ASPHALT-SURFACED AND CONCRETE PAVEMENTS FOR AIRPORTS†

Paper No. 6375

The requirements for airfield pavement surfaces

by

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Paper No. 6374

Asphalt surfacing for airfields

by

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and

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Paper No. 6376

The suitability of concrete for airfield runways

by

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Discussion

Mr J. Alston (Superintending Engineer, Air Ministry) said that for many years the airfield engineer had been chasing the tail of the aircraft designer, who appeared to concentrate his efforts on improving the performance of his aircraft in the air, without apparently any real regard for the facilities which might be necessary to allow it to land. The problems of the airfield engineer were continually changing. Until fairly recently, his main problem had been to provide a runway long enough for taking off, but today it was to provide one long enough to land on. Until a few years ago the demand had been for the smoothest possible runway surface, but then the airfield engineer, having achieved this, was told that runways were too smooth. Surface-dressing treatments followed, and the complaint was then made of excessive tire wear. These points had been enumerated to show that the requirements for airfield pavement surfaces (the title of Mr Cooper's Paper) were in no way fixed for any length of time.

34. Mr Cooper had listed twelve fundamental requirements for airfield pavements, and Mr Alston would suggest another two: longitudinal and transverse runway gradients, and effective drainage of the runway surface.

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† Proc. Instn civ. Engrs, vol. 14, p. 19 (Sept. 1959).

35. In recent months considerable thought has been given to the braking-force coefficient of runway surfaces and the Road Research Laboratory had produced braking-force coefficient figures for many airfields up and down the country for various types of surface. Although those results could have only limited application when related to actual aircraft landing conditions, they did form a basis for comparison of the behaviour of different airfield surfaces in this respect. Recent results of the braking-force coefficient of an actual aircraft during landing tended to indicate that there could be a very wide divergence between the result obtained by the Road Research Laboratory trailer at 80 m.p.h. and that of the landing wheels of an aircraft at the same speed. That was to some extent to be expected, because of the number of variables involved. Up to the present the indications were that the braking-force coefficient between an aircraft tire and a runway surface was not affected to any great degree by varying tire loads or by tire pressures above 150 lb/sq. in., and that although the figure fell appreciably up to a speed of 80 m.p.h., there seemed to be a tendency for it to rise slightly at landing speeds above that figure when tire pressures were in excess of 150 lb/sq. in.

36. It had been acknowledged that on a wet surface a type of hydroplaning action seemed to develop between the surface of an aircraft tire and the water film on the runway surface, which did not allow the full effect of the braking-force coefficient to develop. To reduce this film of water there might be a need for increased cross-falls or some form of grooving of the runway surface which would aid local drainage. Mr Alston agreed with Mr Hill that attention should also be paid to the tire tread, because he did not think that the answer lay entirely in roughening the runway surface or in increasing the cross-falls. There might be room for improvement in the braking system of the aircraft to ensure that the maximum effect of braking was being achieved, which was when there was about a 15% slip between the aircraft tire and the pavement surface.

37. Mr Cooper had quoted a braking-force coefficient of 0·4 at 80 m.p.h. as being the requirement for runways, but he was, of course, well aware that this was only one of a number of aspects of a runway surface which would determine whether or not it was satisfactory to the user. There were runways in existence where the braking-force coefficient was appreciably higher than 0·4, but the stopping power of the runway was low, because its roughness caused aircraft to bounce and become momentarily airborne, so that braking effect was lost.

38. One other surfacing which might have a limited place, at least, in airfield pavements, was dense tar surfacing, or surfacing to Marshall control using a tar binder. This material had the advantage of being unaffected by fuel spillage, and its stability compared well with that of asphalt surfacing, and it was probably cheaper in particular localities than the equivalent thickness of asphalt surfacing.

39. Referring to § 31(*f*), Mr Alston suggested that a braking-force coefficient of 0·2 at 80 m.p.h. was somewhat lower than was being achieved with a brush-finished concrete surface. § 31(*l*) indicated what was in his opinion a very expensive way of achieving white markings. A much simpler and cheaper method which had been adopted successfully on some runways was to have alternate black and white centre-line markings, with touch-downs in white, edged in black. With regard to the over-slabbing in concrete, referred to in § 31 (*m*), the Air Ministry were now specifying a minimum thickness of 5-in. reinforced concrete overslabbing for airfield pavements. There were problems relating to airfield pavements which had prevented them from going to lesser thicknesses, even though they were being used satisfactorily in road construction.

Mr C. G. Giles (Senior Principal Scientific Officer, Road Research Laboratory, D.S.I.R.), referred to the skid-resisting properties of runway surfaces, and said that from the point of view of those who used runways it was their surface characteristics which were of the greatest importance. Mr Cooper had mentioned these in relation to runway lengths and the high landing speeds of modern aircraft, but they were also important in helping the pilot to maintain proper directional control as the aircraft slowed down, and the normal control surfaces lost their effectiveness.

41. Problems of this kind and the friction coefficients available on wet runways at high speeds had first been brought to the notice of the Road Research Laboratory by the Air Registration Board, and it had been largely as a result of their initiative, supported by the Ministry of Transport and Civil Aviation, that the Road Research Laboratory had first developed its small trailer apparatus for skid-resistance investigations at high speed, which had enabled the first investigations to be made in Britain at speeds up to more than 100 m.p.h. Since then the Road Research Laboratory had used the same apparatus and techniques extensively in testing runway surfaces for the Air Ministry, and now had available data for the results of tests on nearly seventy different runways of all kinds. It was this information on skid-resistance to which reference was made in the Papers.

42. While the Road Research Laboratory were reasonably confident that these measurements gave a fairly realistic picture of the relative merits of the different surfaces tested, the conditions of test were of necessity very different from those imposed by actual aircraft tires, and it could not be assumed that the results gave the actual coefficient values which aircraft would experience. The load on the trailer wheel was only about 300 lb., the inflation pressure was 20 lb/sq. in., and the tire only 16 in. in diameter. In their measurements they made no pretence whatever at approaching the kind of contact conditions of a typical aircraft tire, and it was very difficult to estimate in what way changing those conditions would influence the results. This was something which they were anxious to investigate, and work was in hand for the purpose. The Ministry of Supply had arranged for an aircraft to be completely instrumented, so that the frictional coefficients could be measured on selected runways, and the results of some of the early measurements had already been mentioned. If anything, it looked as though the coefficients which would be obtained with actual aircraft would be even lower than the values obtained with the small trailer machine, which was rather disturbing.

43. The Road Research Laboratory were co-operating with the Ministry of Supply in the development of a very much scaled-up skid-testing machine for use on runways. This machine was being designed for a testing speed of at least 60 m.p.h., using a full-size aircraft tire and braking system, with wheel loads up to 11,000 lb. and inflation pressures up to 300 lb/sq. in., but it would be some time before this would be in operation. In the meantime, the question might be raised of what evidence there was to support Mr Cooper's suggestion that under wet conditions a coefficient of 0·4 at 80 m.p.h., as measured by the Laboratory's small trailer, was required if a surface was to be considered satisfactory. The best evidence came from tests which they had made on runways where experience had clearly shown that in wet weather the surface was unduly slippery. So far they had tested ten, and in every case the coefficient had been below 0·3 at 80 m.p.h., whereas runways found by experience to be very good in similar conditions had given figures of 0·4 or more at this speed. That seemed to be reasonable evidence to justify the figure given by Mr Cooper.

