European Developments in Prestressed Concrete Pavements for Roads and Airports

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This is a general review of developments in the field of prestressed concrete pavement in England, Germany, Belgium, Switzerland, Spain and Italy, as compared with French developments in the same field. The paper concludes with a brief economic study based on data collected during the tests on experimental slabs at Orly, together with fairly complete descriptions of the tests themselves.

● IN A PERIOD where prestressed concrete is undergoing considerable developments in the United States and tests on prestressed pavements are being carried out in various American laboratories and on test strips, it may be of value to make a survey of European experiments in this field.

Preliminary information on the subject was presented by the author at the International Concrete Road Conference at Rome in 1957. In this report more recent work and particularly the projects carried out in 1959 in Germany, Belgium and France are described.

ENGLAND

The lecture delivered by James Pearson Stott, in charge of research work at the Road Research Laboratory of the Institution of Civil Engineers on March 1, 1955, gives a detailed account of the tests carried out in Great Britain up to 1954.

The author obtained further details during a visit to that country some time ago. The tests carried out in Great Britain are given in Table 1.

Tests were performed on individual slabs, prestressed by longitudinal cables without transverse prestressing or by diagonal cables symmetrically arranged in two directions in relation to the center line of the slabs, or by longitudinal and transverse cables at tight angles to each other.

The South Benfleet test was particularly interesting on account of the fact that after the road was constructed, it became necessary to cut it open thus eliminating the longitudinal prestress for a time. This experience showed that it is not much more difficult to repair a prestressed concrete road than an ordinary concrete one.

GERMANY

The earliest prestressed concrete paving project in Germany was the tank testing platform constructed for the French corps of engineers at Spire in 1954. This platform consists of a series of slabs 50 to 70 meters long (164 to 229 ft). The pavement has a total thickness of 20 cm including a 14-cm subcourse and a 6-cm wearing course. The slabs are laid on a 30-cm river gravel base course with a 2-cm fine sand topping. A layer of Kraft paper was placed between the sand and the concrete pavement. The total length of the platform is 1,500 meters (4,900 ft).

The prestress system used is of the Leoba type with a stress of 30 tons per element. Each unit consists of 6 steel cables the extremities of which are provided with threaded rods and bolts by which they may be placed under tension.

TABLE 1

Date	Site	Length (ft)	Width (ft)	Thickness (in.)	Prestressing Longit.	Prestressing Tran.	System of Prestressing	Present Condition
1950	Crawley, Sussex	393	19	6	210 psi	22.4	Diagonal cables	Good
1951	Wexham	108	10	6	182	-	Long. cables only	Good
	Springs	127	10	6	126	-	Long. cables only	
	Buckinghamshire	196	11	6	252	-	Long. cables only	
1951	London Airport	328	118	6.3	560	560	Triangular slabs, Orly type	Good
1951	John Laing's Ltd	50x164= 8,200	11	6	294	-	Longitudinal cables	Good
1952	Basilton, Essex	13x164= 2,232	15	6	280	-	Longitudinal cables	Good
1952	Woolwich	3,280	16-26	6	252	28	Diagonal cables	Good
1954	Port Talbot	1,476	19	6	280	Varying	Longitudinal diagonal cables with jacks	No information
1954	South Benfleet	328	19	4	532	49	Flat jacks in longitudinal cables in transverse direction	Good after reinstatement of the longitudinal compressio

The total sectional area of the 6 cables consisting of 12 strands is 2.65 cm^2. Stress is equal to 80 percent of the elastic limit. The slabs are separated by transverse joints with bituminous coated dowels at the base. The upper part of the joints is filled with a special joint compound.

This platform has been in use since 1954 and no appreciable wear has been noticed to the present time. Because of the length of the slab elements, the joints are several centimeters wide, however, and variations in the width of the joints due to differences in temperature cannot be taken up by the joint compound.

This condition is not serious as far as tank traffic is concerned but a certain spalling of the joint edges has resulted. Transverse prestress units exist only near the joints. On the whole the using services are satisfied with the manner in which the platform has stood up under exceptionally heavy traffic.

Various tests performed in Germany in 1954 were described in the reports of the Concrete Pavement Committee of the German Pavement Association. Three systems were tested. The first, used in the slabs constructed at Mergelstetten I and II, included both longitudinal and transverse prestress cables. The slabs were 120 meters long (393 ft), 8 meters (26 ft) wide and 15 cm thick. Longitudinal prestress values were 22 and 17 kg/cm^2 (308 and 238 psi transverse prestresses 8 and 3 kg/cm^2 (112 and 42 psi). The fact that pavement continuity was interrupted at 120-meter (393-ft) intervals made it necessary to provide special and costly cable holding devices and did not avoid the joint problem. At Mergelstetten III cable prestressing was also used but the cables were placed diagonally, thus partly avoiding the joint problem. Cable anchorages were set in prefabricated lateral strips which were necessarily costly.

As a result of these tests, the government decided to construct a by-pass at Bingen with a 1,000-meter (3,280-ft) prestressed concrete section). Design specifications provided for a very wide safety factor so that the pavement would stand up under any circumstances. The section is overdesigned. The prestressed pavement is 16 cm thick; longitudinal prestressing is 50 kg/cm^2 (700 psi) with a total tension of 65 tons per cable; transverse prestressing is 15 kg/cm^2 (210 psi) with a total tension of 9 tons per transverse bar.

The slab is placed on a 3-course hot-laid bituminous concrete foundation 15 cm in thickness. The upper course of the foundation has a very smooth surface and is composed of sand compacted in a bituminous binder. To reduce friction, the bituminous concrete was covered with two layers of talc-coated paper before the prestressed concrete was placed. The coefficient of friction was thus reduced to 0.35 instead of 0.8, the figure on which design was based. In places, the paper is replaced by plastic sheets which give the same results.

An "antifrost" base was provided under the bituminous concrete foundation. This base is 40 cm thick and consists of sand and gravel compacted by a vibrating roller

to 98 percent of the Modified AASHO optimum corresponding to a dry density of 2.4 (that is, an extraordinarily high degree of compaction).

This base was placed on compacted unclassified Rhine Valley fill material.

The section consists of 150-m (492-ft) long slabs separated by steel and rubber joints similar to those described in HRB Proceedings, Vol. 37, pp. 150-193.

Longitudinal prestress cables consist of jack-prestressed strands in thin sheet metal tubes. Transverse prestressing is provided by 7.50-meter (30-ft) bars fixed at one end and prestressed by jacks at the other. Prestress tension is maintained by a bolt which is tightened.

The by-pass at Bingen is in service at the present time. The plate-and-rubber joints appear to be standing up well and to be very slightly affected by traffic.

At the same time, under the influence of organizations grouping highway research specialists and concrete and cement technicians, prestressed concrete made great strides in the field or airfield runway construction.

In 1956 a test runway was constructed at Memmingen by the contracting firm of Dyckerhoff and Widman. It consists of 100-meter (328-ft) slabs, 7.70 meters (30 ft) wide and 14 cm thick with an increased thickness at the edges bringing the total thickness to 20 cm. The ends of the slabs are spaced at a distance of 1 meter and the slabs are prestressed by single cables 10.2 mm in thickness. Prestressing is both longitudinal and transverse. The transverse cables cross the entire 45-meter (147-ft) width of the runway. A special system was provided in the spaces between the slabs in order to insure satisfactory tensioning of the cables. After the cables have been tensioned, concrete is placed so that a space of only 3 cm is left for longitudinal movement of the slabs. The cables are inside metal tubes whose diameter is only slightly greater than that of the cables.

The tubes are left in the concrete at the time it is placed. The cables are then introduced into the tubes and tensioned. The space between the cables and the inside of the tube is then filled with grout injected so as to provide a strong bond between the cables and the slab.

The success of this runway led the contractor to include a prestressed concrete alternate with his bids for construction of runways at Wunstorff, Hopsten and Nordholtz. The alternates were accepted in all three cases as being both more economical and technically more satisfactory.

The proposed project was to be a bituminous concrete runway on a 20-cm stabilized macadam foundation. The ends of the runway were to include 300-meter (984-ft) long sections of concrete 22 cm thick on a stabilized macadam base. The alternate proposed by Dickerhoff and Widman was a prestressed concrete runway 14 cm thick and 20 cm thick at the outer edges. The pavement was to be placed directly on a 45-cm thick anti-frost sand base with a 2-cm thick fine sand topping covered with a double thickness of paraffinned paper. Elimination of the stabilized macadam foundation (materials for which had to be transported from a great distance and which the contractor found superfluous if not actually harmful when used under a prestressed concrete slab) made up for the difference in cost between prestressed and ordinary concrete. The total cost per square meter of prestressed concrete was 27 DM as compared to 22 DM for a 22-cm ordinary concrete slab. The saving on foundation costs largely compensates the 5 DM difference.

