

4. D. V. Isaacs and L. L. Simon, "Concrete roads and runways". P.I.A.R.C., 10th Congr., Istanbul, 1955. Section 1, Question 1A.
5. J. P. Stott, "Prestressed concrete roads". Proc. Instn Civ. Engrs, Pt II, vol. 4, p. 491 (Oct. 1955).
6. A. Paduart, "Pistes d'envol en béton précontraint". Bull. Tech. A.I. Br. No. 2, 1948.
7. "Prestressed concrete runway on London Airport". Concr. & Constr. Engng, vol. 47, 1952, p. 36.
8. C. van der Veen, "Loading tests on concrete slabs at Schiphol Airport". Proc. 3rd Int. Congr. Soil Mech. Fndn Engng, Part II, p. 133.
9. Various authors, "Nouveaux revêtements en béton précontraint". Travaux, vol. 39, June-July 1955.
10. Cot, Becker, and Lorin, "Détermination de la force portante des pistes d'aérodromes". Travaux, vol. 39, Nov. 1955.

CONVERSION FACTORS

1 in.	= 2.54 cm	1 cm	= 0.394 in.
1 ft	= 30.5 cm.	1 m	= 3.281 ft
1 yd	= 0.91 m		= 1.094 yd
1 sq. yd	= 0.84 sq. m	1 sq. m	= 1.196 sq. yd
1 lb	= 0.46 kg	1 kg	= 2.205 lb.
1 ton	= 1,010 kg	1 kg/sq. cm	= 14.2 lb/sq. in.
1 lb/sq. in.	= 0.07 kg/sq. cm	1 kg/sq. cm/cm	= 36 lb/sq. in/in.
1 lb/sq. in/in.	= 0.028 kg/sq. cm/cm	1 guilder	} = 2s. approx.
		1 Dutch florin	
		1 guilder/sq. m	= 1.82s./sq. yd

The Paper, which was received on 9 August, 1956, is accompanied by three photographs and twelve sheets of diagrams, from which the half-tone page plates and the Figures in the text have been prepared.

CORRESPONDENCE on this Paper should be forwarded to reach the Institution before 15 January, 1957. Contributions should be limited to about 1,200 words.—SEC.

Discussion

The Author introduced the Paper with the aid of a series of lantern slides.

The Chairman, opening the discussion, referred to the French estimate (§ 41(a)) that the 1946 prestressed runway at Orly had cost about 40% more than the conventional type. When visiting Orly in 1946 or 1947 the Chairman, however, had been given to understand that the cost had been about the same as that of the conventional type of runway. It had been partly to test that that the prestressed section of taxiway had been constructed under his direction at London Airport. It was true that at London the cost had been very much greater than that of the conventional type of track, largely because of the necessity for two massive abutments, which formed a very large part of the construction in a length of 360 ft. For a prestressed runway the cost of the two abutments would have been spread over a length of 1,500 ft or more.

94. More important than the cost comparison was the time factor. At London Airport it had taken as long (9 months) to construct the short length of taxiway as it would have

done to construct a whole runway by conventional methods. It was true that that period had included the time for preparation of the cables and building the abutments—again a common factor in a long or short pavement; but still the time factor seemed to rule out the possibility of ever considering that form of construction in the future. It had been very interesting, therefore, to learn of the further developments which had taken place at Orly in 1953 and at Maison Blanche, where mechanical methods of concrete laying had shown the meticulous care previously taken with small slabs to be unnecessary. He welcomed that development.

95. Would the Author comment on what would happen if discontinuities were introduced into a prestressed runway? At modern airports it was frequently necessary to cut into the concrete for the construction of various service trenches. Moreover, runways might be required in time of war to withstand attack by bombing. What would happen to a prestressed runway if it were seriously damaged by a bomb? Would it collapse? Could reinstatement be effected by filling up the bomb hole with concrete, or would the runway be put out of use?

Mr J. M. Watson (Superintending Civil Engineer, Air Ministry) said that one of the most interesting points about prestressed runways, if they could be made economic, was that transverse joints could be avoided almost entirely. At Maison Blanche there was a discontinuity only every 300 ft of the runway length, where intermediate jacks had been put in for stressing immediately after construction. It did not matter how small was the discontinuity at the joint; what mattered was that regularly spaced joints induced sympathetic vibrations in the vehicle passing over them, parts of which might become resonant. Resonance in the instrument panel of an aircraft, for example, could be very serious.

97. The increasing weight of aircraft was leading to the need for concrete thicknesses of the order of 15, 18, or 20 in. for normal methods of design and the prestressed concrete runway now had a chance of becoming economic. If it could be made to have the same strength with a thickness of only 6 or 7 in., there would be a big margin before it became uneconomic.

98. Referring to § 19, what was the area over which the 84·5-ton load was imposed on the test slab at Turin?

99. In § 26 (b) the Author had pointed out that a “falling-off of the value of the prestress from the edges of a slab towards its middle must be allowed for.” The alternative was designed so that it did not occur. That had been attempted in the most recent experiment, which was still in progress and to which the Author had referred in § 72.