44. Mr Giles had said that they had now tested more than seventy runways, so that the next question was how their performance compared with a criterion of this kind. He thought that the answer was encouraging. Rather more than half the runways had given a coefficient of 0·4 or more at 80 m.p.h., and for nearly 65% the coefficient was higher than above 0·3. A figure of 0·4 at 80 m.p.h. was probably what it was necessary to meet. It seemed clear that special consideration might have to be given to the means by which this kind of coefficient could be achieved, and that raised the question of what was the important property which the good surfaces possessed. He thought the answer was clear; it was that all the runways which gave high coefficients were of the coarser-textured kind. Surface dressings had been mentioned. The best coefficients had been given by runways which had been surface dressed, and runways of asphalt with pre-coated chippings were also in the higher group, but runways which had a fine-scale, sandpaper texture did not show up particularly well at speeds of the order of 80 m.p.h., and with such surfaces even having a good pattern on the tire did not make up for the lack of coarseness in the texture. There seemed to be clear evidence that, whatever

form of surface was being considered, to get high coefficients at high speeds it was necessary to have rather a coarser texture than had been considered in the past.

45. He thought that this was connected with the question mentioned by a previous speaker of the hydroplaning effect which seemed to occur at speeds of the order of 60 m.p.h. on wet surfaces. From recent work it seemed clear too that care should be taken to avoid concentrations of water on the surface of runways. Deep water on the surface could apparently give quite low coefficients, even on a surface which was otherwise good, and could also cause considerable drag. He could endorse, therefore, what had just been said about the need for good drainage. An interesting point was that a coarse runway surface might be thought to give rise to problems of tire wear. Mr Cooper had not listed low tire wear as one of the criteria for a runway. Whether or not coarseness of surface led to greater tire wear was a question on which evidence was wanted. Had Mr Cooper any comments to make on that?

Mr N. J. Payne (Partner, Frederick S. Snow and Partners, Consulting Engineers) stressed one aspect of Mr Giles's comments. Consultants and other engineers concerned with design needed some lead and guidance on how to produce surfaces which had good characteristics at high speed. It seemed obvious that the Road Research Laboratory were well on the way to being able to give it. The sooner that quantitative and qualitative results were available the better from the design point of view. It would then be possible to approach runway construction with a definite result in mind instead of adopting the hit-and-miss methods used in the past.

47. Turning to the question of prestressed concrete runways, he felt that it was necessary to go the whole way and eliminate the joints in concrete construction completely. He did not think that the solution lay in using reinforced concrete pavement, but he believed that there was a great future for prestressed concrete pavements, which were now beyond the stage of research. On a quick survey carried out recently, without any extensive investigation, his firm had found thirty-nine experimental and actual constructions of prestressed concrete pavements existing in the world today. They had arranged a visit to what was probably the only large prestressed concrete runway in use for some time in the world, at Maison Blanche. This runway had now been down for 5 years, and had suffered no trouble at all. He believed that the time of prestressed concrete runways had come and that they should be regarded as out of the experimental stage and in the stage when they ought to be constructed. They eliminated any of the troubles at which §§ 31 (*f*), (*g*), and (*k*) were aimed. High bearing strength was obtained automatically; the only problem to be overcome was that of the friction characteristics, so ably dealt with by Mr Giles. No doubt there would have to be some joints with prestressed concrete pavements, but there would be so few that it would be possible to concentrate on them and overcome the joint problem. Mr Payne's firm hoped to construct some prestressed concrete pavements in the near future, because they believed them to be the only way of developing high-bearing-strength concrete pavements.

Mr N. B. Bourne (Departmental Manager, Geo. Wimpey & Co. Ltd) suggested two further additions to Mr Cooper's list of requirements: resistance to frost—i.e. protection of the sub-base from frost, which was quite important in this country and more important still in some others—and resistance to tropical temperatures, which had a considerable effect on asphalt surfaces.

49. He questioned the statement that concrete was cheaper. Relative costs must depend very much on site conditions and available local materials. If the subgrade was bad, as it often was, it was always possible to put a fill on top of it which was somewhat better than the subgrade and gradually strengthen it, so that, having improved the immediate base, a flexible surface could be successfully used. The statement that concrete was always cheaper could not be borne out.

50. There had been some suggestion of putting asphalt on concrete. As a rule asphalters did not like it, because the cracks came through and the asphalter tried to avoid cracks. The asphalter would, Mr Bourne believed, suggest that asphalt could be

laid on asphalt, and if greater thickness was needed a weaker asphalt could be put underneath. Another suggestion, which might be linked with the proposal to use prestressed concrete, was to put concrete on asphalt. That would mean putting down a good impermeable base of asphalt, which would keep the water out of the subsoil and give reduced friction on the base of the concrete, and would make possible the use of a very thin slab of prestressed concrete, which would cope with the high point-loads.

51. It was claimed for both types of surface that they could prevent moisture penetration, but he thought that the balance was on the side of asphalt. Although the discussion was concerned only with surfacing, the effects of moisture going through the surface to the sub-base had already been seen.

52. The second Paper involved the question of stability. Many engineers did not like the Marshall test, but there was a good deal of confusion between the "Marshall test" and "Marshall design". Marshall design involved quite a different material from that of B.S.594:1958, where there was a matrix of sand and bitumen holding a little stone, whereas Marshall looked for stability to the interlock of stone and therefore used higher stone contents and lower bitumen contents.

53. The Authors of the second Paper had introduced a very dangerous little formula (which, incidentally, he did not think was quite correct) taken from the work of Dorman and Jarman, who said that the stiffness must be at least 120 times the tire pressure (which was questionable) and that the stiffness was $S_E = \frac{40P}{fl}$, *fl* being the flow measured in hundredths of an inch. He thought that the formula ought to be $P = 3p.fl$. If the tire pressure were taken as 300 lb/sq. in. and a figure of 15 taken for the flow, that would give the unlikely figure of $P = 13{,}500$. The difference was that the Marshall test was done at 60°C and with a loading time of about 5 sec. The conditions on an airfield in the United Kingdom, even when an aeroplane was taxying slowly, would probably be that the ambient temperature would be no more than 40°C (94°F) and might be lower, and at 20 m.p.h. the absurd figure of 13,500 would come down to about 750, which was quite easy to attain. Even at 50°C (112°F) one would need a stability figure of only 1,875, and that seemed to bring asphalt back into the picture again. It was true that the Marshall figures were often inconsistent, and Mr Bourne's firm's laboratory had found that the same Marshall mix gave varying figures according to the origin of the bitumen.

54. There was reference in §§ 25–27 to the fine achievements of the asphalt industry, but also a faint suggestion that it was only the industry which had produced the results. It should be part of the function of engineers to tell the industry not only what they wanted as a result, but how to do it.

55. In § 31 (*a*) (iii) the statement was made that "It follows that concrete pavements for airfields are generally more economical." By putting something on top of a bad sub-base with a low C.B.R. that C.B.R. could be raised.

56. The question of treaded tires had been raised in § 31 (*f*), but probably the special rubbers that had been mentioned by Dr Glanville in his James Forrest Lecture should have considerable application. Could one of the Authors throw any light on that?

57. Finally, referring to § 32, prestressed concrete would eventually come into its own, but the statement that slabs of only 3-in. thickness could give more strength than greater thicknesses of other materials seemed self-evident. The final question, of course, was what the cost would be.

Dr A. R. Lee (Deputy Director, Materials and Construction Division, Road Research Laboratory) said it had been interesting to see how well the asphalt industry had been able to make and lay, on a big scale, asphalt to the new specification which the Air Ministry had introduced into Britain from America. This technical achievement showed that the industry was reasonably progressive and, he thought, could be said to be as flexible in its methods as the product which it made.

