A EUROPEAN SYNTHESIS ON DRAINAGE, SUBBASE ERODABILITY, AND LOAD TRANSFER IN CONCRETE PAVEMENTS

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European research and field practice from 1977 to 1981 are described as concerns load transfer (at contraction joints of nonreinforced short slab pavements), drainage of slab-subbase contact, and subbase and shoulder erodability. For non-doweled pavements, new developments leading to better load-transfer efficiency concern mainly the reduction in slab length, the extra slab width beyond shoulder line, the reduction in hydraulic and thermal shrinkage, and the increase in coarse aggregate diameter. For doweled pavements, new developments concern the reduction in the number of dowels, anticorrosion and slipping devices, placement accuracy and vibration placement equipment. Water problems encountered in Europe for pavements with and without dowels are presented; the new draining cross-sections used in each country are described together with measurements characterizing their efficiency. After an analysis of the risk of faulting as a function of the origin of the fines, recent theoretical and practical research results on pumping hydrodynamics and subbase erodability are presented: leave slab water ejection rate equations, cement content threshold to avoid erodability in cement-treated subbases, use of internally vibrated lean concrete. The second part of the paper gives the results of an international survey (26 countries, performance evaluation of 74 old pavements). Three classes are chosen for climatic conditions, and three for erodability. Traffic limits observed on the oldest pavements in good condition are given for nondoweled and for doweled pavements. Finally, quantitative recommendations are proposed in terms of compatible daily commercial vehicle traffic limits with or without dowels, for each climate and different erodability conditions. The conclusion presents a historical synthesis and an outline of future research needs.

This paper presents the developments of the last four years of European laboratory research, test sections and field practice (16,31) concerning drainage, subbase erodability, load transfer in concrete pavements and the combined effect of these three factors. A more detailed report on the same subject is available (29).

To get directly into the core of the subject: To dowel or not to dowel? Is it the right question?

One aim of this paper is to attempt, in light of seemingly contradictory practices found in various countries, to provide an answer showing the specific field of application of each design, defining in particular the factors which must be considered in replying to this question in each case.

What appears to be a real question is: to design a short-slab concrete pavement under given traffic and climatic conditions with satisfactory results from the technical and economic standpoints, what coherent set of decisions should be made with respect to the following three main alternatives:

1. Whether or not to use dowels.
2. Whether or not to use a special drainage system.
3. Choose such and such a material (erodable or not) for the shoulder and for the subbase of the pavement?

To provide a certain amount of information for replying to the precise question just set forth, the first part of the paper will analyze the separate influence of each of the three main factors under consideration, and the second part will deal with the combined effect of these three factors.

Intentionally, the thickness of the concrete slab is not mentioned among the preceding factors (cf. Combined Influence of the Three Factors - Methodology Used, and 28 Appendix 9, 29).

Influence of Each Factor

Load Transfer

Load Transfer in the Case of Undoweled Slabs.

Influence of Crack Opening at Joint. The existence of this influence was demonstrated long ago (5). Unfortunately, it is too often misunderstood in practice. Among the new information concerning the means of achieving crack opening reduction, the following may be mentioned:

1. As regards the action intended to reduce hydraulic shrinkage, several experimental projects

have been carried out in France since 1976 with extremely dry pavement concrete, compacted and not internally vibrated, in particular for medium or light traffic roads. Very dry and compacted concrete was also used with substantial additions of flyash in Great Britain for special concrete pavement applications.

2. A very effective means of significantly reducing thermal shrinkage is to use coarse and medium aggregate with a low heat expansion coefficient, limestone for example. For road and superhighway pavements, the application of chips to fresh concrete now makes it possible to use limestone aggregates. The technique used in Belgium on side forms has recently been extended to slipforms in Belgium and in France (34).

3. As regards the role of the subbase on joint opening, research carried out in several countries (10) is leading to wider use of cement treated subbase materials in order to avoid excessive irregularities in crack opening during construction as well as to partially control concrete shrinkage (6).

4. A new aspect concerns the longitudinal creep of the concrete. Longitudinal creeping in concrete slabs has been observed in the German Dem. Rep. when dust particles fill the cracks at joints and when high temperatures create intensive longitudinal compression in the concrete (25).

Influence of Slab Geometrical Characteristics.

1. Thickness; today the precise recording of deformations on experimental thick-slab sections (12) have demonstrated qualitatively that the dissymmetry of slab-end deformations was not substantially modified and that an increase in thickness could only change the faulting rate.

2. Length of undoweled pavement slabs; very short slabs lead to better load transfer at joints; the slab length should be even smaller than 3.7 m so that the opening of 1 mm is exceeded as infrequently as possible (6). Very short slabs also reduce the risk of pumping: for a given negative temperature gradient, the shorter the slab, the more limited is the distance between the underside of the curled slab and the subbase. As the water ejection rate from the leave slab toward the approach slab upon the passage of a load over the curled slab ends is proportional to the square of the height of the cavity (20,21), it may be estimated that halving the slab length can reduce the water ejection rate by a factor of about 4. Assessment of recent experiments with very short slabs in Europe: in the USSR (18), allowance for very different climatic effects in the various regions (the number of design thermal stresses can vary in a ratio of 10 and their intensity in a ratio of 2) has led the designers of Soyuzdornii to recommend the systematic reduction of slab lengths by 1 m in continental regions, as compared with temperate regions; the advantages of very short slabs have led French researchers since 1975 to set up experimental sections on which a check was made of the extent of the reduction in slab and deflection (29). Reducing the average length of slabs thus appears to be a very interesting tendency for the technique without dowels: easy to implement, it automatically leads to a permanent improvement in load transfer, to a reduction in stresses within the slab and to a limitation of the risk of the initiation of pumping and faulting. This tendency, which is moreover not costly (2 to 4%), should thus be considered carefully by designers in the future years.

3. Joint skewing; the use of the 1/6 skew is general practice today in Europe for undoweled pavements carrying heavy traffic. Present investigation methods, in particular the measurement of water pressure under slabs and the calculation of stresses by the finite element method, could perhaps enable progress in research to determine if 1/6 is the optimum skew considering the following three objectives: maximum reduction in approach-leave loading dissymmetry, avoiding the creation of excessive transverse dissymmetry, and avoiding the breaking of sharp angles under the effect of temperature gradients and heavy loads.

