Airport pavement design for heavy aircraft loading

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With the rapidly increasing aircraft weights, it is not possible to develop performance records and experience needed to guide the designer for airport pavements for new generation aircraft. Therefore, it is necessary to rely more heavily on basic principles for future airport pavement design. This paper shows how previous experience with lighter aircraft and fundamental principles can be combined to develop the criteria for the new heavier aircraft.

1. INTRODUCTON

Consideration of pavement designs for the proposed new terminal development at Heathrow Airport in England triggered a need to review the airport pavement design criteria. Existing pavements at Heathrow and Gatwick airports were showing distress, and a need was felt to determine the causes. The BAA also felt a need to make modifications in pavement design procedures and criteria to handle the new generation aircraft.

The predominant aircraft using Heathrow and Gatwick airports over the past several years was the Boeing 747-200. This aircraft has a maximum gross weight (MGW) of approximately 351 metric tons. The heaviest aircraft currently operating at Heathrow and Gatwick is the 747-400 with MGW of approximately 388 metric tons. Several projected new aircraft scheduled to come into service in the mid 1990's will have much greater MGWs, and others with lower MGWs will, because of fewer number of wheels and less favorable gear configurations, cause greater pavement damage than the 747-200 aircraft.

For the past half century and longer, nearly all concrete pavement design procedures for airports were based on theories for an elastic slab supported on a dense liquid subgrade. (the Westergaard model (1)). This approach has served the industry well, but the model has some severe limitations for fully analyzing concrete pavements. Among the limitations are those of slab size restrictions, the inability to analyze the effects of load transfer efficiency across cracks and joints, and the inability to properly assess the effect of stabilized subbases on pavement behavior and performance.

In recent years the development of finite element models (2,3,4), and the introduction of high speed computers have provided the engineer with new tools to evaluate pavement systems and the factors which influence pavement behavior and performance. This paper describes how these tools are used to evaluate the design criteria for the new pavement systems, illustrates the recommended design procedure changes, and the effects of these changes.

2. CURRENT PAVEMENT SYSTEMS

Pavements at Heathrow Airport generally consist of a jointed plain portland cement concrete (PCC) slab between 350 and 400 mm thick on a rolled lean concrete base 200 mm thick, over approximately 200 mm of unbound granular material. The PCC slab was jointed at approximately 5 to 6 meter intervals in both the longitudinal and transverse directions, with no mechanical load transfer devices at the joints. Pavements at Gatwick airport generally consisted of a plain jointed PCC slab 400 mm thick on a rolled lean concrete base 200 mm thick over a 200 mm thick granular layer. Joint spacing at Gatwick was also approximately 5 to 6 meters in both the longitudinal and transverse directions.

Results back calculated from FWD tests on pavements at Gatwick airport provided the following properties for the existing pavements:

Modulus of subgrade reaction,	
k, (dynamic)	147 N/mm^2/m
Concrete modulus of elasticity,	
Ec	36,815 MPa
Load transfer efficiency,	
transverse joints	48 %
longitudinal joints	20 %
Longitudinal cracks	85%

Load transfer efficiency (LTE) is defined by the relationship:

$$LTE = \frac{\delta_u}{\delta_l} x100 \qquad (1)$$

where:

δ_u = deflection of the unloaded slab,
δ_l = deflection of the loaded slab.

Heavy vehicles and roads: technology, safety and policy. Thomas Telford, London, 1992.

3. LOADING CONDITIONS

The aircraft referred to in this paper and their maximum gross weights are designated as follows:

Aircraft- Approximate Weights

747-200 - 351 metric tons
747-400 - 388 metric tons
747-400E - 426 metric tons
MD-11 - 304 metric tons

A check with the dominant manufacturers of wide body commercial aircraft (Boeing, McDonald Douglas and Eurobus) indicated that by the mid 1990's, the 747-400E and MD-11 aircraft could be added to the fleets of many airline carriers. These new aircraft will significantly impact airport pavement designs for future use. Proposed new aircraft by Eurobus would not impact the pavement designs.

The gear configuration for the 747-400E is essentially the same as shown in Figure 1 for the 747-200 aircraft. The MD-11 aircraft has a gear configuration as shown in Figure 2. With these weights and gear configurations, the maximum bending stresses in the pavements are significantly greater those produced by current aircraft. This will significantly impact the thickness requirements for concrete pavements.