59. The question arose, however, as previous speakers had mentioned, of why the Marshall procedure should be necessary to obtain asphalt which would resist the high

tire pressures of modern heavy aircraft. Mr Broome himself had shown elsewhere that there was no difficulty in selecting from B.S.594 compositions which would meet the stability values in the Air Ministry specification. Asphalt complying with B.S.594 had a remarkably good reputation for durability and resistance to deformation under the heaviest city traffic, and good resistance to skidding, and it had the advantage of being easy to make and to lay.

60. Dr Lee was puzzled by the claims made in favour of the Marshall procedure. He had been told by the people concerned at Vicksburg, where the Marshall test originated, that it had been adopted by the U.S. Corps of Engineers to enable the non-specialist to decide on the composition of asphalt which would meet the particular requirements of an aerodrome. He was sure that almost any mechanical test would be of some help in finding a solution to the problem of how to make mechanically stable asphalt when a soft or low-viscosity bitumen had to be used. The American Air Force specified a bitumen with a penetration value of 100. This grade was specified for asphalt to be laid in the cold of Alaska, or in the heat of New Mexico. In the United Kingdom that procedure would be regarded as quite out of the question, for bitumen of 100 penetration would be too soft for asphalt carrying heavy traffic on British roads. In fact, the first requirement in asphalt design in Britain was to decide on the hardness of bitumen which should be used for the particular traffic requirements; B.S.594 was clear on this point, and stated that for most purposes a penetration of 40 or 60 was required, and for heavy traffic 30 or 40 should be used.

61. So far as he knew, no research had as yet been carried out in America or in Britain to find what was the best grade of hardness of bitumen to use for asphalt surfacings on aerodromes that had to cater for the requirements outlined by Mr Cooper. Suggestions had been made by the Asphalt Institute of America and by the Road Research Laboratory for full-scale trials to be made at Vicksburg, with asphalt following the lines of B.S.594 and with a bitumen of suitable hardness, and both hoped that there would be an opportunity for experiments of this type to be carried out. A further difficulty arose when a soft bitumen was used; although the resulting tendency to deformation could be partly overcome by the choice of special aggregates and low binder content, as required by the Marshall procedure, the mechanical stability of the asphalt was very sensitive to chance variations in bitumen content. When there was a small increase, there was a much greater reduction in stability than occurred when a harder bitumen was used.

62. The question arose, therefore, of why the asphalt technique adopted by the U.S. Corps of Engineers should be so different from that of the asphalt industry in Britain. Perhaps it had arisen from the fear of the cracking which had been reported to occur on American roads, coupled with reports of earlier investigations of the hardening of asphalt surfacings in the United States. Those investigations claimed that cracking occurred from a hardening of the bitumen within the asphalt, and it was concluded that when the bitumen had hardened to give a penetration of about 20, the asphalt surfacing was bound to crack. It would seem that American asphalt must be very different in character from that which complied with B.S.594, because the Road Research Laboratory had found in their work that when good-quality bitumens were used in B.S.594 asphalt there was no, or very little, significant hardening of the bitumen in the body of the 2 in. of asphalt for 15–20 years. The hardening reported in American asphalt could occur only by penetration of air into the surfacing, and that apparently occurred more easily in American asphalt than in British asphalt. American asphalt was also prone to troubles caused by the penetration of water. The question arose, therefore, of why, in order to provide asphalt suitable for aerodromes in the United Kingdom, was it necessary to specify compositions which differed so radically from some of those in B.S.594, and which produced an asphalt with inferior properties.

63. Dr Lee was not condemning all mechanical tests. He thought that a suitable test could be of assistance in choosing materials and constituents which would give certain properties and might indicate the way to go in designing asphalt for use on aerodromes; but before a mechanical test was put into a specification there should be

very reliable correlation between the results of this test and the performance under the natural traffic conditions on aerodromes or roads. The conclusion from the work done at Vicksburg was that the Marshall stability value was not by itself a satisfactory indicator of whether or not an asphalt would deform under traffic. On the other hand, it was claimed that the flow rate correlated with the ability of the asphalt to resist deformation.

64. It was difficult to understand on what technical grounds such a test should form an important part of any practical specification for asphalt in Great Britain, and clearly evidence of correlation with aerodrome performance was required before the test should be used for the control of asphalt in the United Kingdom.

65. On the question of the properties of this asphalt, the choice of aggregates demanded by the Marshall procedure gave an asphalt which was relatively difficult to compact. Much rolling was required to obtain the necessary density, and, when this had been achieved, there was a danger of skidding at high speeds. British asphalt to B.S.594 could be compacted easily to a dense impervious condition, and when given a surface treatment of chippings it had the surface texture which Mr Giles had said was necessary for good resistance to skidding at high speeds. In conclusion, Dr Lee asked that, in view of the many superior properties of B.S.594 asphalt compared with Marshall asphalt, some consideration should be given to finding out how far the requirements set out so clearly in § 4 could be met by an adaptation of the type of asphalt which had proved so successful on roads carrying heavy traffic in Britain.

Mr J. M. Fisher (Technical Adviser, John Laing & Son, Ltd, London) referred to the question of ease of construction, particularly in regard to airfield pavements as a whole, and not just the surfacings.

67. The construction of a pavement in concrete for a modern airfield required a great deal of equipment, including mixing plant, transport vehicles (which were often of a special type), concrete spreaders, concrete finishers, joint cutters of various types (whether for making joints in wet concrete or for sawing in hardened concrete), and a good deal of formwork and other ancillary equipment. On the other hand, the construction of a flexible pavement could often be carried out with a much smaller range of equipment, which would include asphalt-mixing plant, transport vehicles (which were usually not of a special type), bituminous finishers, and rollers. The finishers could be made suitable for laying lean concrete or granular materials for bases and subbases with only slight modification. The greater range of application of machines of this type must be looked on as making its contribution to greater ease of construction of flexible pavement.

68. The laying of a concrete pavement was usually just one operation, or at the most two, where a lean concrete base had to be laid as a working platform or as an additional safeguard against deterioration of the sub-base, whereas a flexible pavement had to be built up in a number of comparatively thin layers.

69. Adverse weather conditions of rain and frost interfered with the construction of both classes of pavement, but normally in the United Kingdom concrete construction was more likely to be affected than flexible construction; however, some contractors were taking note of Continental practice and lessening the impact of bad weather on concrete construction by carrying out concreting operations under a mobile marquee, and providing protection in the form of movable covers for the first hours when the slabs were particularly vulnerable to weather conditions. An extension of this practice would be of advantage to the concrete interests.

70. With regard to riding qualities, he wanted to mention one point to which he had devoted a good deal of attention for some time. He believed that with the development of long-wheelbase articulated finishing machines and spreaders that really did spread concrete uniformly, a point had been reached where there could be no adverse criticism of concrete as compared with asphalt, but it might be some time before confidence in the ability of the contractor to produce a first-class concrete surface with the same facility as an asphalt surface could be established.

71. The current Air Ministry specification contained the requirement that at any point on a runway the surface level should be within 0·01 ft of that shown on the drawings. This small tolerance in levels was probably a valid requirement, but complying with it was less onerous where concrete was laid between accurately-set forms than it was when asphalt was laid without a precise datum from which to work. Was such a close tolerance in levels really necessary?

