

The difficulties of labour and material shortages and bad weather, in addition to those already described, have not been dwelt upon at any length, since such problems were inherent in all contracts at that time and they were met and promptly overcome by the resident engineer and the contractor.

ACKNOWLEDGEMENTS

The Author would like to acknowledge the assistance so readily given throughout the contract by the staff of the de Havilland Aircraft Company and, in particular, by Messrs A. S. Kennedy, T. C. Grewar and R. W. Sutterby

He would also like to acknowledge the co-operation received in the preliminary stages of the scheme from Messrs James Munro and Sons, Architects for the de Havilland Aircraft Company.

His thanks are due also to the Ministry of Works Soil Testing Laboratory at Barnet, then under the direction of Mr J. N. McFeeters, M.Sc., M.I.C.E., for their considerable assistance in carrying out the experiments on the test slabs; and to the Road Research Laboratory, under the direction of Dr W. H. Glanville, C.B.E., D.Sc., Ph.D., Vice-President I.C.E., for the loan of certain heavy equipment unobtainable elsewhere in Britain.

He would also like to record his appreciation of the help so readily given by his partner, Mr Brian Scruby, and the Resident Engineer, Mr Ellis Courthope, M.I.C.E., without whose valuable assistance this Paper could not have been written.

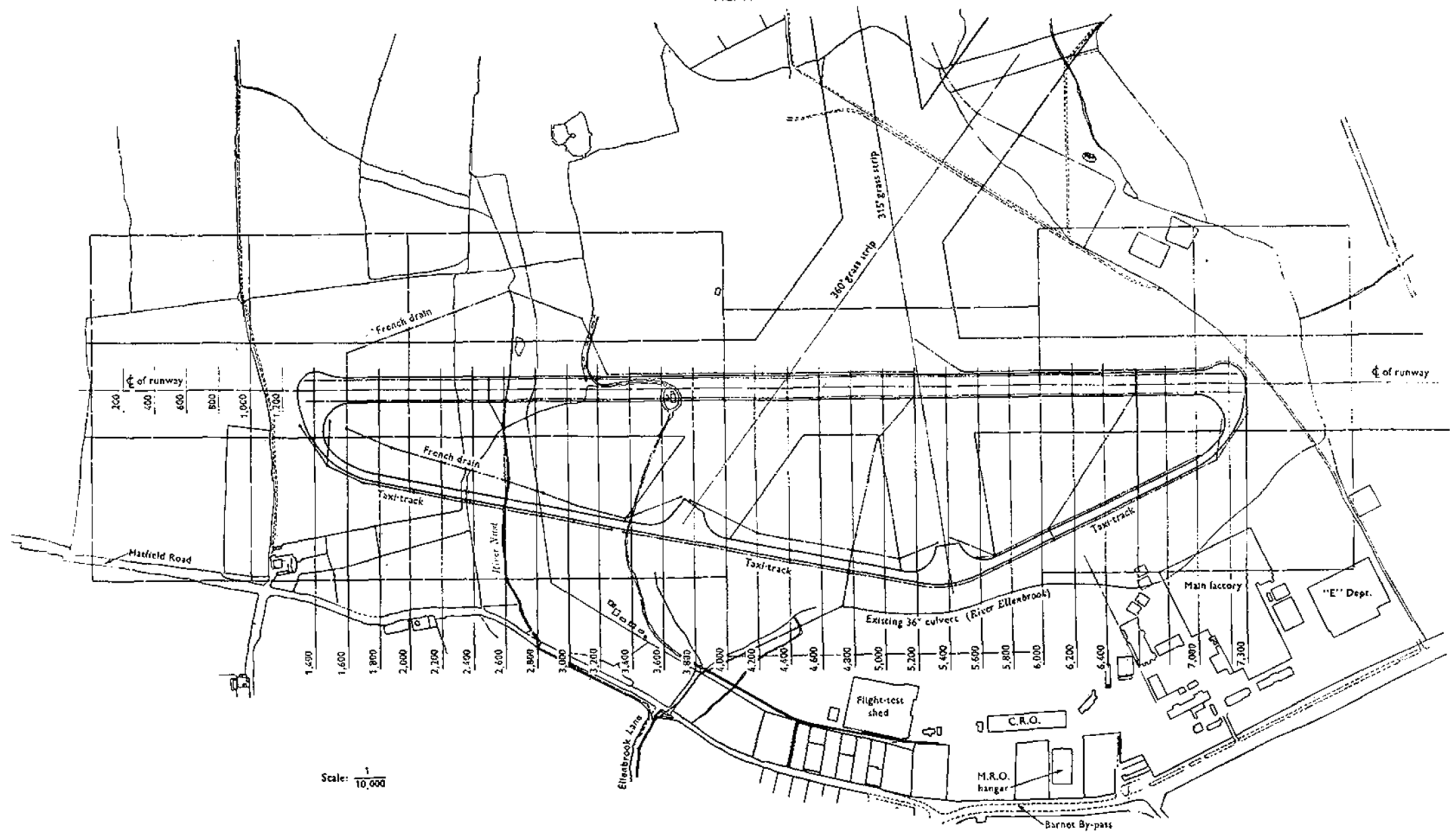
The Paper is accompanied by thirty photographs and eighteen sheets of drawings, from some of which the half-tone page plates, the folding Plates, and the Figures in the text have been prepared.

