# THE DESIGN OF BRITISH AIRPORTS AUTHORITY PAVEMENTS

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## INTRODUCTION

1. The British Airports Authority (BAA) currently owns and operates seven major airports within the United Kingdom, namely the three London airports, Heathrow, Gatwick and Stansted, together with Prestwick, Edinburgh, Aberdeen and Glasgow in Scotland. These seven airports handle 73 per cent of all passengers and 84 per cent of the air cargo traffic in the UK.

2. The BAA is responsible for the development, planning, design and construction of all new projects together with the maintenance of the existing installations at these airports, other than in the few areas leased to airline operators, oil companies and other ancillary service organisations. It undertakes all associated aircraft pavement design and evaluation to its own criteria which incorporate, as a minimum requirement, the technical standards sought by the UK Civil Aviation Authority (CAA) as detailed in their publication CAP 168 "The Licensing of Aerodromes"; the latter incorporates the international recommendations contained in ICAO publication "Annex 14 - Aerodromes". The design and evaluation of the pavements are fundamentally based on the Load Classification Group (LCG) system.

3. The BAA Planning, Engineering, Operating and Management expertise is made available world wide through the Consultancy Service branch of the Department of Planning.

## LOADING

4. The stresses produced in pavement by aircraft are made up of three main factors: the all-up weight, the undercarriage configuration and the tyre pressures. The same considerations also relate to service vehicles and ancillary equipment such as tugs. Speed is ignored; aircraft at touchdown are still partially airborne and, although they can impose relatively large impact loads, the undercarriage design is such that the vertical components are small; it is the static loads that are therefore considered to be critical.

5. Within the BAA the direct load to be used for a particular project is defined in one of three ways:

5.1 The All-Up Weight (AUW), using the manufacturers' published figure for Maximum Take-Off Weight.

5.2 The Operating Weight, a declared maximum stipulated by the airline operators. This is less than the AUW, usually as a result of physical limitations imposed by such factors as the runway length or the height of the aerodrome above sea level.

5.3 The Load Classification Number (LCN) of the aircraft.

6. The LCN system was developed by the UK Air Ministry in the late 1940's after extensive testing of existing pavements. It was a practical solution to the problem of forecasting pavement behaviour under the ever-increasing loads of developing aircraft. The pavements were tested and a relationship established between the failure load and the contact area through which it was applied. As the contact area of a tyre is proportional to the load and tyre pressure, a standard curve was able to be plotted representing the range of loads and tyre pressures for a single wheel load that produced the same stress in the pavement. An arbitrary index termed Load Classification Number (LCN), ranging from 10 to 100 in equal increments of load, was applied to the curve, and a chart relating single wheel loads to tyre pressures at various LCNs was developed. The multi-wheel undercarriages were accommodated within the system by conversion to an Equivalent Single Wheel Load (ESWL) which, acting in isolation and at the same pressure as the related group of wheels, was considered to produce similar maximum stresses as that group.

7. By reverse procedures, and the inclusion of a safety factor dependant upon the anticipated load repetition or number of aircraft movements, the LCN system became a method of pavement design as well as evaluation. In revised form the system was adopted by ICAO in 1957. It was initially published in "Part 4" of the "Aerodrome Manual" and, in 1965, republished in "Part 2" of the second edition of the manual.

8. In 1971 the UK Department of the Environment (DoE) introduced the Load Classification Group (LCG) system. It comprised seven groups, from I down to VII, encompassing a range of modified LCNs representing aircraft which imposed similar stress levels on pavements of defined construction and thickness. Rigid, flexible and composite construction, sub-grade evaluation and the flexural strength of Pavement Quality Concrete (PQC) were accommodated within the single design and evaluation chart.

9. The system allowed, with an acceptable degree of accuracy, a simple comparison between pavement strengths and aircraft having both single and multi-wheeled landing gear. It recognised that mathematical precision was unjustified because of the number of variables involved and the practicalities of construction. BAA use this method of pavement designation and the various data sheets based on the Packard (PDILB) Computer Program published by the DoE. The maximum loading considered in recent projects has been LCG II. The latter classification relates to a group of aircraft of LCN 76-100. The highest figure of the range is used for design purposes.

