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THICKNESS DESIGN OF CONCRETE ROADS

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ABSTRACT

The present design curves for concrete pavements in Road Note 29 are largely based on observations made on experimental roads prior to 1970, when none had carried more than 10 million standard axles. By 1985 these and other experimental sites had carried considerably more traffic and provided broader data on which to base future designs. The performance of 29 unreinforced and 42 reinforced forms of construction were analysed to establish new design curves. The structural performance was assessed and pavement life equations were derived by multiple regression analysis.

Tensile stresses generated, by traffic and temperature, at the underside of the slab, were calculated for a number of different pavement configurations using a multi-layer linear elastic model. The ratio of strengths of the unreinforced concrete to the calculated stresses in these pavements was found to be directly related to pavement life determined from the regression equation. The existence of this unique relationship suggests a possible design criterion and supports the realism of the regression equation by indicating a credible mechanism of pavement deterioration.

Good agreement was found between slab designs derived from the regression models and those obtained by the AASHTO design method; this enabled the enhanced performance expected from pavements with tied shoulders to be evaluated.

1 INTRODUCTION

The design tables for concrete roads issued by the Department of Transport (1976) were based on the third edition of Road Note 29 published by the Road Research Laboratory (1970); this relied heavily on the observed performance of experimental pavements at a number of road sites, none of which had carried more than 10 million standard axles (msa). However recent and probable future growth in the number and weight of heavy commercial vehicles has resulted in the need to design concrete roads to carry approximately 150 msa cumulative traffic over a 20 year period, and progressively more if that period is extended.

Since the third edition of Road Note 29 was published the experimental roads have carried substantially more traffic, up to 30 msa, and other experimental roads that were not included have now carried sufficient traffic to yield valuable performance data. Consequently a further appraisal of the performance of concrete roads has been made. The greater body of data from a total of 29 types of unreinforced and 42 types of reinforced concrete pavement has enabled performance to be interpreted in terms of the effect of the major pavement variables, namely slab thickness, concrete strength, amount of reinforcement and foundation support.

Equations have been established relating pavement life, in terms of standard axles, to the major pavement variables for both reinforced and unreinforced concrete. Structural theory has shown the consistency of the relationship, for unreinforced roads, for a range of pavement designs.

Design curves have been presented that are based on the experimentally established relationships; they take account of the probability of survival of the pavement to the required design life and of the strengthening effect of providing a tied shoulder or hardened edge strip.

2 EXPERIMENTAL SITES

In the present work performance data from seven experimental concrete road sites have been analysed. Details of the types of construction, traffic carried and the ranges of construction variables are given in Table 1. The majority of the unreinforced and reinforced pavements were last inspected in 1985 and 1982 respectively.

The total length of carriageway of the seven sites was just over 50 km. The length of each section of unreinforced construction varied between 8 bays (36.6 m) at Alconbury Hill and 1 413 bays (6.5 km) at Long Bennington Bypass. For the reinforced construction the lengths ranged from 1 slab (36.6 m) at Alconbury Hill to 515 slabs (11.9 km) at Tuxford Bypass.

3 INSPECTIONS

Inspections of the experimental roads were usually made annually throughout the life of the pavements with all visible defects recorded on site plans.

The performance of the sections was assessed by the amount of visible cracking, pumping and repairs that were evident in the nearside lane which, in all cases, had carried the majority of the commercial traffic.

Cracks were classified by width as hair, fine, medium, wide or repaired. Hair cracks can be seen more clearly when the concrete is drying out after rain and do not detract from the performance of the