Discussion

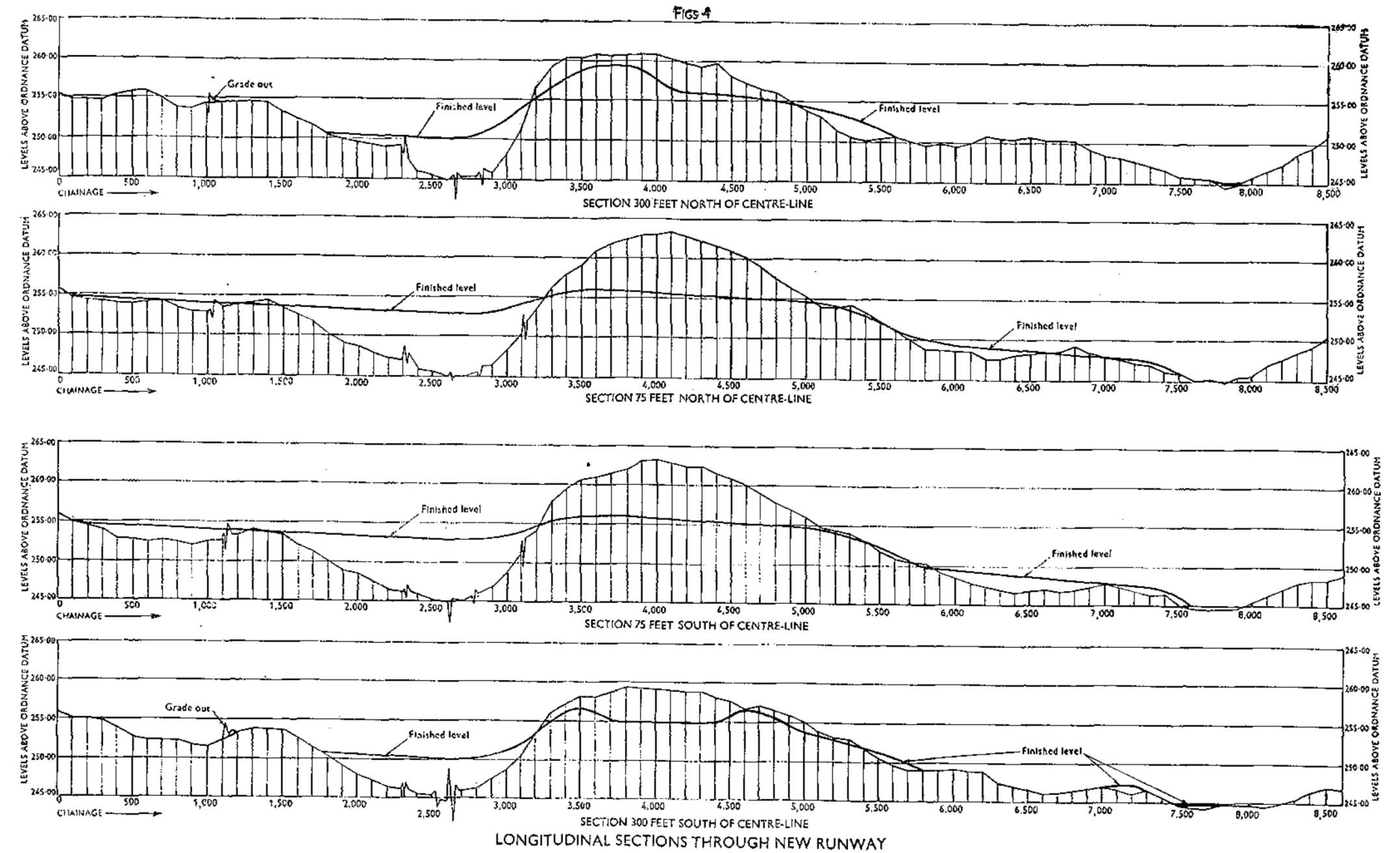
The Author introduced the Paper with the aid of a number of lantern slides.

Mr J. N. McFeeters said that he regarded the work described as a very good example of collaboration between a Consulting Engineer and a Ministry. In 1944, when the work was started, there were very few Consultants carrying out airfield works, and Government departments had almost a monopoly of the information on the technical questions involved, which had come to them from America and from their own work in the United Kingdom. It might have been possible to evolve a form of co-operation whereby the Ministry did a lot of calculations and passed them on to the Consultant, but that was not considered to be the best way of

FIG. 1.



AERODROME LAY-OUT



LONGITUDINAL SECTIONS THROUGH NEW RUNWAY

dealing with the matter. What happened, therefore, was that the Ministry of Works, acting for the Ministry of Aircraft Production, indicated its general requirements and supplied the Author's firm with all the information at its disposal and gave every help for which it was asked. The Ministry did not lay down the law as to the thickness of runways, and so on; on the contrary, it believed that only the person whose reputation was at stake in carrying out the works, and who was responsible for running the job and for the expenditure of money, was in a fit position to decide on most points, and that only he could take the courageous step of fixing finally upon a design.

When, therefore, the Author, as a result of the information given to him, had come forward with various designs, the Ministry had contented itself by saying "It is your responsibility, but we should like some tests to be carried out, because slab calculations are far from conclusive." That had been done, the Ministry giving all possible help in the carrying out of those tests. Thereafter, the Author's firm had been left to carry out the work, with the minimum number of visits by the Ministry, who had made no attempt to interfere in the running of the job.

The tests, unlike a research job, had been carried out under very difficult conditions, in winter, with all the weather difficulties which were associated with a runway. Their object had been to indicate whether the design of the Hatfield runway was safe—not to establish anything wider than that, although the Ministry wished to take advantage of any additional information which might accrue.