100. Would the Author enlarge on the statement in § 34 (a) that “The reversibility of a fraction of creep strain on release of stress has been observed”? At Orly, according to § 36 the runway constructed in 1946 “was required to support a service load of 85 tons on a circle of 2 ft 9 in. dia., giving 230 lb/sq. in. tire pressure.” Presumably it was a loading plate pressure not a tire pressure; and that, of course, was to be compared with the ICAO Class I loading of 45 tons.

101. According to § 40 (c) a test load of 100 tons had resulted in a deflexion of 0·41 in. without any detectable cracking on the upper surface. Upon removal of that load the runway had recovered, but what had happened to the subgrade? To what extent had the pavement at Orly been loaded by heavy aircraft in the past 10 years?

102. The section of prestressed taxi-track at London Airport had first been tested with a 60-ton roller, and readings taken with an ordinary engineer's level. They had indicated that the deflexions were not measurable more than 10 ft away from the load. After that, plate loading tests had been made on 15-, 18-, 24-, 30-, and 36-in. plates, up to a deflexion of 0·15 in.; the maximum load applied had been 65 tons. There had been an almost straight-line relationship in the latter half of the deflexion curves up to the maximum deflexion measured. One half of the taxiway had been constructed on compacted brick-earth and the other half on an 8-in. layer of compacted gravel on brick-earth. Fig. 16 showed the deflexions plotted against load for the various sizes of plate on the brick-earth

section. On the section with 8 in. of gravel sub-base a load of about 10% greater had been required to give the same deflexions. For comparison purposes, the heaviest civil aircraft which were coming into service, the Boeing 707 and the DC8, came at the points marked A and B on the curve, and the Britannia at about point C. The ICAO Class 1 loading was at about point D, i.e. 100,000 lb. at 120 lb/sq. in. tire pressure, which corresponded to a deflexion of about 0.09 in. The strength of that pavement was therefore considerably above present-day civil requirements, and he believed that it had considerable strength in hand.

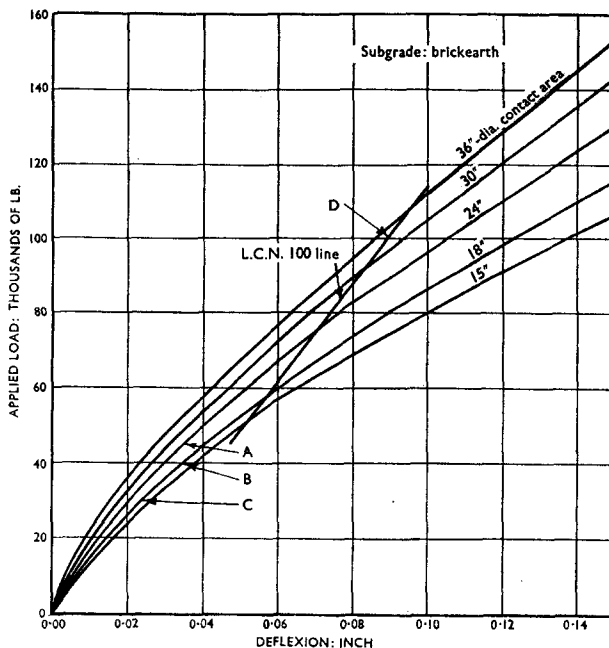


FIG. 16.—RELATION BETWEEN LOAD AND DEFLECTION FOR VARIOUS CONTACT AREAS

103. Would the Author say more about the subgrade at Maison Blanche? In § 68 it was stated that the base had been laid in three 4-in. layers, of which the middle one had been graded to act as a drain. It seemed odd, on the face of it, to conduct water under the surface of the runway, and the purpose of the drain was not clear.

Dr P. B. Morice (Head of the Structures Department of the Research and Development Division, Cement and Concrete Association) described a proposal put forward by Dr Williams of the Ministry of Supply. Although it had not yet been applied in practice it had interested Dr Morice for some time. The principle was to overcome subgrade-support unknowns, particularly in the case of poor subgrades, by inserting between the prestressed concrete runway and the subgrade a continuous system of individual water-bags extending over the whole area of the runway (see Fig. 17). Such a scheme had the theoretical advantage of providing a defined state of loading to the pavement because, owing to the relative incompressibility of water and the flexibility of the pavement, the supporting pressure of the pavement and the applied pressure on the subgrade very

nearly equalled W/A where W was the applied load and A was the area of the water-bag under the load. The ground pressure could therefore be adjusted to suit the conditions by adjusting the size of the water-bags. It had also been calculated that a 100-ton aeroplane could be carried on an 8-in. slab with 20-ft-square water-bags. Another advantage would appear to be that there would be the minimum subgrade preparation because small errors would be unimportant, also subgrade settlement could be taken care of by occasional interconnection of the pressures in the water-bags. In respect of prestressed concrete construction there would be a minimum of friction to straining movement of the runway.