TABLE 1

Experimental concrete sites

Site	Year opened	Type of construction	Year of last survey	Total traffic loading at last survey (msa)	Experimental variables			
					Slab depth (mm)	28-day compressive strength (MPa)	Reinforcement area per metre width (mm²/m)	Foundation equivalent modulus (MPa)
Alconbury Hill (A1)	1957	Unreinforced	1985	30.8	203–279	43.8 & 63.8	None	54
		Reinforced	1982	24.6	127–254	43.8 & 63.8	507–920	54–699
Cromwell Bypass (A1)	1966	Unreinforced	1985	19.9	175–279	31.0	None	472–1700
		Reinforced	1982	14.3	254	31.0 & 33.4	598	106–1142
Eaton Socon Bypass (A1)	1971	Unreinforced	1985	12.8	254	34.6 & 39.2	None	251
		Reinforced	1982	9.3	254	34.6	636	251
Long Bennington Bypass (A1)	1968	Unreinforced	1985	14.3	254	41.3	None	48 & 458
Oxton Bypass (A6097)	1948	Unreinforced	1964	2.3	76–203	37.0	None	142
		Reinforced	1964	2.3	76–203	37.0	312	142
Stanwell Moor Road (A3044)	1949	Unreinforced	1979	16.5	203	39.0	None	140
Tuxford Bypass (A1)	1967	Reinforced	1982	12.3	229	32.4	636	293

road. Fine cracks are defined as those up to 0.5 mm wide. Medium cracks are between 0.5 mm and 1.3 mm wide and are accompanied by the potential loss of aggregate interlock across the fracture. Wide cracks are defined as those which exceed 1.3 mm in width and are associated with a complete loss of aggregate interlock and a failure of the steel in reinforced roads. Crack repairs were made to keep the road serviceable; treatment to the slab depended on the severity of the problem and included full depth replacement, partial depth replacement (usually to replace spalled material), stitching and crack sealing. Records were kept of these treatments, their extent and how long they lasted.

The total length of cracking in the nearside traffic lane of each experimental section was evaluated and normalised by expressing it in metres of cracking per 100 m of road.

Pumping of water from joints, cracks or edges of the concrete pavement under the action of vehicle wheel loads was also considered to represent a failed condition. Pavements that had not already suffered failure due to some other cause rarely exhibited pumping. One reason for the rarity of pumping failures may have been relatively efficient joint sealing, which was shown by Gregory (1986) to inhibit pumping.

4 TRAFFIC

Traffic has been defined as the number of equivalent standard 80 kN axles, with design lives specified in terms of cumulative standard axles; the same approach was adopted in Road Note 29 (1970). The heavy commercial traffic carried by the experimental roads was established from annual vehicle counts made up to the General Traffic Census (1985), and is thus more accurately defined than the estimate made at the design stage for a new road. A standard method proposed by Addis and Robinson (1983) was used to convert the vehicle count data to equivalent standard axles.

5 PAVEMENT SUPPORT FROM FOUNDATION

The support offered by the foundations to the concrete slabs of the experimental roads was evaluated in terms of the Young's modulus of an equivalent uniform elastic foundation of infinite depth. Equivalence was defined as the uniform elastic foundation with the same surface deflection, under a standard wheel load, as that of the actual foundation.

Odemark's (1948) method of equivalent thickness was used to transform the pavement's foundation layers to an equivalent single layer supported on a uniform elastic medium. Boussinesq's (1885) equations were then applied to the transformation to calculate the surface deflection and hence the equivalent modulus. The computation was made on a programmable calculator using the simplified method devised by Ullidtz and Peattie (1980).

The adequacy of the method was checked by comparing evaluated deflections with the predictions from the more complex, but widely used, multi-layer elastic analysis by Thrower (1968)(1971). The correlation coefficient between the results from the two methods was 0.99 and justified the use of the equivalent thickness method to determine equivalent foundation moduli for this type of structure.

Lean concrete sub-bases have all been assumed to be intact and to act as a continuous layer. This simplifying assumption is supported by observations on a number of sites where sub-bases have been exposed and, apart from well-spaced interlocking transverse thermal cracks, the sub-bases have appeared to be substantially intact.

The elastic properties of the various foundation layers used in the analysis, were either those measured at the time of construction or values estimated using the methods given by Powell, Potter, Mayhew and Nunn (1984) which give low but realistic values of Young's modulus for the subgrade and unbound granular materials.