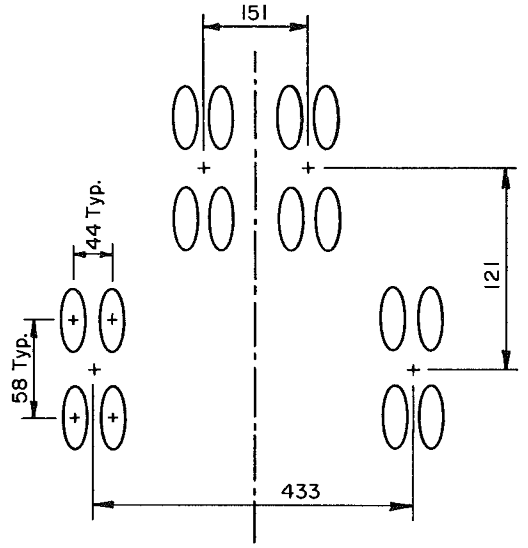

Fig. 1 Main gear configuration, 747 aircraft.

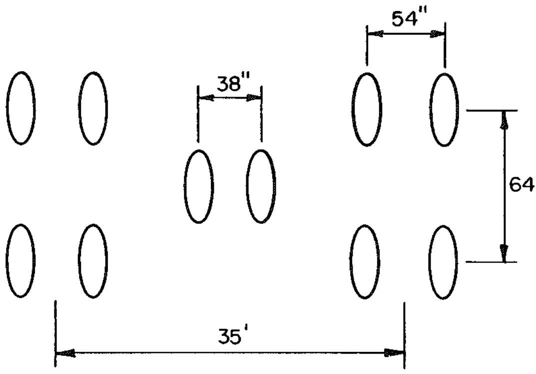

Fig. 2 Main gear configuration, MD-11 aircraft.

4. ANALYSIS PROCEDURE

Pavement responses to load and climatic factors were analyzed using the finite element model ILLI-SLAB (2,3,4). The ILLI-SLAB model is based on the medium thick plate theory and utilizes the 12 degree of freedom element RCB12, as described by Melosh and others (5,6). The ILLI-SLAB model has the capacity to analyze: slabs with any arbitrary loading condition; pavement systems made of two layers either fully bonded or unbonded; the effect of load transfer across joints and cracks; and curl stress due to temperature gradients through the slab.

5. DESIGN PROCEDURE AND CRITERIA

Thickness design of pavement slabs is based on accumulated fatigue damage due to combined load and curl stresses. Maximum stress in the slabs due to gear loads at the critical location are calculated and combined with curl stresses to determine the critical combined stress. Aircraft coverages at specific times of the day and year are used to determine accumulated fatigue damage at the critical locations in the slabs.

5.1 Concrete Fatigue:

Fatigue damage was calculated using linear damage function normally referred to as Miner's Rule (7). According to the rule, the cumulative damage at a point can be calculated using the Equation:

$$\sum_{i=1}^{k} \frac{n_i}{N_i} = M \qquad (2)$$

where:

n_i = the number of stress repetitions at the ith stress level,

N_i = the number of loads to failure at the ith stress level,

M = the cumulative damage, referred to as Miner's Number.

Failure assumed to occur when M = 1.

Concrete fatigue is usually evaluated from failure of simple beams under repeated loads in a laboratory setting. The results are usually presented using log-normal graph, often referred to as a Wöhler diagram. Based on results from laboratory tests from several sources, Darter (7) proposed the following equation to characterize concrete fatigue:

$$LogN = 17.61 - 17.61(R) \qquad (3)$$

where:

R = the ratio of σ/Mr,

σ = the stress in the concrete,

Mr= the concrete modulus of rupture (flexural strength).

While there is significant scatter in the results, Simes (9), after a comprehensive statistical analysis of fatigue data from several sources, concluded that for constant amplitude tests, the variability in the results can be explained by the variability in the flexural strength. He further concluded that the linear damage model (Miner's Rule) is adequate for the analysis of variable amplitude tests results.

