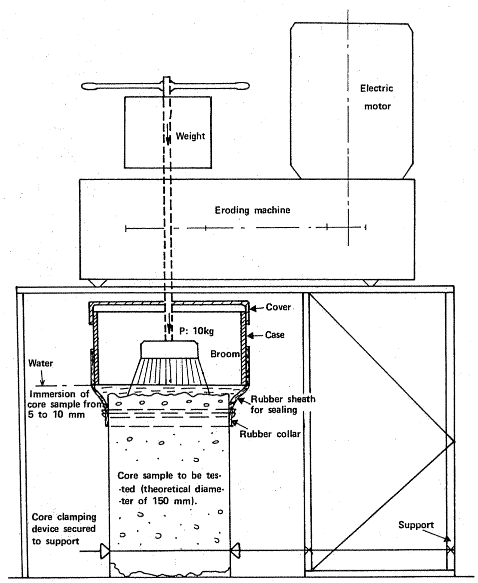
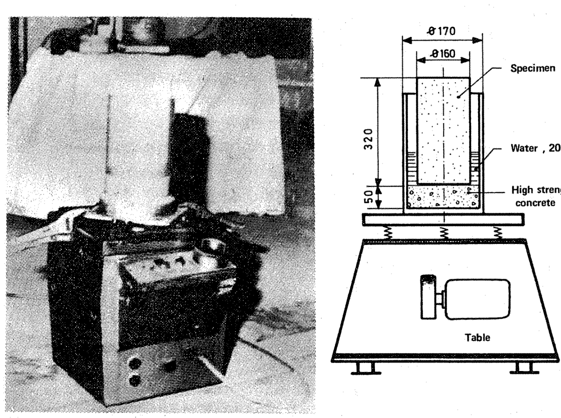


Figure 18. Apparatus mounted on vibrating table.
- Frequency 160 Hz
- No-load acceleration ± 13 g
- Specimen weight set at 12 kg

Simple test very close to phenomenon of hydraulic erosion under slab.



material is not recommended for heavy traffic and for rainy regions.

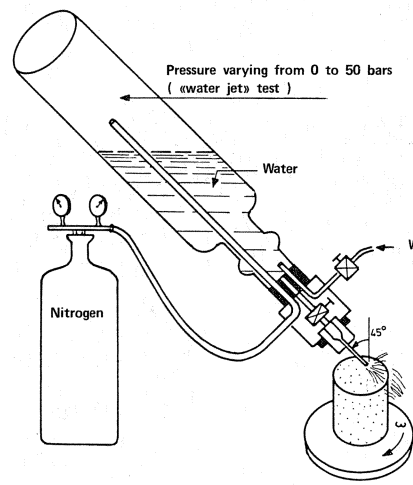
This test also made it possible to define a pre-classification in three erodability classes:

1. Very erodable materials: v < 5 m (16.5 ft)/s.
2. Medium erodability materials: v > 5 m (16.5 ft)/s, but scattering of values due to heterogeneities of material in place. (Example: cement-treated material with 3.5 percent cement.)
3. Very low erodability material: v >> 5 m (16.5 ft)/s, small scattering of values with minimum >5 (16.5 ft)/s. (Example: lean concrete with 150 kg/m3 (250 lb/yd^3).)

The rotary brushing test permitted the introduction of an erodability index based upon a comparison between a result or any material and a reference

Figure 19. Apparatus for measuring critical speed by water jet.
- Nozzle diameter: 1 mm
- Distance from specimen face to end of nozzle: 20 mm
- Specimen rotating speed: 4 rpm.

Complex test allowing connection in relation to theory of erosion of materials.



material consisting of a cement-treated granular material with 3.5 percent cement. Such an index is a convenient basis of comparison which incorporates in a single figure a set of data derived directly from field and laboratory observations.

The graph in Figure 20 locates the materials currently encountered in subbases and roadbeds of concrete pavements in relation to each other according to the erodability criterion.

It shows that:

- a cement-treated material with 3.5 percent is 10 times more erodable that a lean concrete with 7 percent cement,

- the value of 3.5 percent cement constitutes a critical threshold below which erodability increases very rapidly inversely with respect to the proportion of cement.