The equivalent modulus of other foundations, capable of providing an all-weather working platform for road construction, were also evaluated and are given in Table 2. These foundations were either similar to those presented by Powell *et al* (1984) for bituminous roads or had cemented sub-bases which were considered more suitable, for concrete roads, because of their resistance to erosion by pumping under the influence of heavy traffic.

6 PERFORMANCE OF THE EXPERIMENTAL ROADS

6.1 LIFE

A range of design variables was incorporated into each of the various experimental roads with a consequent and essential influence on pavement life.

TABLE 2

Equivalent foundation modulus for a range of typical foundations for concrete pavements

Sub-base						Subgrade		Equivalent foundation modulus (MPa)
Upper layer			Lower layer					
Type	Depth (mm)	Modulus (MPA)	Type	Depth (mm)	Modulus (MPa)	CBR	Modulus (MPa)	
Granular Type I	150	150	Capping layer	600	70	1.5	23	68
				350	70	2	27	65
	225	150	None			5	50	89
Lean concrete (C10)	150	28 000	Capping layer	600	70	1.5	23	261
				350	70	2	27	268
				150	70	5	50	358
			None			15	100	683
Lean concrete (C15)	150	35 000	Capping layer	600	70	1.5	23	277
				350	70	2	27	285
				150	70	5	50	383
			None			15	100	732

It had been hoped that the cumulative traffic carried by the road at the time of structural maintenance would give a measure of the life of a section. However because of financial constraints and the requirement to limit traffic disruption structural maintenance was carried out on only a few occasions. The weaker sections deteriorated to a state which would not usually be considered acceptable on a non-experimental trunk road, while some other sections were repaired prematurely. Consequently it was not possible to define adequately the life of an experimental pavement as the traffic carried up to the time of structural maintenance. Failure criteria associated with actual structural condition and linked to identifiable defects were therefore devised to define pavement life.

6.2 UNREINFORCED CONCRETE PAVEMENTS

6.2.1 Failure criteria

The bays of experimental unreinforced roads were judged to have failed if any of the following defects were present:—

(i) a crack of width equal to or greater than 0.5 mm crossing the bay longitudinally or transversely

(ii) a longitudinal and transverse crack intersecting, both starting from an edge and greater than 0.5 mm wide, and each longer than 200 mm

(iii) corner cracking wider than 1.3 mm and more than 200 mm radius

(iv) a bay with pumping at a joint or edge

(v) a replaced or structurally repaired bay.

The surface, joint condition and vertical settlement of the bays were also recorded. These defects occasionally developed to a condition where they were starting to become a traffic hazard and at this point local maintenance was carried out.

The unreinforced concrete pavements consisted of individual slabs divided into bays by contraction joints with an experimental section often containing more than one slab. Failure of sections usually proceeded gradually over a few years bay by bay and this enabled the failed percentage of bays in a section to be evaluated at each inspection. The performance of each type of unreinforced concrete pavement was judged, at the time of inspection, by the percentage of that type of bay that had failed.

The effect of concrete slab thickness, concrete strength and foundation support on pavement performance was then examined. These variables were chosen as those most likely to influence pavement life because of their influence on the way in which a pavement responds to vehicular and thermal loading; they had also been considered important by other researchers including Nowak (1968), Croney (1977) and AASHTO (1985).

6.2.2 Performance analysis

Data were available for 29 different types of sections; these had a wide range of design variables, as shown in Table 1.

Multiple regression of these data gave the regression estimate of cumulative traffic (L), in msa, that can be carried before failure as:

$$\text{Ln}(L) = 5.094\ \text{Ln}(H) + 3.466\ \text{Ln}(S) + 0.4836\ \text{Ln}(M) + 0.08718\ \text{Ln}(F) - 40.78 \quad (1)$$

where Ln is the natural logarithm

H is the thickness, in mm, of the concrete slab

S is the 28-day mean compressive strength, in MPa, of cubes made from the pavement concrete

M is the equivalent modulus, in MPa, of a uniform foundation giving the same slab support as the actual foundation

F is the percentage of failed bays.