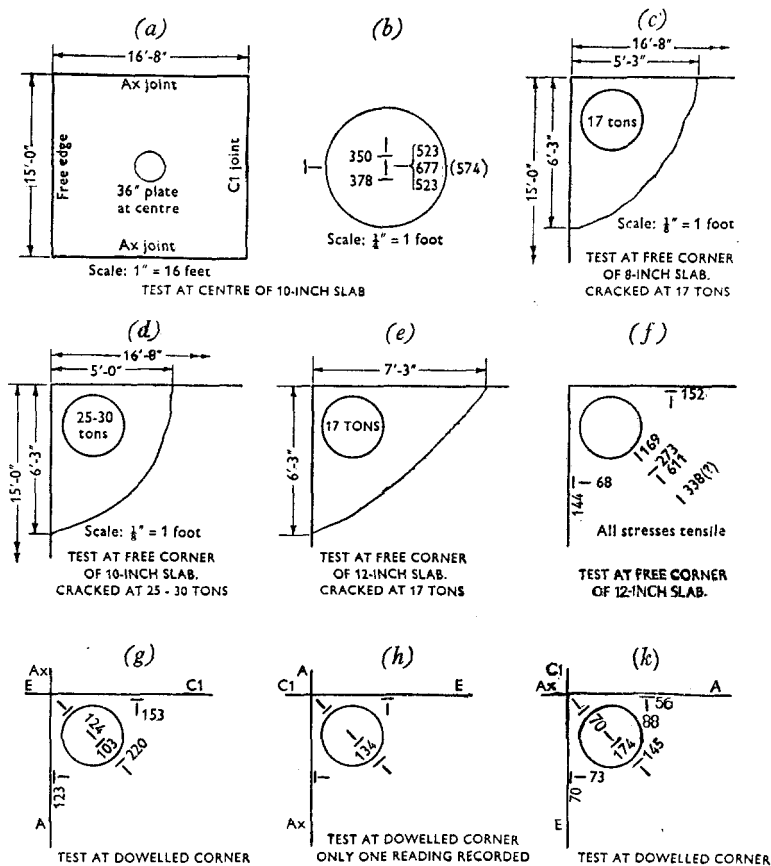
All sorts of difficulties had cropped up during the tests; techniques had had to be improved, apparatus borrowed or made, and staff trained. The tests could not have been carried out without the co-operation of the Admiralty, the Road Research Laboratory, and the Building Research Station, who had been kind enough to lend apparatus and to give their help and instruction.

Accurate assessment of the results would require a perusal of all the data that went to make up the final stress figures. In certain cases the gauge readings had not been as accurate as in others, and to that extent a certain amount of interpretation was needed. Test No. 10 (*Fig. 20 (k)*) was the best starting point. As would be seen, an edge loading of 60,000 lb. caused very high stresses on a free edge, whilst with dowels those stresses were very considerably reduced, as would be seen from *Figs 20 (a), (b), and (d)*.

In Test No. 3 (*Fig. 20 (c)*) it would be seen that a dowelled corner exhibited very high stresses in an unexpected direction, perpendicular to the diagonal. The question had arisen at that stage of whether the engineers had conquered the difficulties of edge stress by dowels, only to fall down on account of the corner stress and, accordingly, some further tests had been made. *Figs 35 (a) and (b)* showed a centre test on a 10-inch slab. There was a maximum stress of 574 lb. per square inch in the middle.

Fig. 35 (c) showed a corner with an 8-inch slab : it had cracked with a load of 17 tons. Fig. 35 (d) showed a corner with a 10-inch slab which had cracked at between 25 and 30 tons. Fig. 35 (e) showed a corner with a 12-inch slab on which a load of 17 tons had been left overnight. During the night the temperature had fallen to 28° F. and, from theory, it was

Figs 35



HATFIELD RUNWAY. ADDITIONAL TESTS WITH 30-INCH-DIAMETER PLATE, LOADED TO 60,000 LB. (EXCEPT WHEN CRACKED)

known that that increased the stress very considerably. The slab had cracked at the 17-ton load. Fig. 35 (f) referred to a 12-inch slab, with no dowels, where a very high tensile stress occurred behind the load and in the top of the slab, in accordance with theory.

Fig. 35 (g) referred to a dowelled slab. The maximum stress was quite

small, being about 220 lb. per square inch, as compared with the very large stress shown in *Figs 35 (b) and 20 (c)*. In *Fig. 35 (h)* only one gauge reading had been recorded, the others being rather erratic, but again the stress was small. *Fig. 35 (k)* showed a third doweled slab, for which again the stress was low.

Those were additional tests, and it would be seen that the corners appeared to be quite reasonably strong. The results shown in *Fig. 20 (c)* were accordingly thought to be unusual. Either there was an error in the gauge or a soft spot under that corner. The work described above had been carried out under Mr McFeeters's supervision while he was an officer of the Ministry of Works.

Mr Ellis Courthope endorsed what Mr McFeeters and the Author had said about the co-operation between the Ministry, the Contractors, and the Consultants. Naturally, arguments had arisen, but all of them had been friendly; it had helped enormously to have Contractors who were so competent and so co-operative. He had never regarded the Contractor as the natural enemy of the Engineer; but he felt that still more co-operation was essential to the carrying out and production of first-class work.

On p. 31, the wording used by the Author might give the impression that the aggregates for the concrete had been merely what was normally described as "as-raised." That was not quite true; the aggregates had been screened and washed. What had really happened was that at the pit a certain proportion of coarse and a certain proportion of fine had been loaded into the same lorry, and the aggregate had been brought on to the site as a mixed article, roughly graded by intelligent guesswork but, nevertheless, washed material.