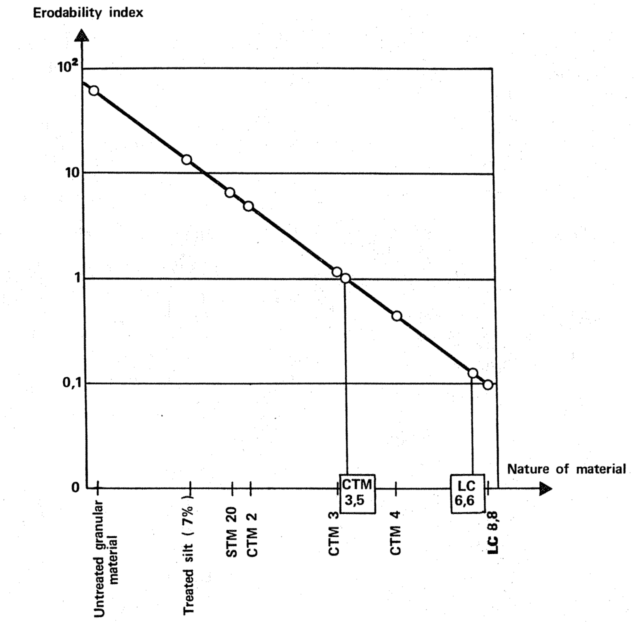
It is to be noted that these results are very consistent with the observations which have been made in a number of countries and in Spain in particular (26).

In the United States, J.H. Woodstrom (22) conducted erodability tests using a machine derived from a water sensitivity test applied to asphalt materials (Figure 21). The results obtained on different mix designs for lean concrete and cement-treated materials completely corroborated the French results, i.e. that the threshold value for cement-treated materials is of the order of 4 percent with significant superiority of lean concrete over cement-treated granular materials.

The author would moreover like to draw attention to the fact that the cement-treated materials tested in the laboratory in the form of recomposed materials involved ideal compacting and moisture content conditions, which are seldom found in the field. He proposes the reduction of the values obtained by about 40 percent to take into account this reality which is observed moreover in many countries (22) (27).

These theoretical and laboratory studies should be compared more systematically with field observations. J.P. Christory (27) has demonstrated the relationships between the erodability of subbases

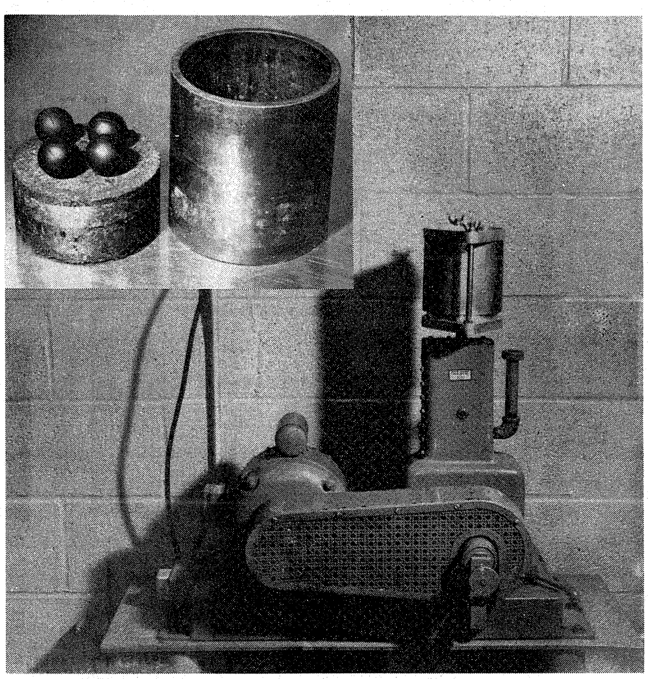
Figure 20. Erodability index of materials usually encountered in subbases or roadbed of concrete pavements.



SYMBOLS :

STM 20 : Slag treated material with 20% granulated slag.
CTM 2–3–3.5–4 : Cement treated material with 2,3,3.5, and 4% cement respectively.
LC 6.6 – 8.8 : Lean concrete with 6.6 and 8.8 cement respectively.

Figure 21. Surface abrasion test equipment.



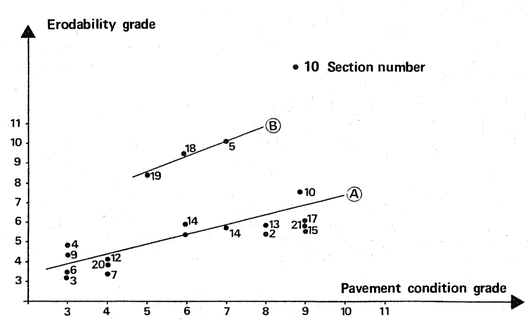
and the traffic behavior of undowelled concrete pavements. Several European countries have contributed to this study, taking samples (subbase pore samples) of characteristic pavements and proceeding with the investigations necessary for the documentation of these samples.