The multiple regression analyses indicated that 75 per cent of the variability in performance of these unreinforced pavements was accounted for by the chosen variables and that thickness was the most significant variable examined; this accounted for 67 per cent of the variation in observed performance. To illustrate the variability of the experimental observations and to establish statistically a relationship between slab thickness and life having a selected probability of survival, the effective thickness (He) of the concrete slab in each section was calculated for a set of selected values of the variables. These were a concrete 28-day mean compressive strength of 50 MPa, an equivalent foundation modulus of 270 MPa and 30 per cent failure of bays. For these values of the variables Equation 1 becomes:

$$\text{Ln}(He) = \frac{\text{Ln}(L) + 24.22}{5.094} \quad (2)$$

The characteristic of this equation is illustrated in Figure 1, together with the experimental observations plotted as observed life versus effective thickness; from these results the Standard Error has been found and a line evaluated representing the 90 per cent probability of an experimental pavement's survival. It is estimated, from the work of Powell *et al* (1984), that for non-experimental roads this probability curve would be equivalent to the 85 per cent confidence limit because of the uncertainty in the predictions of traffic and greater variability in pavement thickness and quality that pertains to non-experimental roads.

A limited amount of additional information for non-experimental roads was available from the work of Gregory (1986). These data were treated in the same way using Equation 2 and are also plotted in Figure 1. The performance of the non-experimental roads was more variable but was certainly no better than that of the experimental roads.

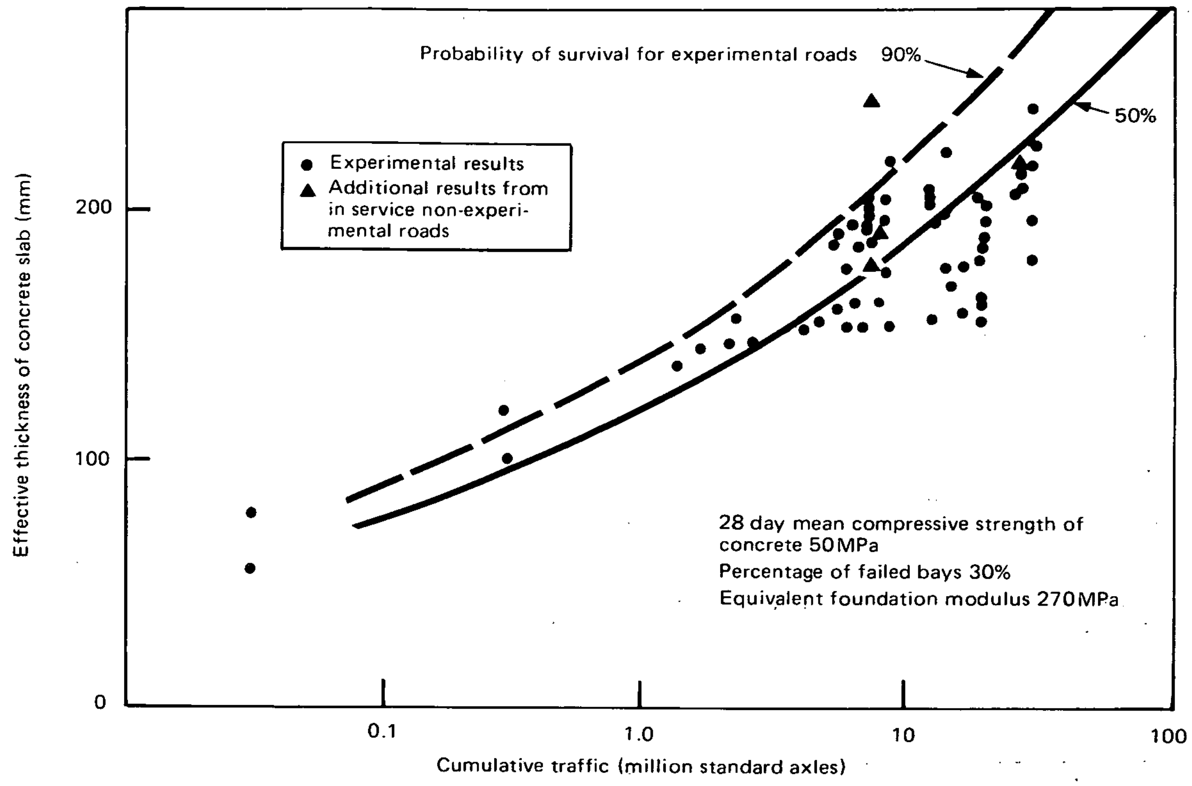

Fig. 1 Relation between thickness and life of unreinforced concrete experimental roads