Because the slab rests directly on sand, compaction of the latter was carried out with particular care. Vibrating caterpillar compacters were used and, at Hopsten, with a fine, slightly silty sand, a modulus of reaction of 14 kg/cm^3 was obtained (that is, an extremely high value).

The critical point was to find a method of construction which would insure pavement continuity between successive slabs and permit longitudinal cable prestressing and movement of the slabs caused by variations in temperature after prestressing. Calculations indicated that a space of 6 cm would be required between slabs. Experience made it possible to reduce this width to 3 cm.

In addition, for longitudinal cable prestressing, jacks had to be placed between successive slabs and tension applied so that the required displacement could be obtained. The ends of all cables were stamped to provide a projecting screw thread, the diameter

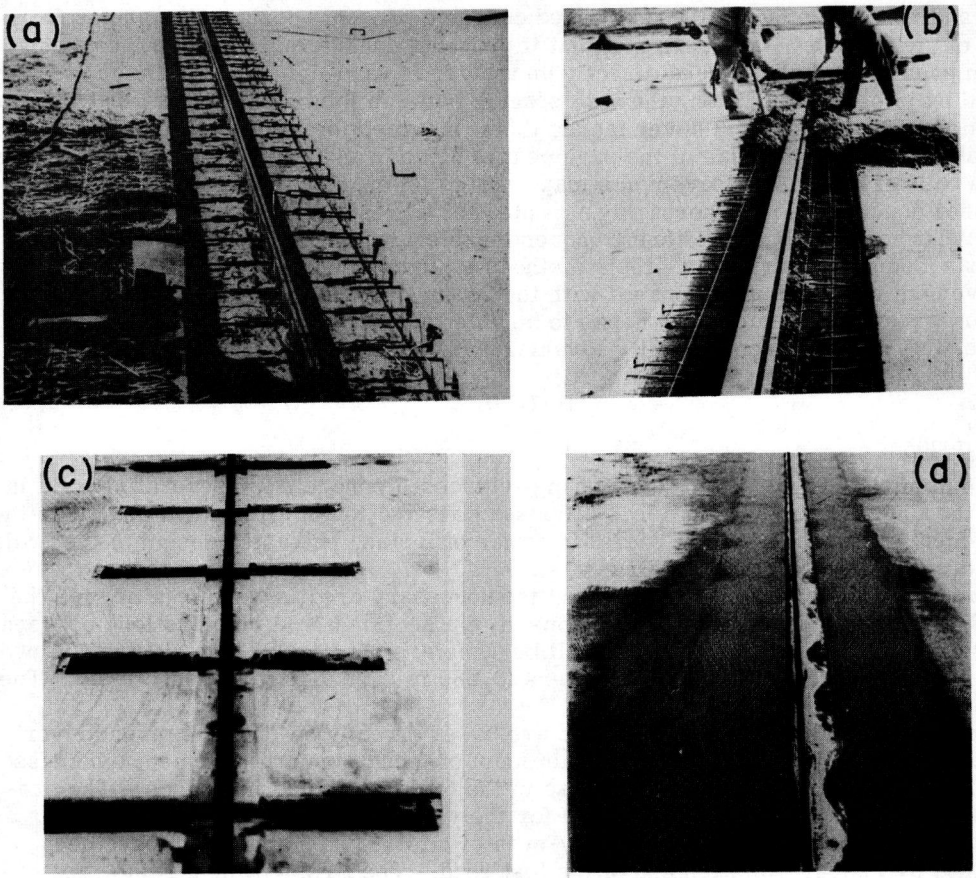


Figure 1. Hopsten Airport, Germany. Stages in construction of a joint using the Dywidag method: (a) cables placed and connected to central steel railing; (b) concrete hand placed in joint leaving room for jacks; (c) joint ready for jacking; (d) finished joint.

of the groove being equal to that of the cable. This made it easy to fix the cables to the jacks and is one of the patented features of the Dywidag system (Fig. 1).

Placing the jacks, supporting them against fresh concrete surfaces with the use of metal elements to provide the required 3-cm joint space, placing metal joint covers, fixing cables and filling the space between slabs with concrete would, at first, seem to be a rather complicated series of operations but it is claimed that the work proceeds automatically when a trained crew is employed. In any case, it is certain that the company using this method of construction has already built a two-section, 1,276-meter (3,828-ft) long runway at Wunstorff and a 3,000-meter (9,842-ft), 30-meter (98-ft) wide runway with a parallel taxiway of the same length at Hopsten (that is, a total prestressed concrete paving area of 170,000 m^2. The firm has now begun design of installations at the Nordholtz airfield near Cuxhafen. Construction will include a 2,900-m (9,514-ft) long, 45-m (147-ft) wide runway and additional paved areas bringing the total surface to 260,000 m^2. These are NATO fields and pavements and are designed for 20-ton wheel loads. The thickness thus remains at 14 cm. Concrete will have a compressive strength of 450 kg/cm^2, (6,300 psi) and a tensile strength of 60 kg/cm^2 (840 psi). Rhine valley sand and gravel will be used for aggregate as well as crushed rock. An air-entraining agent and a plasticizer will be used as is customary. Under these circumstances, four 130- by 7.50-meter (426-ft by 29-in.) slabs can be placed per 12-hr shift which represents 450 m^3 of concrete placed per day.

In addition to the fact that prestressed concrete presents certain advantages from the point of view of cost, the users feel that it presents considerable technical advantages. A thin prestressed slab placed directly on a layer of sand is highly elastic and is preferred by pilots. In addition, the wide spacing between joints and the fact that they are provided with a metal joint cover makes them imperceptible to the pilot as he runs over the pavement. The surface of the pavement is cleaner and free of loose gravel which, in the case of bituminous pavements may damage jet engines on group flights. Prestressed concrete is now thoroughly accepted for use in airfield pavement construction in Germany as a technique offering unquestionable advantages. The Dyckerhoff and Widman Company plan to apply their methods to highway construction. The reduction of pavement thickness as compared with the 14 cm thickness of runway pavement cannot be very great, but the company hopes to be able to reduce thickness to 10 cm and, at this figure, to provide an economically advantageous alternate.

BELGIUM

Test Road

Belgium has shown a keen interest in prestressed concrete for several years. In 1957 the Centre d'Etudes Routières proposed construction of a test road and, with the agreement of Hondermarcq, General Director of Roads, entrusted design of the project to Paduart of the University of Brussels.

The project was designed in 1958 and the necessary credits were obtained for the fiscal year 1959. The test road will consist of a section 3½ kilometers long between Zwartberg and Meeuwen. The road will be 7 meters (26 ft) wide and will include two curves with radii of 1,000 and 500 meters (3,280 ft and 1,640 ft), respectively. The terrain is practically horizontal.

The characteristics of this test road are based directly on the experimental work conducted at Orly in 1957, that is, a minimum of foundation and pavement thicknesses fixed at 8, 10 and 12 cm as was the case in the tests conducted in France. The prestress system is the same as that used for the runway at Maison-Blanche (that is, flat jacks in active joints spaced at 270-m intervals). Fixed abutments have been designed by Paduart for each end of the test road. The first will be a reinforced ordinary concrete slab anchored by 80-cm spuds driven into the ground. The other abutment will also be a thick reinforced concrete slab anchored in the soil by six thin parallel fins, each 1 meter high and 15 cm wide (Fig. 2).

The most original feature of the project is the system for preventing relative movement of the slabs at the active joints. These joints are constructed over tunnels 1.70 meters deep which may be used for cable and utility crossings.

The slabs rest on the vertical supports of the tunnels. Upward movement of the slabs is prevented by bars grouted into the concrete at the bottom of the tunnel and bent and imbedded in the concrete of the road pavement slabs. These bars are free-standing for their entire height and permit slight horizontal movement of the slabs through their elasticity.

This extremely original and very simple solution would appear to give results comparable to those obtained by the more complicated system adopted at Maison-Blanche.

The soil on the test road site is a slightly silty sand, easily compacted and of good quality. This sand will be used for the foundation. It will be compacted for a width of 8 meters, waterproofed by spreading cutback and covered with 2 cm

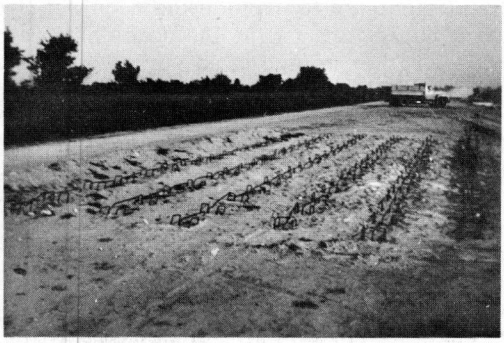


Figure 2. Test Road between Zwartberg and Meeuwen, Belgium: One of the abutments—fins poured and reinforcements placed. Slab will have to be poured afterwards.

of sand to facilitate movement of the slabs. The thin layer of sand will be covered with Kraft paper on which the concrete will be placed.