10. The LCG approach is currently the subject of improvement, although of necessity at the expense of its prior simplicity. The considerable experience gained has enabled the empirical approach to be modified and expanded to encompass more detailed pavement descriptions, particularly of those regarded as flexible. The aircraft LCNs will be listed separately for rigid and flexible pavements, and the related evaluation/design charts will be similarly separated. Composite construction will be considered with rigid pavement. It is anticipated that the DoE will publish the revised edition late in 1976.

11. Owing to the vulnerability of underground services to the increasing weight of successive generations of aircraft, the BAA has increased the relevant design load for ancillary structures from approximately 455,000 kg (1,000,000 lb) to 567,000 kg (1,250,000 lb) AUW or 34,000 kg (75,000 lb) per wheel. These loads exceed those on which the pavement designs are based.

## PAVEMENTS

12. The BAA has, at one or other of its airports, examples of virtually every category of pavement. The bulk of them were designed and constructed by a variety of agencies before BAA was formed. Throughout development, design has been considerably influenced by the need to provide pavements which are as economical and as maintenance free as practicable.

13. In the UK, rigid slab construction of Portland cement PQ concrete is more economic than flexible construction of equivalent strength in which all, or a major part, of the various courses are in bitumen or cement-bound material. This situation has existed for a number of years, although there was a short period in the early 1970s when, for pavement for all but the heaviest civil aircraft, cement-bound material with an asphaltic concrete surface became an economic alternative.

14. However, the rapid rise in oil prices since October 1973 has re-established and, indeed, increased the price differential. These circumstances have also been aggravated by the shortage of coal tar resulting from the increased utilisation of natural gas from UK off-shore fields. When making this comparison it must be remembered that high wheel loads and tyre pressures on bitumen bound material make the provision of thick layers essential for a heavy duty flexible pavement.

15. Given good design and workmanship, a Portland cement concrete surface is fundamentally more durable than the surface of any unmodified bituminous material. Good concrete is unaffected by freeze-thaw temperature cycles and does not deteriorate through oxidation. Surface texturing can be re-established on rigid pavement relatively cheaply when compared with the short life or very expensive proprietory remedial treatments of a flexible surface. A further very important quality of Portland cement concrete is its resistance to oil, fuel and aircraft hydraulic fluids.

16. The BAA believes that concrete should be used in all areas where fuel spillage may occur, i.e. aprons, taxiways, holding areas and runway ends. In practice this means that any other type of construction is only considered for the centre portion of a runway, runway shoulders and over-run areas.

## PLAIN CONCRETE

17. In recent years the rigid pavements designed by BAA have been plain slab ordinary Portland cement (OPC) PQ concrete constructed on a 150mm (6in) lean concrete base on a prepared formation of either natural material, a further nominal 150mm (6in) depth of lean concrete or, more usually, a 300mm (12in) minimum depth of sub-base material. This last level of construction has been required to have a minimum modulus of sub-grade reaction on a 760mm (30in) diameter plate ($K_{30}$ value) of $55MN/m^2/m$ (200 $lbf/in^2/in$). This may be compared with the original pavement laid at Heathrow on an in-situ granular material which had a minimum $K_{30}$ value of 299 $MN/m^2/m$ (1100 $lbf/in^2/in$).

18. It can be demonstrated that, for a single circular contact area, all the established and proposed formulae for the thickness design of a rigid slab produce much the same results within the fairly narrow limits of medium to heavy duty concrete pavements, provided appropriate design factors are used. Although the curves vary in shape, the useful parts form almost parallel straight lines.

19. The most commonly used formula is Westergaard's interior case which considers the infinite slab with a dense liquid support. However, the

BAA believes that it is more appropriate to use the edge and corner case formulae as these usually produce the critical stress. In all cases the stress resulting from temperature variations must be added.

20. Alternatively, there are several methods which incorporate an allowance for warping, of which Teller and Sutherland's semi-empirical modifications are preferred. These equations give an acceptable degree of accuracy for the current heavy aircraft loading. When a codified loading such as the LCN/LCG system is used, the ESWL derived from the Packard PDILB Program may be reduced by about fifteen per cent for the Teller and Sutherland corner case calculation.

21. The lean concrete base course utilises 40mm all-in aggregate at an aggregate/cement (OPC) ratio of between 15 and 20 : 1. Minimum crushing strengths, obtained from 150mm (6in) cubes, of 7 $MN/m^2$ (1000 $lbf/in^2$) and 11 $MN/m^2$ (1600 $lbf/in^2$) at 7 and 28 days respectively are required.