6.3 REINFORCED CONCRETE PAVEMENTS

6.3.1 Failure criterion

Reinforced concrete roads generally remained uncracked, or with a limited amount of early-life cracking, for a period of time and then started to develop cracks at a fairly constant rate. It was shown by Loe (1955) that, for thin slabs, complete failure was associated with 300 m of cracking per 100 m of road, Croney (1977) used a figure of 250 m per 100 m of road (equivalent to about 64 lane-width cracks per 100 m) when analysing the performance of slightly thicker pavements. However Nowak (1979) observed that the Alconbury Hill experimental slabs thicker than 152 mm failed before cracking had reached this level. This confirmed the findings at Grantham Bypass reported by Nowak (1970), where slabs 230 mm to 255 mm thick became progressively more cracked with traffic, but failed before any section exhibited more than 135 m of cracking per 100 m of road. The 127 mm thick slabs at Alconbury Hill had in excess of 380 m of cracking per 100 m and remained in a serviceable condition. Clearly, therefore, a method using total length of cracking to define slab failure must take account of the ability of thin slabs to accommodate a greater length of cracking before failure than thick slabs.

From the Alconbury Hill experiment it was possible to determine the total length of cracking and the cumulative traffic carried by individual sections when the amount of wide cracking exceeded one lane width per bay. This length of total cracking was then defined as the failure condition because it was shown to represent the time when the rate of deterioration increased and the reinforcement ceased to be effective. Supporting evidence for the choice of this criterion comes from the Alconbury Hill experiment where inspections revealed that eleven of the sixteen sections which suffered a wide crack, across the bay-width, developed at least four more such cracks during the following year; three of the remaining sections rapidly deteriorated and were reconstructed that year. The total length of cracking and cumulative traffic at failure are plotted in Figure 2 for each of these sections and a mean line defining failure drawn through the points.

The lives of the remainder of the reinforced concrete sections under investigation were evaluated as the value of cumulative traffic at which their total crack length versus cumulative traffic characteristic cuts the failure line of Figure 2. The lives of sections that had not developed sufficient total cracking to reach the failure line were estimated by projecting their characteristic to the failure line; typcal examples are shown in Figure 3.

6.3.2 Performance analysis

The multiple regression analysis technique was then used to examine the effect and significance of the variables that were thought most likely to influence pavement life expressed in terms of cumulative traffic (msa). Data were used from 42 types of experimental