Due to a number of factors including specimen size, ratio of maximum to minimum stress during fatigue testing, failure patterns in slabs versus beams, etc., concrete fatigue characteristics developed from simple beams in the laboratory to not translate well to full size slabs under field conditions. Figure 3 shows the calculated cumulative fatigue damage at failure (50% slabs cracked) for full scale slabs tested under simulated service conditions. These results can be summarized as:

$$LogN = -1.28258\,(R) + 4.284 \quad for\ R < 1.25 \qquad (4)$$

$$LogN = 1.89289\,(R)^{-1.456} \quad for\ \ R > 1.25 \qquad (5)$$

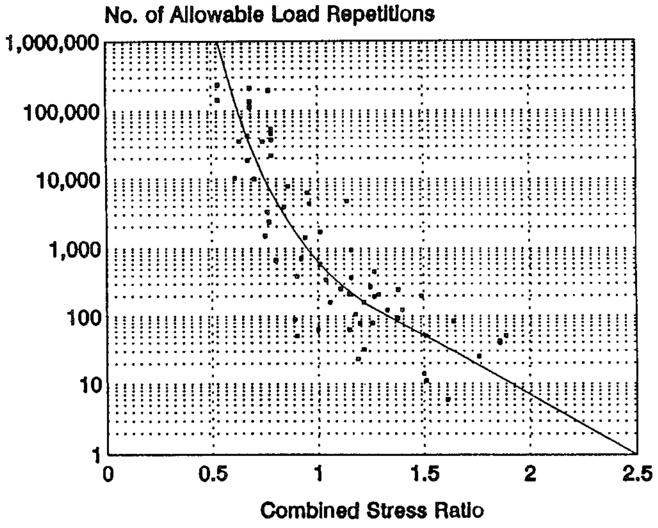

Fig. 3 Fatigue results from full scale slabs.

Where N is the number of coverages to achieve 50 percent of the slabs cracked, and R = σ/Mr, as defined for Equation 3.

For probabilities of failure other than 50 percent, Equation 4 can be rewritten as:

$$LogN = \left[\frac{-\left(\frac{\sigma}{Mr}\right)^{-5.367} * Log(1-p)}{0.0032}\right]^{\frac{1}{4.394}} \qquad (6)$$

where p is the probability of failure, and all other symbols are as defined for equations 4 and 5. Equation 6 is valid only for σ/Mr less than 1.25.

Comparison between the mean results from beams in the laboratory (Equation 3) and the mean results from tests on slabs in service (Equations 4 and 5) are shown in Figure 4. When the number of load applications/coverages exceeds about 100,000, the two curves are nearly parallel, and lie in close proximity to each other. This suggests that the fatigue characteristics between simple beams and slabs is very similar whenever the stress is in the elastic range, but there is significant deviation in the findings whenever the concrete stress exceeds the linearly elastic range.

Concrete fatigue characteristics based on results from field slabs (Equation 6) were used to develop the thickness design standards presented later in this paper.

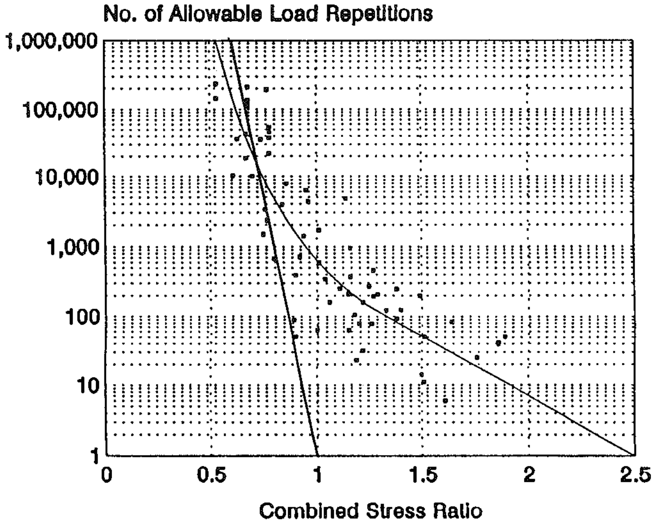

Fig. 4 Comparison of laboratory and field fatigue results.

5.2 Load Stresses: The critical location for fatigue in airport pavements is when the main gear of the aircraft is approaching a transverse joint. For this loading condition the joint load transfer efficiency (LTF) has a significant effect on the stress level due to load. Figure 5 shows the effect of LTE on maximum bending stress for a pavement 400 mm thick, with 747-400 aircraft. At one hundred percent LTE the maximum stress should be one half of the stress at zero LTE. Note that the FWD test results from Gatwick indicated a LTE of 20 percent for the transverse joints.

