Prestressed concrete pavements

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The paper stresses the importance of prestressed concrete pavements in these days of jet and heavy commercial aircraft. The old and new concepts of the failure of prestressed pavements are discussed, and the advantages and disadvantages of prestressed pavements dealt with at length.

Although considerable developments have taken place in the field of prestressed concrete structures such as bridges, building frames, arches etc, its use for highway and airfield pavements has advanced only comparatively recently in the past two decades. The search for a rational method of design of prestressed concrete pavements has been in progress in Europe since 1944, and in the USA since 1952. There have been only very few major prestressed concrete airfield pavements built and brought into service during the past fifteen years.

In so far as is known, little work has been done in this country for the development of a design procedure for prestressed concrete pavements. In view of the trend towards increasing use of heavy aircraft for transporting passengers and goods, and also for military purposes, it would seem that there is a need for more investigation in this field.

The properties of the material are not taken full advantage of in conventional concrete pavements. Since concrete is weak in tension and strong in compression, the tensile stresses due to loads, temperature gradient, subgrade restraint and moisture variations tend to cause transverse cracks in the pavement. These stresses increase as the length of the slab increases, resulting in more cracks and indicating the need for greater thickness of pavement. The pavement, therefore, has to be laid in shorter stretches, and this entails the provision of a larger number of joints which in turn will raise the cost, affect adversely the riding qualities, increase the number of highly stressed points, and lead to more pumping and the ultimate failure of the pavement. These difficulties may be overcome by using either reinforced concrete or prestressed concrete slabs.

Reinforced concrete slabs do not serve to counteract all these faults, but the performance of the pavement is improved to a great extent. The provision of reinforcement puts up the cost considerably, and even then it is not possible to eliminate cracks under heavy wheel loads. Effective compressive stress in pavements, however, might make possible thinner slabs, more effective design, long uncracked slabs, and improved performance.

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Need for prestressed concrete pavements

During the second world war, the necessity of an alternate method of construction for airfield pavements was keenly felt, particularly for carrying the heavier wheel loads due to the increased use of jet and commercial aircraft, and for meeting the adverse climatic and soil conditions in places of strategic importance. This has compelled the airfield designer to take into account new considerations such as heavier gross aircraft weight, higher frequency of operations of individual aircraft, need for longer runways, and the effects of blast and fuel spillage. Prestressed concrete is considered to provide to all these questions a satisfactory solution. Besides, prestressed concrete construction has been proved to be more economical, and makes significant savings in cement and concrete ; these are factors of no mean importance to this country.

Mode of failure under wheel loads

The presence of prestress in the pavement makes it behave like an elasto-plastic material. This, in turn, results in increased load-carrying capacity of the pavement as compared with a design based on elastic theory.

It was at first thought that the only function of prestress was to increase the flexural strength of concrete pavements by the amount of prestress. This concept was studied by means of the well-known method of analysis due to Westergaard. It was assumed that the failure of the pavement would take place when the first crack occurred at the bottom of the pavement due to positive moment from the applied load. Naturally, from an economical point of view, this did not yield much advantage from prestressing. It was only in 1945-46 that small experimental test slabs were built at the Orly airport near Paris, and tested for static loads. These slabs were then found to have a substantially greater load-carrying capacity than what was indicated by computations based on increasing the flexural strength by the amount of prestress and assuming failure when the first crack due to positive moment occurred under the load.

The present-day concept assumes the failure of pre-

When the formwork supporting a beam or slab is removed, it will have to support at least its own weight, and this may result in deflections exceeding those which would occur in a fully matured member under load.

It is desirable to establish an optimum temperature cycle and modify it to suit economic and practical considerations.

Temperatures may be raised in various ways. The production of heat by the chemical action of setting in the cement (possibly accelerated by chemical additives) may be utilised by insulating the formwork and exposed concrete surfaces. The mixing water and aggregates may be pre-heated. Finally, heating may be applied either internally to the concrete or externally to shutters and exposed surfaces.

All these raise the question of the effect of the cooling likely to take place when the formwork is removed and of possible stresses within the concrete due to different temperatures and setting characteristics within the mass of the concrete, (this has long been recognised in the case of large masses of concrete such as occur in dam construction).