72. The question of skid resistance had already been dealt with at some length, but the comment might be made that concrete, when still unhardened, was in a condition amenable to any surface treatment that might be necessary. Brushing was already done to alter its characteristics. There seemed to be no great difficulties in devising some form of texture and the necessary machinery to apply it, so as to increase the braking-force coefficient to a degree that would prove entirely satisfactory.

Mr M. J. Tomlinson (Chief Engineer, Central Laboratory, Geo. Wimpey & Co. Ltd) said that since the engineering performance of the two types of surfacing were claimed to be equally good, the comparison could be made only on the basis of costs. It was therefore necessary to look at the problem as a whole and consider the whole pavement and not merely the surfacing. In the case of roads, the experience of his firm in tendering for major new construction work in the United Kingdom when alternative tenders were asked for, asphalt and concrete pavements for the same job, on the same soil, and under the same traffic conditions, was that the asphalt surface on a flexible or lean-mix concrete base was nearly always cheaper than the rigid concrete pavement.

74. So far as airfields were concerned, the Authors of the three Papers under discussion had all taken rather a narrow view of the type of airfield about which they were writing. They had all taken the case of airfields for very heavy civil or military jet aircraft with high landing and take-off speeds. In the world as a whole, however, very few airfields were required to carry aircraft of this type; the vast majority of them, in the civil field at any rate, were of the transcontinental or inter-city type, where the standard of runway performance could be very much lower. High quality of surface finish and surface level were not needed and the total construction thicknesses were comparatively modest. In fact, he had previously suggested[8] that in many parts of the world, and for aircraft of light or medium weight, there was no need for any pavement at all. On such airfields, which were in the great majority, a very economical form of low-cost construction could be used by putting a few inches of asphalt or bitumen-sand either directly over the subgrade soil or, where the subgrade was not good and climatic conditions were unfavourable, a few inches of asphalt over a crushed stone base. That form of construction could be carried out at a fraction of the cost of rigid concrete runways. Such runways would not be expected to give 100% satisfactory performance, but it seemed to him wasteful to cover a vast area of ground with a pavement having a high safety factor when, in the life of the pavement, only a very small proportion of it would receive any appreciable traffic load. Why not design to a factor of safety of less than 1, and accept a certain amount of repair work? From this point of view the asphalt surface, with its ease and rapidity of maintenance, had a great advantage over concrete.

75. The concrete pavement appeared to have advantages for the type of airfield about which the Authors had written, where the savings in overall thickness given by high-quality rigid paving were significant. For example, Snow and Payne[9] claimed that 12 in. of high-quality concrete over 4 in. of lean concrete had a strength equivalent to more than 50 in. of flexible construction on a clay subgrade of 3% C.B.R. An international airport might justify the use of concrete runways, but the advantage tended to be with asphalt flexible construction for the airfield of medium size where high performance standards were not required.

Mr H. Jennings (Superintendent, Air Ministry Directorate General of Works, Airfield

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[8] References 8 *et seq.* are given on p. 89.

Testing Laboratories, Cardington) remarked that with the tire pressure of modern bomber aircraft rising to 250 lb/sq. in., and of fighter aircraft to 300 lb/sq. in., the need for a surface having high stability, i.e. resistance to deformation under load, was essential. In the interests of durability, impermeability was equally important.

77. The second Paper emphasized that in the Marshall method of design and control, the stability value was only one of several criteria used as a basis for the design. It was very important to remember this and to remember also that the Marshall method related to asphalt mixtures within fairly narrow limits of mix proportions and aggregate grading. It was not a fundamental research tool and should not be used to compare materials having widely different characteristics. At present it did not seem possible to correlate the results of the Marshall test with any other mechanical test, except that, in general, material which satisfied the Marshall criteria seemed to perform well under full-scale wheel-tracking tests. One great virtue of the Marshall method of testing was the extreme portability of the apparatus, which made it a very convenient test to carry out in a site laboratory. It was also comparatively rapid in producing results, sufficiently so to enable material which had been laid and which the test indicated to be faulty in composition to be removed before it hardened.

78. There was need for fundamental research into those properties of aggregates and mixtures of aggregates which led to high stability. A rough surface texture was one, and absorption also seemed to have a big effect. Mr Broome, in introducing the second Paper, had referred to a stability of 2,750 lb. on Christmas Island with a coral aggregate, largely due, no doubt, to the high absorption of the coral. Mr Jennings's department had found even higher results with Malta Corallian limestone. The influence of particle shape also deserved thorough investigation. In the main, the inherent qualities of the aggregate and the particle size distribution had the major influence on the stability, and the stiffness of the binder was of relatively minor importance in this respect except at high pavement temperatures.

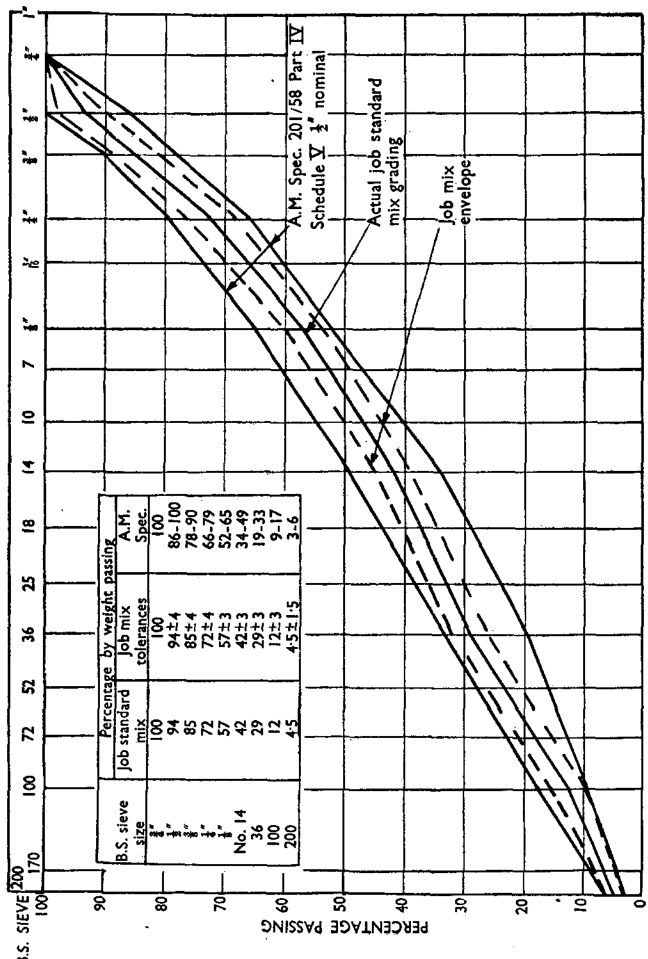
79. On the question of specifying stability at a temperature of 60°C, there were three considerations which Mr Jennings regarded as important. The first was that during the recent summer there had been experience of pavement temperatures of 130°F, measured on asphalt. That was 54°C—not far short of 60°C, and it did not leave a great margin of safety, even in Britain, and it should be remembered that the Air Ministry's interests in this respect were world-wide and therefore higher temperatures might have to be met. Secondly, to lower the test temperature would increase the loading on the machine, and that would increase the weight of the machine and its cost. Thirdly, a change in the test temperature would mean that the results obtained in Britain and America would be difficult to correlate and standardization would be lost.

80. Research seemed to be necessary into the causes of the scatter of Marshall stability test results, and the degree of repeatability and reproducibility which was possible.