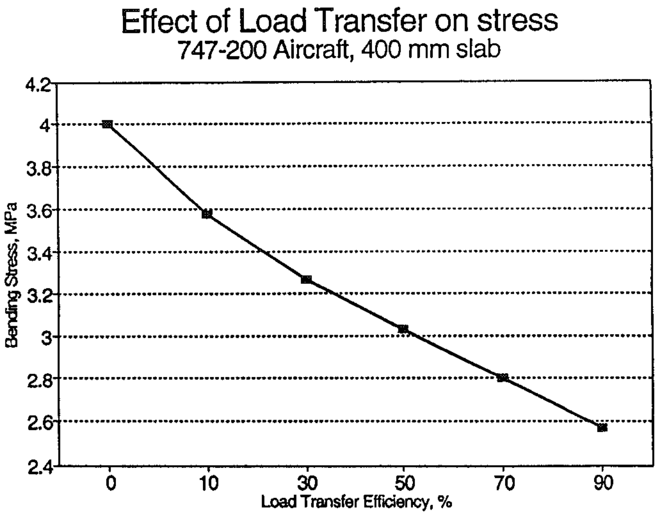

Fig. 5 Effect of load transfer on bending stress.

Maximum stresses (based on ILLI-SLAB analysis) versus slab thickness for three aircraft (747-200, the 747-400E and the MD-11) are shown in Figure 6, for a range of slab thicknesses and a LTE of 33 percent. Although the MD-11 is the lightest of the aircraft used in the analysis, it causes the highest stresses in the pavement.

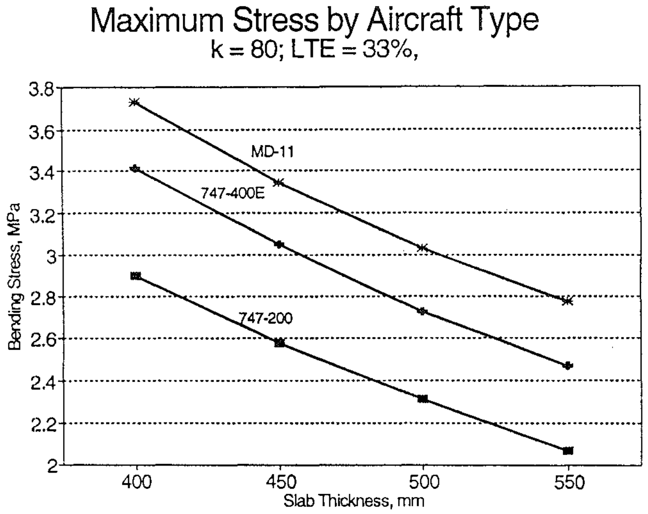

Fig. 6 Effect of aircraft type on maximum bending stress.

5.3 Curl Stress: By definition, curl is the stress caused by a temperature differential between the top and bottom of the slab. Figure 7 shows some temperature profiles through a 400 mm thick slab for Central England at various times of the day. These temperatures were calculated using the CMS model (7) and actual climatic data from Gatwick Airport. The maximum positive temperature gradient (i.e., top of slab warmer than bottom) usually occurs between 2 and 4 pm, while the maximum negative temperature gradient occurs between 3 and 6 am. The maximum positive and negative values also change throughout the year. Figure 8 shows a plot of the temperature differential through the slab throughout a typical day at five different times of the year for Central England. These are average values based on 30 years of data. Maximum positive and negative temperature differentials for the pavement throughout a typical year are shown in Figure 9.

The typical year was divided into monthly increments, an average temperature differential estimated for each month. The accumulated fatigue damage due to combined curl and load stresses were calculated for each month. The total fatigue damage for a typical year was determined by summing the fatigue damage for the 12 months. A weighted, equivalent uniform temperature differential effective over the entire year, (i.e., one which produces the same fatigue damage for the year as the total from monthly increments) was determined.