The designers have thus reduced foundation thickness to a minimum. Inasmush as the soil is not susceptible to frost and can carry truck and heavy equipment traffic in all weather conditions, this solution would appear to be a satisfactory one.

The pavement consists of 8-, 10- and 12-cm thick slabs prestressed by jacks placed in the active joints (as previously described).

Different prestresses will be adopted for longitudinal jack prestressing and for transverse prestressing. The latter may be replaced by reinforcement or eliminated altogether. A total of 26 sections with different characteristics are planned. Up to the present time, only the abutments and the tunnels for placing active joints have been constructed. The remainder of the work was completed in the winter of 1960.

Runway at Melsbroek

Some time after design was begun on the test road, the management of the Melsbroek Airport near Brussels decided to invite bids for construction of a 3.3-km runway 45 meters in width designed for jet planes.

The runway was to be constructed of ordinary concrete. Bidders learned, however, that they could present alternate designs for prestressed concrete. Paduart, who had just finished design of the test road, accordingly proposed construction of a prestressed concrete runway to be executed in collaboration with the Wegebo Company.

The ordinary concrete runway was to consist of a slab 45 cm thick composed of two courses 22.5 cm in thickness, the lower course to be 325-kg concrete and the upper 400-kg concrete.

The base was to consist of a layer of 0.60 quarry run aggregate laid on the natural soil, a sandy silt. The alternate proposed by Paduart was a prestressed 18-cm slab placed on a 2-cm layer of sand above a 20-cm base course. The upper 10 cm of the base course was to be 0.60 quarry run aggregate and the lower 10 cm compacted sand.

The prestressed concrete proposal offered a saving of approximately 5 percent as compared with ordinary concrete and was selected by the Airport authorities. Work began in the spring and the completed runway was opened to traffic on 15 December; that is, after 6 months work. Results seem, at the present time, to be quite remarkable. Five of the six 7.50 strips have already been placed for the entire 3.3-km length. Practically no cracks are noticeable and the joints covered with concrete will be imperceptible when completed.

Certain features designed by Paduart which were to be tested on the test road before being used in permanent construction were used on the Melsbroek runway before being tested. It would appear, however, that the conditions under which they were designed make it possible to anticipate that they will stand up well in use.

The original features which were described in connection with the test road have been used for the Melsbroek runway. The abutments are of the ribbed type and are ordinary concrete slabs 40 cm in thickness connected by reinforcement to fins 40 cm in width and 1.20 m in height measured from the lower surface of the slab. The ribs were placed without forms in the natural soil which had been excavated by a specially designed machine like a mechanical trencher. The soil was sufficiently cohesive to permit trenching without shoring and placing vibrated concrete without caving in of the trench walls.

Contraction joints 5 cm deep have been provided in the upper part of the abutments.

The abutments are extended by large ordinary concrete slabs which connect the main runway to the taxiways. In the event that the abutments should prove insufficient to absorb expansion of the runway in warm weather, measures have been taken so that they can be reinforced by uniting them to these end slabs.

The active joints above utility tunnels described in connection with the test road are also found at Melsbroek (Fig. 3). Slab thicknesses have been increased 18 to 25 cm at these joints. Active joints are spaced at 330-m intervals (1,082 ft). Temporary joints were placed every 110 m (360 ft) following the example at Maison-Blanche. These joints make it possible to compress the concrete 24 hr after placing and it is

because of them that the 110-m long slabs show no fissures due to contraction.

Transverse prestressing will be provided by cables spaced at 1.75-m intervals. Each cable will consist of twelve 7-mm strands tensioned at 100 kg per mm^2 for a breaking strength of 150 kg. Cables will be placed directly in the slab without tubes. Passages for the cables were provided by setting pipes on concrete blocks at the time the slabs were poured.

These pipes were removed when the concrete had sufficiently set.

The different strips which go to make up the runway were successively placed, each of them serving as a form for the following one. It is anticipated that the fissures between the strips which were caused by contraction will be eliminated at the time of transverse prestressing.

At Masion-Blanche, the longitudinal joints were protected by strips of paper before transverse prestressing. The contractor at Brussels expects to obtain similar results by scraping out the interior of the fissure with a knife before applying compression.

The foregoing are the chief features of the Melsbroek runway. When opened to traffic, it will be the largest prestressed concrete runway in operation. It will be extremely interesting to see how it stands up in a climate which is appreciably different from that of Algiers.

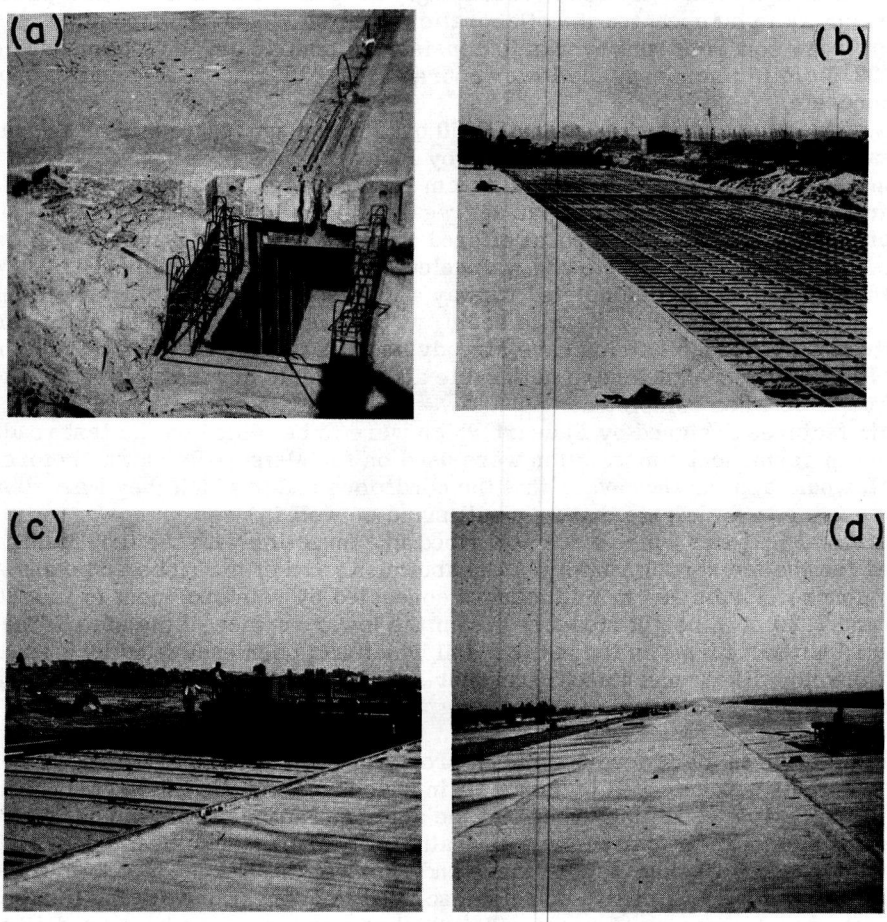


Figure 3. Melsbroek Airport, Belgium: (a) active joint under compression with underpass; (b) construction of a 22-ft wide lane; (c) concreting operations; (d) 2.5-mi long runway without any visible joint (one more lane to pour).

Experimental Taxiway at Melsbroek

A prestressed concrete test taxiway section was constructed at Melsbroek in 1958. This section is 350 m (1,148 ft) long and 23 m (75 ft) wide and 10 cm thick. The pavement rests on a 30-cm layer of compacted sand above the natural soil compacted for a thickness of 30 cm. The pavement consists of prefabricated slabs in the form of parellelograms 12 m (39 ft) long and 1.24 wide. These slabs are prestressed by grouted strands at the time they are manufactured. They are joined together in 18 strips to make up the total width of the pavement. These slabs are set directly on the sand base course and held together by transverse cables consisting of eight 7-mm strands. The cables are spaced in openings provided in the slabs at 80-cm intervals. Each cable exerts a pull of approximately 26 metric tons. Transverse prestressing is approximately 33 kg. The oblique joints in the slabs are staggered from one strip to the other so that each of the joints is crossed by one cable. Because the joints are oblique, the transverse stress transmitted by the cables gives a component perpendicular to the joints thus insuring a longitudinal prestress bond between the butt ends of the slabs. There has not been sufficient time to determine how this taxiway section will stand up under traffic.

The fact that the Administration did not accept this system for the construction of the Melsbroek runway would appear to be an unfavorable indication, however.