4. Slab width; without playing a decisive role as concerns load transfer itself, extending the width of slabs of the truck lane into the shoulder area (by 0.25 to 0.75 m, generally 0.5 m) significantly reduces deflections on the slab edge and corners. This design, called "extra width", is being used increasingly in Europe since 1973 by countries not using dowels (France, German Dem. Rep., and Spain in certain cases) as well as countries using doweled slabs, West Germany in particular (11).

Load Transfer in the Case of Doweled Slabs. Very broad and long experience on the use of dowels in several countries of Europe (West Germany, Great Britain, Switzerland, Austria, in particular) has made it possible to clearly specify the specific advantages of dowels and the main conditions necessary for their proper performance.

As an illustration of this importance, mention may be made of the data collected during an international survey conducted in 1977 within the framework of the PIARC. These data (Table 1) represent an approximate evaluation of the mileage with or without dowels for superhighway pavements and heavy traffic pavements, hence normally excluding urban and rural roads, old pavements covered with bituminous products, as well as continuously reinforced-concrete pavements or reinforced long-slab pavements.

Table 1. Lengths of concrete pavement with or without dowels (short nonreinforced slabs). (These lengths are expressed in number of km of equivalent dual two-lane pavement.)

Countries or Provinces having replied to the Questionnaire (excluding the U.S.A.)	Kilometers with Dowels	Kilometers without Dowels
South Africa		96
Austria	500	16
Belgium	1000	
Quebec		60
Ontario	190	55
Denmark		14
Spain	8	254
France	15	500
Great Britain	460	
Italy	5	13
Japan	1560	
German Dem. Rep.	95	325
West Germany	4000	
Switzerland	906	
Czechoslovakia		250
Total:	8739	1583

As regards European countries alone, this evaluation leads to a length of about 7000 km with dowels, and 1400 km without dowels. If we add the lengths obtained from all countries (including the U.S.A.), these values amount to about 18,000 km of nonrein-

forced pavement with short doweled slabs and 15,000 km of short-slab pavement without dowels.

Specific Advantages of Dowels. Without going back to the study of the part played by dowels in the distribution of stresses within the slabs, the two most important effects of dowels, recognized very widely in Europe, are the following:

1. Dowels make load transfer variation less sensitive to joint opening: this property however requires concrete of excellent quality at the contact of the dowels and good concrete vibration at joints. When concrete quality is not sufficient, the dowel hole in the concrete becomes ovalized after a time. The international survey showed that ovalization ranging up to 10 mm has been observed in Japan. On very old pavements, average ovalization measurements have given figures from 0.4 to 3 mm.

2. Dowels block faulting: if dowels only improved load transfer quality and durability, significant faulting would be observed; another function which appears to be fulfilled by dowels when they are properly positioned, well dimensioned and durable is the direct mechanical blocking of faulting at a value near the ovalization height of the dowel hole. Even if present specifications take the necessary precautions to avoid any substantial ovalization, the property described has a twofold value: firstly, the exceptional durability of certain doweled pavements in West Germany, notably, and this in spite of the existence of untreated subbases and traffic not initially expected, shows that the use of dowels affords very considerable safety; secondly, this property of blocking faulting without necessarily providing a load transfer in the strict sense of the term can furnish ideas contributing to finding a solution costing less than conventional dowels.

New Requirements for Proper Dowel Performance.

1. Design (31): what was discussed with regard to interlocking (apart from joint skewing which is not necessary here, and the reduction in slab length which would be too costly with doweled joints) is applicable to dowel stress rate reduction and certain dowel design methods take this into account (33). Research conducted in West Germany has resulted in a considerable reduction in the number of dowels (Figure 1) while increasing their spacing where they are less necessary (fast lane and outside of wheel tracks on heavy-traffic lane (9,11,15). For repair work (Figure 2), only six dowels per lane are needed (17).

Figure 1. Standard and special dowel design for transverse joints.

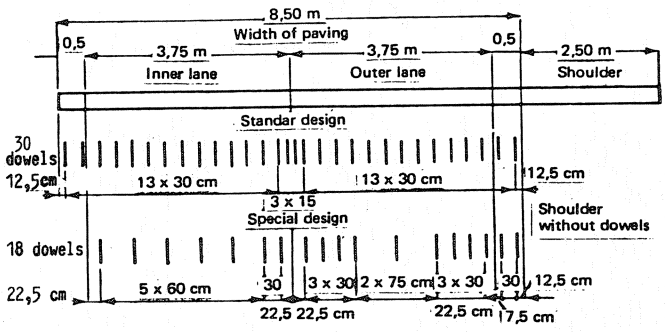
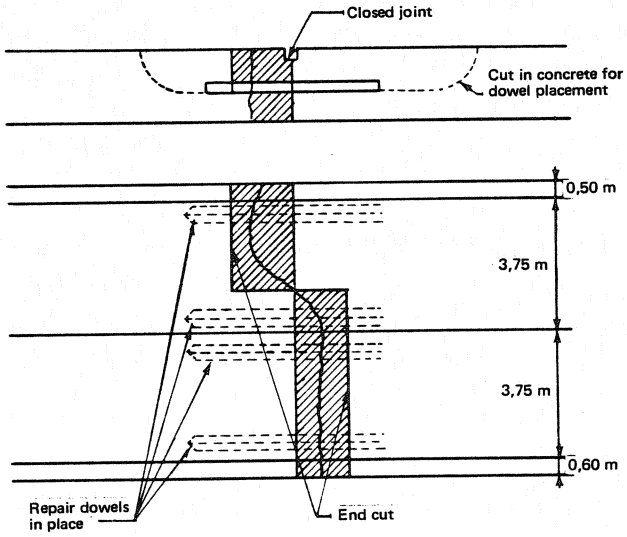


Figure 2. Repair system used in West Germany for a crack near a closed joint.



2. Anticorrosion and slipping devices: research carried out in Great Britain has led to wider use of plastic-coated dowels to reduce the bond between steel and concrete to small levels (38).

