Title No. 55-53 reports on experiment and achievement in prestressed pavements throughout the world. Six factors selected for discussion include: design practices; choice of prestressing methods; types of aggregates and cements; methods of reducing subgrade friction; load tests and performance records; cost comparison with conventional pavement.

Prestressed Pavement

a world view of its status

Reported by Subcommittee VI, ACI Committee 325*

SUBCOMMITTEE VI OF ACI COMMITTEE 325 was assigned the task of preparing a report on the status of prestressed concrete pavement throughout the world. It was not intended that the subcommittee should pass judgment on the work already accomplished nor was it intended that the report should include firm recommendations for work to be undertaken in this country. It was merely intended that various factors related to prestressed pavement be briefly discussed so that the subcommittee might be able to recommend where emphasis should be placed or where attention might first be focused in future studies. In other words, it was anticipated that the report might reveal a preliminary definition of the subcommittee's future work and it was hoped that by presentation of the report interest in prestressed pavement might be stimulated.

Sources of information for the material in this report are letter contacts with those agencies abroad which have conducted the work, technical and semitechnical papers and articles describing the foreign work, the close association of subcommittee members with the investigations undertaken in the United States, and papers describing the local work. A partial list of the literature reviewed is included at the end of the text.

The largest share of investigative work in the form of field slabs and tests has been undertaken in England and France, and a review of the design procedures employed in these countries was presented at the 36th annual meeting of the Highway Research Board in 1957.[1] There are reports of work done in Australia, Germany, India, Belgium, and Russia but in most cases there

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are not sufficient technical details immediately available to permit study and analysis of these works. Efforts will be made to obtain these details, however, and all the problems involved and their solutions will be studied before a guide to prestressed pavement design and construction is prepared.

In assembling information for this presentation the six factors selected for discussion were:

1. Design practices
2. Choice of prestressing methods
3. Types of aggregates and cements
4. Methods of reducing subgrade friction
5. Load tests and performance records
6. Unit costs

There are, of course, many other items of interest which could be included but it is believed that in this preliminary discussion these represent the principal factors with which the committee is concerned.

DESIGN PRACTICES

Prestressing functions in pavement slabs to augment the strength of concrete in tension by the application of an initial compressive stress before the slabs are subjected to loads. To induce this initial stress two systems of design and construction have been employed. One is the "continuous" type of slab wherein no prestressing steel is used and the stressing is effected by using hydraulic jacks between abutments and the slabs to be stressed, or between the slabs themselves. Slabs of this type are continuous in that there are no expansion joints, and the use of jacks results in gaps that are subsequently filled. The other system is the "individual" type of slab in which stressing is accomplished through the use of high tensile strength cables which are post-tensioned or stretched after the concrete is hardened.

Cables or prestressing wires have been used in a variety of patterns, the most common being longitudinal and transverse. In a number of instances,[3] however, wires have been placed at angles to the center line (e.g., 18½ deg, 30 deg, 45 deg).

Most experimental slabs have been rectangular, but on some jobs triangular slabs have been employed and on the London Airport rollers were inserted between these triangular slabs.

Design methods to date have been somewhat empirical. Enough prestress is applied longitudinally to prevent transverse contraction cracks. Contracting slabs generally are subject to simultaneous temperature warping restraint stress involving compression in the bottom fiber, assisting the prestress in decreasing tension stresses due to load and contraction. Expanding slabs are subject to the greatest combined flexural bottom fiber tension from load and daytime warping restraint, which is counteracted by the prestress as well

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as by frictional restraint stress under the expanding slabs.[15] The prestress design value accordingly is not limited to the amount of residual prestress near midlength of contracting slabs, variously recommended at 100 to 300 psi. Investigators differ in their opinions on the magnitude of residual prestress necessary, but the range given represents a consensus of the authors of reports reviewed.

Slab thicknesses have been *selected* rather than *designed,* generally with estimated necessary cable cover as the determining factor.

The amount of longitudinal prestressing applied when longitudinal cables only or combinations of longitudinal and transverse cables have been employed on highway slabs has varied from 90 to 410 psi with an average of 225 psi. On airfield slabs with these same cable arrangements the average has amounted to about 450 psi. Where diagonal cables were used to effect the longitudinal prestress the average was about 275 psi.

There have been several instances where gap jacks were used and in these cases an average of 575 psi of longitudinal prestress has been applied, considerably higher it will be noted than when cables were used.

Transverse prestressing, as such, has not been universally employed. It was induced as a component of diagonal prestressing when those patterns were used and was the only stressing employed on those works where triangular shaped slabs were constructed. It does not appear to be necessary except where slab widths exceed about 12 ft.