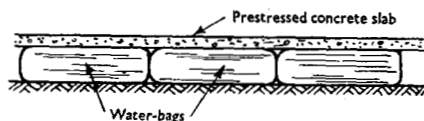


FIG. 17

105. On the other hand, water-bags, presumably of rubber, would be somewhat expensive, and their guaranteed life, even in the dark and without contact with air, could not be more than about 30 years.

106. Dr Williams had made a model using wooden slabs and had carried out tests by applying a 1,000-lb. load. The structure had shown very considerable stiffness, and stresses and deflexions had agreed closely with theoretical predictions. The model had been constructed from individual slabs on each water-bag connected with shear-carrying joints. It had been estimated that a full-size runway of that form would carry 100 tons, under which the deflexion would be about $\frac{1}{2}$ in. In the case of full-size structures gravity forces provided a valuable contribution to stiffness.

107. A structure of that type, with very small inherent damping, might be expected to be excited into natural frequency oscillations by aircraft movements.

108. Practical calculations indicated a critical speed of about 5 m.p.h. and presumably it would be possible to avoid lingering in that speed range.

109. It had been said that it was important to be able to cut holes in a runway. Dr Morice had evolved two methods by which that might be done. One method involved prestressing a system of individual slabs in pairs by overlapping prestressing cables by one slab length in alternate bays. Release of any one slab could then be accomplished by releasing selected cables in the eight surrounding slabs.

110. An alternative method was to provide a shear joint only, between slabs, by means of steel tongues cast into the slab, the joint being formed by bolted connexions.

111. Full-scale tests on those two jointing methods had indicated that the required shear strength of 10 tons/ft could easily be achieved by both methods.

Dr J. P. Stott (Senior Scientific Officer, Special Problems Section, Road Research Laboratory) referred to the lack of experience of tests similar to those described in the Paper—involving repetitions of loads stationary in one place as compared with moving loads—and he wondered what was the significance of a deflexion as large as 0.41 in.

113. The method of prestressing by flat jacks would arouse enthusiasm in anyone concerned with the design of prestressed concrete runways. The biggest difficulty of prestressing a large area by cables was the inclusion of the cables, especially since prestress was necessary in two directions so that some cables must run through the formwork. The use of flat jacks to apply prestress in one direction greatly reduced that difficulty and had many other advantages. The idea would take time to gain general confidence because, Dr Stott imagined, most people would think that there were increased possibilities of slabs buckling if prestressed by flat jacks. Although calculations were purported to

show that the slabs would not buckle or suffer other detriments, it seemed wise to wait and to see how the French runways at Orly and Maison Blanche performed.

114. Dr Stott then commented on the magnitude of subgrade restraint, especially over a long term, and the consequential possibility of initially uneven prestress in a slab evening-out with time. He had been interested to see the values given in § 60 (c) and derived from Orly in 1953. Those values lay between 1.0 and 1.7. They agreed well with values obtained in Britain for prestressed concrete roads. He wished to know if, together with those values, the Author would still put forward the value of 0.2 reported to have been obtained at Orly in 1946 and mentioned in § 40 (a). That value, Dr Stott thought, had led to several prestressed concrete roads in Britain being under-designed. The Author had proposed that an initially high value of subgrade restraint would gradually diminish to zero. Dr Stott would be interested to see data supporting that proposal. He had carried out tests in which a slab was pulled by machinery over a sliding layer of sand. The pulling effort, applied through a proving ring, had been arrested for 18 hours and in that time a 10% reduction of force had occurred. During a similar test with a sliding layer of bitumen, the pulling force had fallen to zero. He thought that subgrade restraint due to a sliding layer of sand might decrease in time to a limiting value but not to zero.

115. The Author had suggested that concrete which was cured under an applied compression would acquire an increased tensile strength, and there was reference in § 15 (b) to some relevant publication about which Dr Stott wished to have details. Dr Stott had carried out two tests with plain concrete columns which had first been cured for 3 days in water and had then been maintained for a week under a compressive stress of 1,000 lb/sq. in., one being contained in a water jacket and the other painted with bitumen. They had then been tested to failure in bending and their strengths compared with those of similar columns which had not been maintained under compression during the curing period. There had been no significant difference between the tensile strengths.

116. After reading what the Paper said about pavements at Orly and Maison Blanche, Dr Stott thought that more information about their present condition would be valuable. He understood that the runway at Orly was cracked on the west side and he would like to see a plan of the runway with the cracks shown. Also, he would like to know whether or not there were any cracks at Maison Blanche.

117. In § 16 the Author had postulated that in the ultimate phase of loading a prestressed concrete slab it might act like a dome, at which stage the prestress would be increased at the expense of tension in the surrounding concrete. Dr Stott was unable to visualize such a dome and thought the Author must mean an inverted dome, in which case there would be no increase in prestress but an increase in tension all round.