As illustrated in Figure 8, there is a significant variation in temperature gradients throughout the day. However, no weighted average daily temperature gradient was calculated as most of the aircraft operations take place between 0600 and 2200 hours. During this time period the temperature gradient is normally positive and approaches its maximum value for a significant portion of the time. The weighted average positive temperature differential for a 400 mm thick slab in Central England was determined to be just over 4°C., and the weighted average negative just over 3°C. Assuming a coefficient of thermal expansion of 3×10^{-6} per °C, and pavement slabs 400 mm in thickness, 6 meters per side, supported on a subbase with a k value of 135 N/mm^2/m, the weighted average positive curl stress at the slab edge is approximately 0.6 MPa and the weighted average negative curl stress approximately 0.4 MPa. These stresses should be added to the load stress when making fatigue calculations.

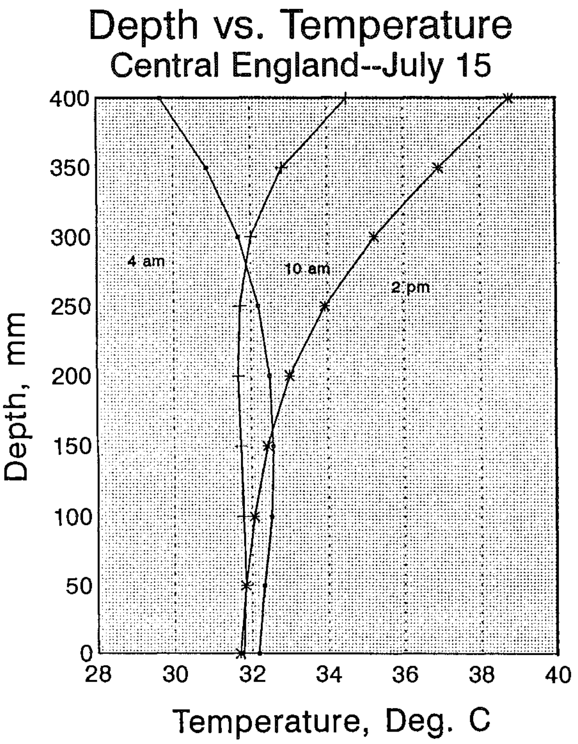

Fig. 7 Temperature gradients for Central England.

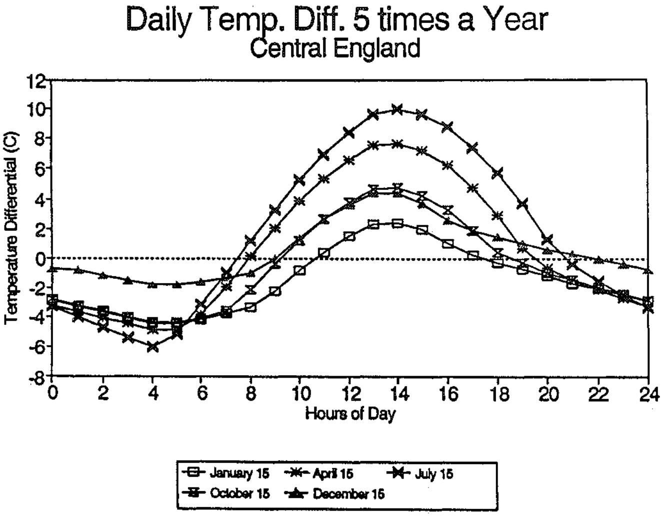

Fig. 8 Temperature gradients throughout a day at various times of year.

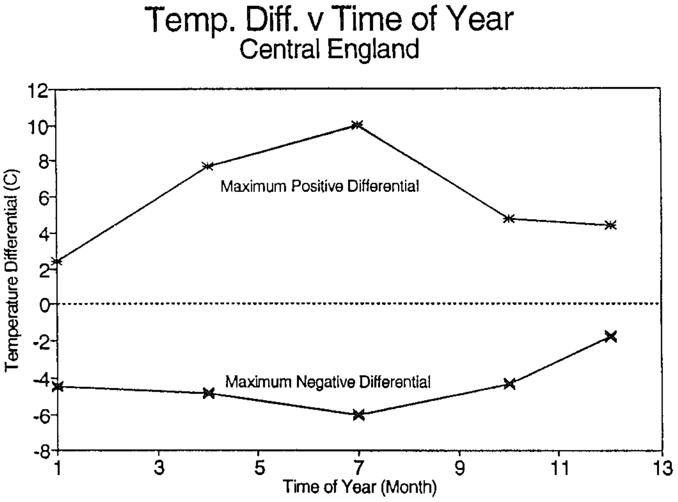

Fig. 9 Maximum and minimum temperature gradients throughout the year.