SWITZERLAND

The first two tests made in Switzerland by the Concrete Road Association included two sections each 500 m (1,640 ft) long. In the first of these, longitudinal compression is obtained by means of flat jacks placed every 70 m (229 ft) with a fixed abutment at one end and a natural rock abutment at the other. In the second section compression was obtained by means of wedges placed at 120-m (393-ft) intervals. One end of the slab is held by a fixed abutment, the other end abuts against an existing road. The longitudinal prestresses are quite high : 60 kg/cm^2 and 70 kg/cm^2 (840 and 980 psi), respectively.

On the other hand, the transverse prestress has a low value. In the first case it is produced by single strand cables (7 mm diameter) 1 m apart and tensioned so as to produce an initial compression of 4 kg/cm^2 in the slab. In the second case there is no transverse prestress but the slab is provided with light reinforcement. It should be noted that in both cases the slabs are narrow; namely, 2.5 m and 5.5 m wide, respectively. British experience has shown that in such circumstances transverse prestress may be eliminated (these two slabs form part of a concrete country road). An interesting feature of the second test is that the slab included a curve in the road; this curved portion has behaved well up to now.

SPAIN

An experimental road is to be built in the Madrid area in the course of 1960 under the supervision of Escario, Professor of Road Technique at the Technical College for Bridges and Highway in Madrid. The necessary credits have been put at his disposal. This road will include a prestressed concrete section more than 1,000 m (3,280 ft) in length. The methods which will be applied are still under study.

ITALY

A part of a road has already been constructed under the supervision of Lévi and was the subject of a special report at the International Concrete Road Congress at Rome in 1957.

FRANCE

Early Experiments

French tests on prestressed concrete roads were conducted by Dollet, Chief Engineer of Bridges and Highways. He was responsible for the construction of slabs at

Luzancy and at Esbly while he was Engineer at Meaux. Later he built the experimental road at Bourg-Servas, in the department of Ain, where he is now Chief Engineer.

In its issue of January 1954, the review "Travaux" devoted an article to the experimental road at Bourg-Servas. The authors of the article were Dollet and Robin. The main points are summarized here.

At Luzancy there are two slabs, 6 m wide and 24 and 26 m long, respectively, forming two sections of National Highway 369 between La Ferté sous Jouarre and Château-Tierry. These slabs are 16 cm thick at the center line and 20 cm thick at the edges.

The prestress is obtained by means of cables placed at an angle of 45 deg to the center line of the road. These cables consist of 10 strands of 5-mm diameter and are arranged to form 50-cm meshes. The prestress varies from 17 to 21 kg/m^2.

These slabs were constructed in 1945-46 on fill at both approaches to the Luzancy bridge. Tests carried out on a 16-cm thick prestressed concrete slab at Orly at the same time showed that it could support 130-ton load distributed over a circular area 70 cm in diameter. Of course, roads are never designed for such heavy loads. The Luzancy slabs were therefore well on the safe side. They have stood up perfectly in spite of the low bearing capacity of the subgrade.

The slab at Esbly, which was constructed in 1949 on the heterogeneous backfill on the left-bank abutment of the Esbly bridge, is 48 m (157 ft) long and 15 cm thick. It was constructed between two precast curbs which hold the anchorage cones. The prestress is insured by a grid of cables composed of 12 strands 5 mm in diameter forming 1-meter meshes. The prestress is 16 kg/cm^2 (224 psi). In spite of poor subgrade conditions, this slab has also behaved remarkably well since its construction.

Encouraged by these two successes Dollet, Chief Engineer at Bourg, decided to carry out a test on a larger scale on a section of National Highway 83 between Bourg and Lyon. The length of this experimental section was originally to be 1,000 m (3,280 ft) but its length had to be reduced to 300 m for budgetary reasons.

To preserve the uniform appearance of the road it was decided at the outset that the prestressed concrete should be covered with a bituminous surfacing 4 cm thick. The presence of this surfacing has prevented long-term observations and somewhat detracted from the value of this otherwise extermely instructive test.

The essential difference between the Bourg-Servas road and the slabs at Luzancy and Esbly is that the longitudinal prestress was produced by means of flat jacks instead of cables. This meant that abutments had to be provided to prevent movement at the ends of the slab.

It is not necessary to go into detail about the features of this project and about the abutment system which was adopted. The experience gained in this connection at Algiers has yielded data which would suggest that minor modifications could be made.

In any case the Bourg-Servas road was the first in which the longitudinal prestress was obtained without cables and consequently much more economically. This test held out a prospect that it might some day be possible—perhaps under special but nevertheless frequently occurring conditions—to construct a prestressed concrete road whose cost would not differ from that of an ordinary concrete road, the thickness of the slab being designed to obtain comparable strength.

The design of the Bourg-Servas road was prepared by Freyssinet and the Société Technique pour l'Utilisation de la Precontrainte (STUP). The information furnished by this test proved of great value in the design of the airfield runway at Algiers.

Present Status: Slabs at Orly

The remarkable success of the prestressed concrete runway at Algiers led the author to take up the question of road tests in the light of the results obtained. It seemed that the only economical method of obtaining longitudinal prestressing was to use "active joints" containing one or more flat jacks, and to use cables or bars for transverse prestressing. The question of the abutments cannot be investigated experimentally as long as the final location of the road has not been decided. Local conditions should be used in the best possible way; advantage should be taken of areas where a strong subgrade is available or of a curve where the natural configuration of the terrain can

take up the horizontal thrust, so as to obtain the most economical abutment in each particular case. Therefore no tests were made on this point, but a fixed "frame" was provided in which the slab unit to be constructed would be enclosed. This frame was also made of prestressed concrete, the two short sides acting as abutments.

The question of the spacing of the active joints had been solved in Algiers, where these joints were spaced at 300 m (984 ft).

Actually, temporary joints were placed at every 100 m. Twenty-four hours after the slab had been concreted, compression was applied at these joints to prevent the formation of shrinkage cracks. After the concrete had set, the temporary joints were packed solid and the continuity of the slab was restored before applying compression to the actual active joints. The experience gained in Algiers showed that the stresses in the slab which were at first concentrated at the active joints were gradually distributed and that the slab as a whole acted as if the friction of the concrete on the sand base were zero for extremely slow movements such as those due to temperature variation.

Provided that the slab is laid on an appropriate sand base, the active joints can easily be spaced at 200 or 300 m (656 or 984 ft) as in Algiers.

An important feature of the tests is the design of the base. One of the chief advantages of prestressed concrete is the absence of joints, which secures the continuity and the impermeability of the slab. If a prestressed slab of practically unlimited length is compared with an ordinary concrete slab without dowels, it will be noted that in the first case the slab acts as if the loads were always applied at the center or, at most, at the two edges of the road, but never at a corner. The function of a road foundation, that is, to transmit loads acting on the surface of the slab to the natural subgrade so that only elastic deformations are produced, is thus reduced by one-half or even by three-quarters. It was assumed (and the object of the test was to check this) that the layer of sand indispensible to permit traffic of the contractor's equipment on the job was sufficient to support the prestressed slab and to prevent permanent deformations of the subgrade.

The thickness adopted for this layer of sand was 15 cm on account of the moisture content and the poor quality of the soil, a clayey silt with a CBR value between 1 and 2. If the tests are confirming, a considerable saving can be effected on poor ground which will reduce the cost of prestressed concrete construction to nearly that of ordinary concrete or perhaps even below it.

Another point which is to be investigated is the question of slab thickness. Previous tests and the experience gained in connection with airfields has shown that a 16-cm thick slab could without appreciable permanent deformation withstand a practically unlimited number of 100-ton loading and unloading cycles applied to a circular plate 70 cm in diameter. On a road the loads acting on an area of similar size will never be more than 10 tons corresponding to a 20-ton wheel load, which is higher than anything yet existing in practice. It would appear that a slab 8 cm thick can withstand alternating loads of 10 tons. The question at issue was whether it was possible to level the surface of the sand base so as to permit the easy construction of a slab of 8 cm uniform thickness, and whether this thickness would be sufficient to accommodate the cables without weakening the slab.

Accordingly, it was decided to divide the test slab into three parts with thicknesses of 8, 10 and 12 cm, respectively. The base course was accordingly levelled with particular care and was finished to a tolerance of ± 1 cm. This presented no exceptional difficulties and merely necessitated careful compaction with a light roller. The prestressing was obtained by means of single strands of 10 mm diameter with a bituminous coating. Experience has shown that such wires, which are supplied on reels, have no tendency to curve once they have been straightened and that before tensioning they can be easily held in position during the placing of the concrete by supporting them on small concrete blocks or wire chair spacers. These wires behaved very well during the tensioning. Once the initial friction had been overcome, only a small force was needed to move the wires, which showed that the bituminous coating was uniformly distributed along the length of the wires and was satisfactorily performing its function as a lubricant. Besides, the special Freyssinet cones are easy to install and economical. Although an alternate using transversal bars with threaded ends had first been considered,

it was found that wires were easier to transport than bars 11 m long and could be placed just as rapidly. The idea of the bars was accordingly abandoned.