English practices

Prestressed pavement slabs in England have, for the most part, been of the individual type—that is, using cables with expansion joints separating the slabs. The relative merits of the individual and the continuous types of slabs have been argued at length in England and proponents of the former appear to have advanced the more overweighing advantages. The principal one of these is the fact that the amount of prestress, except for the effects of subgrade friction, will remain nearly constant in pavements in which expansion is permitted by the joints. Since the continuous slabs, formed using jacks, require abutments to resist end thrust, and the jack gaps are filled, the slabs cannot expand freely and so the stresses vary with moisture and temperature changes with the result that it is difficult to predict the amount of initial stressing necessary to produce the desired residual.

English engineers have used slabs of 6 in. constant thickness extensively but the triangular slabs at the London Airport were 6½ in. thick. The largest section of prestressed pavement constructed there had a 10 in. thick constant section and on one slab where gap jacks were used the thickness was 4 in.

Longitudinal prestressing in England has conformed to the average figures mentioned above and transverse prestressing was limited to less than 50 psi except in the triangular slabs.

Experience in France

In France both individual and continuous type slabs have been constructed. In 1947 the 1365-ft section at Orly Aerodrome consisted of triangular slabs with transverse cables and abutments; on the 1953 project at the same site gap jacks were used along with transverse cables on continuous rectangular slabs. Other works[10] such as those at Luzancy and at Esbly involved the use of diagonal cables while the 984-ft section at Bourg-Servas was continuous with gap jacks and abutments.

One experimental pavement was a slab with the edges thinner than the center but the rest were of a uniform section averaging about 6 in. thick. Longitudinal prestressing applied to slabs in France has been of the same order of magnitude as in other countries except on the Bourg-Servas Road where a total of 740 psi initial prestress was induced, this in a continuous slab with abutments and gap jacks. French engineers are not in agreement on the need for transverse prestressing.

Germany and other countries

Some of the early analytical work on prestressed slabs in Germany,[6,7] antedates that undertaken in other countries but the application of their theories has been for the most part in connection with slabs supported as bridge floors, roofs, etc., and not with pavement slabs. German engineers have designed and constructed at least two experimental pavement sections and their design practices have been much the same as in other countries

In Belgium, Algiers, and Australia prestressed pavements have been constructed using essentially the same practices as have been employed in other countries. In Australia, however, a 2¼ in. thick section has been constructed in the center of an already existing concrete runway. No details of the prestressing techniques on this overlay type pavement are presently available.

United States

As implied previously only a few prestressed pavements have been constructed in the United States. The largest project to date was the well known effort of the Bureau of Yards and Docks at the Patuxent River Naval Air

Station in 1953-54.[11] This was a 500 ft long, 12 ft wide, and 7 in. thick slab prestressed with longitudinal cables to approximately 700 psi initially. The design techniques and details of this pavement may be found in Reference 11.

In 1955 the U. S. Army Corps of Engineers constructed an experimental pavement at their test area in Sharonville, Ohio. This was a 4 in. thick overlay type section with the initial compressive stress induced by the *pre-tensioning* of cables longitudinally and transversely to perimeter abutments.

In 1956, as part of a cooperative research project between the U. S. Bureau of Public Roads, the Missouri State Highway Commission, and the University of Missouri, 16 field slabs 25 in. wide and 222 in. long were built, including 5½ and 8-in. depths, dense and air-entrained concrete, and uniformly distributed prestress of 0, 100, 300, and 500 psi. The prestress is maintained constant by spring assemblies and the project is intended for continuing observations of creep and warping under field conditions for different prestress levels. As far as is known, nothing to date has been published on this experimental work.

The only other significant field effort in the United States has been the Jones and Laughlin Steel Co. experimental highway pavement project in Pittsburgh undertaken during 1956 and 1957. This was a 400 ft long, 12 ft wide, and 5 in. thick pavement prestressed longitudinally in such a manner as to produce approximately 450 psi at the slab ends. A complete description of this project was presented at the 37th annual meeting of the Highway Research Board.[12]

CHOICE OF METHODS OF PRESTRESSING

There are two general methods of inducing the necessary initial compressive stress in the concrete of pavement slabs: post-tensioned steel cables; and jacks reacting against abutments of some description. Basically these are techniques used to accomplish the same result and the end products, as Harris points out,[4] should be referred to as "mobile" or "immobile" depending on the degree of freedom from subgrade restraint. There are, of course, advantages and disadvantages inherent in both systems and there are many factors involved when weighing one against the other.