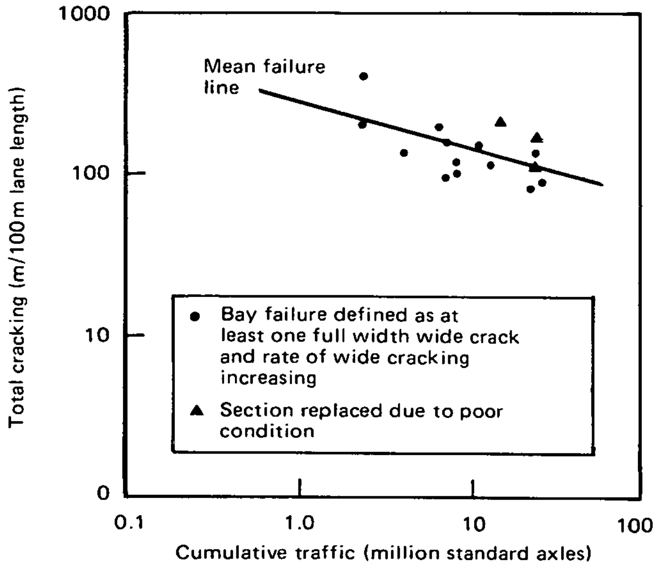

Fig. 2 Total cracking in reinforced sections when failure occurred

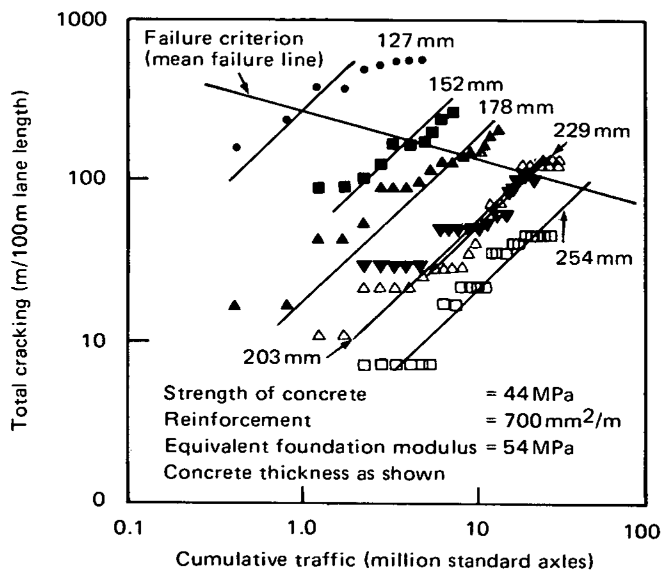

Fig. 3 Relation between cracking and traffic carried by reinforced concrete pavements

sections; the range of design variables covered by these experiments is given in Table 1. The regression estimate of cumulative traffic (L), in msa, that can be carried before failure is given by:

$$Ln(L) = 4.786Ln(H) + 1.418\ Ln(R) + 3.171\ Ln(S) + 0.3255\ Ln(M) - 45.15 \quad (3)$$

where Ln is the natural logarithm

H is the thickness, in mm, of the concrete slab

R is the amount of reinforcement in mm^2/m, in the pavement quality concrete measured as cross-sectional area of steel per metre width of slab

S is the 28-day mean compressive strength, in MPa, of cubes made from the pavement concrete

M is the equivalent modulus, in MPa, of a uniform foundation giving the same support to the slab as the actual foundation.

The regression analysis indicated that slab thickness was again the most significant variable; it accounted for 67 per cent of the variation in observed performance. The remaining variables in order of significance were amount of reinforcement, concrete strength and foundation stiffness. The four variables accounted for 91 per cent of the variation in observed performance. Performance data were obtained from bays with lengths of 9.1 m, 24.4 m and 36.6 m.

Again, to illustrate the variability of the experimental observations and to establish statistically life versus thickness curves with a selected probability of survival, the effective thickness (He) of the concrete slab of each section was calculated for a set of selected values of the variables. The values chosen were mean 28-day concrete compressive strength 50 MPa, reinforcement 500 mm^2/m and an equivalent foundation modulus of 270 MPa. For these values of the variables Equation 3 becomes:

$$Ln(He) = \frac{Ln(L) + 22.11}{4.786} \quad (4)$$

The characteristic of this equation is illustrated in Figure 4, together with the experimental results which have been plotted as observed life versus effective thickness; from these results the Standard Error was found and a curve established at the 90 per cent probability level of survival for experimental pavements; as before this has been assumed to correspond to the 85 per cent probability level for a non-experimental road.

6.4 SURFACE DETERIORATION

Surface damage to the joints and edges of the experimental slabs approximately followed the structural deterioration of the concrete pavements. Edge and joint deterioration were reduced where air-entrained concrete was used. The strength of the concrete, however, had the most effect on reducing edge deterioration; this was particularly well illustrated by the nearly perfect edge condition of the high-strength (64 MPa) granite aggregate concrete slabs at Alconbury Hill after they had carried more than 32 msa.

Repairs to the deteriorated edges of the experimental slabs were almost universally unsatisfactory. Even though a variety of repair techniques were used it was rare for a repair to last more than two or three years.