6. SUBBASES FOR PCC AIRFIELD PAVEMENTS:

It is generally agreed that subbases serve a useful function under PCC pavements. The FAA (10) specifically requires that a stabilized subbase be used under all PCC pavements designed to accommodate aircraft with a MGW of 100,000 pounds (45.4 metric tons) or greater. Most engineers consider the benefits of a stabilized subbase as:

a. Prevention of mud pumping,
b. Providing an impermeable, uniform and strong pavement support,
c. Elimination of subbase consolidation,
d. Expediting construction by providing a stable working platform under adverse weather conditions
e. Providing a firm support for paving train and/or side forms which contributes to the construction of a smoother pavement.

In most design procedures (10,11,12), the structural benefits imparted to a pavement section by the stabilized subbase is reflected in the effective modulus of subgrade reaction (k). Charts are provided by these agencies to guide in the selection of the effective k value for various soil support values and subbase thicknesses. In general these charts indicate a significant increase in the k value as a result of the stabilized subbase.

As will be shown, estimates of the "effective k" provided by these agencies, significantly over estimates the effectiveness of the stabilized layer in decreasing pavement deflection and stress. An evaluation of the effect of the subbase on pavement responses can be done using the ILLI-SLAB finite element model. In this model the two layers (slab and subbase) can be assumed to be either fully bonded or have a perfectly smooth interface. Unless steps are taken to assure full bonding between the slab and the subbase, it must be assumed that the two layers are unbonded.

Pavement systems consisting of three slab thicknesses, three subbase thicknesses with the MD-11 aircraft were analyzed using the ILLI-SLAB fem. Results presented in Figure 10 show that the subbase has relatively little effect on stresses in the PCC slabs loaded with heavy gear multiple wheel loads. These results were obtained assuming a concrete modulus of 31,000 MPa, and a subbase modulus of 7,000 MPa. A subbase layer with a higher modulus of elasticity would yield marginally greater influence on the stresses, but not enough to significantly effect the conclusions.

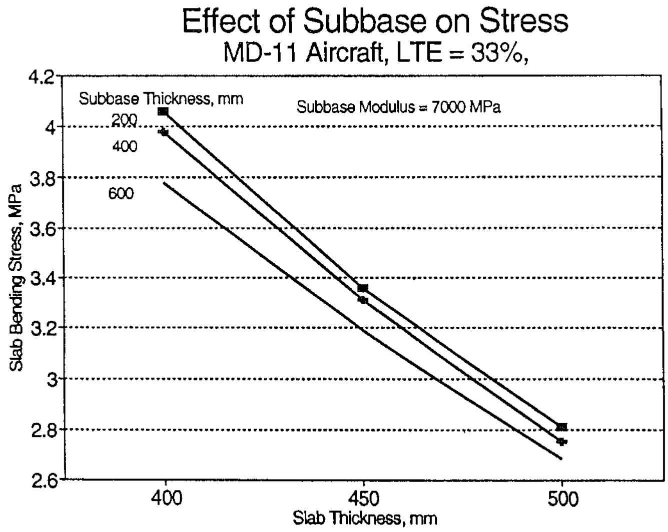

Fig. 10 Effect of subbase on maximum bending stress.

Results presented in Figure 10 show that increasing the slab thickness by about 25 mm will result in a stress reduction of approximately the same magnitude as achieved by increasing the subbase thickness from 200 mm to 600 mm. Thus, one would conclude that 25 mm of added concrete thickness is approximately equal to 400 mm of subbase with a modulus of 7,000 MPa. These results do not take into account the effect that increased subbase stiffness has on curl stress In general, the firmer the slab support, the higher the curl stress.

Purposes of a subbase under a PCC pavement should be to prevent pumping, to provide an impermeable support, to prevent frost penetration, and to provide a construction platform. The maximum thickness for a stabilized subbase should be that necessary to carry the construction traffic, and protect the subgrade against frost penetration. It is generally not economical to increase pavement structural capacity by increasing the subbase stiffness or thickness. This can be accomplished more economically by a nominal increase in slab thickness.