Another object of the tests was to ascertain whether an anti-buckling device such as the interlocking system used at Maison-Blanche was necessary to prevent any lifting of the slab near active joints as a result of some assymetry in the arrangement of the joint. Of the two joints, one was of similar construction to those at Algiers, whereas the other consisted merely of an additional slab thickness and a sleeper beam under the joint.

Construction of the Slabs.—Construction which began in early April, was completed on June 15, 1957. It comprised the construction of the base, the frame, and finally the slabs themselves (Fig. 4).

The foundation was obtained by stripping the natural ground and spreading a base course consisting of a mixture of 0-60 mm sand and gravel obtained from the Seine.

Measurements for determining the modulus of subgrade reaction were carried out on the soil and on the base course after compaction with a light roller. The following values were obtained:

Subgrade	0.75 - 2kg/cm^3	(8 - 24 lb/cu in.)
Base course	1 - 1.2 kg/cm^3	(12 - 15 lb/cu in.)

It was obvious that the subgrade soil was very poor. Its quality certainly improved on drying after the rainy season. Measures have been taken so that it can be saturated again at the end of the test, however.

The enclosing frame was constructed in accordance with the design prepared by the STUP and was prestressed without any special difficulties.

Finally, concrete for the three slabs, with a total length of 50 m (164 ft), was placed inside the frame. The slabs were constructed so as to bear against the frame at their two ends only. Only the center slab, 20 m (65 ft) long and 8 cm thick was placed between two active joints. The other two slabs which are 15 m (49 ft) long and 10 and 12 cm thick, respectively, were placed between the abutments and the active joints.

Transverse prestressing was obtained by means of jacks, using special cones for single strand cables developed by the STUP. No difficulties were encountered except for the snapping of one cable which was replaced immediately.

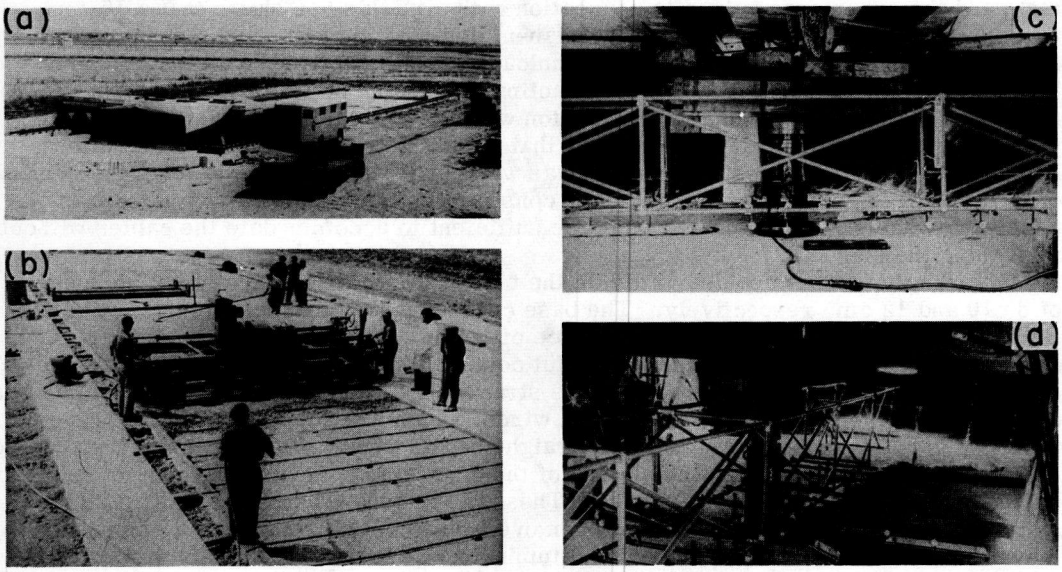


Figure 4. Slabs at Orly: (a) general set-up of test slab; (b) pouring slab—transverse strands placed; (c) testing set-up—repeated loading operations; (d) deflection measurement.

Once the initial resistance had been overcome, the bituminous coating proved to be effective and the frictional resistance became negligible. Longitudinal prestressing was effected by means of flat jacks which were inflated by hand after being first filled with water and subsequently with oil. In order to be able to continue the tests, the jacks will not be filled solid with grout as is usually done. After a few applications of compression, the joints were impervious and the pressure could be kept constant without difficulty.

Test Program. —Strength tests were started on July 4, 1957. The equipment used was described by Cot and Becker in articles on the 1953 tests which were published in "Travaux." The machine makes it possible to apply alternate loading and unloading cycles at a rate of 1,000 in a 6-hr period. The test is extremely severe because the load is constantly applied at the same point instead of being distributed in an irregular manner over the surface of the pavement as a whole, as it normally would be in the case of a road. It entails a risk of causing permanent deformation of the road base, whereas, in reality, there would merely be some settlement of the latter.

To begin with, 15-ton loads were applied with a uniform transverse and longitudinal prestress of 10 kg/cm^2 (140 psi) and the permanent deformations of the slab were observed. In reality, a load of 15 tons is more than 50 percent higher than the heaviest conceivable wheel load and is therefore amply sufficient.

In a second series of tests, the average transverse prestress was reduced to one-half its value by putting every alternate cable out of action, while maintaining a load of 15 tons.

In a third series of tests, the longitudinal prestress was increased from 10 to 100 kg/cm^2 (140 to 1,400 psi) which corresponds to a rise of 30 C in the temperature of the slab without a change in the moisture content. The transverse prestress was 5 kg.

Elasticity of the Slab and Deformations of the Subgrade. —At the very first test, a considerable difference was noted between the deformations of the pavement under load and the deformation remaining after unloading, thus demonstrating the well-known elasticity of prestressed concrete. While the deformation of a 10-cm thick slab was 2.3 mm under a load of 15 tons, after 100 tests, the residual deformation was less than 1 mm. Thus, the slab underwent an elastic deformation of about 1.5 mm. The foundation under the load should, like the slab, be increasingly deformed with the number of cycles to about 2 mm. But the subgrade has very little elasticity and should not recover its initial volume on unloading. A certain vacuum would tend to form under the slab if the latter continued to receive loads constantly applied at the same point. But in reality a road slab would receive loads distributed over the whole width of the pavement so that instead of a localized deformation the subgrade would undergo a uniform settlement, the slab constantly resting on the ground which would simply sink 2 or 3 mm.

The risk of vacuums forming between the slab and the ground is therefore, neither in the case of a road nor in that of an airfield runway, a real one, because the loads are distributed on the central strip which would settle uniformly under the effect of the compressions distributed over the whole surface. A wide safety margin should be allowed, however; that is, the deformations which lead in due course to uniform settlement should be strictly limited. It will be seen that the necessity of limiting loads at the edges of the pavement makes this safety margin imperative. But the risk of seeing vacuums form, as after the tests, between the slab and the ground is non-existent. The distribution of the loads will insure the uniform settlement of the base; that is, will maintain constant contact between the under surface of the slab and the ground.

Alternate Load Tests. —Tests were carried out on each of the 10-, 8- and 12-cm slabs, first at the center of the slab, then at a distance of 30 cm from the edge.

Longitudinal and transverse prestresses were both 10 kg/cm^2 (140 psi). The following loads were applied on plates 30 cm in diameter:

At center of slab	15 and 30 tons
At edge of slab	10 and 15 tons

The tests showed that 30 tons probably corresponds to the maximum load for the 8-cm slab. Deflection was more than 7 mm at the first loading and increased to 11.4

mm after 600 loadings. Residual deformations were 1.30 mm after the first loading, increasing to 2.5 mm after 600 loadings. It would appear that the loading limit was reached in this case. Because the maximum load admissible for a given slab is limited to what the slab can support at the edge, deformations at the center should remain very slight.

Figure 5 shows the comparative deformations of the 8-, 10- and 12-cm slabs for a load of 15 tons applied at the center; Figure 6, for a load of 10 tons applied at the edge. Both loads were chosen as corresponding to linear deformations as a function of the load. It is seen that in both cases the extent of the deformations is the same; that is, at 30 cm from the edge the bearing capacity of the slab is approximately two-thirds of what it is at the center. The diagrams also show that the tests corroborate the observations previously made by the Services de l'Aéroport de Paris concerning the nature of deformations of prestressed slabs. When these deformations are expressed as a function of the number of loading cycles on a logarithmic diagram, it is observed that the deformation varies as the logarithm of the number of the cycles. This observation obviously only holds true for relatively weak loads, the repetition of which produces progressive settlement of the subgrade. In the case of heavier loads, stabilization of the subgrade is reached more rapidly. This is of interest inasmuch as the observation of less than 100 loading and unloading cycles makes it possible to plot a complete curve of the deformations.