Several classifications of materials were established on the basis of various criteria, from a classification by simple visual observation of pore samples to a classification encompassing all the erodability tests conducted.

An overall interpretation of these results was outlined showing the relationships between the condition of the pavements, on the one hand, characterized by a degradation coefficient, slab deflection and faulting and, on the other hand, the erodability of the subbase evaluated by the pore sampling "grade", rotary brushing resistance and vibrating table resistance.

Two families of pavements were observed (Figure 22) in which the more numerous (population A) clearly shows the privileged role of the erodability criterion on the behavior of pavements.

Figure 22. Relationship between erodability grades of foundations and pavement condition grades. The higher the grade, the more erodable the subbase or the poorer the condition of the pavement.



These data enable us to propose a graduation of the axes of the graph with three dimensions (traffic, erodability, climate harshness) designed by M. Ray in order to define a maximum utilization surface area for concrete pavements with undowelled joints with respect to which the investigated pavements were classified (Figure 23).

When modern design methods are combined with careful workmanship and efficient application of engineering techniques, it is possible to propose the adoption of the recommendations for the maximum allowable traffic on undowelled pavements mentioned in Table 7.

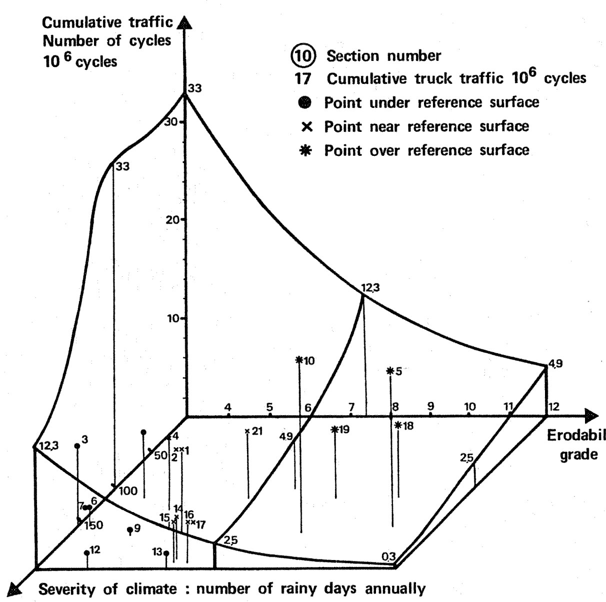
Concluding this analysis, it has been demonstrated that the erosion resistance of subbases plays an extremely important role in the behavior of undowelled pavements. It was proven, on a significant sampling of French pavements and on pavements in other European countries, that the subbase erosion phenomenon constitutes, in the final analysis, the main cause of pavement damage. This conclusion is entirely consistent with the one offered by R.G. Packard and S.D. Tayabji concerning the development of the new PCA structural design method which shows that, for heavy traffic pavements, the "Erosion" component often overshadows the "Fatigue" component in the evaluation of damage accumulated by the structure during the life of the pavement.

Table 7. Recommendations regarding maximum traffic (number of trucks daily) according to harshness of climate and erodability of subbase.

SUBBASE ERODABILITY GRADING	12 to 8		8 to 5		5 to 5	
CLIMATE: NO. OF RAINY DAYS ANNUALLY	13 t	9-10 t	13 t	9-10 t	13 t	9-10 t
Harsh 150 d	150	300	300	750	750	2000
Average 50 to 150 d	300	750	750	2000	2000	5000
Favorable 50 d	750	2000	2000	5000	2000	5000

1 t = 1,103 short ton

Figure 23. Location of sections studied in the allowable maximum traffic reference graph.



II.3 Design Arrangements

Finding practical solutions for controlling the detrimental effects of materials having a low erosion resistance is important because any error in the quality of the subbase and shoulder edge in this respect is liable to have irreparable consequences in the long term.

It is to be noted that the papers on the whole attach as much importance to the shoulder materials as to the actual subbase materials, which is altogether justified by theory (18), (28), (29).

F. Verhée (29) shows that the design arrangements applied in different countries all converge towards the use of materials more resistant to erosion, at least wherever this is indispensable, i.e. at the level of the subbase and in a trench of 40 to 50 cm (16" to 20") of shoulder adjacent to the concrete slab. This is reflected in:

- a tendency to abandon the use of untreated materials in which fine elements can be easily dislodged by pumping,
- higher cement proportions in cement-treated materials (26),
- the use of lean concrete in the subbase (29),
- the design of cement concrete shoulders secured to the concrete slabs.