118. He had some comments to make on what was called the "elastic abutment," which had been used at Orly and Maison Blanche. The "elastic abutment" was designed to yield to the movements of a slab caused by temperature (etc.) changes, while maintaining an approximately constant thrust against the end of the slab. The purpose of that arrangement was to limit the thrust experienced by the abutment, and hence the necessary size of the abutment, to some maximum value. By comparison, a rigid abutment would experience varying thrusts according to the conditions of temperature (etc.) restraint in the slab and the thrust in hot wet weather would be considerable. The point he wished to make was that an elastic abutment should exert a thrust at least as great as the average between the maximum and minimum thrusts experienced in the slab. Otherwise, the prestress might fall below the designed minimum and the slab might even contain a zone of tension. A usual condition of design was that there should be a minimum thrust, and hence prestress, in the slab under all conditions.

119. The changes in the stresses which he thought would cause that state of affairs were illustrated in Fig. 18. The line A-B represented the stress due to the elastic abutment, the line A-C-D represented the stresses in the slab following a rise in temperature, and the line A-E-F-G represented the stresses after a fall in temperature. Now, the stress at any point along the slab and at any time depended upon conditions such as the initial stress, relative temperature, etc., and upon any change of strain due to movements of the slab.

Considering the stress-line A-C-D, the stress C-D due to a temperature increase was greater than that exerted at A by the elastic abutment. The elastic abutment would therefore yield. That would allow the slab to move between A and C until the difference in stresses would be balanced by subgrade restraint, and there would be a loss of strain between A and C. Considering the stress-line A-E-F-G after a fall in temperature, the stresses between A-C would fall to a parallel line passing through E-F, i.e., lower than the "locked" stresses F-G because of the loss of strain. The thrust of the "elastic abutment" would tend to restore the loss, but subgrade restraint would now act in the reverse direction so that the final stress-line would be A-E-F-G.

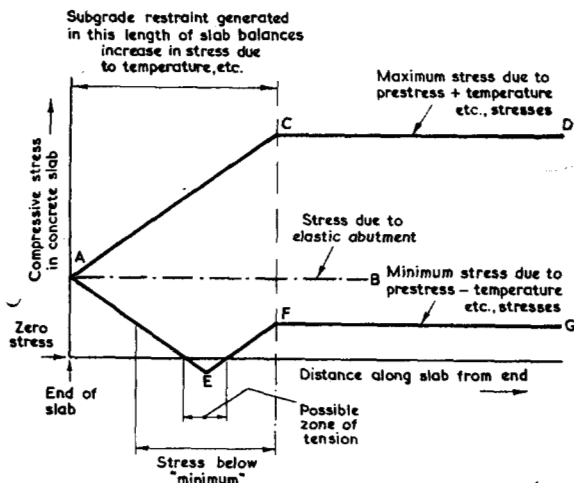


FIG. 18.—STRESSES IN A CONCRETE SLAB, PRESTRESSED BY JACKS AGAINST AN ELASTIC ABUTMENT

Mr D. R. Sharp (Head of the Roads Division, Cement and Concrete Association) referred to the Patuxent River Naval Air Station, where, he believed, had been laid the only prestressed slab of the kind under discussion so far constructed in America. Constructed in the summer of 1953, it was 500 ft long, 12 ft wide, and 7 in. thick. It had twenty-three seven-wire longitudinal cables, each of 0.6 in. dia. Transverse prestressing using the same cables had been provided, but only at three selected points where test instruments had been concentrated. The longitudinal cables had been installed at two levels, both near the centre of the slab, and each set had been stressed independently to produce compressive stresses in excess of 300 lb/sq. in. The two sets had been used independently and in combination during the tests.

121. The sub-base was 2 ft deep and composed of sand, clay, and gravel; upon it had been placed a 4-in. layer of sand and clay, and upon that again a 1-in. layer of sand covered with building paper. That construction, of the four which had been tried, had produced the lowest frictional restraint. The concrete used had an average flexural strength of 805 lb/sq. in. and a compressive strength of 5,200 lb/sq. in., both at 28 days; i.e., the concrete was good but not exceptional. The cables were hot-galvanized and wrapped in a plastic material.

122. After extensive testing, the Americans had arrived at the following conclusions, which were believed to be applicable to future design. First, there had been no practical difficulties to indicate that such a prestressed concrete runway would not be competitive with conventional methods. Secondly, the losses after prestressing had not been excessive,

and it had been estimated that for that type of slab they would not exceed 10%. The efficient development of the prestressing forces depended primarily, of course, on the effectiveness of the friction-reducing layer under the slab. For the method used, a friction coefficient of 0.5 had been attained, which was commendably low, but it was thought that that could be achieved in practice in the field.

123. Thirdly, it had been shown that repeated prestressing was beneficial in developing the prestressing loads uniformly along the entire length of the slab. Fourthly, load tests had proved that the slab had a load-carrying capacity well beyond normal design practice. As would be expected, deflexions had been introduced which were unacceptable so far as the subgrade was concerned but which were not detrimental to the slab. They could achieve no moment failure at intermediate points with loads up to 90 tons, and it was considered that the slab would resist loads up to 150 tons. It had been concluded that for the future a minimum prestress of 100 lb/sq. in. should be provided in the slab in addition to the stresses which might be dissipated by base friction.