In slabs of the individual type, with expansion joints between slabs, the stress changes due to variations of weather and moisture will not be great unless the distance between joints is excessive. Analytical and experimental studies show that when expansion joint spacing exceeds about 400 ft the stress changes become substantial and the pavement tends to become continuous. This length is an average figure and, as mentioned, is dictated by the restraint to slab movement occasioned by the physical characteristics of the subgrade.

One factor important to consider in selecting a method or technique (in prototype pavement but not necessarily in experimental work) is the comparative difficulty involved in making necessary repairs to the pavement and to utilities which must cross under the prestressed areas. The pavement stressed by jacks may have the advantage on this point.

The problems involved in prestressing pavement on vertical and horizontal curves have been much discussed by investigators. It is apparent that attempts to prestress anything except short sections of curves by either method would be a difficult task.

Probably the largest single factor discussed by investigators in advancing the relative merits of the two general methods of prestressing pavements, apart from the technical considerations, is engineering economics. The cost of abutments versus steel for cables, jacks versus joints, and other cost comparisons have been issues which sometimes appear to govern the choice of methods or techniques.

AGGREGATES AND CEMENTS

Few of the publications describing prestressed pavement work do more than briefly mention the aggregates, cements, and resulting concretes used. It follows, however, from the comments of most authors that the necessity of using high quality concretes composed of sound, dense aggregates (with ordinary or high-early-strength cements) cannot be overemphasized. It is also apparent that water-cement ratios should be kept to a minimum to avoid the possibility of undue loss of prestress due to creep. Compressive strengths at 28 days ranging from 3000 to over 8000 psi have been reported, and moduli of rupture of 300 to over 750 psi have been used.

In some instances high-alumina cement has been used but the only advantage cited lies in the high rate of concrete placing possible.

The records examined fail to indicate the use of accelerators or workability agents apart from some early investigative work in laboratories.

METHODS OF REDUCING SUBGRADE FRICTION

It is important to reduce friction between the pavement slab and the subgrade to a minimum since the restraint to movement of the slab is the major contributing factor in prestress loss, and governs the length which can be used. Much work has been done and is underway on techniques of reducing restraint, and coefficients of friction as low as 0.5 have been obtained in laboratories. On practically every field venture, however, tests have been conducted to determine a coefficient and to define the method to be used for reducing friction on that particular job. These tests generally have taken the form of pull tests on small slabs resting on sand, paper, stone chips, etc., carefully placed. In almost all cases the coefficients thus determined have been appreciably lower than measured in the field slab. This is as expected because on the large jobs laboratory controlled conditions are usually not possible.

Various techniques have been employed, with a sand layer or a sand layer covered with waterproof paper being the most commonly tried. Efforts have been made, however, to use bituminous materials for a sliding layer, but as yet these have not been too successful. A refinement of interest was an attempt to use a thin layer of one particle size sand, with spherical shaped grains acting much like ball bearings. An extensive investigation on possible friction reducing techniques is underway in England's Road Research Laboratory and it is quite probable that similar studies are in progress in research establishments in this country.

LOAD TESTS AND PERFORMANCE RECORDS

The proof of success of any pavement is, of course, the manner in which it sustains the loads imposed and its long term performance. It is apparent from the published reports on prestressed pavement that in all cases the load carrying capacity of this type of pavement has greatly exceeded that of conventional pavement of similar thickness. The records of those pavements which have been in actual service for some time also indicate that performance from the standpoint of maintenance and repairs needed compares favorably with conventional pavement. Load tests, as such, have been conducted for the most part on slabs in or simulating airfield pavements, with some notable exceptions such as the Jones and Laughlin highway slab.

Extensive load tests were made on a test slab at the Orly Aerodrome in 1946 and excellent load-deflection data have been published.[8] Loads in excess of 140 tons were sustained with minor residual deflection on a subgrade with $k = 55$ psi per in. This represents a load carrying capacity nearly ten times that which could be expected on this subgrade with a conventional pavement. Repetitive load tests were made on this pavement also and none of the loadings resulted in distress in the form of permanent cracks.

Load tests were also made on the experimental section of the London Airport and on the full scale work at Maison-Blanche with essentially the same comparisons with conventional pavement being possible.

The U. S. Navy's load tests on the 7-in. pavement at the Patuxent River Naval Air Station were sufficiently extensive to confirm what may be expected of a prestressed slab as far as load carrying capacity is concerned. Plate sizes in these tests ranged from 2 to 20 in. in diameter and loads were imposed on the interior of the slab, at the edges, and at the locations of some shrinkage cracks which developed.