22. The BAA does not subscribe to the view that a 100mm (4in) base course thickness of lean concrete constitutes a sensible working platform. Experience has proved that the normal heavily laden site trucks, cranes and even concrete delivery vehicles can damage this depth of base course to a degree that can cause failure of the underlying formation. The ensuing discussions regarding liability, together with the actual remedial work, can cause considerable delay to a construction programme; hence a 150mm (6in) minimum thickness is specified.

23. It has been suggested that any additions to the minimum design requirement should be made by the contractor, the intention being that defined access routes are established. Paving is by nature a continuous procedure; thus most of the mobile plant requires to use most of the base course some of the time. The cost of temporary works is fed back into the contract sum, and thus this approach can result in tendering on a dissimilar basis to a degree that can make true comparison difficult.

24. In the past, the depth of pavement has been influenced by the high probability of early loading and by the increasing incidence of poor sub-grades uncovered as developments progress across infilled borrow pits and the disturbed ground of the original airports. The thickness of PQ concrete to give LCG II, capable of taking all aircraft up to new LCN 100, has varied between 300mm (12in) and 400mm (16in) dependant upon the subgrade conditions. These thicknesses have been reduced by up to 25mm (1in) when the expected traffic over a projected twenty-years life has been less than 100,000 repetitions of the critical design load.

25. A reduction of as much as 50mm (2in), which represents a complete classification group, can be justified where channelised traffic draws off all but the occasional loading, as at the edge of runways, taxiways and aprons. However, in practice, paving forms are not only a major initial expense for a contractor but continue as such throughout a contract due to the costs of maintenance and replacement that can result from mishandling and heavy usage. It is not therefore necessarily an economy to vary slab thicknesses if more than one set of forms is required.

26. Additionally, experience has shown that airport development usually progresses from the outer bays of any area; any bays of reduced thickness have then to be broken out and brought up to the overall strength of the pavement. Thus, the original reduced construction can be an ill-conceived economy in the long term. Similar situations occur when heavier loads than were originally envisaged arise from the development of such ancillary equipment as fire tenders, aircraft tugs, airside coaches and fuel bowsers.

27. The development of existing airports usually entails disruption to the normal operating pattern. This may be minimised by phased construction which, during periods of peak traffic, can result in the early loading of newly completed pavement. Care therefore needs to be taken to ensure that design thicknesses relate to both the short-term and long-term properties of the concrete.

28. The BAA normally specifies the minimum flexural strength of PQ concrete at 28 days as 4.0 $MN/m^2$ (580 $lbf/in^2$), with a failure rate of one per cent, when obtained by testing 150mm x 150mm x 750mm (6in x 6in x 30in) beams. Cores, of not less than 175mm diameter, cut from the finished pavement must attain an equivalent compressive cube strength of 32$MN/m^2$ (4650 $lbf/in^2$) at 28 days. These strengths are obtained by specifying nominally single-sized - 40mm, 20mm and 10mm ($1\frac{1}{2}$in, $\frac{3}{4}$in and $\frac{3}{8}$in) - coarse aggregates, a coarse sand where practicable, an ordinary Portland cement content of not less than 300 $Kg/m^3$ and a water/cement ratio not exceeding 0.5 by weight. The aggregate/cement ratio usually lies between 5.5 : 1 and 6 : 1. Air-entraining admixtures may be used at airports in the south-east of England but are mandatory for the Scottish airports with their less favourable climatic conditions.

29. To ensure stress relief between the PQ concrete slab and the lean concrete base, 'sub-grade' restraint is kept to a minimum by the inclusion of a heavy gauge polyethylene membrane.

30. The BAA requires plain slab PQ concrete to be laid, spread and compacted by self-propelled machines, between forms and in a single layer. Hand laid concrete is permitted in small or inaccessible areas. The approximately square bays specified are about fifteen times the slab thickness in their overall dimensions. If aggregates of low thermal expansion, such as limestone, are used, then the bay sizes may be increased by up to 25 per cent. The pavement is laid in separate lanes with longitudinal joints between each lane. Contraction joints across the lanes are induced by reducing the effective slab depth by a quarter, either by saw cutting or inserting a top joint former and incorporating a bottom crack inducer where necessary.