3. Placement accuracy: TRRL research led to quantitative recommendations to avoid defective dowel positioning. As concerns the placement of dowels in Europe, it may be stated that placement by vibration is widely used with side forms (11,30). In the case of slipforms, Great Britain uses cradles (38); in Belgium, increasing use is made of a slipform paver which stops at each joint and inserts the dowels by vibration (7); in West Germany, a contractor recently developed a process which allows the use of cradles with a slipform paver without preventing front loading by trucks. In spite of these innovations, the problem of the placement of dowels with slipform pavers remains, in the present state of available equipment, one of the causes of the reluctance to use dowels in certain countries, German Dem. Rep. for example (36).

Conclusion. In the case of undoweled pavements, the developments which appear to be of the greatest interest for improving load transfer and/or the reduction of joint deformations are the following:

1. The use of limestone aggregate accompanied by pavement surface chipping.
2. Reducing the average slab length.
3. Extending the width of the slab in the truck lane into the shoulder and/or using a concrete shoulder linked with the slab by means of tie bars, whenever this is justified economically.
4. Using a slab thickness variation in the cross section, adapting the thickness variation to suit the distribution of heavy traffic between the different lanes.
5. Avoiding concrete placement during high temperatures; otherwise, cooling the concrete by any suitable means.
6. Increasing the aggregate diameter up to values of about 60 mm.
7. Protecting the joints to prevent the ingress of fine particles.
8. Using concrete which is dry enough while remaining vibratable.

Two other possibilities, even more novel, should be tested before they can be used as standard techniques:

1. Thick slab without subbase, resting on a draining course.
2. Concrete which is very dry while remaining rich in cement, compacted and not internally vibrated.

For the doweled slab design, the developments could be:

1. General use of devices allowing the placement of dowels by vibration.
2. Pooling of the research efforts of different countries for more thorough optimization of dowel characteristics (diameter and length) according to slab thickness.
3. Optimization of intervals between dowels, as proposed by West Germany.
4. Greater allowance, in dowel dimensioning, for load transfer obtained through the other factors.
5. In the long-term future, research into devices different from dowels and of more economical design.

In this conclusion, mention should be made of the extensive experimentation conducted in Belgium near Namur in 1978 and 1979. The design of the different sections was carried out by a subgroup of the PIARC Concrete Pavement Committee headed by M. Dermience. The data which varied are directly related to the questions developed in this report: doweled and undoweled sections; sections with a reduction in the number of dowels in accordance with the standards of West Germany and sections with regular dowel spacing; sections with or without side drainage by porous concrete; undoweled sections with normal slab length and sections with reduced length; and sections with or without sealing products (hot or cold) in the joints.

Drainage of Slab-Subbase-Shoulder Contact

In nondoweling European countries, pumping and faulting phenomena have occurred since 1973 on some sections in France (26), in East Germany (36) and on one section in Italy (19). Recently, three specific cases of pumping were pointed out in Europe in countries using dowels:

1. In Great Britain on a section having a subbase in untreated material 75 mm thick (38).
2. In Austria, on several old and more recent sections, in spite of the use of nonerodable bituminous concrete subbases.
3. In West Germany, on several very old doweled sections resting on untreated subbases.

For a better understanding of these phenomena, water action mechanisms have to be analyzed. In addition to the well known direct effects of water (3), mention should be made of the following two effects:

1. Moisture continuously present on the underside of the slabs can lead to a slight almost permanent differential swelling of the concrete, thus producing slab curling up to 0.5 or 1 mm for a 5-m slab as found in the German Dem. Rep. (25). This phenomenon creates a free volume under the slab corners and thus favors the initiation of erosion under the slab leave ends.
2. Water pressure measurements (21) have demonstrated the existence of a depression when the approach slab is lifted. This confirms observations indicating that free fines can be "sucked in" (up to a distance of 400 mm in the shoulder) at the concrete-subbase interface.

To avoid water traps, drainage may be provided through the subbase or the shoulder. In France (12) since 1975, an experimental jobsite and two sections several tens of kilometers long have used thick concrete slabs resting on a very porous untreated layer. In 1976, an experimental section used a slab of normal thickness and a subbase course in porous concrete. Various facilities (runway, taxiway, parking area) representing about 550,000 m^2 of the Roissy-Charles de Gaulle airport have been constructed (1979-81) with a porous concrete layer of 100 mm between the pavement slab and the cement-treated subbase.

This vertical drainage arrangement reduces the time water is present under the slab by a factor greater than 500 (3,12). It appears to be particularly well suited to very large subgrades when the heavy loads move outside of the lateral ends (airport runways or very heavy traffic roads with more than two lanes in each direction), and to climates characterized by a very high rainfall frequency, even if the rain is not intense.

The present limits of this approach are conditioned by the uncertainty regarding long-term stability under heavy traffic of a porous material when it is not treated, and by the "pointed" (i.e. very sensitive) nature of bitumen- or cement-treated porous materials during construction.

What has entailed the greatest amount of research and the most applications during the past 4 years is the transverse permeability of the shoulders, either through the use of porous materials or of longitudinal and transverse drains. This action seems to have made it possible in Europe to reduce the saturation time under the concrete by a factor between 10 and 100 (13,27).

Recent Developments in Drainage Techniques. This use has taken place gradually, with the definition of the corresponding requirements of each country: in France, as of 1974, in Spain as of 1977 (an asphalt road already had such a lateral drainage before 1974) and then on an experimental basis in Belgium in 1979 and in Austria in 1980. In certain countries, Great Britain for example, achieving adequate drainage is an objective indicated in the specifications since 1978.

Drainage of Concrete Pavements in France since 1974 (13). In the case of new pavements, in all about 140 km of pavement have used the porous shoulder design. After 5 years of experience on experimental sites and large projects, a technical and economic study has led to the following recommendations concerning three typical solutions, each adapted to a special context:

1. The narrow trapezoid in porous concrete located against the slab and its subbase is a technical and economic compromise adapted to the case of medium traffic superhighways and national roads having a paved shoulder.
2. The concrete of the shoulder, thinner than the pavement slab, over a porous untreated material, is adapted to heavy traffic superhighways.
3. The drain (at slab-subbase contact) over which is placed a waterproof film is adapted to roads having an unpaved shoulder made up of materials

capable of containing free fines.

For new pavements, these solutions do not present any risk during construction and everything seems to indicate that they will remain effective for a long time, but the engineer must check the overall results by full-scale water testing as soon as part of the pavement construction is completed.