The Author had stated, on p. 34, that there was little to choose between the machines. That meant that there was little to choose in performance. On the job in question the two machines had given more or less equal results, but there had been a preference for the Stothert and Pitt vibrator, as being more compact and workmanlike than the other. What had struck him about the Aveling-Barford machine was that the controls, which were largely built up of steel cables running over pulleys, had shown a tendency to come unstuck at critical times, causing a certain amount of delay.

Mr Alan P. Lambert observed that the Paper was of special interest to him, because he had played some part in building the runway.

He appealed for a realistic and practical approach to the question of the preparation of clay foundations on the part of those who prepared specifications for roads or runways on clay sites. So far as the actual construction of the runway in question was concerned, he had no complaints to make; the Contractors had received very reasonable treatment from the Consultants and from the Resident Engineers. The actual specification itself, however, had been drawn up in a way to which it was quite impossible to work unless one had the right weather conditions;

in point of fact, such weather conditions had not been experienced. All through the summer of 1946, there had been an average of 0.6 inch of rain per week, and it had not been possible to satisfy a specification which called for compaction at optimum moisture-content in weather of that sort. The specification had stated, somewhat naively, that where the material was too dry it might be wetted by spraying with water, but had not said what should be done if it was already much too wet when one got there. The only thing to do was to sit down and wait for it to dry, and that was what had been done for a great deal of the time. He felt that those who prepared the specifications would do well to bear in mind that, whilst the Contractor could be blamed for almost everything, he could not be blamed for the English weather; it was, therefore, necessary to have a sort of escape clause, an alternative method of construction which could be adopted if the weather conditions made the ordinary specification unworkable.

Mr Courthope had mentioned the question of the all-in or "as-raised" aggregate, and it might be of interest to amplify what he had said. There was a great deal of difference between "as-raised" aggregate, which meant aggregate as it came out of the ground, and all-in aggregate. No "as-raised" aggregate had been used anywhere on the job, let alone in the top slab. The Contractors had, in fact, relied on all-in aggregate.

There was an interesting story concerning the supply of the aggregate. When tendering for the work described in the Paper, the Contractors had received two types of quotation from a reputable firm of ballast merchants, one for split aggregates and sand and the other for all-in aggregate. The cost per cubic yard of concrete would be less if the aggregate were bought at the all-in price, and the Contractors had therefore said to the ballast merchants "This is an extremely tough specification, and the aggregate has to be of really good quality and graded within reasonable limits. Are you sure that you can do it?" The reply was "Yes, you have nothing to worry about; we shall send you exactly what you want." The Contractors had based their tender on that, but it was not long before they discovered the answer; the aggregate had been sent in lorry-loads with the large aggregate at the bottom, a sandwich of sand in the middle, and some other aggregate on the top. It had been possible to show, by a very simple experiment, that that involved the Contractors in a loss of 14 per cent. when the material was mixed, and the suppliers, when taxed about it, had agreed to rectify the situation. Bins had been arranged so that the different-sized aggregates were put into a communal bin which was reserved for use on this job, and so the Contractors had received mixed aggregate without having the grading under their own control. Although the arrangement resulted in very good concrete, Mr Lambert was still not an advocate for all-in aggregate. On the other hand, rather too much emphasis was sometimes laid upon the grading of concrete materials. There was no real virtue in grading for its own sake; the virtue in grading

was to make it possible to compact the concrete. Vibration by machines sufficiently powerful to ensure full compaction would result in perfectly good concrete, even if the aggregate grading were not quite ideal.

All the aggregates had been tipped on to a large concrete apron and bulldozed an average of 60–70 feet, and so the identity of any particular lorry-load had been completely lost at the mixers. The result had been that the material offered to the mixers was very uniform, even if not absolutely right. The Author had mentioned that a minimum compressive strength of 4,500 lb. per square inch was asked for at Hatfield, in comparison with 4,000 lb. per square inch at Heathrow, but he had not stated that his mix was $6\frac{1}{2} : 1$, as against $6 : 1$ at Heathrow. In other words, the Author had hit at the Contractor both ways, but it had been possible to satisfy him.

Mr W. P. Andrews asked several questions, of which the first concerned the reinforcement. On p. 13, reference was made to the extremely useful purpose served by the reinforcement in the course of the construction of the runway. That was a very controversial point, and it would be interesting to have it elaborated. He felt that, given a really well compacted subgrade, with a minimum thickness of concrete of 10 inches, the value of the reinforcement was very questionable. He recognized its value with a thinner slab, but not with a slab of that thickness on what he assumed to be a well compacted subgrade.

It was interesting to note the reference in the Paper to the compaction of the soil and to the fact that it was superior to equally well compacted hardcore, because a good deal of misunderstanding existed about hardcore. He did not think that hardcore could be satisfactorily compacted to give a dense foundation.

On p. 32, reference was made to the water/cement ratio being slightly altered. That was a point on which a good deal more research could be done with advantage. He knew that the Road Research Laboratory had done experiments with a Holman compactor and had found that there was an optimum water/cement ratio at which the best compaction was obtained, whilst concrete drier or wetter than that optimum did not give as good results.

Mr Andrews asked about the effect of jet engines on runways. Some people said that concrete was quite impervious to, and was not damaged by, the jets. American reports indicated that the concrete was not injured by the jets, but Mr C. E. Foster, M.I.C.E., in a recent Paper,¹ had stated that even high-quality concrete had been seriously affected. That was a point on which a good deal of research was needed, and on which the Author's views would be of interest. Mr Andrews felt that if the temperature of the jet at the point where it impinged on the concrete was such as to damage the concrete, the joint-sealing compound which had been

¹ "The Problem of Airfield Design in Relation to Aircraft Design." J. Instn Civ. Engrs, vol. 32 (1948–49), p. 484 (Oct. 1949):

used in that case would not be satisfactory. Concrete would withstand a temperature of up to 300° C. at least, but above that temperature he did not think that any joint sealer in the world could possibly resist the heat.