124. Finally, some tests had been carried out on the slab to investigate the effect of blast from jet engines, and it had been concluded that no damage to tendons would be caused by the temperatures reached.

125. Those conclusions were not spectacular, but they showed that the Americans had come to conclusions similar to those of engineers on the Continent who had done the same type of work.

126. Recent Papers presented to the Institution indicated that there was now available a great deal of experience of prestressed concrete and its application to roads and airfields; in Mr Sharp's view the problems to be overcome now were practical and not theoretical. One intriguing reference in the present Paper was to a 2½-in.-thick test slab in Australia, constructed in 1954. When considering slabs of that type, the idea of placing the prestressing cables outside the slab became attractive. There were difficulties in placing cables accurately in thin slabs in situ. When placing thin slabs of that type, extreme accuracy of formation was necessary in order to obtain a reasonable riding surface. Experience on concrete road construction had shown that, using subgrade planing and compacting machinery, formation accuracies of the order of $\frac{1}{8}$ in. in 10 ft could be achieved. Those machines were very often adaptations of orthodox concrete-finishing machines, and were extensively used on the Continent and in the United States of America. What were the Author's views on how a prestressed slab, 2 to 3 in. thick, might be constructed, how it might be stressed, and how it might be expected to behave under load?

127. The Author had classified prestressed runway construction into mobile and immobile types. In the mobile type, every attempt was made to free the slab from restraint, to obtain minimum variation in prestress along the length of the slab. The Author had listed the implications following from that requirement, the most important of which referred to joints. If slabs were free to move, and if long slabs were involved, the movement at joints was going to be considerable. That had more application, perhaps, to road work than to airfields. The design of a cheap and efficient joint to cope with large movements presented many problems and Mr Sharp felt that the immobile type of pavement showed the greater promise. If prestressed concrete pavements were to be advantageous they would have to show a considerable advance on present-day orthodox reinforced concrete techniques. It was now possible to construct reinforced concrete slabs 300 ft in length, which were perfectly sound in every way.

Professor A. D. Ross (Professor of Civil Engineering, King's College, University of London) remarked that the Author required no champion to rescue him in the discussion, but he wished to refer to the question of recovery and creep which had been mentioned by Mr Watson. That was an interesting matter which Professor Ross also regarded as important. Fig. 19 showed the familiar type of strain/time diagram (excluding shrinkage) which was obtained when concrete was subjected to a constant sustained stress. If, after say some months, the stress was removed (for thermal or other reasons), there was an elastic recovery, followed by a time recovery. The question was how did the time recovery

compare with the creep? There was a good deal of evidence to show that if the concrete was loaded early in life the time recovery was small compared with the creep and would not therefore be a very significant factor in retaining the stress; but if the concrete was loaded at a mature age, then the recovery, although never complete, was a larger proportion of the creep and could be of some importance.

129. Dr Morice had put forward a suggestion and Professor Ross hesitated to add a further one, but in the discussion some concern had been expressed about creep and

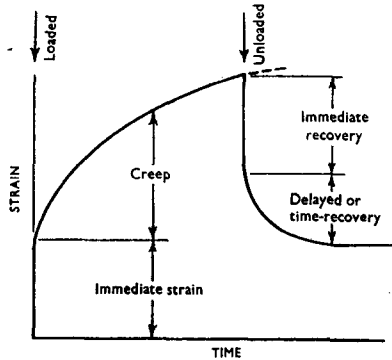


FIG. 19

shrinkage and the resulting loss of stress. Indeed, Dr Stott had mentioned that unwanted regions of tension might occur and the Author had referred to the need for "topping up" the stress over a period of time. On the other hand, if the weather were warm and wet the maximum stress would be obtained, and other speakers had been anxious about the possibility of a "blow up" or instability at the jack under those conditions. It seemed that the slab might often suffer from either too much or too little stress.

130. Would it not be possible to get rid of all those doubts and anxieties by retaining a permanent hydraulic pressure in the flat jacks? A number of jacks could be connected to a common source of pressure by a pipe which could be of quite small diameter and it would not be difficult to maintain a controlled pressure over a long period. That would mean that a mile or more of pavement could be stressed in one operation, and for ever afterwards one could be sure of the actual stresses. Professor Ross disregarded for the moment the effects of subgrade friction, which would, of course, modify the stress at points remote from the jack. With positive control assured under all conditions one could be content with quite a modest stress. After the lapse of some years, when creep and shrinkage were virtually finished and when there had been ample time to observe the actual behaviour of the runway, the joints could be permanently filled. One answer which the Author might make to that suggestion would be that the flat jack was not suitable for reversals of movement, and that might be a very serious objection to it; but it should not be impossible to design a jack which could be used in that way and the advantages seemed to encourage such a development.