As pointed out by Cholnoky[11] no moment failures occurred under loads of 200,000 lb and there were indications that loads up to 350,000 lb could be sustained without distress. It was concluded from these tests that the prestressed slab had a capacity well beyond what a conventional pavement would have on the same subgrade and that deflections normally considered excessive may be experienced without distress in the pavement structure.

The details of the load tests conducted on the Jones and Laughlin experimental highway slabs are described in Reference 12; the results indicate that this 5 in. thick slab was apparently satisfactory for edge loadings up to 40,000 lb. In other words, there was a tremendously increased load carrying capacity induced by prestressing. The description[12] of this test section contains many details of the instrumentation, quantities measured, and testing procedures which would be of interest to anyone concerned with prestressed pavement.

The 4 in. thick overlay type pavement of the Corps of Engineers was stressed to failure by using dual wheel loads up to 100,000 lb, and the first sign of failure did not occur until after some 3000 passes of this load.

UNIT COSTS

While a number of analyses have been made comparing the cost of prestressed pavement with conventional pavement, it is not possible, at this time, to present significant figures. This is, of course, due to the fact that a large share of the work accomplished to date has been experimental and so the costs are naturally higher for prestressed pavement than might be expected or hoped for. It is apparent, however, that costs will be reduced when certain techniques are perfected to the point where they are more or less commonplace, and when a sufficient number of contractors are experienced enough to create competition. Reports from abroad indicate that in some countries conventional and prestressed pavement differ little in cost of construction, and while it is too early to define maintenance costs over a long period, it is becoming apparent that the prestressed pavement may be more economical to maintain. This, however, cannot be definitely established until more service records are available.

Studies, such as those made by Jones and Laughlin, which include recommendations for possible cost reductions are extremely valuable in effecting a competitive situation in this country between prestressed pavement and what is now considered conventional.

The U. S. Navy's Bureau of Yards and Docks has had engineering studies made in connection with some of their proposed work in which the feasibility of using prestressing has been seriously analyzed and considered. In some cases, the cost differential is slight and it is probable that some prestressed pavement will be used in their airfield construction in the near future.

SUMMARY

After reviewing articles originating in many parts of the world over a 15 year period, there are several points which may be listed as indicative of the present status of prestressed concrete pavement:

1. It is possible to augment sufficiently the strength of concrete in tension by inducing an initial compressive stress that a pavement slab so constructed will have a load bearing capacity many times that of a conventional concrete slab of the same thickness on the same subgrade.

2. The two general methods or techniques by which the concrete may be so strengthened are, namely, through the use of post-tensioned cables or through

the use of hydraulic jacks reacting against abutments. A number of pavement slabs have been constructed with each technique.

3. A number of arrangements of cables have been used, the most common being longitudinal and transverse, but diagonally placed cables have been used in a number of instances as have combinations of cables and jacks.

4. Slabs of both rectangular and triangular shape have been constructed.

5. Thicknesses appear to have been selected with the cable cover considered necessary as the determining factor. In most cases constant thickness sections have been used.

6. Slabs may be "mobile" or "immobile" depending on whether or not they may freely expand. In the former, the prestress remains more or less constant while in the latter, the prestress losses may be substantial because of changes in length due to temperature and moisture variations. In either type it is necessary only to induce sufficient initial compressive stress that regardless of what happens there will be a residual prestress of 200-300 psi—this being an average figure varying with the loads the pavement will be expected to sustain.

7. Restraint to movement of the slab is a function of the friction between subgrade and slab. Friction must be reduced to a minimum if undue losses are to be avoided, a coefficient of 0.5 being suggested as a maximum. This value has been approached using sand or sand and paper as the friction reducing layer. This restraint to movement is the major factor in limiting the length of prestressed slabs and more study on feasible methods of reducing friction is needed.

8. High quality concretes composed of sound, dense aggregates with ordinary or high-early-strength cement should be used. Water-cement ratios should be kept to a minimum to reduce prestress loss due to creep.

9. Prestressed pavement is not yet competitive from a cost standpoint with conventional pavement, but it is becoming so. The cost differential will be reduced as contractors gain experience and techniques are perfected.

10. Few prestressed pavements have been constructed in this country but programs under which this type of construction have been undertaken have been exceptionally well conceived, carried out, and reported. There is little doubt that the experiences of those agencies which have had the programs will stimulate and benefit other investigators in their search for answers to the remaining unsolved problems.

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