On p. 35, the Author had mentioned that damage to the edge of the concrete slab was caused by the flanges of the wheels of the spreading and vibrating machines. *Fig. 36* showed how that trouble had been overcome on a road in South Wales. The concrete had been dumped in heaps out of lorries by tail tipping. In the centre of those heaps the concrete had been pre-compacted, and, although spread by the machine in the background to a uniform level, it had not been of uniform consistency before the passage of the compacting machine. There was clearly a need for some type of controlled spreading before the distributor came on to the job. On the left could be seen the rails attached to the forms. In that case both the spreader plant and the compacting plant had travelled, not on the forms, but on the rails, and so the damage to the edge of the concrete referred to in the Paper had been obviated. The rails used were light rails in short lengths.

Fig. 37 illustrated the method adopted by the County Surveyor of Glamorgan, Mr E. John Powell, M.I.C.E., with a concrete road, and showed the bar coming through the form seating on top of the joint filler; it could easily be pulled out, and it anchored the filler to the form and prevented it departing from the vertical.

Mr F. N. Sparkes considered that, in the formulae quoted on pp. 9-10, it was very much open to question whether the assumptions made were valid for all conditions during the life of the runway. For example, it had been necessary to assume a purely arbitrary degree of support at the corners and edges of the slabs and, in the formulae for the edge and corner loadings the stress to have been increased by 20 per cent. to allow for upward and downward warping. That arbitrary degree would be purely a matter of opinion, and it was difficult to place a great deal of reliance upon the stresses which were calculated from those formulae.

Elsewhere in the Paper, reference had been made to the modulus of subgrade reaction of the soil being about 450 lb. per square inch per inch; the laying of a 3-inch layer of lean concrete on top of that soil had increased the value of k from 450 to 1,770 lb. per square inch per inch. He wondered whether that meant a *real* improvement in the supporting power of the subgrade, because the modulus of subgrade reaction was based on the conception that the soil was a homogeneous material throughout its depth. The placing of a 3-inch layer of lean concrete provided a layered system instead of a homogeneous one and if, at the time when that runway was designed, the Author had had available the work which had since been published by Burminster¹ in America, and by Fox² in the United Kingdom,

¹ D. M. Burminster, "The theory of stresses and displacements in layered systems and applications to the design of airport runways." Proc. 23rd Annual Mtg Highway Res. Bd, vol. 23, 1943, p. 126. *Discussion*, p. 144.

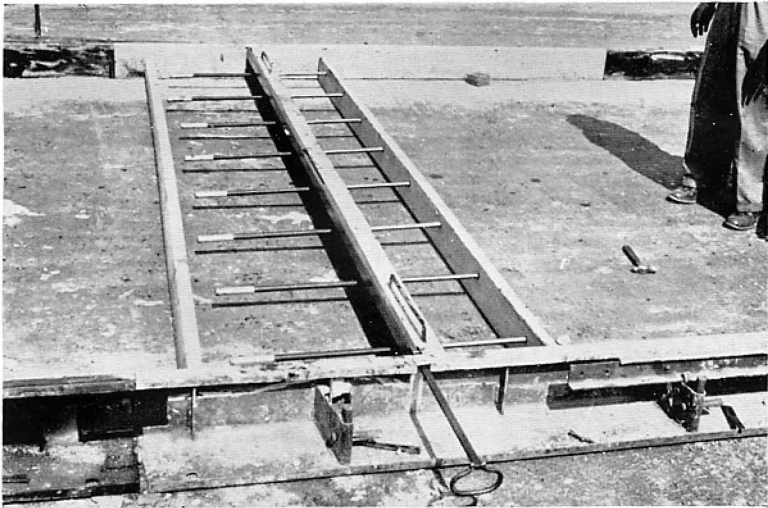
² L. Fox, "Computation of traffic stresses in a simple road structure." D.S.I.R., Road Research Technical Paper No. 0. H.M.S.O., 1948.

Fig. 36



CONCRETE DUMPED ON FORMATION IN FRONT OF BLADE SPREADER. ON THE LEFT ARE RAILS, TO CARRY SPREADING AND COMPACTING PLANT, SECURED TO SIDE FORMS

Fig. 37



EXPANSION-JOINT FILLER HELD IN POSITION BY A BAR PASSING THROUGH A HOLE IN THE SIDE FORM

on the stresses in layered systems, he might have found a reason for the very marked increase in strength caused by placing the 3-inch layer of concrete. The relationships between the layers in those new formulae were expressed as relative elasticities of the layers, and that would give a much better idea of the increase in bearing power of the subgrade which had in fact been achieved.

The formulae for warping stresses were based on Westergaard's original formulae, which assumed that the temperature gradient through the slab was a straight line. There were many confirmatory data showing that the temperature gradient was not in fact a straight line but a curve, the actual degree of curvature depending very largely on the previous temperature history of the slab.¹

Those points showed how difficult it was to apply mathematical analyses to so complex a problem as the design of concrete runways and road slabs. In addition, certain stresses had not been calculated or included by the Author, because there was no way of knowing how they could be calculated. There were the frictional stresses imposed by the overall movement of the slab over the subgrade, the stresses caused by moisture gradients through the slab, and the effects of impact on the runway. Those factors might or might not be important, but one could not afford to neglect them just because one did not know how to estimate them. Thus it was not surprising that the measured stresses approximated to the calculated stresses, which also did not take those factors into account.