In the case of lateral drainage as repair work for old pavements, about 200 km of such pavements were provided with a lateral drainage trench. Ten experimental sections (13) have made it possible to test each particular element; the conclusions are the following:

1. The subbase should not be completely grooved, in order to avoid the weakening of the lateral support of the slabs. The slight grooving of 1 to 3 cm is intended to favor the rapid drainage of the concrete-subbase contact.
2. The fine particles produced by the trenching machine must be removed by suction.
3. The trench width of 20 to 25 cm constitutes a compromise between the requirement of minimum cost and the need to remove the old materials which are either poorly compacted on the edge or degraded by the evolution of the pavement (35).
4. Porous concrete (13,27) is compacted and contains (per cubic meter) 200 to 300 kg of sand, 1300 to 1500 kg of 5/20, 150 to 250 kg of cement, 70 to 120 liters of water, and an air entraining agent. Depending on the case, one obtains porosities ranging from 10 to 28% and compressive strengths after 28 days ranging from 7 to 10 N/mm^2 (MPa).
5. The bituminous mix 30 to 50 mm thick is intended to provide a certain waterproofing at the surface of the porous concrete and allow rapid reopening to traffic.
6. The size of the 80-mm diameter drain should normally allow periodic cleaning.

Based upon experience acquired up to the present time, this type of trench is suited to existing pavements in good condition: it can retard or prevent the appearance of pumping and its consequences. On the other hand, such a device is to be avoided for any old pavement having begun to deteriorate considerably, particularly when the cause of this deterioration is a high degree of erodability in the subbase and water continues to enter the structure. In the latter case, the drainage trench accelerates the removal of fines and leads to slab failure even more rapidly than without a drain (4).

Drainage of New Concrete Pavements in Spain. The construction of a 61-km section of the Mediterranean superhighway in 1977 entailed the construction of a drainage system with longitudinal perforated drains and nonwoven fabric at the slab-subbase-shoulder interface. At the low points of the longitudinal profile, drainage is also provided on the median side right next to the slab.

In the future Spanish recommendations, untreated crushed material without fines is specified for the shoulder subbase.

Experimental Drainage in Belgium. The construction of the experimental pavement mentioned earlier included the setup of a lateral drainage system with porous concrete, for doweled sections as well as undoweled sections.

Drainage in Austria. Austrian authorities decided to use a lateral drainage trench on an old section and a porous concrete shoulder on a new section.

We should also mention that South Africa has been using drainage systems for several years, particularly as the low points of the longitudinal profile.

Analyzing the Effectiveness of Drainage Systems.

Hydraulic Aspects. For all countries having used drainage systems, for new pavements or for repairs, in porous material or with drains, it has been noted that there were high water flowrates after rain. In addition, in the case of old pavements, the first consequence of the setup of lateral drainage trenches has been the complete elimination of pumping, and of the rising of water and fines upon the passage of loads.

In-depth experimentation (13) conducted in France has made it possible:

1. To verify the water movements within a shoulder made of porous concrete (horizontal propagation rate evaluated at about 1 m/min for low flowrates and with a slope of 2%).
2. To determine the drying time under the pavement, either after localized injection of water (a few minutes) or after a rain (from 2 to 4 h).
3. To measure the concentration in solid fine particles in the water which comes out of the drains on an old pavement as a function of the erodability of the subbase (4), the presence of a nonwoven material if any, and rain frequency.
4. To verify the durability of the porous concrete by accelerated tests.

Effect of Drainage on Mechanical Behavior of Pavement. This is a delicate area because short-term (1 to 4 years) measurements are not easy to extrapolate; however (13):

1. Comparative measurements of approach and leave slab deflection on old sections with and without drainage tend to show an increase in this characteristic after drainage, probably owing to a certain progressive removal of fines blocked before under the approach slab and under the longitudinal edge of the concrete.
2. Faulting measurements would appear to show a stabilization.
3. A visual inspection does not reveal any significant development in degradations.

Subbase and Shoulder Surface Erodability

As regards countries not using dowels, several observations made in Europe since 1975 (France (27), Italy (19), German Dem. Rep.) are in line with the conclusions of American reports (14,32): slag-treated, bitumen-treated and cement-treated subbases are erodable, in particular where surface defects exist (water or binder proportioning, loss of surface compaction, curing defects, frost at early age, etc.). Table 2 allows the following conclusions:

1. The abrasion of the lips of the joint is one origin of fines which can be neglected.
2. Fines coming from outside the pavement can be prevented to some extent from moving under the slabs if joint waterproofing products are maintained.
3. The movement of fines coming from layers under the subbase can be stopped by suitable subbase design and construction.

Table 2. Risk of faulting as a function of the origin of fines.
(Orders of magnitude calculated or observed for an equivalent daily traffic of 300 to 2000 commercial vehicles in each direction over a 20-year period)

Origin of Fines	Consequences Evaluated in Terms of Possible Faulting Values			Observations
	Probable Maximum[a]		Usual Values (additives) (mm)	
	Approximate Evaluation Assumptions	Values (mm)		
Abrasion of lips of crack in concrete (case of soft aggregates, LA 40)[b]	0.2 mm of average wear on surface of joint (7.5 x 0.25 m) gives 0.5% of material per joint distributed over about 1 m^2 giving about 0.5mm of faulting.	0.5	0.05 to 0.1	Negligible effect
Exterior fines coming from unsealed joints (case of superhighway with accumulation of dirt or case of pavement wear)	The wear of the pavement, tires and dirt of all kinds are of the order of 100 to 200 l of material per meter of superhighway, representing 500 to 1000 l per joint. It may be estimated that 0.1 to 0.2%, or 0.5 to 2 l, of this amount enters the joints and causes about 2 mm of faulting.	2	0.5	Negligible if the joints are relatively waterproofed; may be higher than the indicated values in extreme cases.
Edge of shoulder (case of a poorly compacted treated material)	0.25 m on edge of slabs without cohesion gives about (5 x 0.25 x 0.20) 220 l of treated material containing 5 to 10% fines, or about 20 l of material which, distributed over about 1 m^2, gives about 20 mm of faulting.	20	0 to 5[c]	Variations relatively proportional to the amount of free fines available.
Subbase surface (case of poor quality treated material) - by dry wearing	0.5 mm of wear over a strip of about 0.20 m on each side of the joint, representing about 1 l of material which, distributed over 1 m^2, gives about 1 mm of faulting.	1	0.1	Effect often negligible[d]
- by erosion under water	Existence of a cavity no thicker than 10 mm and a surface no greater than 2 m^2, or 20 mm for 1 m^2.	20	0 to 5[e]	Depends on erodability presence of water and transfer[d]
Subgrade: pumping under water (case of a silty sand type material)	This phenomenon is manifested especially by very significant discharging onto the shoulder. Observations on superhighways in service suggest that the subgrade is a source of fines capable of causing as much faulting as the erosion of the subbase.	20 and especially external pumping	0 to 5	Closely related to subbase quality (thickness, cracks) and to the erodability of the subgrade[d]

[a] When the phenomenon is very intense and occurs alone.