Mr F. N. Sparkes (Head of Technical Services Division, Road Research Laboratory, D.S.I.R.) said he had been surprised by a remark made by the Author when introducing the Paper. In mentioning tests which had been carried out to estimate the stress in the concrete, the Author had referred to stresses of the order of 850 lb/sq. in.—presumably the reference was to measured strains from which the stresses had been calculated—and had

then said that against that stress of 850 lb/sq. in. a prestress of 200 lb/sq. in. or so was not of much significance.

132. It seemed to Mr Sparkes that if there was a tensile stress of the order of 850 lb/sq. in. in the concrete and it had not cracked, then it must be very near cracking, and the effect of deducting, by prestressing, about 200 lb/sq. in. might make all the difference between failure and success. He would have thought that the value of that prestress would be higher when there were fairly high tensile stresses in the concrete than when those were low ones. Perhaps, however, he had misunderstood the Author's remarks.

133. Fig. 11 showed the deflexions plotted against the number of applications of load. How had those tests been carried out? It seemed to him that the slope of the straight line would depend on the rate at which the repetitive loads were applied. If the loads were applied very rapidly there would tend to be, he thought, a steeper slope than if the repetitions were applied very slowly. Concrete had the ability to recover between applications of load, and the extent to which it recovered presumably depended on the intervals between applications, that was, on the frequency. Could the Author give any information on the effect of the frequency of the repetitions on the slope of the curve. It seemed to him that in applying laboratory tests or field tests on a runway slab, the application of the load at frequent intervals might have very little relation to the way in which the loads were applied to a runway slab in service. Were the results of such tests of any value in trying to assess the performance of a runway slab under the conditions of comparatively infrequent loadings on any one point which would presumably apply in practice?

Mr A. Goldstein (Partner, Messrs R. Travers Morgan and Partners, Consulting Engineers, London) referring to the tension of 850 lb/sq. in. mentioned by Mr Sparkes, assumed that although stresses were given it was in fact strains which had been measured. Did the Author really believe that that 850-lb/sq. in. alleged tensile stress, interpreted from some strain, was in fact the stress in the concrete? The Author had implied that there was some foundation for believing that there might be sufficient tensile creep to promote tensile strain without necessarily causing stress. In that connexion, would he say how quickly the test loads had been applied, because clearly the time of application of those loads would to a large extent answer the question of whether such a strain without stress could take place? Mr Goldstein thought that the doubt as to whether the real stresses were the same as those calculated from observed high tensile strains applied particularly to the type of test in question.

Mr E. Becker (Ingénieur des Ponts et Chaussées, Aéroport de Paris) stated that the problem of pavings to support very heavy aircraft had now been solved, both technically and economically as was shown by the construction of the Maison Blanche runway.

136. The appearance of transverse tracks in the trial taxiway at Orly had been due to insufficient longitudinal prestress, the magnitude of which had been chosen as a result of deliberately optimistic hypotheses as to the amplitude of thermohygro-metric variations. Besides which, the delicate problem of the mutual longitudinal reactions of paving and ground had still not been entirely solved and it was therefore wise to work to a safety margin when constructing permanent works.

137. With frost-sensitive ground, a sub-base of thickness appropriate to local conditions should be provided using material stable under the action of frost.

138. The calculation of prestressed concrete pavings was based on currently accepted hypotheses as to the behaviour of the ground and the distribution of the load over the neutral plane of the slab; those hypotheses were moreover verified by the close agreement between calculated and observed values of both deflexions and stresses.

139. Prestressed concrete behaved extremely well under repeated loads, even when the deflexions were very large.

140. An experimental length of 1,500 m of prestressed concrete road was now being designed; its thickness would be about 10 cm. It would be constructed in the spring of 1957 and preliminary tests would be made during the winter of 1957. That would permit the solving of the problem of runways for aircraft of less than 100 tons weight.

The Author, in reply, said the Chairman had referred to the cost of the first runway at Orly. The Author had heard many conflicting views on the matter but he thought the best testimony to its cost was the fact that it had never been repeated. When, 6 years later, the engineers at Orly had found that it had behaved well and required no maintenance whatever, and in consequence were convinced that prestressed runways were sound and worth developing, they chose a totally different method of construction. Action in such matters spoke louder than words.

142. The Chairman had also mentioned damage to runways, and first of all by trenches. The problem of digging a trench through a prestressed concrete runway was the same problem as underpinning a wall and could be tackled in the same manner. It was a question of digging the hole in short lengths, leaving a piece to carry the load, and re-establishing a state of stress with jacks before finishing the job. The question of the effect of bombing could be answered by another question: which bomb? Weapons were now available which were capable of completely devastating an area far greater than that of a runway. The question of how big a bomb would in fact be used on a runway was a matter of military appreciation and as such was outside the Author's competence. All that could usefully be said, perhaps, was that, with grouted cables, very large holes could be made in a pavement without inducing overall collapse. The problem was again similar to that of underpinning; the runway acted as a wall loaded in two dimensions and lying on its side.