The theoretical approach to the design of runways had been the subject of two or three recent Papers, and Mr Sparkes thought that the time had come to consider very carefully whether that really was the best way to tackle the whole business of runway design. Millions of pounds were being spent, and more full-scale tests should be done than were indicated in the Paper. Valuable information was obtained from the tests referred to in the Paper, but it was desirable to have a bold programme of full-scale tests in which wheels, loaded up to 60,000 and 90,000 lb., were carried round a special track containing slabs of various thicknesses until some failures occurred; in that way one could alter the variables and see what sort of economic design could be achieved. The fact that no important failures had occurred on existing runways might be due to the fact that they were much thicker, and therefore more expensive, than they needed to be and the expenditure of money on full-scale experiments could be justified on that score. That was no criticism of the Author, who had taken advantage of all the information available to him at the time. The airport designer had no past experience to fall back upon; he could not say "Let us have a look at this runway, which has been down for 20 years, and see how it has behaved." Did the Author agree

¹ J. Thomlinson, "Temperature-variations and consequent stresses produced by daily and seasonal temperature cycles in concrete slabs." *Concrete Constr. Engrg*, vol. 35, 1940, part 6, p. 298; part 6, p. 352.

that there was a need for full-scale experiments with moving loads on special tracks, or was he satisfied with the experiments done in connexion with the Hatfield work ?

The cost of the concrete had been extremely low, and reflected very creditably on the organization which could produce concrete at that price to-day. He took the price, from the data in the Paper, to be 1s. 6d. per inch per square yard. Was that a real figure ?

The modulus of the rupture of the concrete had been specified on two occasions not to exceed 700 lb. per square inch. It was not clear whether it was not allowed to exceed that figure, but it read as though that was the maximum to be achieved. Mr Sparkes could not see any objection to a much higher modulus than that, if it could be obtained.

The comments on the use of hot cement were of interest. The subject was a controversial one. Some people said that hot cement had no effect on concrete slabs, whilst others considered that it induced shrinkage cracking and so on.

Mr Brian Scruby, referring to the tests described in the Paper, observed that engineers in the position of the Author, and others, had not the time or the money to spend on such tests. It would be very well worth while if more time and more money could be spent on further research into the problems of the comparison between design and practical application.

Several previous speakers had questioned whether load transfer by means of dowels was really worth while, and whether it was considered to be economical. Mr Scruby offered some figures which he had worked out on a square-yard basis. The 3-inch concrete sub-base, including the building paper, worked out at 3s. 0½d. per square yard, and the top 10-inch slab at 9s. 8d. per square yard. All the joints, including the formwork, the jointing material, and the dowels for both the longitudinal and transverse joints, amounted to 2s. 9d. per square yard of runway, and of that 2s. 9d., 1s. 8d. was for the dowels themselves. Bearing in mind that those figures were based only on the concrete section of the final accounts for the job, and did not include anything for recoverable expenditure, overtime, travelling time, and so on, that figure of 1s. 8d. for the dowels, which might be taken at 2s. altogether, amounted to only 4·3 per cent. of the net cost of the contract, omitting the recoverable expenditure, and even the whole cost of the formwork, at 2s. 9d. per square yard, was only 5·9 per cent. of the contract. If they had designed the runway without the use of dowels they would have been forced to consider slabs of the order of 14 inches thick, or possibly thicker, and the question of temperature stress would have again reared its head. On the figures he had just quoted, that would have amounted to an additional 1s. per inch of thickness ; adding 4d. for the excavation, the total extra would have been 4s. 4d. per square yard. That was far greater than the 2s. 9d. for the whole of the joint work, so that he considered that the dowels for load transfer were very economical.

He thought that the dowels had been looked upon as a bogey, but they were not such a problem after the first few weeks of the job, when the teething troubles had been overcome. The forms had had to be there in any case and, though the dowels might have been a nuisance, they were only, in one sense, something which was added to the forms and joints.

Mr Lambert had raised the question of soil compaction, and had seemed to suggest that the specification was too stringent. That was probably the responsibility of the Ministry. When it came to the ballast, the reverse was the position; the specification had been made as open as possible and asked only for concrete with a minimum cube or core strength of 4,500 lb. per square inch, it being left to the Contractor how he produced that concrete. Efforts were made in the specification to force the Contractor to use separate coarse and fine aggregates, but the Contractor had prevailed and, which was more, had produced a very good concrete.

On the question of whether the reinforcement was necessary Mr Scruby could say a great deal. He agreed that it was inconsiderable structurally, but thought that it was very necessary in the practical laying of the concrete. Mention had been made in the Paper of cracks due to hot cement and so on and, even from the point of view of preventing cracking after the machines had passed over, he thought that the steel did a useful job.

Experience at Hatfield had indicated no detrimental effect from jet aircraft on concrete. It could not be stated whether anything would happen over a period of years, but there was as yet no damage, although some of the jet machines had been standing on one section of the runway very consistently. There were, however, signs of trouble in the joints, but Mr Scruby believed that the matter was being thoroughly investigated by the various manufacturers at the present time.

Dr T. P. O'Sullivan referred to a number of Papers, submitted in the past 2 or 3 years to the Airport Engineering Division, which touched on the fundamentals of the design of concrete runways in one way or another, and he thought that the present Paper constituted a very great advance, in giving some practical insight into how the modulus of subgrade reaction and Westergaard's theory worked out in practice. The Paper contained a wealth of information in that respect, showing where the test loads were applied and what their effects were; it also showed the great difficulty of getting the desired results.