7. DESIGN CONSIDERATIONS

Based on the results presented above, it is concluded that designs for future facilities should consider ways to increase the structural capacity of the pavements to accommodate present and future aircraft. The three practical ways to improve the structural capacity of jointed PCC pavements are:

1. To increase the concrete flexural strength.
2. To increase slab thickness
3. To increase the LTE across the joints.

Since there is no evidence of faulting at the joints at either Heathrow or Gatwick, the use of load transfer devices to improve LTE is questionable on economic grounds, especially in areas where the traffic is not concentrated in narrow channels. Dowels will significantly decrease the maximum tensile stress in the slabs, but are difficult to place properly and are expensive. Consideration might be given to improving the LTE by using a larger maximum size crushed aggregate, which might enhance aggregate interlock across the joints. Use of the larger maximum particle size might also increase the concrete flexural strength, thereby allowing a slight decrease in pavement thickness.

Increasing slab thickness is usually the most cost effective way to increase the pavement structural capacity. In general, for a given loading situation, the maximum stress will decrease as the square of slab thickness increases, while slab stiffness increases as the cube of the thickness. The increased stiffness reduces the maximum deflection, and the concomitant stress on the subgrade. Also, for a given joint spacing, typical of those used for airport pavement construction, thicker slabs will have less curl stress than thinner slabs. Finally, the cost of increasing slab thickness by several 25 to 50 mm will usually have only a nominal effect on the overall pavement cost, but can result in a significant increase in pavement life. Thus, there are a number of advantages to increasing pavement thickness to improve pavement performance.

Increasing the concrete flexural strength will also improve pavement performance by decreasing the stress/strength ratio of the concrete. This will result in greater fatigue life for the pavement. The strength ratio changes linearly with concrete strength, so, over a wide range of thicknesses and concrete strengths, increasing slab thickness is generally more cost effective than increasing concrete strength for improving pavement performance.

Stabilized subbases have an important function in the pavement system. It is recommended that some minimum level of stabilized subbase be provided. The subbase, even when stabilized, does not significantly improve the pavement structural capacity.

8. PAVEMENT DESIGN RECOMMENDATIONS

Applying the principles discussed above, design thicknesses were developed for three aircraft, two concrete strengths, two subgrade conditions, two levels of load transfer efficiency. All designs were based on slabs on 200 mm thick granular layer and 150 mm thick rolled lean concrete. Design thicknesses were developed for both 75 and 85 percent reliability assuming two failure criteria (1 and 10 percent slabs cracked) using Equation 6 to determine the allowable fatigue. Slab thicknesses are shown in Figures 11 for 85 percent reliability and 10 percent slab cracked. Figures 12, 13, and 14, show the relative influence of concrete strength, subgrade support and load transfer efficiency respectively on the design slab thicknesses. The effects of varying design reliability and percent slabs cracked are shown in Figure 15.

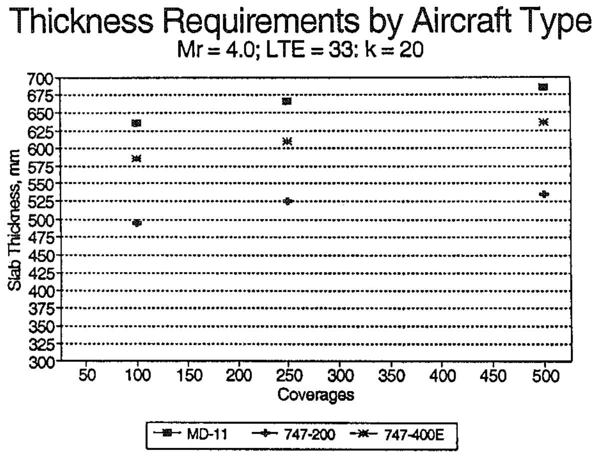

Fig. 11 Thickness requirements for design aircraft.

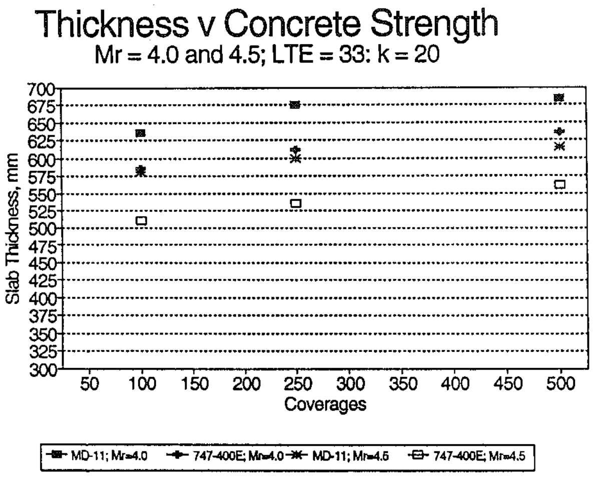

Fig. 12 Effect of concrete on thickness requirements.