31. Unreinforced Portland cement concrete with load transfer devices across the joints has been used extensively for aircraft pavements and, in the UK, it is the usual type of construction for concrete roads. It is the best form of construction when high density traffic demands good rideability, e.g. motorways and trunk roads. However, it is the view of BAA that the inclusion of such devices presents difficulties in design, construction and performance. Fixed and sliding steel dowels tend to cause bearing failure of the concrete, thereby increasing the effective length of the dowel in bending and progressively reducing the effectiveness of the device. Keyed or tongued and grooved undowelled joints tend to fail in shear, usually at the top of the groove. Except in very thick slabs, this condition is not eliminated by the inclusion of ties no matter how substantial and how well anchored.

32. Other shapes of longitudinal joints to produce load transfer by concrete in shear are difficult to assess in design. The tied warping joint has the inherent disadvantage that it mechanically links the slabs, which would otherwise move independently to a relatively small extent, to form a length that warrants frequent dowelled expansion joints and, in some cases, contraction joints as well.

33. It has been shown that in both the edge and corner cases the critical loading is usually caused by two wheels of a group of four. Some loss of apparent load transfer efficiency must occur when the remaining two wheels are on the slab to which the load is transferred. It appears impossible to design a load transfer mechanism which will

permanently reduce edge and corner stresses to the magnitude of the stress at the centre of the slab.

34. The BAA no longer use load transfer devices, although they still exist in some of the older pavements. It has been the BAA's experience that all load transfer devices become less efficient in time, either by corrosion of the steel dowels or, in the absence of ties, by the movement of the slabs themselves.

35. The omission of expansion joints, although desirable, has rarely proved to be practicable. They are an essential requirement where there is a variation of the thickness and orientation of abutting concrete, and at deep obstructions such as light bars, box gutters, manholes, at junctions with existing pavement and at taxiway curves. The construction of an expansion joint is a disruptive element of work in the general paving operation.

36. On occasions it has been found that a large initial expansion movement takes place within the normal annual temperature cycle, the jointing material is compressed and thereafter, without tied joints, contraction relates solely to the individual adjacent bays, leaving the expansion joint in a degree of permanent compression and the contraction joints open.

37. Usually joints are sealed with a pouring grade sealant; experiments with a variety of preformed sealants have proved unsuccessful. Currently a cold poured, pitch modified polysulphide or a polyurethane is used for expansion joints; all other joints are sealed with a hot poured, butyl rubber pitch based fuel-resistant compound.

## REINFORCED CONCRETE

38. Non-continuously reinforced concrete is little stronger than plain concrete unless the reinforcement is structural and is not included just to resist the effects of temperature and shrinkage. In the latter case, joints would still be required and the construction would be uneconomic. Top and bottom structural reinforcement is expensive and satisfactory placing of the steel is difficult.

39. Opinions vary as to the amount of steel that will satisfactorily control cracking in a continuously reinforced concrete slab, usually lying within the range from 0.5 per cent to 1 per cent of the section. This type of construction could be economical in the UK if the main reinforcement could be limited to 0.3 per cent, an amount insufficient to control cracking in an exposed slab but one which has been widely used for composite construction.

40. The greater the quantity of steel, the closer and narrower the cracks become. With more cracks, the possible incidence of spalling is increased. The resultant re-surfacing to remedy the situation decreases the likelihood of economic viability in the long term. A further facet is that in recent years in the UK steel has become not only costly but has had a fluctuating availability. The BAA do not use reinforced concrete pavement.

## PRESTRESSED CONCRETE

41. A truly prestressed concrete slab, as distinct from a minimal stress induced either by the omission of expansion joints or the use of shrinkage-compensating cement, can be argued to be economical. A well-designed and constructed prestressed slab can be virtually free from cracks and, in this way, be superior to a continuously reinforced slab. Experience has shown that changes usually have to be made to both the

configuration and to the associated underground services during the life of most pavements. In such circumstances, any resultant cutting of the pavement structure would destroy the continuity necessary for the success of a prestressed slab, and the alternatives would be costly.