R.G. Packard (28) reports on this latter point of the recommendations which were established in the United States for the design of concrete shoulders based upon the application of this technique on a very large scale yielding excellent results.

The design arrangements adopted for erosion control are often combined with action on the drainage structure. Very interesting results reconciling the two objectives were obtained with pervious material of the porous concrete type on the edge of shoulders, and even in subbases in the case of very wide roadbeds (airport runways).

The use of asphalt materials in an intermediate layer between the slab and the subbase remains quite controversial. Cited as valuable by J.H. Woodstrom (22) for covering cement-treated materials when lean concrete cannot be used in the subbase, this technique is, on the contrary, considered to be unsatisfactory by J. Eisenmann, D. Birmann and G. Leykauf (20) because it does not provide a good bond between the slab and the subbase, considered to be essential in the German Federal Republic. This bonding technique moreover appears to have been fully mastered in Germany for dowelled joints, applying simple precautions (thorough cleaning of subbase surface and watering prior to concrete placement).

Note will also be made of the interesting experiment carried out in Czechoslovakia and described by E. Slachta (24) using the image of a slab floating on a viscous fluid which does not undergo stresses resulting from temperature gradients if it remains constantly in contact with the fluid. The best material for the subbase surface would be characterized by a high modulus of elasticity during rapid slab loadings and by a much lower modulus for slow deformations caused by thermal stresses. The asphalt materials used, having a high binder content in principle, do not pose any erosion problems but, under the action of heavy traffic, can cause faulting due to the creeping of bituminous mixes. In this case, the phenomenon can be accentuated quite rapidly by dynamic loading. This interesting idea appears to be applicable in the present state of the art only to pavements handling medium to light traffic.

However, on the whole, it appears that this technique of inserting a bituminous layer between the concrete slab and its subbase is being used less and less.

Conclusions - Outlook

Review of Present Questions

The following questions are either entirely new ones or old ones formulated in light of the present technical and economic situation, or questions dealt with within the particular context of one or more countries. In this regard, the authors would welcome any information offered in response to this paper by other countries.

I - Assessment of Specific Value of Lateral Drainage at the Concrete-Subbase-Shoulder Interface

I.1. Effective drainage can reduce the residence time of water at the concrete-subbase interface by a factor as high as 100. This design revision, relatively recent compared with others, can consequently modify the answers to some former questions. It would be of interest to quantify the following:

1. The effect of drainage on the reduction of pumping and of the faulting speed.
2. The other consequences of the adoption of drainage. For example, the reduction of water content gradients in slabs, and hence the corresponding deformations, the reduction of frost action (D - cracking, etc.), the improvement of water contents in deep layers and subgrades.
3. The comparative costs of the different designs adopted for the drainage systems to achieve the best cost-effectiveness and reliability (immediate effectiveness and its conservation throughout the desired service life). Supervision and maintenance of these structures is in fact a guarantee. An inventory of what is known and what remains to be learned will make it possible to avoid costly field investigations. The first approach should consist of an inventory of the problems (even if specific local problems are involved). A criterion such as "less than 4 percent passing 0.4 mm (0/016 in.)" for an untreated subbase would provide a very concrete and simple guide.

I.2. Drainage structures raise new questions today:

I.2.1. When an engineer wishes to correct pumping on an old road section designed initially without drainage and whose condition is worsening rather rapidly, what are the limits of the use of lateral drainage (erodability of old subbase layer, climate, traffic, effectiveness of load transfer, and so on)?

I.2.2. With regard to treated porous materials, what precise recommendations should be given for their mix design and compacting so as to obtain the best compromise between strength, permeability and durability?

I.2.3. What are the characteristics to be required on synthetic textiles used as filters in drainage trenches provided subsequently on old pavements and what is their effectiveness?

I.2.4. Under what circumstances can the adoption of a drainage system obviate the need to seal the joints? Importance and effects of negative gradients on variations in joint openings. Relationship to type of waterproofing and to the fatigue of joint products. Advantages of bridging-type solutions provided on a surface dressing prior to additional surfacing.

I.2.5. What are the precise climatological data which determine, for a given structure, the intensity of the pumping phenomenon? Which thresholds appear to be the best suited for classifying the climates as a function of their influence on pumping and erosion? Research and definition of practical criteria.