As can be seen, even in the case of the 8-cm slab, a concentrated load of 10 tons applied on a surface so that the pressure exerted is 10 kg/cm^2 (140 psi) does not produce residual deformations greater than 1 mm for about 1,000 cycles. When the load is always applied at the same point, the deformations under load increase from 2 to 3.7 mm.

Mention has already been made of the extent to which this test situation is an artificial one. As, in the point of fact, loads would actually be uniformly distributed on the slab, there would be no deformation but a uniform settlement. For an 8-cm slab with a load of 10 tons, which seems permissible, this settlement would reach approximately 2.5 mm at the end of a very long time.

Calculations have been made based on the results of the foregoing tests by applying the Westergaard method which makes it possible to calculate deformations of a concrete slab as a function of the modulus of reaction of the subgrade. In the case under consideration, the deformations were known and also the modulus of elasticity of the concrete. From this it was possible to determine the modulus of subgrade reaction. The value found was 1.4 kg/cm^3, which corresponds very nearly to the value as measured directly.

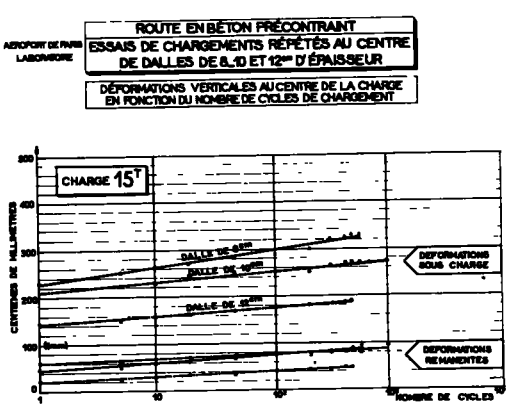


Figure 5. Orly test results: deflections under 15-ton load at center of slab after 10, 100, and 1,000 repetitions.

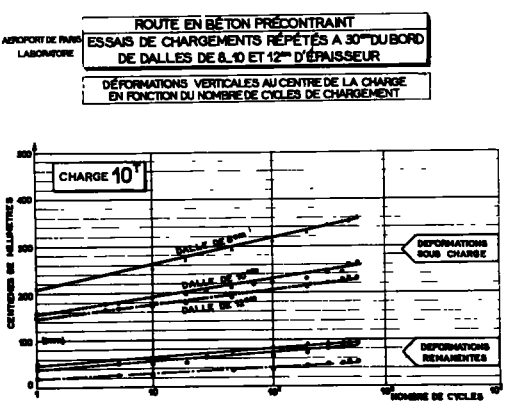


Figure 6. Orly test results: deflections under a 10-ton load on edge of slab and after removal of load.

This is of interest because it confirms the fact that the strength of the foundation ascertained before construction at the end of the rainy season had not appreciably improved during the course of the summer. The measurement of moisture content made by the laboratory in a hole drilled through the surface gave a similar result. It is interesting to check it with the usual formulas.

All the tests of which an account has been given were made on slabs 8, 10 and 12 cm in thickness without increased thickness at the edges. The possible reduction of the bearing capacity of a slab at its edges is a matter which was given attention and the Orly slabs had a thickness of 12 cm on one edge. Tests were made along this side at the very edge of the slab. They showed that the increased thickness made it possible to rely on a strength at the edge of the slab practically equal to that of a 12-cm slab regardless of the thickness at the center. It would, especially in the case of runways for light aircraft, make it possible to use the full bearing possibility at the center of a thin slab by simply increasing the thickness at the edges.

Effect of Variations in Temperature. —During the first tests the rate of longitudinal and transverse prestress was kept uniform at 10 kg/cm^2 (140 psi). The object of the following test was to determine the advantage of an anti-buckling device; that is, to see if, when a sudden rise in temperature is reflected by an increase in the stresses within the slab, a possible eccentricity of the flat jacks could cause one of the slabs to move upward in relation to the other. This test was carried out on August 22. In spite of the presence of various measuring devices, the results obtained were only of a qualitative nature. They have, however, unquestionably shown the necessity of anti-buckling devices. For one of the two joints in which only an extra thickness and an under-slab had been provided, inadmissible differences of level were ascertained between the two edges of the joint when jack pressure was applied. On the other hand, the other joint which had been provided with an anti-buckling device supported increases in pressure without the edges of the slabs showing a perceptible difference in level.

The test was effected by increasing the pressure in the jacks to their maximum. A pressure of 150 kg/cm^2 (2,100 psi) was thus reached, giving an average pressure in the slab of about 75 kg/cm^2. This corresponds to an increase of 65 kg/cm^2 as compared with the initial prestress rate; that is, a difference in temperature of the slab of more than 20 percent. This figure would amply correspond to diurnal temperature differences which may produce differences in level between the edges of the joints. Regarding the type of anti-buckling device to be recommended, the test simply showed that the system used at Maison-Blanche functions satisfactorily. Unfortunately, it is complicated to construct. A proposal permitting a considerable simplification has been put forward and has been tested. Tests showed that the device, although preferable to the simple increase of slab thickness at the joint, was not sufficiently effective to prevent vertical displacements measurable in millimeters. So far, only the device used in Algiers can be considered as completely effective.

Reduction of the Transverse Prestress. —The first tests were made with a uniform prestress of 10 kg/cm^2 in two directions at right angles to each other. The results were favorable and it was decided to reduce the transverse prestress by one-half, by relieving tension in alternate strands. A complete series of tests is to be made before winter. The first tests, made in the center of an 8-cm slab showed deformations under a weight of 25 tons similar to those observed under 30 tons with an average of twice as much transverse prestress (Fig. 7). At the edge the difference observed was some 10 percent in spite of the fact that the spacing between the tensioned strands was twice as great. It is clear that the tolerance of the slab thickness was only about 1 cm (½ cm at the top and ½ cm at the bottom). Displacement of the loading due to variations in the thickness of the slab may accordingly cause variations in the deformations of as much as 15 percent. The first tests performed after eliminating the tension in alternate strands, nevertheless, show that the influence of transverse prestress on the bearing strength is weak in the case of a slab that is not cracked and that a reduction of this transverse prestress by 50 percent reduces the bearing capacity only 10 to 20 percent. This fact was sufficiently arresting to warrant continuation of the tests by doing away with all transverse prestress in a certain area to see how the slab would behave.

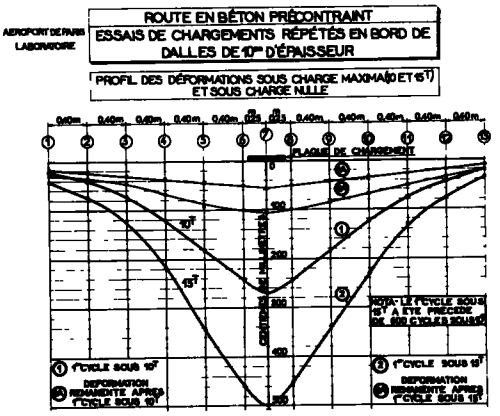


Figure 7. Orly test results: transverse deflections under load.

These tests were first made at various points in the 12-cm slab. It is interesting to compare results of the tests made with a 15-ton load applied at the center of the 12-cm slab with the tests made at the same point with the same weight but without transverse prestress. It was noted that the deformations under load as well as the residual deformations were very close to those observed with the transverse prestress, the difference being of the order of magnitude of test errors.

Other tests were performed with a 10-ton load applied at a distance of 30 cm from the edges with transverse prestresses of 10 kg, then reduced to 5 kg and finally completely eliminated. Here also, the deformations were similar. Residual deformations were clearly lower in the case of the 10-kg transverse prestress, however. These tests would tend to make one conclude that, in the case of roads, transverse prestressing is not essential. This conclusion is probably over-optimistic. Actually all the tests performed with a prestress of 10 kg/cm^2 (140 psi) were carried out within a few months after construction of the slab. The tests with reduced or with no prestress were made a year later, however. That is, the strength of the concrete, especially of concrete set under prestress and which therefore had no cracks, was greater in the second case than in the first. This point should be checked further.

Tests for the bending strength of the concrete were performed during construction. It would be of interest to prepare test specimens now and to determine the bending of strength of the concrete once more. These tests would make it possible to see to what extent the slight deformations under loading of the slab without transverse prestress may be due to an increase in the strength of the concrete.

Another point which the tests have not succeeded in elucidating is the extent to which the concrete near the longitudinal construction joint at the center line of the slab would react to the absence of transverse compression. To the present time tests have been performed at the center of the slabs or near the edges. Do the results of these tests apply to the area near the central joint and can it be deduced accordingly, that, in a slab that has at no time undergone transverse prestressing, the longitudinal prestressing would be sufficient to produce the results which have been noted?