[b] This refers to the most unfavorable case, estimated by overevaluation.

[c] This value of 5 mm can be approximately doubled when the base of the shoulder is not treated and the climate is humid. Fines can be drawn in to distances of about 40 cm.

[d] See Surface Erodability of Materials in section on Subbase and Shoulder Surface Erodability.

[e] This value of 5 mm can be approximately doubled, or even tripled, when the subbase of the pavement is not treated.

The analysis of reports and replies to the questionnaire, the observation of many concrete pavements throughout the world, and the sampling of fines, have led to the evaluation of the risk of faulting as a function of the origin of fines (Table 2).

Hence, it is the creation of fines coming from the subbase and from the shoulder which is the most difficult to prevent in practice. The erodability of these two last types of material must consequently be limited and, to accomplish this, it is necessary to determine the quantitative influence of the different parameters, from those relative to the structure itself to those of the composition and the construction of these layers.

Regarding the structural parameters, mention should be made of the influence of adherence between

slab and subbase. French observations (27) have shown that in French conditions this phenomenon existed particularly during the early age of the pavement but that its extension and its disappearance could vary greatly depending on the case and could be conditioned by factors which are still poorly controled. In West Germany, the work of J. Eisenmann entails research into durable adherence between the slab and its cement-treated subbase (10) to reduce, by an overall inertial effect, the deflections and stresses in the concrete. As regards the risk of erosion, it is certain that adherence between the slab and subbase is very favorable. However, there are differing opinions in Europe today regarding the durability which may be expected from such adherence.

Situation in Europe Regarding Erodability. In order to appreciate the range of subbase types used in the past in Europe and the utilization specificity of each, each country was asked to indicate in the questionnaire the approximate percentage of the utilization of such and such a type of subbase, as well as its utilization limits, in terms of the average daily truck traffic existing on the pavements for which this material is specified (29, p. 58).

Shoulder and Subgrade Materials. The use of treated materials in the base of the shoulder has been fairly general practice in Europe for several years. Since 1975, this treatment has been made obligatory even in regions having a relatively dry climate, as on the eastern coast of Spain. Materials properly treated with bitumen and properly compacted do not undergo erosion in Italy, for example, but their use is costly today.

To prevent erodability, certain European countries (Belgium, West Germany, Great Britain) continue to use concrete shoulders successfully. If one considers its construction cost, the concrete shoulder appears to be particularly well suited to (i) superhighway pavements with very intense traffic, and (ii) areas where superhighway entries and exits are at close intervals.

It is noted in general that this arrangement is suited to regions with a rigorous climate or a high population density. For heavy and intense traffic, the treatment of these subgrade materials is advantageous. In France, the repair of a very heavy traffic superhighway initially having a subgrade consisting of very fine untreated sand began with the treatment of this old subgrade in situ. This type of treatment is tending to develop in Europe.

Trends in Subbase Erodability Specifications. In the German Dem. Rep., faulting of 3 to 6 mm has been observed after six years on superhighways having a cement-treated subbase in direct contact with the undoweled slab. A test using a lean concrete subbase was carried out in 1970. At the present time, an intermediate layer in bituminous concrete 40 mm thick is used, and faulting is limited to about 3 mm (36). This type of layer is also used in Czechoslovakia.

For concrete pavement subbases for intense traffic, the French 1977 Catalog of Structures no longer authorizes slag-treated materials, and gives a choice between lean concrete and cement-treated materials, the latter then calling for major precautions during its placement. In practice, during recent years, intense traffic pavements have been built with lean concrete to avoid any erodability and in view of the other advantages afforded by this material (8,27).

Along the same lines, but without adopting the same remedies, since 1978 Spain has increased the amount of cement used in cement-treated materials up to 5 to 6 percent and prevents the fine-grading of this layer after compaction.

As concerns heavy traffic pavements using dowels, most European countries (Belgium, West Germany, Austria) have been specifying treated subbases for several years. In Great Britain, untreated materials were traditionally used, but there have been recent developments; however, the gradual adoption of cement-treated materials is also due to reasons other than erodability.

Bituminous concrete subbases from 100 to 150 mm thick used in Austria can be classified in the category of nonerodable materials.

Cement-treated materials, using 2.4 to 4 percent binder, are employed in West Germany for heavy and medium traffic pavements. Thanks to the use of dowels, the performance of these subbases is presently good (11).

Quantitative Analysis of Pumping Hydrodynamics. A recent study conducted by LCPC in Paris (20,21) made use of the following:

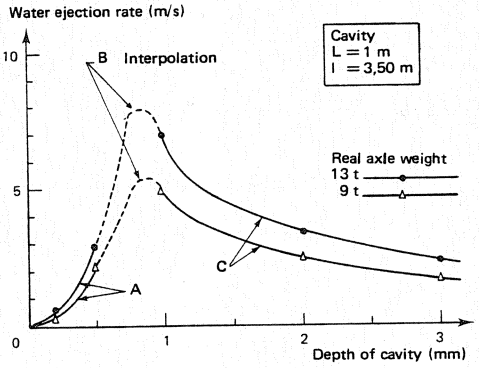
1. Equations of water movements under slabs upon the passage of heavy axles.
2. Results of water pressure measurements within pavements in service.
3. Experimental research characterizing, in particular, each material by a critical water speed necessary for eroding its surface.