I.3. Reconstruction of heavy-traffic lanes. Is longitudinal drainage necessary for the light-traffic (and/or medium-traffic) lanes?

II - Drainage through Subbase. Some major expressway and airport projects were recently designed in the United States and France with drainage structures going through the subbase. This technique raises several questions:

1. Which circumstances justify the use of this solution (pavement width and characteristics of traffic, climate, etc.)?
2. What specifications may be laid down with regard to each design aspect of this solution (thickness and permeability of drainage layer, use of treated or untreated porous materials, strength of materials chosen as a function of nature of traffic, minimum properties of material immediately under the drainage layer)?

III - Pursual of Studies on Erodability and on Nonerodable Materials.

III.1. Characterization of erodability on the surface of each material used in the subbase.

III.1.1. By means of technological tests or directly on the basis of the water speed as of which a given material begins to erode, would be of interest to characterize each material used customarily in each country, by:
- an average erodability,
- a range of variation in this erodability when the materials or the placement and conservation techniques vary within the limits normally observed on the jobsite. Such research could also make it possible to determine the most economical and effective means of reducing this subbase surface erodability on the jobsite.

III.1.2. Along with these tests, it would be necessary to investigate the action of frost-thaw and of de-icing salts on the erodability of the surface of the subbase and shoulder. This action would have to be compared with the purely mechanical or hydrodynamic action.

III.1.3. The finalizing of a simple erodability test which can be used for checking subbase surface quality on the jobsite before concrete placement would be necessary, notably where use is made of conventional cement-treated materials and when the climate and jobsite traffic have caused damage to the subbase surface.
The search for a referance test to measure erodability and to allow comparison of the data obtained in different countries would be useful.

III.2. The customary use by several countries of an asphalt layer a few centimeters thick between the slab and its cement-treated subbase raises the following question: besides the role of such a layer in securing better evenness of the concrete pavement, under what conditions (thickness, asphalt content) does this layer modify the erosion phenomena and how?

III.3. In order to prevent erosion phenomena on the edge of the shoulder, what structures and what materials should be recommended according to the traffic, climate and service level expected?

III.4. Certain subgrade erosion phenomena have been encountered. Under what circumstances is it necessary to use low-erodability subgrades under concrete pavements (effect of subbase thickness, its cracking and correspondence between this cracking and the joints of the concrete)?

III.5. What are the respective advantages and drawbacks of the three non erodable materials used today: lean concrete (California, other states of the United States, France), asphalt concrete (Austria, Belgium), cement-treated materials with high cement content (Spain)?

III.6. In the particular case of vibrated lean concrete used in the subbase, what are the minimum properties to be required (mechanical strength, erodability) to obtain the best cost-performance compromise?

III.7. If nonerodable materials are used, which sources of fines are to be avoided and how (fines coming through joints - need for waterproofing)?

IV - Comparison of the Effectiveness of Different Systems for Avoiding Pumping and Faulting under Present Technical and Economic Conditions. Compared with all the other systems making it possible to prevent or reduce pumping and faulting (dowels, extra slab thickness in heavy-traffic lane, extra-wide slabs, very short undowelled slabs, concrete shoulders with tie bars, and so on), it would be of interest to characterize the effectiveness of different drainage systems as well as the options concerning the nonerodability of subbase and shoulder materials.

An economic study of these different options and their most effective combination would make it possible to adopt the various technically coherent and economically equivalent solutions on experimental sections chosen on a heavily trafficked road.

While the list of the combinations of systems mentioned above is long, four sets of these combinations appear to be of particular interest today as concerns testing and are under discussion in several countries. The questions which are really posed can be formulated as follows:

IV.I. For heavily trafficked pavement, with drainage and nonerodable subbase, are dowels a strict requirement today?

IV.2. Up to what traffic level and under what climatic conditions is it possible to use the undowelled drained structure with a cement-treated subbase having a sufficiently high cement content?

IV.3. For drained structures with very thick undowelled slabs, what subbase layers should be provided based upon the traffic handled by the road?

IV.4. Does the search for a durable bonding between the concrete slab and its subbase (only one paper discussed this subject at the seminar), particularly in the case of dowelled pavements, obviates the need for lateral drainage and for nonerodable materials in the subbase and low-erodability materials in the subgrade? In this connection, it would be important to investigate more fully the duration of slab-subbase bonding and its subsequent attenuation, which leads to a rapid increase in deflections when it disappears completely.

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