81. An asphalt surface had to be impervious if it was to be durable and free from recurring maintenance costs. B.S.594 asphalt had a great reputation in this respect and experience had shown that a Marshall-designed surface having not more than about 5% air voids would be impervious. This could be ensured by careful attention to void ratios at the design stage and close control of field compaction. The importance of this, owing to the relatively low binder content used compared with B.S.594, could not be over-emphasized. A good deal of the criticism levelled at the Marshall method of design had been directed at the resulting relatively low binder contents with the suggestion of poor durability, but the grading of the complete aggregate mixture was closely controlled, with the result that not only the voids in the aggregate mixture, but also the specific surface, were held reasonably steady. It was therefore practicable, not only to use less binder, but also to maintain the percentage of binder at a fairly constant figure, and, if the required degree of control was maintained, it would be as durable as the traditional asphalt, which, though normally richer in binder, was not subject to the same tight control.

82. The quality control of asphalt was limited to certain tests in B.S.598. The

introduction of the Marshall test had supplemented the analytical tests with a comparatively rapid physical test on conformity to specification, giving results controlled by the five specified criteria of density, stability, flow, total voids, and voids filled with binder. Fig. 1 was a typical grading chart for a Marshall-designed wearing-course mixture, showing the actual job standard mix grading, the job mix envelope (derived



B.S. sieve size	Percentage by weight passing		
	Job standard mix	Job mix tolerances	A.M. Spec.
3/4"	100	100	100
1/2"	94	94±4	86–100
3/8"	85	85±4	78–90
1/4"	72	72±4	66–79
1/8"	57	57±3	52–65
No. 14	42	42±3	34–49
36	29	29±3	19–33
100	12	12±3	9–17
200	4·5	4·5±1·5	3–6

FIG. 1.—TYPICAL GRADING CHART FOR MARSHALL-DESIGNED WEARING-COURSE MIXTURE

from the job standard mix by applying the specific tolerances), and the overall grading envelope permitted by the A.M. Specification. Quite small changes in particle size distribution, which might arise from errors in batching or a load of badly graded or segregated material in the stockpiles, etc., might lead to big differences in stability, and relatively small variations in binder content would immediately affect the voids ratios. It was therefore possible, without carrying out a complete analysis of the mixture on every occasion, to indicate tendencies to deviate from the specified job standard mix.

That was the mix which, based on the laboratory designed mix, was accepted as the best which the plant could produce with the selected aggregates. Limits above and below that selected mix were specified, the resulting job mix envelope usually being well within the overall permitted grading limits. Two stages of quality control were therefore available—Marshall physical testing and B.S.598 analysis. The former gave a warning when the physical properties tended to depart from the accepted criteria for the job, and the latter gave confirmatory evidence of deviations from the job standard mix in respect of grading of the aggregate (including filler) and/or binder content. Further experience should enable a statistical basis to be given to this method of control, which would then compare favourably with the best in concrete practice. So far as Mr Jennings was aware, this had not been exercised, so far, in the production and laying of asphalt.

83. There was probably room for further development in rolling techniques, not so much to ensure satisfactory densities, which seemed readily attainable if care was taken, as to improve the texture of the material at, and immediately below, the surface. The use of self-propelled rubber-tired rollers was one possibility which looked promising.

Mr A. J. Harris (Consulting Engineer) said that prestressed concrete runways had been mentioned, and in Mr Hill's Paper there seemed to be a suggestion that they were unnecessarily strong and of doubtful economy. It might be useful, therefore, to give the test results and a breakdown of the cost of an apron which had been completed a year or so ago in front of the Transair hangars at Gatwick. It was only about 7,000 sq. yd in all, but was of somewhat eccentric shape, laid in situ by hand in longitudinal lanes of 15 ft, prestressed longitudinally the day after laying, and later prestressed transversely. After longitudinal prestressing it had been necessary to add an extension at one end, which had required some delicate and expensive stabilizing operations but had been carried out successfully. The slab was 5 in. thick, lying on 3 in. of dry, lean sub-base, lying directly on the ground with no compaction whatever. The cable was laid in the 5-in. thickness.

85. After completion of stressing the apron had been fairly extensively tested by the Road Research Laboratory, with fourteen loading points in all. He would describe a few which were fairly typical. One had been loaded with an 18-in.-dia. plate tangential to one of the longitudinal joints. There had been 1,000 applications of a 19-ton load on that plate, and a further 1,000 of 27·5 tons, and then a further 330 applications of 41·2 tons. (27·5 tons corresponded to L.C.N. 100 and 41·2 tons to L.C.N. 100 × 1·5, which they had regarded as very satisfactory in view of the fact that the runway was designed for L.C.N. 75.) In addition, a number of isolated point-loads had been applied up to values of 69 tons. The earlier test produced some spalling round the edge of the loading plate, which of course was rigid, and a surface crack appeared about 3 ft away from the centre of the load, which in the familiar manner closed up again when the load came off, and it had been impossible afterwards to find where this loading had taken place. That had been followed by numerous single applications of loads of from 60 up to 69 tons.

86. The prices had worked out as followed:—

	per sq. yd
Excavation	*9d.*
Concrete sub-base	8*s.* 2*d.*
5-in. concrete slab	19*s.* 11*d.*
Stressing	19*s.* 10*d.*
Total cost (average)	48*s.* 8*d.*

One or two comments might be made on those prices. That for the 5-in. concrete slab included the alleged lubricating layer of ¾ in. of sand and wax paper. The stressing figure covered everything—the tendons in their ducts, the anchorage blocks, the stressing-up, and the gauging after completion. That figure required some comment. It had been a very small job and there had been special features in it.

87. Where would economy be expected on a larger job, a full-scale runway, having the same characteristics? The excavation figure might well go up; they had been fortunate in having very little excavation to do, though naturally, having a very thin slab, they might expect it to be lower. No comment was needed on the second item. The 5-in. concrete slab had been laid by hand, and on a larger job appreciable economy should be obtained by the use of machinery. So far as stressing was concerned, on a large runway it would be possible to stress by the use of steel tendons in one direction only. Mr Payne had made the point that it was desirable to reduce transverse joints to the minimum. It was in fact possible to dispense with them entirely. There were four different ways of doing this, and, since it was desirable in any circumstances, it should generally be done. By doing this the quantity of steel and all the labour included in the stressing figure would be divided by two, so that there would be a saving of nearly 10*s*/sq. yd. There would be some additional expense owing to the various other devices which had to be employed, but the cost of these was very much smaller than the saving.

Dr R. H. H. Kirkham (Head of Concrete Section, Road Research Laboratory) said that there were a few points concerning concrete construction where experience on roads might be relevant. In considering the economics of construction, Mr Cooper had suggested that the thickness of concrete might sometimes be too great for a single slab and that in these conditions composite construction with an asphalt wearing surface on a concrete base might, if it enabled a single base slab to be used, prove cheaper than concrete construction. With modern techniques of compacting concrete pavements, however, it seemed unlikely that it would be found necessary to use twin slab construction. Washbourne and Bell[10] had mentioned a maximum thickness for airfield pavements of 23½ in., and suggested that although surface vibrating machines were usually incapable of compacting slabs of this thickness, it could be done by heavy-duty finishers equipped with internal vibrators. That type of machine had not been popular in the United Kingdom, probably because internal vibrators would not deal with concrete of as low a workability as could be handled by a surface vibrator, and because many engineers felt that the use of internal vibrators might lead to planes of weakness in the concrete.