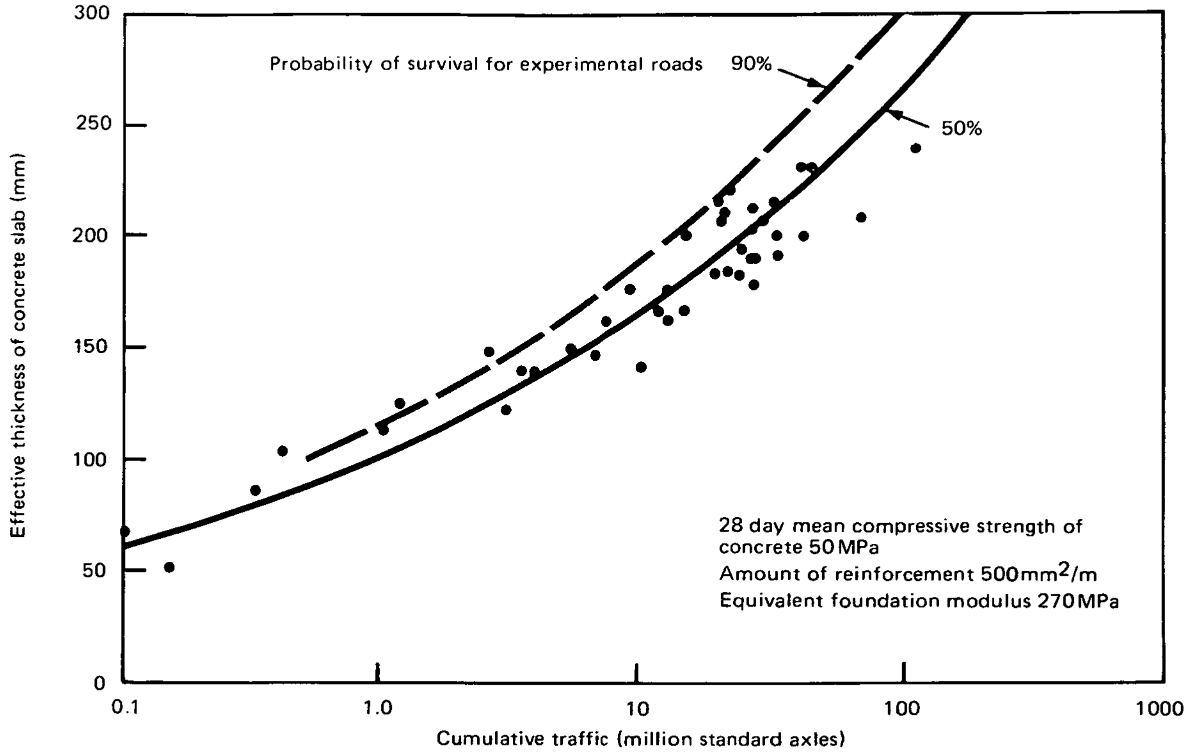

Fig. 4 Relation between thickness and life of reinforced concrete experimental roads

7 PREDICTION OF PAVEMENT PERFORMANCE BASED ON STRESS ANALYSIS

With the exception of corner loading the most likely cause of concrete pavement failure is the horizontal tensile stress developed in the underside of the slab by the combined effects of wheel load and thermally induced internal and restrained warping stresses. This combined stress was evaluated for mid-bay loading for a range of unreinforced concrete pavements to determine if the magnitude of the combined stress was linked to the pavement life predicted by the regression Equation 1.

The traffic stress was calculated for a 40 kN single wheel load acting in the centre of the slab. The multi-layer linear elastic model developed by Thrower (1968) (1971) was used with the values of moduli and Poisson's ratio for the various layers being those measured on material from the Alconbury Hill experiment or those used by Powell *et al* (1984) for a similar analysis. The values of internal and restrained warping stress were calculated from an analysis by Thomlinson (1940). Traffic and thermal loading were substantial but not the most adverse possible.