Study of aggregates

While, of necessity, a variety of concrete mixes must be investigated, it is important to include also the individual effects of different aggregates such as gravels, crushed granites, etc. With the increase in the use of synthetic, especially lightweight, aggregates, these should be included in the study.

Research sponsored by the Construction Industry Research and Information Association is proceeding on a number of these problems in universities and research establishments but a great deal remains to be done to give firm ground for the design and programming of construction.

In all these activities, the need to ensure that measures taken to solve construction problems do not prejudice the quality of the finished structure, should not be lost sight of.

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Concrete wearing finish

As a wearing finish, concrete has its greatest application for floors in industrial, commercial, and agricultural buildings. Although it is primarily a purely functional flooring material, many applications can also be found where appearance is a primary requirement. The material usually used for this latter purpose is a terrazzo finish in which the surface is ground smooth. A wide variety of colours can be introduced by incorporating coloured cements and marble aggregates. The following notes are taken from a recent issue of the *Financial Times* of London.

Where intensive traffic is likely, whether it be in factories using heavy fork-lift trucks or in commercial premises where the nail-head tips of stiletto heels produce some of the highest stresses experienced in building, it remains true that a well-laid concrete floor can last the life-time of a building with little or no maintenance other than cleaning. Granolithic concrete, which is made with Portland cement and a proportion of crushed granite aggregate, trowelled after laying to produce a hard-wearing finish, will withstand almost all the loads and traffic experienced in industrial work together with a wide range of chemicals, including most solvents, alkalis, and mineral oils.

Other chemicals such as animal fats and vegetable oils which can damage concrete only do so at such a slow rate that the use of such concrete often remains an economic proposition. The range of chemicals which can be withstood can be extended by the use of special cements, such as high alumina cement, particularly where dilute acids are used.

Both granolithic concrete and terrazzo can be laid either in the wet state as an *in situ* material or as precast tiles or slabs. The former has the advantage of being a little cheaper and of being laid to suit the shape of the particular area, whereas the latter makes for easy and rapid replacement in the event of excessive wear or damage. In addition, terrazzo flooring benefits by being laid as tiles because a greater range of colour effects can be obtained in this way.

As with many forms of flooring, good and bad examples of the use of *in situ* concrete can be found. Between the good and the bad, there occur all too many examples of the mediocre floor which is allowed to remain in service. This arises because concrete is a material giving a wide margin for error in its use—a margin which is too often exploited in attempts to reduce costs.

Concrete provides a relatively cheap form of flooring, yet this advantage can be lost through a poor construction which may lead to costly maintenance and loss of production out of all proportion to the cost of the flooring itself.

There is, therefore, a good case to be made for raising standards of design and construction by the equivalent of a few shillings per square yard and thereby reducing maintenance commitments without losing the advantages of concrete as a relatively cheap flooring. Examples can be found of poor concrete floors which lead those concerned into using some of the most expensive surfacings as repair materials when a little more forethought and a slight increase in initial cost would have produced a first-class result in concrete in the first attempt.

Concrete is, of course, an established material, and no major changes in application or technique have occurred in recent years—though several minor extensions of use and improvements have been developed. For example, one of the primary uses of concrete in

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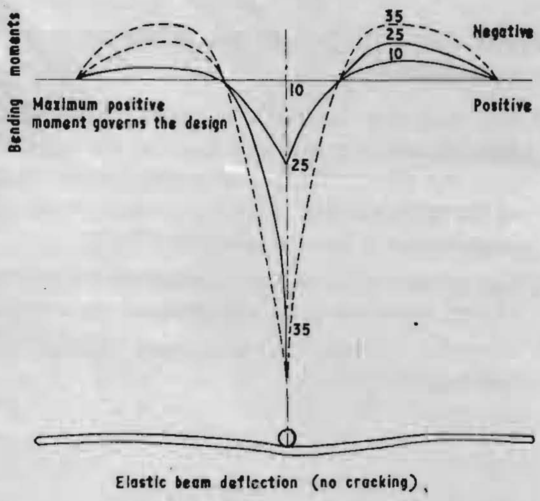

Fig 1 Bending in elastic range

stressed concrete pavement when the first crack appears at the top of the pavement due to negative bending moment, as it is thought that the cracks at the bottom close due to the compressive force of the prestress as the load moves on. As successive increments of loads are applied, the slab deforms elastically to the point at which the stress due to maximum moment beneath the loaded area exceeds the sum of the applied prestress and the flexural strength of concrete. At this point, a crack under the load occurs in the bottom of the slab. This initial bottom cracking acts as a 'partial plastic hinge' (see *Fig* 1).