Several conclusions of general scope are brought out by the hydraulic part of this study:

1. Water behaves like a viscous fluid when the depth of the cavity under the leave slab is small (curling by temperature gradients). Under these circumstances, water pressure under the slab is important and the average ejection rate is proportional in particular to the weight of the axle and to the square of the depth of the cavity, and inversely proportional to the dynamic viscosity of the water, to the width of the cavity and to the square of the cavity length (Figure 3, Curve A).
2. Water behaves like an ideal fluid when the depth of the cavity under the leave slab exceeds about 1 mm (case of a high degree of erosion). In this case, water pressure under the slab is low and the average ejection rate is proportional to the slab end deflection rate and to the length of the cavity, and inversely proportional to the difference between cavity depth and slab end deflection (Figure 3, Curve C).
3. Between these two extreme behaviors, there is a transient flow and the water ejection rate goes through a maximum.
4. Each pavement structure, described essentially by the value of the load transfer at the joint, the deflection and by the average geometrical characteristics of the cavities can be characterized by an average water ejection rate. This rate is, for example, between 1 and 4 m/s for a pavement having a low load transfer and cavities under slabs.

All of these theoretical and experimental means appear to be capable of constituting a valid research tool in the future, in particular for quantifying the specific role of certain structural modifications on the pumping and/or faulting process. As an example, and under the operating conditions considered (21), it has been found that the skew (1/6) of the joint reduced the water ejection rate from the leave slab toward the approach slab by about 30 percent. Similarly, it has been found that an extra slab width

Figure 3. Water ejection rate as a function of real axle weight and size of cavity.



reduced this ejection rate by 50 percent, but reduced by only 30 percent the water ejection rate from the leave slab toward the shoulder, which was recently illustrated on a superhighway (without lateral drainage-by intense longitudinal pumping in spite of the presence of an extra slab width.

Surface Erodability of Materials.

General Conclusions. The study described in the preceding paragraph has made it possible to continue research of a fundamental nature by measures which are more technological but just as important in practice (22). It was possible to draw general conclusions:

1. The surface erodability of materials can be characterized by one of the following: the critical water flowrate beyond which the material is eroded (this rate can thus be used directly for the theoretical hydrodynamic study), the weight loss of a specimen subjected to a test (vibrating table) simulating erosion under the slab in the presence of water, or the weight loss following forceful rotary brushing of the surface (this test is the one which can be easily transposed to the project site).
2. For each treated material and for a given water ejection rate, there is a critical binder proportion under which erosion can be very high and continuous (Figure 4).
3. A method is proposed for characterizing each material by a single figure combining its average erodability and the variability of this erodability for typical variations in the parameters of composition, placement and conservation.

The Threshold Phenomenon Constituted by Erosion. The ejection of water is characterized by its rate which depends on the pavement structure. In the case of high temperature gradients, the cavity under the slab can reach the value which leads to the maximum water ejection rate Vm.

The surface erodability of subbase and/or shoulder materials in contact with the slab is characterized by a water flowrate Ve for eroding them; there are thus two cases: (i) when Vm $\geq$ Ve, erosion begins and continues as long as this inequality exi exists. Cavities are formed under the slab and develop in their three dimensions; the pumping of fine particles exists and faulting occurs if it is not blocked mechanically by dowels; (ii) when Vm < Ve, the water is ejected without the removal of fine particles from the pavement; the phenomenon is not

Figure 4. Graph showing the existence of a critical cement proportioning threshold.

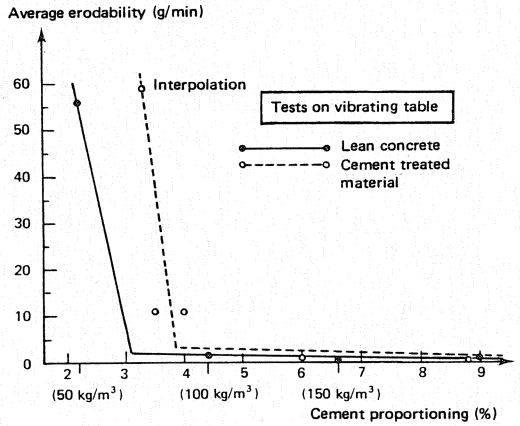
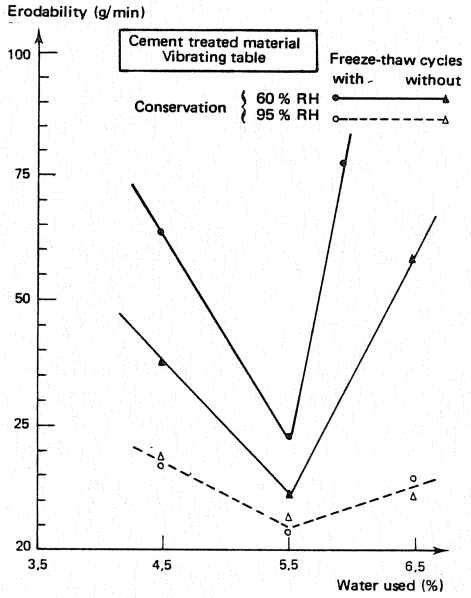


Figure 5. Variability of cement treated material erodability as a function of amount of water used for compaction, curing defects and freeze-thaw cycles.



liable to accelerate and the slab bearing conditions are maintained.

It is the analysis of all these phenomena which has made it possible to define the three erodability classes used in the report (see Combined Influence of the Three Factors). They are the following:

1. Very erodable materials are characterized by an erodability rate Ve which is lower than the maximum water ejection rates Vm usually encountered in conventional structures. As an example, for an untreated material, Ve $\lesssim$ 5 m/s.
2. Materials of average erodability are characterized on the one hand by a normal erodability rate of the material relatively higher than Vm, but on the other hand by a high variability of this erodability rate according to construction and loading conditions. And, this variability is liable to lead to an inversion of the inequality Vm < Ve. As an example, for a conventional cement-treated material

containing 3.5 percent cement, Ve can be higher than 50 m/s but it can also drop below 5 m/s after a certain number of freeze-thaw cycles if there have been slight cumulative proportioning, compaction and curing defects (Figure 5).

3. Very low erodability materials are characterized by an erodability rate higher than Vm, even if slight construction defects appear. For example, the erodability rate of a lean concrete containing 150 kg of cement per cubic meter normally remains in all cases higher than 50 m/s. Likewise, it appears that bituminous concrete containing a proper percentage of bitumen can be placed in this category, along with cement-treated materials having a cement content higher than or equal to 5 or 6 percent.