89. Research work on the compaction of concrete from the top surface had shown, however, that depths considerably in excess of the conventional 12 in. could be compacted with one pass of the vibrator. Work done with an experimental vibrator, in which it was possible to vary the characteristics of the vibration, had shown that the depth of compaction could be increased by increasing the amplitude of vibration, or the weight of the beam or by increasing the number of vibrations by reducing the forward speed of the machine. By doing all those things together it was possible to get, therefore, a considerable improvement in the depth of good compaction. For concrete with a compacting factor of 0·82, the depth could be increased to over 20 in. in a very thick slab, and on a slab where there would be some reflexion of the vibration from a well-compacted base, thicknesses up to those asked for by Washbourne and Bell[10] could be achieved. Also, tests carried out at the Technische Hochschule at Stuttgart, with modern German equipment, had shown that it was possible, using the slightly more workable concretes that were common on the Continent, to get full compaction to a depth of 23–25 in. It seemed, therefore, that for airfield construction it should in future be necessary to consider only single-slab construction.

90. Reference had been made by several speakers to the need to achieve good riding quality in airfield pavements. It had been suggested some years ago in America[11] that at high speeds rhythmic irregularity was the most objectionable form of unevenness, and in the past joints had often been blamed for this. Experiments during the construction of a number of concrete roads, however, had suggested that some of the rhythmic irregularity which had been attributed to joints might more correctly be attributed to

errors in the setting, or to settlement of the formwork. Irregularity due to the forms could be removed most easily if the finishing machine was modified so that the finishing screed was supported between the framework of the machine and a trailing bogie. Mr Fisher had already suggested an articulated machine. Irregularity indices on a road constructed in 1959, before and after this modification was made, had been obtained. Before the modification the average figure was 48 in/mile, and after the modification it was 33 in/mile. It was clear that with proper techniques it should be possible to lay runways with an irregularity index of less than 40 in/mile.

91. The problem of skidding with the increasing speed of jet aircraft needed consideration. It was a difficult one, because measurements on a new surface might not always give a complete picture of the skidding resistance of the surface throughout its life. The results of weathering and traffic on skidding resistance had been examined on an experimental road constructed about 10 years ago. When the surface had been new the sideway force coefficient at 30 m.p.h. varied from 0·4 to 0·7, these differences being related to differences in methods of construction. After 7 years under traffic, however, those differences had largely disappeared and all the sections in the fast lane had coefficients between 0·52 and 0·59. In the slow lane the skidding resistance was appreciably less, but again there was little difference between the sections. After several years weathering and traffic, therefore, the surface treatment appeared to have little effect on the skidding resistance. In making comparisons between surfaces, therefore, the time at which the test was made was of considerable importance.

92. The same sort of difference had been shown on another experimental road, where there were different types of surface finish. The concrete, made with a flint gravel aggregate and compacted with hand-operated vibrating screeds, had some sections left untreated, while others had been treated with hair, bristle, or wire brooms. It had been found that the use of a soft broom had no value, even when the surface had been new, in increasing the skid resistance, and although the skidding resistance of the new surface could be improved by brushing with a stiff broom, there had been little difference after 2 years of traffic. Although the traffic on runways was likely to be less than that on roads, this should obviously be borne in mind when considering brushing as a possible treatment to give high skidding resistance.

Mr A. W. Jarman (Shell Mex and B.P. Ltd) observed that the Papers indicated that the law of demand and supply had reached a very happy balance. A service department had stated its requirements logically and functionally, and the industries concerned had explained how well their present materials fulfilled those requirements. Had there been some marked conflict of views between the various Authors it might have been interesting to have debated the respective arguments, but it would be impertinent to challenge the harmonious tranquillity which evidently existed.

94. It was acknowledged that the Papers dealt specifically with airfield surfacings as distinct from complete constructional design, and that may have avoided some of the more contentious points which exercised the minds of those concerned with the scientific exploration of the latter subject. There was, however, still the question of testing, and the reference to 23,750 tests conducted during the surfacing of a single airfield indicated the consideration which may well be given thereto.

95. Testing could be classified into at least three categories: design, control, and performance.

96. Testing for design was intended to determine the composition expected to give a satisfactory performance; testing for control should ensure uniformity of execution; testing of performance was a measure of the extent to which both of those objectives had been achieved.

97. In the field of asphalt, as perhaps in many others, much of the testing was largely arbitrary and its validity sometimes doubtful. Messrs Attwooll and Broome had indicated that the Marshall system might have been introduced into the United Kingdom chiefly on account of its convenience and its existing acceptance in the United States.

Both were worthy reasons, but they were not scientifically convincing and some explanation of its validity would have been helpful. Similarly, the performance tests quoted were impressive but they lost some significance through lack of comparative data on alternative surfacing compositions to indicate their sensitivity. Control testing was an accepted industrial precaution, but its extent was a matter of opinion. Did the Authors believe that as many as 23,750 tests were really justified?

98. There was little doubt that the asphalt industry had reacted with commendable enterprise to the demands of current airfield surfacing. It was encouraging to learn that it already had some margin of safety in hand over existing requirements, and that it could face with equanimity the prospect of them becoming more onerous.

99. It was comforting to reflect that the suitability of asphalt rested upon many years of satisfactory experience, and that while minor modifications might be adopted to meet particular specifications, its intrinsic merits could be accepted as well proven.

Mr A. F. J. Grant (Superintending Civil Engineer, C.E. in C's Department, Admiralty) was surprised that Mr Hill had made such scant reference to double-slab construction; in § 30 it had been mentioned, in connexion with 18-in. slabs merely as a preference. The experience of the Admiralty with airfields for Royal Naval Air Stations had generally, under the conditions studied, led to a preference for double-slab construction, which offered definite advantages. In the past, the limitations of the sort of plant that had been available to contractors in the United Kingdom for compacting beyond 12 in. had been in favour of the double slab. If an assurance could be given that British contractors generally had available the type of plant described by Washbourne and Bell[10] the question of compaction need not be taken into account; but there was still a very large factor in favour of double-slab construction, namely, the economic factor.

101. Recently the Admiralty had made a detailed study of an airfield in which they had compared the cost of double-slab work with the cost of single-slab work. The double-slab construction was a 7-in. upper slab on a 6-in. lower slab, separated by waterproof paper or polythene sheet, laid on 4 in. of consolidated hardcore. The transverse joints and longitudinal construction joints formed 15-ft-sq. panels and all joints in the top slab were staggered relative to those in the bottom slab. The advantages claimed for that form of construction from the point of view of temperature effects, load distribution, and so on were too well known to need repeating. Against that, the single-slab construction consisted of one 13-in. slab of concrete with dowel-bars at expansion joints and tie-bars at all construction joints. The paving slab was laid on a 4-in. base-course of dry lean mix, which was considered necessary for this form of construction. Those two forms of construction had been priced, based on alternative tenders submitted by contractors for another job.

102. In analysing the costs of these alternatives it had been found that the actual concreting itself cost about the same, whether there were two slabs with a separating membrane or a single slab, but the dowels and tie-bars put the cost of the single slab up about 3½% more than the cost of the double slab. There was then the question of the dry-lean-mix base-course under the single slab, whereas under the double slab there was simply hardcore. That sent up the cost of the single-slab construction by another 16½%. They had found, therefore, that apart from the greater strength of double-slab construction it had definite economic advantages. It might be objected that the 13-in. double slab was over-designed for its load, because it was capable of carrying a greater load than the 13-in. single slab, but that might be of advantage in future. With greater slab thicknesses the relative advantage of double-slab construction became greater. Generally speaking, therefore, they felt that double-slab construction for airfields had definite advantages.

The following contributions were received in writing.