Test Road at Fontenay-Trésigny

The interest in the techniques of prestressed concrete construction has led the French government to undertake construction of an experimental road on which various prestressed road systems may be tested.

The 2.5-km long by-pass of the Paris-Strasbourg road at Fontenay-Trésigny which will be subject to heavy traffic was selected for this purpose.

To benefit from developments in the field of prestressed concrete realized by various specialized engineering firms, the 2.5-km test road was divided into three sections, each to be constructed by a particularly qualified contractor.

The Société Campenon Bernard, which built the runway at Maison-Blanche, was given a section 1,140 m long (3,610 ft). The Société des Grands Travaux de Marseille was given a 350-m length (1,148 ft), the Société Boussiron 530 m (1,738 ft) and a group of three specialized concrete pavement contractors another 350-m section.

The systems selected by the various contractors were, for the most part, based on the over-all study of the project made by Chief Engineer Peltier, Director of the Central Laboratory of the Ponts and Chaussées, which was published in the October 1958 issue of the "Revue Générale des Routes."

The various proposed design systems correspond to the different possible types of prestressed concrete road construction; namely, external prestressing between two fixed abutments, external prestressing with elastic joints to insure even distribution of slab stresses and internal prestressing by cables.

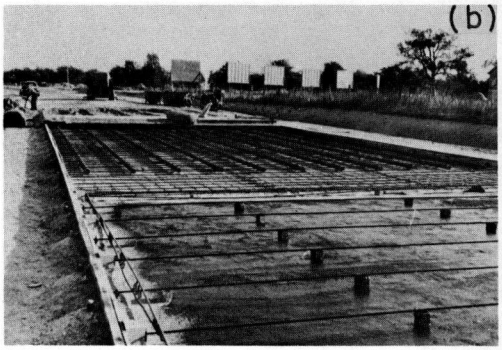
The Government's purpose in proposing the construction of the test road was, in the first place, to investigate various possibilities and to study the largest possible number of different systems. The engineering companies entrusted with the project accordingly divided their sections into several parts jointed by joints, thus affording considerable scope for inventive skill.

The Société Campenon Bernard divided its section into three parts. The first part consisted of a slab prestressed by jacks between two fixed abutments 500 m (1,640 ft) apart (Fig. 8). The second part was also constructed between two fixed abutments but included various types of elastic joints. A last 150-m section was cable prestressed.

The abutments designed by this company consist of thick concrete slabs, the lower parts of which are toothed. The abutment functions through its weight on the one hand and on the other through the resistance furnished by the teeth which act as anchor spuds.

Abutments of this type can be constructed to any desired length and provide high thrust resistance.

In the 500-m (1,640-ft) section with elastic joints, the company proposed three types of joints: one with longitudinal cables in a sub-slab, another with spring joints of the "traction-compression" type composed of tensioned wires in metal tubes, and, a joint consisting of a trapezoidal slab section acting as a wedge between two adjacent slabs. The wedge is pressed against the slabs by springs and its movement between the slabs is facilitated by roller bearings. A beam between the two slabs balances the wedge.



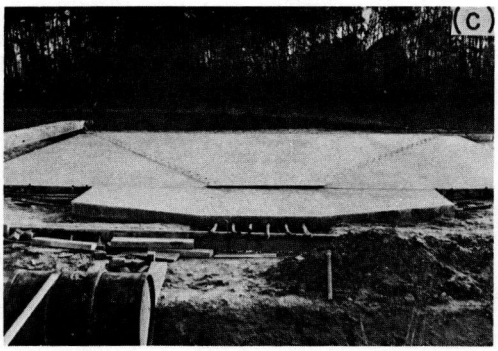


Figure 8. Fontenay-Trésigny Test Road: prestressing with jacks— (a) fixed abutments, foundation ready for pouring; (b) elastic joint before pouring slab; (c) trapeze-shaped elastic joint.

This last system would appear to be based on the first prestressed concrete runway designed by Freyssinet at Orly in 1947. The purpose of the joints was to maintain constant stresses in the slabs in spite of variations in the temperature, the stresses on the abutments being reduced proportionately. The end abutments for this section may be lighter than those for the first two sections. They are of the same type but are simply shorter. Pavement continuity is insured by metal tooth joints between slabs. The company provided transverse prestressing by strands. The slabs are 12 cm thick with additional thicknesses up to 18 cm under the edges and at the joints. Transverse abutments were constructed to absorb thrusts at the outer edge of curves.

The Société des Grands Travaux de Marseille divided its 350-m long section into three parts, each 117 m (383 ft) long. Cables were used for longitudinal and transverse prestressing in all cases (Fig. 9). Prestress values vary from one section to the other, however.

The main objective of this company was to study the problem of insuring pavement continuity between the various sections. Special joints consisting of steel elements and neoprene blocks furnished additional external prestressing.

The Boussiron Company planned two sections, 115 and 415 m (377 and 1,350 ft) in length, respectively. The first section was a 12-cm slab with crossed strands, the second, a mobile slab with elastic joints between two abutments of a new type designed by the company.

Three types of elastic joints were constructed: a spring-type joint with wires in tubes similar to those used by the Société Campenon Bernard; a snythetic rubber strip joint and, last, a pneumatic joint consisting of a rubber air chamber between two cast steel elements which function like pistons. Pavement continuity is insured by a metal tooth joint. The pavement is 12 cm thick as in the preceding cases.

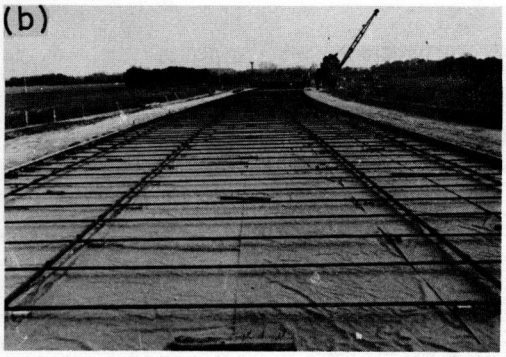


Figure 9. Fontenay-Trèsigny Test Road: prestressing with cables—(a) longitudinal and transverse cables (note small number of longitudinal cables); (b) cables at 45 degrees to axis of slab.

Last, the group of specialized concrete pavement contractors is the only one in which transverse prestressing has been eliminated altogether. Concrete thickness was increased to 15 cm and a longitudinal joint was provided.

The foregoing are the systems under construction at Fontenay-Trésigny. The test road should be terminated before winter 1959, and traffic will be directed over the road as soon as construction is completed.

The test road presently under construction in France will thus provide considerable data which may be added to information obtained by observation of the Melsbroek runway and the Belgian test road. From the economic point of view, the systems being studied in France are certainly more costly than those constructed in Belgium which, from now on, would appear to offer competitive possibilities. It will nonetheless, be interesting to see how the different types of elastic joints will behave and to see if the toothed metal surface joints to maintain continuity of the pavement above the elastic joints will be as effective under traffic as the jack blocks used in the runways at Melsbroek and Algiers.

CONCLUSION

The tests which have just been described show that it is possible to construct prestressed concrete roads, at least on a straight section with a regular gradient, that it can be economical and that, from the point of view of the wearing qualities, the complete absence of joints will give it an unquestionable technical superiority. All the problems raised by this method of construction have certainly not been solved, however. For if airfield runways are always straight and practically horizontal, the same is by no means the case with roads. It is therefore necessary, when designing a road and considering the use of prestressed concrete, to divide the road into straight sections and curves or changes of gradient to be studied individually. The need for abutments at certain intervals, the possibility of constructing these abutments of ordinary or even prestressed concrete with cables anchored in the ground or not—as was demonstrated by the Swiss engineers in the case of a curve—all these problems can be solved in various ways. The credit of the engineers who tackle these problems will first be established by the very fact that they will have to solve them.

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Discussion

PHILLIP L. MELVILLE, Engineer, Airfields Branch, Office, Chief of Engineers; and PAUL F. CARLTON, Chief, Research Branch, Ohio River Division Laboratories—Periodic reviews of developments in the design and construction of prestressed concrete pavements are helpful to engineers engaged in this field. Mr. Mayer's paper is a timely report on the present state of the art in Europe. From his paper it is obvious that construction of prestressed pavements is progressing faster in Europe than in the United States.

It is unfortunate that definite correlations between pavements described by Mr. Mayer and current American practice cannot be established. Such data as are necessary to establish this correlation include: the modulus of rupture of the concrete, the modulus of subgrade reaction, and the configuration and magnitude of the vehicular or aircraft loading. In addition, the inclusion of some reference to the actual design concepts used would have added materially to the analysis of these European pavements.