Combined Influence of the Three Factors

This part presents the results of an international survey (28) involving 26 countries including the United States. In order to work with directly verifiable data, it was decided to use a series of observations made in many countries on old and long (10 to 100 km) real (nonexperimental) pavement sections.

Precise numerical data have been gathered for 74 old pavements carrying heavy traffic with and without dowels. Some of these pavements have already been analyzed by the University of Illinois (1) and by the PCA (24). On the other hand, 30 cases of pavements have been pointed out by replies coming from countries other than the United States; from Europe: 27, but also from Canada: 3.

For each section taken separately have been gathered the data relative to climate, erodability (subbase and shoulder), the load transfer system if any, as well as the real traffic handled. From all these data, an attempt was made to determine for each climate and for the main subbase materials used, the maximum traffic which could be handled by the doweled structure, on the one hand, and by the undoweled structure on the other hand.

Methodology Used

The performance of undoweled pavements was assessed in accordance with the faulting (28, Appendix 12). Doweled pavement performance was assessed on the basis of a series of criteria representing the most frequent pavement degradation modes. The pavements described in the replies to the questionnaire were each characterized by a level of cumulated heavy-vehicle traffic since construction (heavy vehicles refers to those heavier than about 5 tons). In order to express this traffic in terms meaningful to a design engineer, each cumulated traffic level has been converted into an average daily traffic (of heavy vehicles on the most heavily loaded lane) during the first year of service. This conversion was carried out on the basis of an annual growth rate of 7 percent and a reference period of 20 years (2,6). A conversion was made to take into account the difference in the legal axle load (28, Appendix 10, 29). This conversion, indispensable for the study, takes into account the fact that slab thickness is already calculated according to the difference in the legal axle load.

The comparative study of the dimensioning of slabs in different European countries (28, Appendix 9) has demonstrated that thicknesses were very similar from one country to another for equivalent traffic levels and soils. It was thus considered that slab thickness would not constitute a variable parameter for the study. Very thick slabs ($\geq$ 350 mm) and very thin slabs ($\leq$ 150 mm) were not covered. Hence, for each pavement, it was simply checked that the performance defects were not attributable to a dimensioning defect (thickness of slab, subbase, etc.).

Table 3. Definition of climatic classes (6,29).

Average Annual Rainfall (P in mm)	Frost Index (I in °C x day)	Climatic Class
$P \geq 600$	$I \geq 40$	Severe
	$I \leq 40$	Average
$300 < P < 600$	$I \geq 40$ or $I \leq 40$	Average
$P \leq 300$	$I \geq 40$	Average
	$I \leq 40$	Favorable

It was later moreover found that the choice of these climatic classes was coherent with the problem on hand and the practice of the different countries because American states with a favorable climate do not use dowels and those with a severe climate use them (only the average climate concerns the states using one technique or the other). It was decided to adopt also three material erodability classes, namely those described in the section on Surface Erodability of Materials of this report.

A scattering of results was noted by the detailed study of the salient points often led to the confirmation of the general tendencies found: for example, a section with a poorly constructed cement-treated subbase (insufficient binder or compacting in certain places) constitutes an irregular point for the case of "treated subbases" but becomes altogether normal for the case of "untreated subbases".

Circumstances responsible for the best performance are indicated in addition to the recommendations.

Results Derived from Practice

All the data gathered through the international survey, analyzed in accordance with the method previously described, led to the following Tables 4 and 5.

Recommendations

The detailed study makes it possible to use the raw figures described in Tables 4 and 5 to work out recommendations. For this purpose, certain methods have made it possible, firstly, to extrapolate the results obtained on pavements which are old and still in excellent condition, and secondly, to interpolate for intermediate climatic or erodability conditions.

For undoweled pavements, a substantial safety margin was deliberately used compared with the results observed earlier. This position is intended to avoid in the future certain degradations observed today on pavements whose construction exhibited some defects compared with project design. The numbers in parentheses in the tables have reference to the comments following the tables and are of great importance. The order of magnitude of the correction factors indicated is derived from a fine analysis of the range of raw data gathered by the survey.

Table 4. Nondoweled pavements. Traffic limits observed on the oldest pavements in good condition. (Cumulative traffic is expressed in terms of initial daily commercial vehicle traffic).

Erodability (subbase and shoulder)	Untreated Material		Cement Treated or Bitumen Treated Material		Internally Vibrated Lean Concrete or Bituminous Concrete	
Legal axle weight	13t	9-10t	13t	9-10t	13t	9-10t
Severe climate			300	750		
Average climate	300	750	300[a]	750[a]		
Favorable climate	750	2000	750[a]	2000[a]		

[a]As the corresponding pavements are generally in good condition, these values may increase in the future.

Table 5. Doweled pavements. Traffic limits observed on the oldest pavements in good condition. (Cumulative traffic is expressed in terms of initial daily commercial vehicle traffic).

Erodability (subbase and shoulder)	Untreated Material		Cement Treated or Bitumen Treated Material		Internally Vibrated Lean Concrete or Bituminous Concrete	
Legal axle weight	13t	9-10t	13t	9-10t	13t	9-10t
Severe climate	300	750	750[a]	2000[a]		
Average climate	750	2000				
Favorable climate						

[a]As the corresponding pavements are generally in good condition, these values may increase in the future.

Table 6. Recommended traffic limit. (Daily commercial vehicle traffic). For pavements without dowels.

Erodability (subbase and shoulder)	Untreated Material (2)		Cement Treated or Bitumen Treated Material(3)		Internally Vibrated Lean Concrete or Bituminous Concrete (4)	
Legal axle weight	13t	9-10t	13t	9-10t	13t	9-10t
Severe climate	Not desirable with commercial vehicles (1)		150	300	Order of magnitude (4) 750	2000
Average climate	150	300	300	750	Order of magnitude (4) 2000	5000
Favorable climate	300	750	750	2000	Order of magnitude (4) 2000	5000

Table 7. Recommended traffic limit. (Daily commercial vehicle traffic). For pavements with dowels (5).

Erodability (subbase and shoulder)	Untreated Material (2)		Cement Treated or Bitumen Treated Material(3)		Internally Vibrated Lean Concrete or Bituminous Concrete(4)	
Legal axle weight	13t	9-10t	13t	9-10t	13t	9-10t
Severe climate	300	750	750	2000	Order of magnitude (4) 2000	5000
Average climate	750	2000	2000	5000	Order of magnitude (4) 5000	
Favorable climate	2000	5000	5000	Not necessary (6)		

Important Comments.