Mr C. F. Hoare (Superintending Civil Engineer, Air Ministry) stated that while Messrs Attwooll and Broome had quite rightly mentioned that hot-rolled asphalt laid to Air Ministry specification could be attacked by fuel spillage and by jet blast, the Paper ended on a confident note by stating that clearly the asphalt industry had met all the needs of Service and civil airfields without difficulty. However, if asphalt surfacing material was to be improved upon, an asphalt for general use, and in the normal price range, which was resistant to fuel spillage and jet blast, could represent a considerable technical advance over the present material. He was sure the industry would not overlook that requirement, which remained unfulfilled in the normal price range for those materials.

104. In Mr Cooper's Paper insufficient attention had been drawn to the necessity of developing a new pavement material capable of being laid without joints. The problem of producing jointless pavement material was mentioned under the heading "Good riding qualities", and the possible evolvement of a new surfacing material or new techniques was referred to in § 3, but that aspect of development warranted greater emphasis. A large area of concrete pavement was in use and much of the maintenance of pavement-quality concrete surfaces was directly attributable to the joints or to the material in the joints, and Mr Hoare suggested that yet another heading should be added to the twelve fundamental requirements in § 2, and the requirement stated as "Ability to be laid without construction joints". Prestressed concrete was not the complete answer to the problem, and therefore it should be emphasized that research should be directed to the development of a surfacing material which had the qualities of high-grade concrete as regards durability, resistance to fuel spillage and to jet blast, resistance to high point loading, and could be laid without construction joints.

105. Lastly, the Author had specifically stated that no attempt had been made to substantiate a case for either asphalt or concrete in pavement work. Whereas engineers in daily touch with airfield problems knew that in the United Kingdom it was customary to surface certain areas with one material, say asphalt, and to use concrete to meet another set of conditions, Mr Hoare felt that it would be very useful to have current trends recorded. No doubt there were reasons for not summarizing present-day practice in the Paper. Would the Author comment on this?

Mr Cooper, in reply, observed that several contributors had dealt with the question of the design and construction of the airfield pavement in its whole depth, whereas his Paper was intended to deal with the requirements for the top of the wearing surface itself. The word "surfaces" had been included in the title of the Paper for that specific reason. Remarks on the overall design were most welcome, but the fresh points raised would require very length answers if they were to be dealt with adequately. He therefore proposed to cover fully all contributions to his Paper which fell within its original scope, and to provide general comment only on the wider aspects that had been raised. There was clearly scope for further Papers on such subjects as the design of asphaltic mixtures and the use of prestressed concrete for airfield pavements.

107. Mr Cooper fully agreed with Mr Alston that pavements deliberately given a rough surface to eliminate skidding would increase tire wear. That was the penalty for high landing speeds, but the aircraft designer would have to deal with that aspect himself. The reversible propeller was a helpful contribution to this end; reversing of jet thrust was a more difficult problem.

108. There was no doubt that longitudinal and transverse gradients also affected the skidding problem, and standing water, associated with sufficient bumping to cause the wheel to bounce and plane, was a phenomenon that required closer study. Mr Giles had also referred to this point, and there was clearly a need for further research into the behaviour of tires at speeds upwards of 120 m.p.h. on surfaces of various types, particularly when wet, and where water was standing. The design of the surface of the tire itself might well affect its behaviour.

109. Mr Payne and Mr Harris had both put forward the case for prestressed concrete. That was a question of design rather than of surface requirements. However, there was no doubt that a prestressed concrete runway would be built when a suitable opportunity presented itself. Such opportunities were, unfortunately, rare in the United

Kingdom; almost all airfield pavement construction consisted of extension, widening, and strengthening of existing pavements, with all the attendant difficulties of piece-meal planning.

110. Mr Bourne had mentioned two additional requirements, namely, protection from frost attack and resistance to tropical temperatures. Those were, of course, valid additions to the list, which could be extended almost indefinitely. It was not intended to suggest that concrete was cheaper than asphalt; the circumstances in which one or other type of construction would be the more economical had been mentioned in § 2 (*a*).

111. Dr Lee queried the use of the Marshall procedure in the Air Ministry specification. That again was a point not wholly within the scope of the Paper. However, Mr Cooper thought that introduction of the Marshall procedure was intended primarily to meet the need for a rapid site test for quality. No doubt, in time, it would be superseded by something better; the fact that it was included showed anxiety to seek constant improvement in the specification.

112. Mr Fisher had referred to the rather stringent tolerances which the Air Ministry specification laid down for surface levels. Modern aircraft undercarriage configurations, particularly of the fore-and-aft type, were very sensitive to longitudinal undulations as opposed to local bumpiness. A form of rhythmic bucketing could commence under certain conditions, which was obviously extremely dangerous. Undoubtedly, the specification would be relaxed as soon as it was practicable to do so.

113. Referring to Mr Tomlinson's remarks, Mr Cooper agreed that the list of requirements given was that for the large civil or military airfield. He personally had had little experience of the lighter type of airfield for limited, low-loading use, but agreed that considerable economies could be effected. Experience in the United Kingdom with flexible construction had not, however, been altogether happy, primarily owing to the rather unpredictable nature of the climate. He thought that a relatively thin cement stabilized soil or lean-mix concrete base would be preferable to a compacted gravel or stone base; the extra cost would be an insurance against total failure through waterlogging during construction.

114. Mr Cooper was interested in Mr Jennings's remarks which, to some extent, supplemented Dr Lee's contribution and met his comments. He agreed with Mr Kirkham that depths of concrete in excess of 12 in. could be laid satisfactorily in one operation. In fact, 16 in. had been laid successfully on more than one location in the United Kingdom. No doubt industry would develop and produce the forms which were necessary to construct depths greater than 12 in.

115. Dr Kirkham's remarks on the effect of weathering and wear on the skid-resistant properties of a surface were extremely interesting. Obviously, that factor must be taken into account and, where the construction had been designed to provide a surface suitable from that point of view, it must also be capable of retaining the initial properties, or of having them restored periodically in some relatively simple manner. That aspect must be included in any programme of further research on the subject.

116. Regarding Mr Hoare's remarks on jointless concrete, it seemed to Mr Cooper that a certain number of joints would always be necessary. Even if, by some tremendous technical advance, a concrete could be developed that did not shrink on setting and had a coefficient of thermal expansion of zero, there would still be construction joints. There was no doubt that jointless concrete would be searched for as an ideal, although it was doubtful if it would ever be attained. The protagonists of prestressed concrete might not accept that that form of construction would not eliminate joints completely by making use of diagonal tensioning.

117. It was true that the operating conditions did, in some instances, dictate the type of surface to be used for airfield pavements. That, however, applied only to relatively small areas; for example, the construction adopted for the length of a runway, except for the ends, could be in any material that would meet the requirements. The decision on the material to be used depended on many factors and, in the long run, the

controlling factor was one of economics. Mr Cooper was not in a position to summarize present-day practice, nor was this within the scope of his Paper. In any event he doubted the value of such a summary unless each individual case gave the reasons for the choice of the form of construction, and also the loadings and other factors on which it was based.

118. Mr Cooper expressed disappointment that his challenge in the last paragraph of his Paper had gone without comment. He had hoped that something might be said on the possibility of new developments in pavement construction. In the U.S.A. considerable experiment on soil stabilization by chemical additives had been in hand for some time, and he was sure that Britain would not be completely inactive in that field. Mr Jarman had referred to the harmonious tranquillity that the three Papers evidenced, but Mr Cooper hoped that this did not reflect a sense of complacency regarding the two traditional methods of construction.