143. In reply to Mr Watson, the loading plate at Turin was 28 cm square.

144. The reversibility of creep strain had been very well dealt with by Professor Ross, but there was a further feature which Freyssinet had postulated. It was that when a compressive stress was applied over a long period to a piece of concrete, appreciable quantities of interstitial water were driven off. On releasing the stress, according to Freyssinet, there was only a partial replacement of that interstitial water, but the reversibility of the creep would be even more marked if it were possible to ensure that the concrete returned to the state of interstitial water in which it found itself at the start.

145. One of the more significant features of the American runway which Mr Sharp had described—the account of which had been published after the date of submission of the present Paper—was of interest in comparing loadings. It was that the full load of 100,000 lb. had been applied to a contact area of 2 in. dia. and had not produced a failure. A 2-in.-dia. contact area meant a contact pressure of about 30,000 lb/sq. in. The concrete had been indented by $\frac{1}{8}$ in. in consequence, but no cracks had been observed, top or bottom. There had been other intermediate values of the contact area, one or two of 8 in. and one or two of 6 in. It seemed, therefore, that even those extremely intense applications of load produced no distress whatever.

146. Mr Watson had asked what became of the subgrade when the deflexion was 0.41 in. The Author wished he knew. All he could say was that such deflexions had been applied several thousand times without any noticeable deterioration of the pavement (see Fig. 11). Such a test, moreover, was singularly unfavourable in that if the load was repeatedly applied to one point all the compaction of the subgrade occurred at the same place and bending was exaggerated in consequence. Since most runways were made for aircraft to run over them, that type of load did not normally occur at all. There might well be a limiting deflexion of a prestressed runway, but what it was, or whether slab, subgrade, or practical functioning imposed the limitation, was not yet known; there again was encountered the awkward fact that no failure had yet occurred.

147. He would like to mention another feature of the American tests which Mr Sharp had called to his attention, namely that in their own particular subgrade—one could not assume that it was typical—the coefficient of subgrade reaction increased with compaction.

148. The Orly 46 runway formed part of one of the main landing and take-off tracks and had thus been subjected to about 10 years' use by normal inter-continental commercial aircraft.

149. The draining layer of the subgrade at the Maison Blanche runway was formed to a side slope of approximately 1 in 5 for 20 ft in from the edges of the runway and discharged

into a drain. There was thus no question of its leading water under the runway. The purpose of that layer was threefold:

- (a) To drain away water condensing on the lower surface of the slab.
- (b) To prevent wetting of the sub-base by capillary effects.
- (c) To drain away water penetrating through the pavement.

150. The engineers responsible for the work had said that that draining course had been conceived with a classic concrete runway in view; they were aware that it could have been omitted with a prestressed pavement but it had been kept in the scheme as a measure of precaution because of the extreme sensitivity of the sub-base to moisture.

151. It was difficult to see any attraction, theoretical or practical, in the water-bag scheme described by Dr Morice. The following criticisms sprang immediately to the mind.

(a) A uniformly distributed hydrostatic reaction would in general produce much higher bending moments in a slab than were produced by the reaction of a typical foundation, where the reaction increased with deflexion and was concentrated under the load.

(b) The figure of W/L^2 for the hydrostatic reaction was exact only if the side walls of the bag were rigid.

(c) Could one rely for the safety of a runway on buried rubber bags, subjected permanently to load and impossible to maintain or replace?

152. The other two ideas described by Dr Morice were, in the Author's opinion, of no value.

153. Dr Stott was surely aware that the very low figures of subgrade restraint found in certain runways (notably Orly 46 and Schiphol) were not guesswork; those figures were deductions from strain measurements. They differed from the figures found by Dr Stott himself, but were not less valid. The following factors might help bridge the gap:

(a) Dr Stott's tests had been made on a small slab of concrete sliding on a sand bed reposing on a *concrete* subgrade; his readings therefore related to the friction of the sand bed. But if the sand bed was to impose any horizontal restraint on the slab, the reaction would have to be supported by the subgrade, in which stresses would thus be set up. Where shear strength of the subgrade was low, shear failure would occur, giving rise to sliding in the subgrade itself; that sliding might well be viscous and restraint might thus decrease with time. In fact, Dr Stott's figures related to only part of the problem.

(b) Dr Stott's measurements, both on his test slab and on the roads which he had investigated, related to unidirectional movement; in a pavement of the size of an aircraft runway, transverse movements might become appreciable. Now friction acted in the direction of the resultant movement; in a runway stressed longitudinally, a slight transverse strain might cause a large change in direction of frictional forces and a consequent reduction of longitudinal restraint. (That was the phenomenon apparent when twisting a cork to facilitate its extraction from a bottle.) It was possible, indeed, that a series of such changes of direction of movement might lead to a final restraint which was very small; that might be in part the explanation of the fact that at Orly 53 and at Maison Blanche, a high initial restraint had fallen after a few weeks to almost zero. That fact was known as a result of direct measurement of forces acting at the ends of a 100-m segment.