42. Two experimental lengths of prestressed taxiways constructed at Heathrow in 1948 and Gatwick in 1960 have both had to receive major maintenance, the former due to the corrosion and eventual failure of the mechanism used to ensure equal load transference, and the latter due to the 'sub-grade' restraint proving to be greater than was anticipated in the design calculations and resulting in an unacceptable degree of surface cracking.

## COMPOSITE PAVEMENTS

43. Composite pavement comprises a base, and possibly sub-base, course of Portland cement concrete with a flexible surfacing of bituminous material. The occurrence of composite construction at BAA's seven airports is the result of historic expediency rather than specific design. Most of the pavements existed prior to 1966 when the BAA was formed; some of the more important needed to be strengthened due to the increasing aircraft loads. Although disruptive, the piecemeal repair of taxiways was possible on a progressive basis. The runways, however, had to be operational during peak traffic times in order to maintain the commercial viability of both the BAA and the Operators. In 1971 a programme of rehabilitation and strengthening of runways and some associated taxiways was commenced.

44. The basic treatment was to lay 100mm (4in) of high stability (Marshall design and control) asphaltic concrete in two layers of 60mm and 40mm, base and wearing course respectively, on which was laid 20-25mm of porous friction course. The 100mm thickness was considered the absolute minimum necessary to avoid the reflective cracking of the asphalt surfacing.

45. Generally, it proved necessary to increase the crossfall to at least 1.0 per cent to aid the drainage through the friction course, and this was achieved by additional regulatory layers of base course, each no greater than 60mm deep. All work was carried out in sections at night, the sections being suitably ramped for operational use by day.

## FLEXIBLE PAVEMENTS

46. The BAA has made little use of flexible construction other than for runway shoulders and light duty general aviation aprons. The construction of shoulders has varied between the asphalt surfacing of a compacted unbound granular base course and the surfacing of a varying thickness of lean concrete, the latter being an extension of the principle of keel construction giving a reliable transition from the runway pavement to the adjacent margins.

47. As with rigid construction, the lean concrete base material has normally had an aggregate/cement ratio in the region of 18 : 1, but this material has proved stronger than is desirable and recently an attempt has been made to lower the cement content still further. Unfortunately, the use of the cement-bound base as a working platform for surfacing operations, for the installation of services and for general access has precluded much variation.

48. For similar load carrying capacities, flexible pavements in the UK are currently more expensive than rigid. For the purpose of comparison, the BAA has computed the thicknesses of the heavy duty

pavements of LCG IV and above by a layered approach method using:-

48.1 The methods published by Shell International Petroleum Co. Ltd. and the US Asphalt Institute for known aircraft, with some allowance where expedient for future aircraft development.

48.2 Nai C Yang's multiple approach to the treated sub-base.

48.3 The UK Department of the Environment's somewhat empirical approach. There is, however, a problem in relating flexible pavement design and evaluation to a codified loading such as the LCN/LCG system as currently published.

49. Flexible construction disperses multiple wheel loads on an ever-increasing interference pattern, and it is for this reason that tests with 457mm (18in) or even larger diameter plates have produced misleading results. The more wheels on an undercarriage, the greater the spread of the load on the lower layers. When the ESWL approach is made then it is preferred on the basis of equal contact area, i.e. on an area equal to the sum of all the tyre prints in any one wheel group. Light duty pavements (LCG V, VI and VII) have been designed by the CBR method or a modification thereof.

50. Temporary pavements for heavy duty use have been constructed of 100mm bituminous surfacing on a lean concrete base or sub-base which has been presumed to have twice the load spreading capacity of the best unbound materials. The total projected repetitions of heavy loads have been calculated and the design based on the intended limited life, at the end of which some permanent deformation of the surface was anticipated.

51. In the event of flexible pavements becoming economic, the BAA would design the associated asphalt base and wearing courses to the Marshall method of mix design and control. A porous or open macadam friction course would be laid as the final running surface on runways, but not on taxiways.

## SURFACE CHARACTERISTICS

52. In the UK the friction characteristics of paved surfaces for aircraft are usually measured with a Mu-meter, a friction wheel trailer with a self wetting device, which presents a continuous trace of the surface friction properties over the whole length of the pavement tested. Two speeds are used for the tests; 80 mph for control tests and 40 mph for routine and supplementary tests. At 80 mph the readings generally range between 0.3 and 0.75. Although values greater than 0.5 are preferred, the results are by no means definitive; account is taken of such other factors as runway length, runway profiles, surface drainage, prevailing wind and the nature and condition of the surface in relation to anticipated traffic.