With the formation of a plastic hinge under the loaded area, the moments in the slab are redistributed so that with further increase in the load there is no increase in the positive bending moment, but a substantial increase in the radial moment some distance away from the loaded area (see *Fig* 2).

The basis of analysis is that tensile cracking occurs in the top of the slab when the maximum negative radial moment is equal in magnitude to the positive moment which produces the initial cracking in the bottom of the slab. The tensile cracking in the bottom surface of the slab produces visible circumferential cracks. When this condition is reached, failure is said to occur. When the loading is increased beyond this point, vertical shear failure occurs and the load punches through the slab. However, if the load is removed before actual punching takes place, the cracks will disappear and the slab will be saved from destruction.

Advantages of prestressed pavements

The advantages of prestressed concrete pavements over the conventional types of pavement are summarised below :

(*i*) In conventional reinforced concrete pavements, permissible stresses for both steel and concrete are limited to only a fraction of what would be reasonable for either material by itself. Even with low steel stresses, concrete cracks in tension zone due to shrinkage and load, before the steel can develop its tensile force.

In prestressed concrete pavements, this incompatibility of the two materials is overcome by stretching the steel to a high stress while it is free to move independently of the concrete and then transferring this force to the concrete by bond or end anchorage. The only limit of stretch is the ultimate strength of each material, and the entire concrete section is made available to resist the load.

(*ii*) Prestressing provides a spring effect which restores continuity in the event of cracking in the slab due to accidental causes such as, for example, extreme thermal stresses, shrinkage or excessive loads. When these stresses are relieved, the cracks disappear completely.

(*iii*) The number of joints is reduced, and this will contribute to savings in the cost of joints, reduction in pumping, improvement in riding quality, and lesser possibility of water entering the subgrade from the surface.

(*iv*) Since prestressed concrete pavements are thinner in section, there will be savings in the cost of materials, and consequent reduction in transport cost of materials. Prestressed concrete pavements have greater flexibility, and therefore, adapt themselves to the uneven conditions of the subgrade without causing any damage.

(*v*) Due to thin sections, the stresses due to temperature gradient are not appreciable.

(*vi*) Due to its reduced self-weight and improved carrying capacity, it can be used over poor subgrades.

(*vii*) The tensile strength of concrete is increased by the amount of prestress.

(*viii*) Thinner pavements can be made to resist the same loads as by thicker plain or reinforced concrete pavements.

(*ix*) The prestress gives the section a higher shear strength.

(*x*) On account of the factors stated in (*ii*) and (*iii*), the maintenance costs will be reduced.

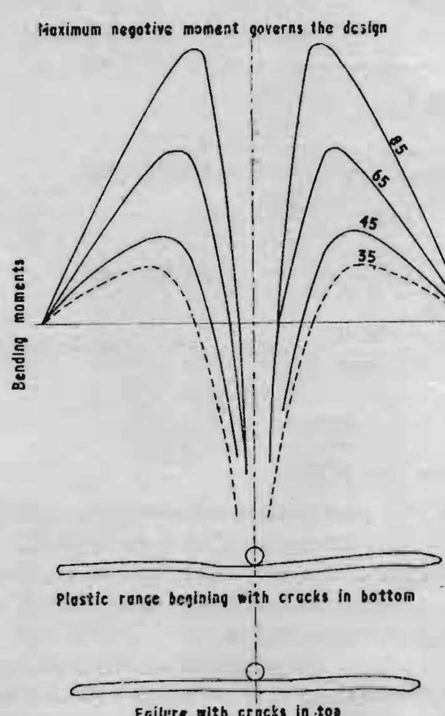

Fig 2 Bending in plastic range

(*xi*) Prestressed slabs are especially suited for airport pavements, since long, smooth, jointless slabs facilitate the take-off and landing of modern jet planes.

(*xii*) In addition, the problem arising out of the materials in the joints getting damaged due to the hot blast from present-day aircraft will be alleviated to a great extent.