Mr Attwooll and **Mr Broome** emphasized that they did not necessarily support the use of the Marshall system for asphalt surfaces generally. It should not be applied at the present time to the design or control of asphalt surfacing for roads along the lines of materials covered by B.S.594. The system had been introduced by the Air Ministry and, in common with others, the Authors had had to follow it. Nevertheless, experience had shown that for the type of mixtures required by the Air Ministry it was a useful system of design, although there was a tendency to over-design some of those mixtures which then inevitably suffered in respect of durability.

120. The Authors agreed with Dr Lee that it was not necessary to employ the Marshall system of control once the specification had been designed. With the narrow tolerances allowed in the Air Ministry specification it would be possible, with suitable equipment, to do the control through composition by analysis, rather than by the Marshall system. That could well be done more rapidly and would obviate two systems of testing which were necessary at present.

121. If some system of mechanical testing was required the Marshall method had advantages, and it was a test that did not require elaborate apparatus, and could therefore be carried out in the field.

122. The question of the temperature of test was a controversial matter which obviously could be amended only if it was necessary to do so as a result of practical experience. It would not have been feasible to introduce this test at short notice, and to try to set up a new set of requirements at a different temperature.

123. The points raised by Mr Jarman were not entirely logical. In § 93 he had, indicated that the asphalt industry had shown that its materials fulfilled the stringent requirements of the Air Ministry, which were presented "logically and functionally"; and yet he had questioned the validity of the system of testing quoted. Here again it must be pointed out that the Marshall method had not been introduced by the asphalt industry, but had been met on the instructions of a Service Department. That also applied to the required volume of testing which Mr Jarman had queried; obviously, if such stringent precautions regarding the uniform stability of the surfacing were laid down, the frequency of control testing must be continuous. That was the justification for the considerable number of tests quoted in connexion with a particular contract. Whether the same results could have been achieved by some other method of testing, such as the Authors had already indicated, was not relevant; the official requirement in respect of method was laid down, and the number of tests had been quoted simply to show that to comply with the specification the Marshall system did necessitate quite extensive personnel and equipment.

124. In reply to Mr Hoare's comments in § 103, the Authors explained that the run-up areas and aprons constituted a very small percentage of the total area of runways—in fact, not more than 2% of the total surface area involved. Special types of flexible surfacing had been evolved to deal with the problem of attack by fuel spillage and jet blast. Even if those limited areas were laid in concrete, as was quite customary, their opinion expressed in the conclusion to the Paper was not affected.

Mr Hill, in reply, referred to changes in the design and construction techniques of concrete airfield runways which had taken place since his Paper had been written. Many of these related to the spacing of joints, which he considered could still be safely increased with advantage and economy.

126. Increasing use was being made of reinforcement in the slab. Modifications of the type of bar and spacing, as well as the quantity of steel, were being tested. It was considered that a steel content of about 0·3% of the cross-sectional area of the slab was sufficient to control cracking to the extent that ingress of water to the subgrade was prevented. In practice that amounted to about 10 lb/sq. yd in a 9-in. slab. With reinforced construction, the need for expansion joints was reduced and their spacing was being increased to 300 ft or more.

127. With unreinforced slabs, the size of bay and the spacing of joints was also increasing. The 20-ft × 20-ft bay was being adopted for slabs 10 in. or more thick, and with slabs of that size expansion joints were often not required, or their spacing could be considerably increased.

128. Mr Hill thanked Mr Alston for correcting the figure for the minimum thickness of overslabbing given in § 31 (*m*); the thickness should be 5 in., not 6 in. He also thanked Mr Alston for drawing attention to the alternative method of marking on concrete runways. Problems regarding the development of efficient jointing and sealing materials had yet to be solved in order to reduce the problem of joint maintenance. That was almost the only problem still unresolved with concrete-surfaced runways.

129. Although only brief reference had been made in the Paper to prestressed concrete runways, Mr Hill was convinced that much greater use would be made of that medium of construction in the future. He thanked Mr Payne and Mr Harris for the evidence they had brought forward in support of that view. Very few joints would be needed and, although they might be larger, the opportunity would arise for a new approach to the problem of slab movement. It was very necessary that in Britain experience of the efficiency of prestressed concrete pavements should be gained, and once it had become an accepted method of construction rather than a novelty it would become cheaper. Economy of material, even when no economy of cost arose, was necessary in the national interest. In reply to Mr Bourne, a thin (3-in.) prestressed concrete slab could be laid on an existing asphalt surface that needed strengthening, but it was uneconomic and unnecessary to lay a new asphalt base to receive such a slab. There were cheaper methods of providing a suitable sliding layer.

130. The question of skid resistance and its relation to the surface texture of the concrete had been mentioned by several speakers, and the discussion had shown a divergence of opinion. In Mr Hill's view that was a matter both for the designer of the aircraft and for the airfield engineer. Attention to the use of treaded tires and special rubbers would reduce the requirements from the runway. A very wide variety of surface characteristics could be provided with concrete, from the smooth sand-paper texture produced by brushing to the rough texture produced by exposed aggregate laid in the surface at the final finishing operation as Mr Fisher had indicated. Once the required surface characteristics were determined, they could be provided in the concrete runway without difficulty and with only slight modifications of existing laying techniques.

131. The confusion arising from the interpretation of test results had been shown in the discussion. The methods of test were not adequately related to practical conditions, and more testing with operational aircraft seemed to offer the best scope for a realistic appraisal.

132. It was possible with concrete to provide any degree of surface characteristic necessary for a specified skidding resistance, and the results of the tests reported by Dr Kirkham were of particular value in showing that initial values could be maintained for many years under traffic conditions.

133. One of the important developments on site projects in concrete in recent years had been the ability to provide a surface profile of very low q-values, and specification limits had been continually narrowed, resulting in improved riding quality. Finality in

this respect had not yet been reached, but it was not at present a factor likely to operate against the use of concrete airfield surfaces.

134. The question of economics had been raised and clearly the only satisfactory solution was to invite competitive tenders in each case considered. Since, however, most new aerodrome sites were in areas where other construction was not economically possible, the strength of the subgrade was lower and a large thickness of flexible construction was the alternative to a moderately thick concrete slab. The heavier the aircraft loadings, the greater the economy arising when concrete was used. An excellent example to illustrate this point arose in the Paper by Snow and Payne[9], where the alternative to a 12-in. concrete slab on a 4-in. lean concrete base was 50 in. of flexible construction. In reply to Mr Tomlinson, a minimum thickness of concrete constructtion would, in certain favourable cases, provide greater strength than was immediately required for a city airfield, and a cheaper form of construction could be provided in alternative materials. With the pattern of development elsewhere as an example, however, it might not be considered uneconomic to provide some insurance against future growth.

135. In considering the cost of airfield pavements, some regard should be made to likely future growth. In the past, undue caution at the construction stage on many airfields had resulted in comparatively costly strengthenings within a few years. Even today, although some authorities doubted whether the overall weights of aircraft would be greatly exceeded in the forseeable future, an increase in traffic density was expected. It was therefore wise to include a strength figure as high as possible when planning a new, or strengthening an existing, airfield; a very small increase in concrete thickness gave a large increase in bearing capacity. It was the duty of the engineer concerned with the design of an airfield pavement to consider this aspect, since resurfacing a few years later was expensive and often caused considerable dislocation to traffic.

136. The relative advantages of thick, single-slab construction and double slabbing had been discussed in relation to overall economy, without a satisfactory conclusion. Mr Hill considered that it was also dependent on the site, the extent of the work, and the plant available to the contractor.

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