He himself had had some connexion with, and responsibility for, the work at Bristol in so far as the floor and apron for the Brabazon hangar were concerned. That work was being carried out at much the same time as the work at Hatfield, and photographs showed that the latter site looked, at times, more like the Norfolk Broads than anything else, so that he could fully appreciate the difficulties encountered there.

Under the heading "Terms of Reference" on p. 5, attention was drawn to a specified load of 60,000 lb. per wheel, which was just under 27 tons. The requirements for the Brabazon were of that order, the aircraft

being of 130 tons all-up weight on two undercarriages, each of two wheels. In that respect, he was inclined to think that, in the future, it would not be necessary to provide for such heavy wheel-loads, because even in the case of aircraft of the size of the Brabazon every effort was being made to substitute four-wheel, for two-wheel undercarriages. The problem of dispersal of load would have to be worked out for four wheels fairly close together, but it seemed likely that aircraft would not become any heavier, and might even be lighter, so that it might be hoped that those were the worst conditions.

One of the most important matters to which attention was drawn in the Paper was mentioned on p. 15, where it was stated that "it is vitally important that subgrades, once opened up and prepared, should be sealed immediately against excessive moisture and drying winds." Dr O'Sullivan thought that the whole method of construction should be investigated. He did not know how those problems would be overcome, but it was very apparent that as soon as the formation was prepared there should not be the least delay before it was sealed off. In actual practice, however, it was not easy to do that, which meant that the moisture content could not be easily regulated, and the formation would be accordingly either too dry or too wet.

He did not know whether the Author had considered a tarmac runway on hardcore as an alternative to concrete. At Bristol, such a construction had been considered, and it had been touch and go, at one time, whether concrete, or tarmacadam or some other bituminous material on hardcore would be used. It was felt that the design was rather more advanced technically, and that better control of the construction would be effected if a concrete construction were adopted. It was interesting to note, however, that quite satisfactory runways had been put down overseas to carry heavy wheel-loads with tarmacadam on hardcore. The method did not seem to be used in the United Kingdom, and it would be interesting to hear the Author's comments on the reason for that.

Mr C. E. Foster, commenting on the question of the jet effect on concrete, said that reference had been made to his Paper,¹ in which he had said that concrete was affected by jets. That was quite correct. At Heathrow a Viking aircraft had been fitted with jet engines, and after running for about 10 minutes it had had a very considerable effect on the concrete, which had been pitted to the extent of about $\frac{1}{4}$ inch. That depended, however, on the angle of the jet. On the Viking machine, which was a tail-wheeled aircraft, the angle had been excessive, whereas with the new type of nose-wheeled aircraft there would be nothing like the same inclination of the jet. On the Vampire aircraft, the maximum angle was about 3 degrees, and that was probably why there had been no effect at Hatfield. In that respect they were very much in the hands of the

¹ See footnote 1, p. 49.

aircraft designers. If the angle could be kept at about 3 or 4 degrees, the concrete should not be affected.

Mr D. H. Little asked what was the undisturbed shear strength of the clay in the excavated areas, and what was its k -value? When that clay was used as a filling, did it consolidate into a homogeneous mass, and, if so, what was its remoulded shear strength?

The calculated stresses in Tables 1 and 2 were divided into those due to load and those due to temperature. Were they based on the assumption that the underside of the slab was in full contact with the ground all over? If so, would not the corner stress be very much higher than was indicated if the load were applied at a time when the corners of the slab were cockled up? Or, if the slab had lifted in the middle, would not the stress be considerably lower than was indicated, owing to arching action? Most testing experience substantiated the belief that the central load that could be placed on a slab might be 4 to 6 times greater than the corner load. The calculations given by the Author were so different from that as to suggest that they needed some qualification.

Considered as a structural problem, the load to be dealt with at the Hatfield aerodrome was 30 tons on an area of 4 square feet, and as a structural problem that was not very alarming. If carried centrally on a footing 13 inches thick and 6 feet square, the ground stress would be less than 1 ton per square foot, and the loading stress in the footing would be almost negligible. The solution, as the Author had said, was to devise a means of keeping that load always central, and it would seem that sandwich construction should be the best method. An experiment had been carried out at a naval air station on the use of sandwich construction, with two layers of 6-inch concrete and what was called a substantial filling between the two layers. Mr Little displayed a sample of that filling, which was $\frac{1}{4}$ inch thick and was made of bitumen and cork. It was resilient enough to allow the corners of the top slab to penetrate, but it was also stiff enough to give adequate support to the top slab. Some rough experimental work on it suggested that the k -value was about 1,200 lb. per square inch per inch. The rather disturbing stress results which the Author had obtained in his two-slab construction might have been due to the rather harsh and grating contact, as it were, between the two layers of concrete, separated only by building paper, which provided a not very strong structural separation. With a thicker sandwich, such as the one to which he had referred, those difficulties might be overcome.

Mr W. R. Rangeley asked how the water/cement ratio had been controlled with such accuracy as appeared to have been the case. It was stated on p. 32 that the suggested water/cement ratio of 0.48 by weight was found to be rather low, and therefore resort was had to a ratio of 0.485-0.49. That seemed to suggest working to a considerable degree of accuracy. On p. 34, it was stated that the field laboratory "was erected near the central mixing plant to enable the checking of aggregate and the

water/cement ratio to be carried out with ease." He had discovered that that could be a big problem in the control of concrete in the conditions in question.

Had any sign of transverse cracking yet appeared between the two A-type joints, because from the construction it appeared that there was no provision of contraction joints. At the time, was consideration given to painting and greasing the tie-bars used in the joints of types B and D? With regard to the percolation of water through the lean-mix sub-base, was the question of spraying the lean-mix slab with, say, a cut-back asphalt or other bituminous solution considered? Apparently that would be much cheaper than doubling the thickness of the slab and increasing the strength of the mix.