Some drawbacks of prestressed concrete pavements

It is necessary to point out that there are certain drawbacks too, associated with prestressed concrete pavements, although they are not of any major import. They are as follows :

(*i*) the difficulty of repairing services beneath the slab, since if a trench is cut across the prestressed slab the whole of the prestressing in the vicinity of the trench is lost ; this is a matter of particular importance in the case of urban roads

(*ii*) the construction of the prestressed slabs require expert supervision by experienced personnel

(*iii*) it poses certain constructional difficulties at bends and curves.

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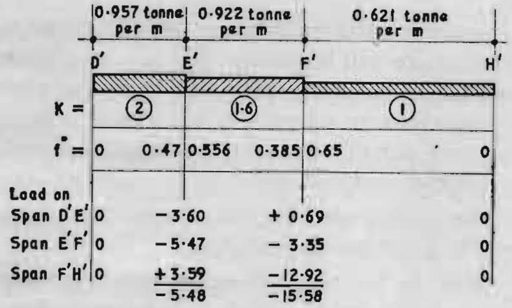

Fig 6 Showing the strips D′E′F′H′ and the results

$$M_{F}' \text{ (right)} = \frac{2 \times 0\cdot65 - 0}{4 - 0} \times \frac{1}{4} \omega_{F'H'} \, L_{F'H'}{}^{2}$$

$$= \frac{78}{960} \omega_{F'H'} \, L_{F'H'}{}^{2}$$

From the graph in *Fig* 1,

$$\alpha_{PQ} = 5 \quad \alpha_{RT} = 5 \quad \alpha_{UV} = 5$$

$$\alpha_{D'E'} = 3\cdot59 \qquad \alpha_{E'F'} = 2\cdot7 \qquad \alpha_{F'H'} = 3\cdot05$$

$$\omega_{D'E'} = \frac{5 \times 1}{5 + \left(\frac{8}{16}\right)^{4} \times 3\cdot59} = 0\cdot957 \text{ t/m}^{2}$$

$$\omega_{E'F'} = \frac{5 \times 1}{5 + \left(\frac{10}{16}\right)^{4} \times 2\cdot7} = 0\cdot922 \text{ t/m}^{2}$$

$$\omega_{F'H'} = \frac{5 \times 1}{5 + 1 \times 3\cdot05} = 0\cdot621 \text{ t/m}^{2}$$

$$M_{E}' \text{ (left)} = \frac{56\cdot4}{960} \times \cdot957 \times 8^{2} = 3\cdot60 \text{ t/m}$$

$$M_{E}' \text{ (right)} = \frac{56\cdot9}{960} \times 0\cdot922 \times 10^{2} = 5\cdot47 \text{ t/m}$$

$$M_{F}' \text{ (left)} = \frac{35\cdot25}{960} \times 0\cdot922 \times 10^{2} = 3\cdot35 \text{ t/m}$$

$$M_{F}' \text{ (right)} = \frac{78}{960} \times 0\cdot621 \times 16^{2} = 12\cdot92 \text{ t/m}$$

The above moments are tabulated in *Fig* 6. The carry-over operations are, M (left) $\times f_{L}°$ divided by 2 to the left of left support moment and M (right) $\times f_{R}°$ divided by 2 to the right of right support moment, changing sign at each carry-over.

Conclusion

The method is perfectly general and is applicable to other types of loading also, if deflection graphs of the nature given in *Fig* 1 are prepared. When there are variations in the slab thicknesses from panel to panel, the actual moment of inertias of the unit width of strips should be computed considering them as beams of varying depths, and the respective stiffness values evaluated.

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floors is in the construction of structural slabs or in screeds as a base for some other type of finish. It has been found that if the structural slab is finished with sufficient care and accuracy the construction of the screed can be omitted altogether.

This has the basic advantage of allowing the omission of one of the wet stages in the construction of a building and of reducing the overall thickness of the floor by some 1½ in. The reduction of thickness can become a significant factor in reducing the height of very tall buildings. This technique can also reduce costs by the omission of the screed, although the more careful, and therefore, more expensive finishing of the main slab reduces this apparent saving.

A broad look at the comprehensive range of flooring materials available today shows many interesting and useful developments, but concrete remains as a basic alternative at perhaps a little over a penny per pound in place, a ridiculously cheap price by any standards.