Mr. Mayer makes two statements in his paper which the writers believe merit further attention. The first concerns the assumption that the transverse distribution of traffic will be such as to produce a uniform settlement of the pavement structure. It is believed questionable that such a condition will obtain, particularly with regard to air-

field pavements. Statistical data, developed by the Corps of Engineers, on the lateral distribution of aircraft show that there is a heavy concentration of traffic along the central portion of such pavement features as taxiways and runway ends. This "channelization" of traffic is a function of the pavement width and the configuration of the aircraft landing gear. Obviously the effect of wheel loads, as related to producing settlement of the pavement structure, becomes more severe as the number of applications of the loading in a traffic lane of restricted width is increased. This has been verified for a number of airfield pavements included in the condition survey program of the Corps. Data on the deformation of both rigid and flexible airfield pavements under the effects of channelized traffic were reported to the Highway Research Board in 1959 by Sale and Foster.[1]

The second statement contained in Mr. Mayer's paper which the writers question concerns the significance attributed to repetitive plate loading tests. Although so-called static loading tests with a plate or an actual wheel will yield much worthwhile information as to pavement strains and deflections, the results cannot be translated fully into parameters of a pavement performance equation. Reliance on repetitive plate tests may lead to unconservative concepts relative to evaluating accurately the load-carrying capacity of pavement structures. Experience of the Corps of Engineers has shown that use of controlled traffic tests enables potential points of weakness to be observed more clearly. The advantages of controlled testing are threefold: stress reversals are produced at all points in the traffic area (especially important for prestressed pavements with their associated high negative moments), the effects of hygrothermal stresses are more fully evaluated, and localized areas of non-uniform subgrade support (if existent) may be detected.

It is also noted that European practice has been, almost without exception, to construct prestressed pavements on high-strength subgrades; that is, k values ranging from 200 to 500 lb per cu in. As a result, little attention is given in the paper as to the effect which subgrade strength has on the design requirements for prestressed pavements. Certainly it would be erroneous to develop the attitude that prestressed pavements are limited to high-strength subgrades only. On the other hand, data recently developed from accelerated traffic testing of two prestressed pavements constructed by the Ohio River Division Laboratories have indicated that while the utilization of low-strength subgrades without special treatment is feasible, the load-carrying capacity of the pavement is greatly influenced by the subgrade strength. For example, the average life of eight items in one of the ORDL test pavements was approximately 1,400 coverages of a 265,000-lb gear load on a 4-wheel twin-tandem wheel configuration having tire inflation pressures approximately 300 psi. This pavement was 9 in. thick and supported by a subgrade ranging in strength from 60 to 85 lb per cu in. The modulus of rupture of the concrete was 880 psi and the net prestress ranged from 200 to 400 psi. By contrast, the life of an almost identical prestressed pavement at Biggs Air Force Base, Texas, and supported on a subgrade having a modulus of 300 lb per cu in. is estimated to be more than 100,000 coverages under the same magnitude of loading.

With regard to the replacement of transverse prestressing with transverse reinforcing, the full-scale accelerated traffic tests referred to have shown that for airfield pavements constructed on low-strength subgrades, transverse prestressing is desirable. This appears to be particularly true where traffic is concentrated along a longitudinal construction joint. In the ORDL tests, the pavement life was increased substantially in test items containing transverse prestressing as compared to items with transverse reinforcing only.

A. MAYER, Closure—It was very gratifying for the author to read the constructive discussion of his paper by Mr. Melville and Mr. Carlton. He will try hereafter to answer their remarks.

The first question is on the existence of a definite correlation between European pavements and American current practice. This can be answered as follows: the concrete used in road construction is practically always a 350 kg/m^3 (6½ bags per

[1]Foster, C.R., and Sale, J.P., "Accelerated Proof-Tests of Runway Pavement, Columbus Air Force Base, Mississippi." HRB Proc., 38:183-218 (1959).

cubic yard) concrete, placed with an $\frac{E}{C}$ factor of 0.4 to 0.45, that is, probably, somewhat dryer than is usual in the States. Compressive strength would be around 400 kg/cm^2 (6,000 psi)[2], flexural strength 60 kg/cm^2 (840 psi)[2] at 28 days.

The modulus of reaction of the subgrade which Messrs. Melville and Carlton would like to know, is something that differs considerably from one site to the other; this point will be discussed hereafter as an answer to their third question.

The loadings for which the different pavements were designed are:

1. For the roads in France, 13 metric tons axle load (that is, 6.5 tons per wheel), which is the French standard; in other European countries, 5 tons per wheel.
2. For airfields, the international standards are used. Melsbroek in Belgium, Köln in Germany, Algiers in France are three Class A airfields designed to handle all types of commercial planes. The three NATO airfields of Wunstorff, Hopsten, and Nordholtz are tactical airfields designed to NATO standards (20,000 lb per wheel, 150 psi tire pressure).

The second question raised by Messrs. Melville and Carlton refers to the writer's assertion that, unlike tests where repetitive loads are constantly applied to the same point, actual pavement loads should be "uniformly distributed on the slab" so that there would be no deformation, but a uniform settlement. The writer agress that his broad statement does not cover all cases and that, especially on taxiways, the traffic is channelized within two lanes. He is quite ready to correct the sentence to "loads would actually be more evenly distributed on the slab." But inasmuch as the loaded area would be broader, the end result would be that, at least to some extent, the local deformation would be less.

Messrs. Melville and Carlton mention that traffic tests give more reliable values than repetitive plate loading tests; they therefore question the value of the Orly experiments. The author would remind them that when he visited the testing station of the Ohio River Division late in 1957, a prestressed slab had been completed several months before and the station was awaiting allotment of the necessary funds before the traffic tests could be started. Such things also happen in Europe, the only difference being that in the United States there may be some hope of getting enough money to carry out traffic tests, whereas at Orly an attempt had to be made to solve the problem without going to such expense. With the setup as it was at Orly 800 loadings could be achieved in a day; this cut down the cost of the tests considerably. It certainly requires using a larger margin of safety, as the applied loads were 10 and 15 metric tons on the edge and in the center of the slabs, as compared to a maximum wheel load of 6.5 tons.

The results of the Orly tests yield worthwhile information but the author quite agrees that these tests must be interpreted before the results are used in actual design.

The following point mentioned in the discussion is the fact that European prestressed concrete pavements have almost without exception been built on high-strength subgrades. This has long been true; it is also true that in so doing European engineers did not take into account the main advantage of prestressed structures, their flexibility and their ability to distribute applied loads. Actually the Orly tests were largely intended to show the possibility of laying prestressed pavements on practically any base, as long as it was strong enought to stand the movement of the construction equipment. The slabs were poured on 6 in. of non-compacted sand and gravel over a sandy silt saturated subgrade with a K value of 1.4 kg/cm^3 (50 pci), which is about as low a value as can be expected anywhere.

But the Orly slabs were test slabs, not actual parts of a final structure. For these structures, the engineers did not want to take any risk, so they largely overdesigned the base. This was certainly the fact for the first Algiers runway, as well as for the Bingen test road. It is not true for some recent pavements, such as the most recent runways built in Germany and Belgium, where the base was restricted to what was

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[2]Measured on cubic samples, which accounts for a difference of ¼ as compared to U.S. results.

actually necessary to prevent frost action. As mentioned in the paper, a reduction in cost of 5 DM ($1) per square meter of base was taken into account in the comparison between prestressed and ordinary concrete for the German airfields. The discussors' remark is important, but the author sincerely believes that it only applies to the first runways built. It is not conceivable that the engineers in charge would not take full advantage of the fact that prestressed concrete, due to the absence of joints or cracks, can distribute the load much better than ordinary concrete, in reducing the strength of the base and thereby reducing its cost. The information Messrs. Melville and Carlton obtained from traffic tests on a 9-in. pavement with a 265,000-lb gear load on a 60- to 85-pci modulus of reaction subbase, is interesting; but would anyone in actual construction build a 9-in. thick runway on a 60- to 85-pci subbase, without placing at least 6 to 9 in. of sand and gravel so that equipment can be used without completely remolding the soil.

Concerning the last point, the author was glad to hear that the full-scale accelerated traffic tests had proved in favor of transverse prestressing. Such has also been the conclusion in Europe for runways and taxiways. For runways, transverse prestressing has proved to be no more expensive than plain reinforcing, and certainly more effective. The only point now under investigation is the question of roads. In Switzerland, road pavements less than 15 ft wide have been constructed without transverse reinforcing or prestressing; the same thing has been done on the test road at Fontenay-Tresigny on one of the sections, but there the slab has been thickened from 5 in. to 6 in. It is believed to be better in all cases to provide for some transverse prestressing, even for roads, with only one strand every 4 ft.