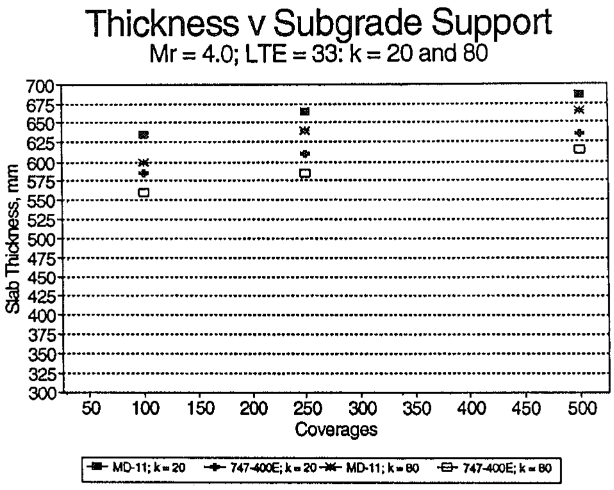

Fig. 13 Effect of subgrade modulus on thickness requirements.

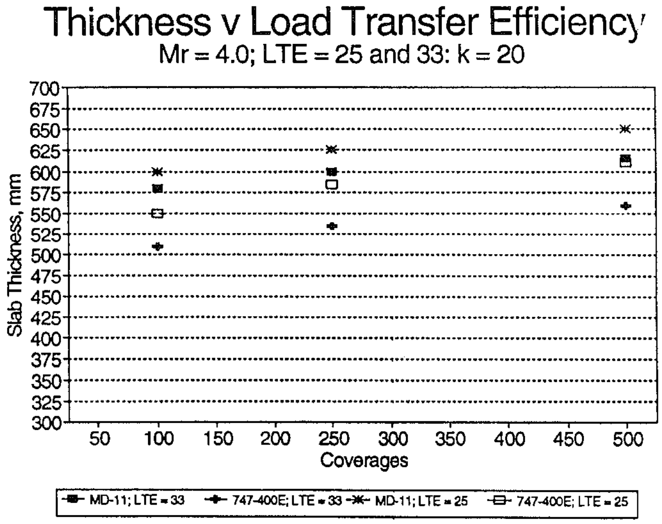

Fig. 14 Effect of load transfer efficiency on thickness.

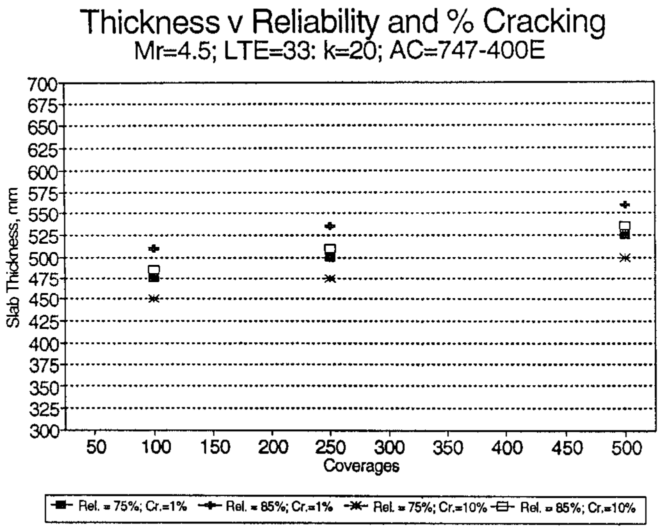

Fig. 15 Thickness requirements for reliability and cracking.

9. SUMMARY AND CONCLUSIONS

Pavement design is basically a judgement by the design agency. This paper illustrates how basic principles can be used to establish guidelines to assist the designer in these decisions. Specifically it illustrates the relative benefits of such factors as subbase thickness, slab thickness, concrete strength, and load transfer efficiency. Thickness design curves were developed to illustrate these principles.

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