The Author, in reply, observed that some of the speakers, notably Mr Sparkes, had questioned the necessity and the value of the large-scale tests. The Author felt that the only way to get results was to disseminate the information made available by such tests and circulate it for criticism and suggestions, as had been attempted in the Paper. Additional information could then be obtained for the benefit of road and airport engineers. In particular, he hoped that the further tests, in which Mr McFeeters had taken a great interest, would be published in due course and so add to the information already given.

Mr Lambert had agreed that the Consulting Engineers and Resident Engineer had treated him very reasonably but had asked why consulting engineers wrote specifications in the way they did. The Author considered that the best procedure for a consultant to adopt was to prepare a specification covering all the points and embodying difficulties which had been experienced over a period of years, bearing in mind up-to-date developments.

In the case in question, the Contractors had been given the option either of doing what the Consulting Engineers had specified or of carrying out a performance test on their own responsibility, which was a sensible arrangement and was being more widely adopted. Actually the Contractors had said—so far as the mixture of aggregate was concerned—"We do not like your specification and we will stand by the performance test." They had been warned that one failure would entail rejection of the whole; they had taken a big contractual risk and had been successful; as a result the Consulting Engineers were proud of the fact that they had been sufficiently up-to-date to include a performance test in their specification and the Author recommended it to other consulting engineers as a means of dealing with the difficulties likely to be encountered on that type of contract, where large quantities of ballast and other materials were required within a very short period.

Mr Foster had mentioned the effect of the jet aircraft on the concrete. There had been little trouble on the concrete at Hatfield, although the joint sealing material had become partially disintegrated owing to the effect of jet exhaust gases impinging on oil spilled on the runway.

Mr Andrews had questioned the value of the reinforcement. In the Author's opinion, the addition of a small amount of reinforcement was advantageous, even though the necessity for it could not necessarily be proved by calculations.

Mr Rangeley had referred to the water/cement ratio. That had been strictly adhered to but for the exceptional occasions mentioned by the Resident Engineer, when in extremely hot weather a slight increase in water had been permitted.

Mr Sparkes had offered some really constructive criticism of the design and had made the point that many of the formulae used at that time had since been enlarged and improved upon. It was still, nevertheless, obvious that far more research was required before all the complications of road and runway design were completely overcome. Undoubtedly, individual clients could not possibly afford to undertake research on such a large scale; therefore, the Author considered that in such circumstances some assistance from a Government Department was clearly indicated and it might well be that such tests could be undertaken by the Ministry of Works Field Test Unit or the Department of Scientific and Industrial Research.

The Author had always advocated a practical approach to all engineering problems and he agreed with Mr Sparkes that there was need for full-scale experiments with many loads, provided that the money and time were available. The Hatfield tests had certainly not been conclusive in any way and, as had been previously stated, there was room for a great deal of work on that subject.

Mr Sparkes had also questioned the modulus of rupture of 700 lb. per square inch, referred to in the Paper. There was, of course, no reason why concrete should not reach a higher modulus than that and, indeed, the high compressive-strength results obtained indirectly proved that it did. The figure of 700 lb. per square inch was merely the maximum stress used in the theoretical calculations.

The Author's experience of the use of hot cement at Hatfield left no margin of doubt. The appearance of short shrinkage cracks was always coincidental with the delivery of hot cement, and for that reason extremely careful records were kept.

Dr O'Sullivan had asked whether a tarmac runway on hardcore had been considered as an alternative. Whilst the Author agreed that that type of construction would easily solve the problem of preservation of a prepared formation, its disadvantages in other directions would, in his opinion, make its adoption quite impossible. In fact, the Author's firm had been called upon to advise on remedial measures to existing tarmac runways constructed during the war. Apart from the distribution of the very heavy loads for which the runway was designed, a tarmac surface naturally required more frequent maintenance than concrete; that was a decided disadvantage on a runway in fairly constant use. What was more

important, however, was that the type of construction would not withstand the effects of aircraft jets.

Mr Little had questioned the value of the excavated clay used as filling. It had been discovered in earlier tests that the maximum dry density at optimum moisture-content varied from 105 to 125 lb. per cubic foot. The specification had called for that material, when used as filling, to be compacted to give a density of 95 per cent. of its undisturbed value and no material would be accepted unless it had a density of at least 100 lb. per cubic foot. A large number of tests had been taken in the field during the construction of the formation of the sub-base and it had been generally found that compaction had far exceeded that specified.

Mr Little's question on the calculated stresses in the concrete would involve a very lengthy discussion on the principles of Dr Westergaard's theory. However, it was true to say that the slab itself had tended to cockle; that deformation was resisted by the concrete, thus producing the theoretical temperature stresses shown in the Tables in the Paper. The relationship between the amount of load which could be carried in the centre of the slab as compared with the corners was, in the Author's opinion, dependent upon the circumstances surrounding the design and in certain circumstances might easily be in the ratio of 1 to 4; but, in the case in question, it had been rather less than 2 to 1.

The Author was interested in Mr Little's description of an experiment carried out with a separating medium of bitumen and cork sheeting, but felt that further full-scale tests were necessary.

Mr Rangeley had referred to cracking at joints types B and D. It should be explained that they were not expansion joints but warping joints and the reinforcement was intended to hold the panels tightly together in order that load transfer should be complete. Any cracking, therefore, which might take place would occur on the underside and the joints would still be sealed against water percolation. Any painting or greasing of those tie-bars would destroy the whole purpose of the joint.