154. The proposition that concrete cured under compression acquired a higher tensile strength was an inference from the fact that tests on prestressed beams in the early days of prestressing had invariably shown a higher cracking load than the strength of a flexural test piece would lead one to expect. That proposition was by no means the only possible explanation of the facts (see "Prestressed concrete" by Guyon, chapters 16 and 17) and Dr Stott's experiments, which tackled the question directly, were thus of great interest.

155. The term "free end" was applied to the extremity of the runway in contact with

an elastic abutment since in fact the nearly constant force exerted by the abutment imposed very little restraint on the movement of that extremity.

156. Dr Stott's analysis of the effect of the elastic abutment on stress in the slab with varying weather was exact except in so far as the effect of time on subgrade restraint had been omitted. It had been seen that that effect was important; the word used in the Paper for the problem posed by it was "inextricable". Alas! the word had to remain. In fact at both Orly and Maison Blanche the abutment thrust was fixed at the estimated mean value; that represented a concrete stress of, in the former case, 470 lb/sq. in. and in the latter 750 lb/sq. in.

157. The cracks at Orly 53 occurred just west of centre, i.e., in the part first cast, in which trouble had been found with shrinkage cracks. Those cracks, as noted in the Paper, closed up again as soon as the temperature rose above freezing point.

158. No cracks had occurred at Maison Blanche.

159. Fig. 20 indicated what the Author meant by a dome when speaking of behaviour at rupture. The ring thrust of the dome would obviously be supported by the surrounding concrete whose tensile strength would be augmented by the prestress.

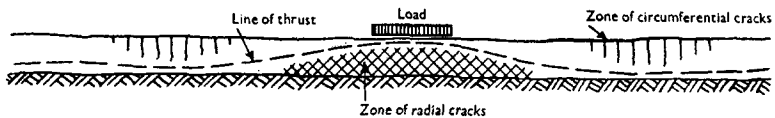


FIG. 20

160. It was rather depressing to find a member of a research organization ready to wait and see if the products of the admirable enterprise of French engineers should buckle. Suppose they never buckled? How much time should one be prepared to waste?

161. Professor Ross had raised the question of maintaining a permanent prestress in a runway by hydraulic pressure. When the Author was in France working on the construction of the Orly 46 runway, Freyssinet had been very keen on that idea. Flat jacks were no good because the repeated movement was enough to work-harden the steel, and it fractured. There were, the Author thought, no materials available at the moment which would be both sufficiently flexible and sufficiently strong. Moreover, the flat jack when filled with liquid constituted a hinge and would in consequence be a severe weakness in the slab. Once it had been filled with grout or resin or something which set, it was truly monolithic, but while filled with a fluid it was an articulation. The answer would be some cheap sort of jack, but it was very difficult to find a jack which was both cheap and satisfactory in function. Freyssinet had investigated the problem thoroughly and had even produced a design with a device for automatically regulating the pressure, but the cost of the jacks had been enough to kill the idea.

162. Mr Sparkes had asked what the Author meant in saying that the prestress was not significant. The test in question had been a test to a little more than twice the working load—the stresses in question had occurred under a load of 100 tons, and the design load for that particular runway had been 45 tons. Under that test load no cracks appeared on top; even had cracks appeared there was every reason to suppose that there was a further margin of safety. With a prestress of about 25% of the apparent stress under such a load, it could not be said that the prestress was making a very significant contribution to the strength of the slab under its design load. Moreover with concrete of that quality, the prestress could safely have been made six times as big.

163. The rate of loading in the repeated load test had been of the order of 1,000 applications a day.

164. Mr Goldstein had referred to confusion between strains and stresses. The

Author had been aware of that confusion and had made the fact that stresses were deduced from strains quite clear in § 8. Did he believe that those stresses existed? Frankly, he did not, but the existence of strains of that magnitude was just as startling. He had tried in the Paper to emphasize the importance of the strain aspect of prestressed concrete. Indeed, it might well be true that one of the major contributions of prestressing to the strength of a runway slab was to enable it to accept large tensile strains, even beyond the cracking point, without exhausting its strength.

165. In response to Mr Sharp's promptings the Author added that he was personally of the view that one of the steps forward for the economy of prestressed concrete pavements for lighter loads and more general use was probably the reduction of thickness. When one heard that a slab 6 in. thick (which was about the minimum which could reasonably be cast) of concrete with a strength of 2,900 lb/sq. in. at 28 days, laid on a completely uncompacted subgrade of singularly poor quality, with the prestress reduced to 140 lb/sq. in., could carry a 140 tons point load, it was clear that one had a structure the thickness of which could be reduced. In reducing the thickness it would be possible to do all those things which engineers hoped to do—reduce costs, reduce consumption of raw material, and possibly increase the speed of laying. Precasting might be one of the means of attacking that problem. The only reservation, which he thought was an important one, was that if they were reducing depth with large loads—i.e., if they attempted to carry large loads on a 2-3-in.-thick slab—they had to be certain of the minimum value of the prestress. At the moment with a slab of approx. 6 in. thickness they did not need to worry much because the reserve of strength was so large.