53. The desired friction characteristics are achieved by various methods of texturing applied to the finished surfaces. The BAA require newly laid PQ concrete to be either manually or mechanically brushed with a broom made from steel tapes. Asphalt surfaces are grooved, nominally 3mm x 3mm ($\frac{1}{8}$in x $\frac{1}{8}$in) at 25mm (1in) centres. Alternatively, an open macadam friction course, sometimes referred to as Porous Friction Course (PFC), is applied to such surfaces as a high stability asphaltic concrete (Marshall method) wearing course.

54. To ensure that a reasonable running surface is achieved, the BAA currently specifies a tolerance of 3mm ($\frac{1}{8}$in) on all concrete levels and 6mm ($\frac{1}{4}$in) on all asphalt levels. In addition, other than across crowns

and valleys, the maximum permitted gap under a 3m (10ft) straight edge is 3mm ($\frac{1}{8}$in). These accord with ICAO recommendations.

## SERVICES

55. Services are an essential adjunct to any facility, and operational areas for aircraft are no exception. The main categories encountered and included in design are Aviation Ground Lighting (AGL), Floodlights, Electrical Power Distribution, Storm Water Drainage, Fire Mains, Telecommunications (Post Office) and Hydrant Fuelling.

56. The BAA has always designed pavements on the basis that no openings appear in new runway surfaces, link taxiways to runways or, as far as practicable, in taxiways and stands proper. The existence of a pit or a manhole presupposes that personnel require access for underground works or maintenance, either of which results not just in disruption but the total closure of the pavement in which they are sited. The inclusion of an ancillary rectangular structure or feature can cause pavement to crack unless supplementary joints are provided. In rigid pavement there must also be a local variation of the bay pattern. Pits and manholes in aircraft manoeuvring areas are constructed of reinforced concrete bases and roof slabs with plain concrete walls.

57. Development of centreline lights has produced a shallow fitting which is associated with a relatively thin seating ring, requiring a circular recess only 45mm ($1\frac{3}{4}$in) deep beneath which a void is formed some 250mm (10in) deep x 125mm (5in) diameter for the fitting itself. Thus the AGL installation can be accommodated in rigid pavement with little disruption. In flexible pavement, and when isolated lights are required, it is obviously necessary to transmit the direct load sustained by the fittings through a concrete foundation pad of base area dictated by the bearing value of the sub-grade or lower levels of construction.

58. The transformers serving AGL fittings are placed in pits generally located in the runway shoulders, approximately two metres from the edges of taxiways to cause the least disruption to paving activities, and, in apron areas, in the interstand roads and equipment areas. The secondary cables connecting the transformers and fittings are fed through ducts let into, and finished flush with, the top of the pavement base course.

59. The larger stop bar lights, which require recesses up to 200mm (10in) deep for the seating rings alone, are accommodated in an especially constructed concrete 'light bar' isolated from the surrounding pavement by an expansion joint on all sides. In this situation the BAA includes the associated pits within the light bar itself but as far removed from the centreline as possible.

60. The usual UK design networks are used for surface water drainage calculations, which take account of the relevant airport profile for a once per year storm. The results are checked against a once in two years storm for runways and other areas draining into the same system. The outfall design depends on the Water Authority concerned, but normally a once in five years storm is considered.

61. Runways are designed with the maximum permitted camber or cross-fall of 1.5 per cent or 1 : 67, taxiways with a crossfall of between 1 : 67 and 1 : 100, and aprons generally between the limits of 1 : 120 and 1 : 150. The run-off is taken to dished channels and gulleys or catchpits in runway shoulders, to slot drains at taxiway and other pavement edges and into box gutters in apron areas.

62. The BAA specifies circular concrete pipes for carrier drains in a bed, haunch or in-situ concrete surround. In the latter case, articulation is maintained by a joint detail similar to an expansion joint. The detail is dependant upon the diameter and class of pipe and the amount of cover. Where necessary, porous drains are incorporated to cut off ground water before it can reach and harm the subgrade.

63. In apron areas all surface run-off is fed through some form of oil interceptor, which is either a purpose built tank or an open reservoir with floating mop or boom.