1. International experience has long proven that it was not desirable, in a region with a severe climate, to build an undoweled pavement with a subbase in untreated material when heavy traffic is to be handled. In any case, if such a design is considered, the traffic should not exceed 20 axles of 13t or 50 axles of 9-10t and it is absolutely necessary for sealing to be excellent and maintained.

2. International experience has demonstrated that the use of an untreated quality material (in the base course of the shoulder and especially the subbase of the pavement) can lead to correct performance outside of the case mentioned in (1), for traffic twice or three times as high as that indicated, provided that water traps are avoided in the structure and that sealing is effective and maintained.

3. In the case of cement-treated or bitumen-treated materials, when a low erodability is guaranteed on the surface of the pavement subbase and the base of the shoulder (absence of any defect in binder proportioning, compacting, curing), the traffic limit indicated can be doubled or tripled. Moreover, when sealing is correctly maintained and a good concrete-subbase interface drainage system is provided, it appears that the traffic limit can once more be doubled or tripled.

4. As international experience is presently rather limited with respect to the use of lean concrete or bituminous concrete in the subbase, the corresponding recommendations are of a tentative nature. When the sealing of these structures is maintained effectively and a good concrete-subbase

interface drainage system exists, the traffic limit given can apparently be doubled or tripled.

5. The recommendations concerning doweled structures are given under the assumption that the load transfer system is effective and durable.

6. In the present state of the art, it does not appear necessary to have recourse to the use of the less erodable subbases in the case of favorable climates and the use of dowels.

Conclusions

Are National Practices in Contradiction?

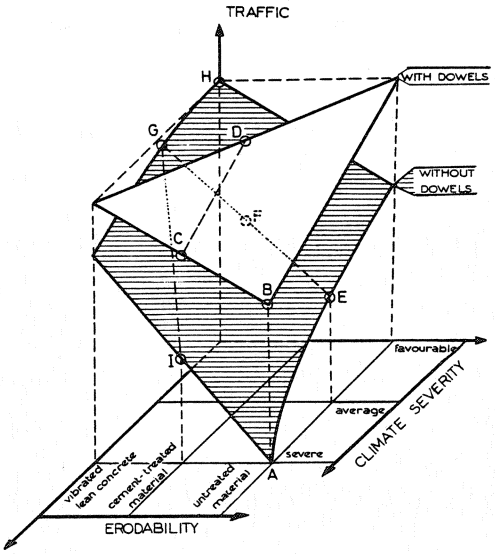
While the opposition between countries using dowels and those not using them could appear surprising, the preceding analysis has shown that this opposition exists only if one considers strictly the load transfer parameter. On the other hand, if in addition one takes into account the erodability of materials at the slab contact and the "water" factor, one finds a certain overall coherence in the results. On certain points, this coherence is even striking.

As we saw, these results can be represented schematically by a traffic limit for each point of the "erodability-climate" space and for each of the two techniques. This is shown in Figure 6.

In this three-dimensional space, the background of the technical modifications applied since the 1930s becomes easily understandable:

1. The significant faulting observed between 1920 and 1936 led several countries in non-Mediterranean Europe and several states of the United States, all having humid climates, to the adoption of dowels (Figure 6: line representative of this evolution: A → B). In the past 5 to 15 years, efforts for obtaining good performance even under very intense traffic have led these same countries to prefer treated materials (Figure 6: B → C).

Figure 6. Traffic limit for each climate-erodability-load transfer condition



In this situation, and particularly when waterproofing is properly maintained and/or a drainage system is provided at the slab-subbase interface (which has the same effect as a "change in climate"), performance can be excellent (Figure 6: C → D).

2. Several western states of the United States having a dry or medium climate adopted, toward 1945, the use of cement-treated materials with undoweled slabs (Figure 6: E → F). Having observed further faulting in certain cases, between 1968 and 1975, they decided on the use of lean concrete in the subbase (Figure 6: F → G), along with drainage and even waterproofing (Figure 6: G → E), and this should also lead to excellent performance.

3. Similarly, but in a more humid climate, certain European countries adopted, in the 1960s, the technique of undoweled slabs over a cement-treated subbase (Figure 6: I). It would appear that by acting on the "erodability" factor and on the "water" factor these countries will also be able to achieve good performance if they wish to conserve the simpler technique without dowels (Figure 6: I → G → H).

Technical Decisions of Each Country

In a given situation of the technique in a country, efforts to improve performance can entail the choice of one or more of the following main approaches:

1. Using dowels, if they have not already been used, or significantly improving load transfer by interlocking using the methods described in the corresponding chapter.

2. Using less erodable subbases and/or shoulder materials than in the past either by changing the materials themselves or by modifying the placement practices with a view to reducing the erodability of the materials without changing their nature.

3. Reducing the time water is present at the concrete-subbase interface either by action on the effectiveness of waterproofing, or by creating a system for draining this interface or by a combination of both. It is the experience of some experts today that in many cases the best way to improve performance at a relatively low additional cost is to provide a drainage system at the concrete-subbase-shoulder interface.

In fact, other important technical and nontechnical factors have also to be considered (29).

Future Research

As stated in the introduction, this report must be regarded as a first approximation to be added to and improved by future research and evaluations.

From this viewpoint, the research which appears to merit priority is the following (28, Appendix 17, which is more detailed):

1. Building experimental superhighway pavements for the comparison of techniques which are or will be alternatives for designers within today's or tomorrow's context. It is exactly this type of research which was undertaken in Belgium near Namur in 1979 after coordination with the main European countries concerned.

2. Supplementing these experiments by laboratory tests which, if possible, do not overlook any of the four major groups of parameters (load transfer, erodability, water, traffic).

3. Developing research and experimentation concerning slab-subbase interface drainage.

4. Acquiring greater knowledge of the surface erodability of materials.

5. Comparing, within each national context, the cost and effectiveness of each arrangement in order

to arrive at optimum types of construction.

This report was drafted in order to permit true exchange of experimental data between the different countries in a constructive spirit. Our thanks go to all the people who participated in the international surveys preceding this report and in all the contacts which made it possible.

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