A range of designs based on Equation 1 were examined for concrete pavements containing gravel aggregates with mean compressive strength in the range 30 to 60 MPa, slab thickness 125 to 275 mm and with granular and cemented sub-bases corresponding to an effective foundation modulus of 80 MPa and 270 MPa respectively. From the equation, the pavements' lives were found to be in the range 1.4 to 152 msa.

The ratio of concrete flexural strength to combined traffic and thermal stress for these pavements was

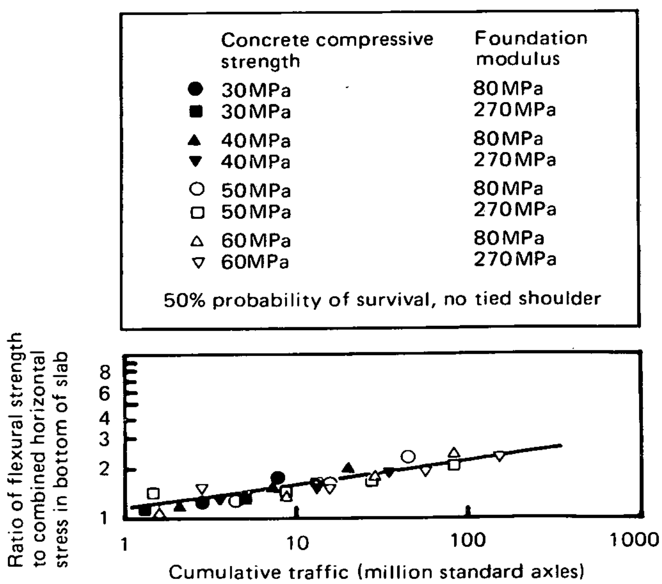

Fig. 5 Ratio of flexural strength of concrete to combined traffic and thermal stress for unreinforced concrete slabs

plotted against their derived lives, and illustrated in Figure 5. The flexural strength of the concrete was calculated from the compressive strength using a relationship established by Shacklock (1974). A unique relation was obtained that held for the wide variations in concrete strength, slab thickness and foundation support investigated. This result suggests a possible design criterion in terms of strength/stress ratio and supports the realism of the regression equation by indicating a credible mechanism of pavement deterioration.

The stress analysis also showed that pavements with intact lean concrete sub-bases were not, perhaps, fully exploiting the stiffness of the sub-base because of the slip layer between the pavement slab and the sub-base. Analysis indicated that when this slip layer was removed and the pavement slab bound to the sub-base, the critically stressed region was no longer at the bottom of the slab; the largest tensile stresses were then developed at the bottom of the sub-base. However these sub-base stresses were no larger than those predicted to exist in the sub-base of the equivalent pavement with a slip layer.

Analytically, at least, this shows that savings might be possible by constructing composite pavements of pavement quality concrete bound to lean concrete bases. This was also suggested by Packard (1984) and by Eisenmann, Birmann and Leykauf (1983). The practical problems associated with achieving a durable bond are considered by Lister and Maggs (1982). However designs which place the weakest bound material in a region of maximum stress would seem to be intrinsically dubious.

8 EFFECT OF TIED SHOULDERS ON PAVEMENT LIFE

Shoulders abutting the carriageway reduce the traffic stress induced in the concrete slab and increase the service life of the pavement. Experience in America described by Sawan and Darter (1978), has shown that for the best performance shoulders should be tied and at least 1 m wide.

The experimental roads, on which the present analyis of performance is based, were built without shoulders. If these findings are to be used to develop designs for the Department of Transport's roads, which are specified with shoulders, account must be taken of the improvement in performance provided by the shoulders. The AASHTO Design Method (1985), based on experimental observations and mechanistic stress analysis, provides a method for evaluating this improvement in terms of reduced slab thickness for equivalent traffic. The use of this method to account for the effect of shoulders in the present analysis is considered justified because the relationship between slab thickness and life developed from Equation 1 is very similar to that given by the AASHTO (1985) design method for unreinforced pavements with the same variables. This similarity is clearly illustrated in Figure 6.

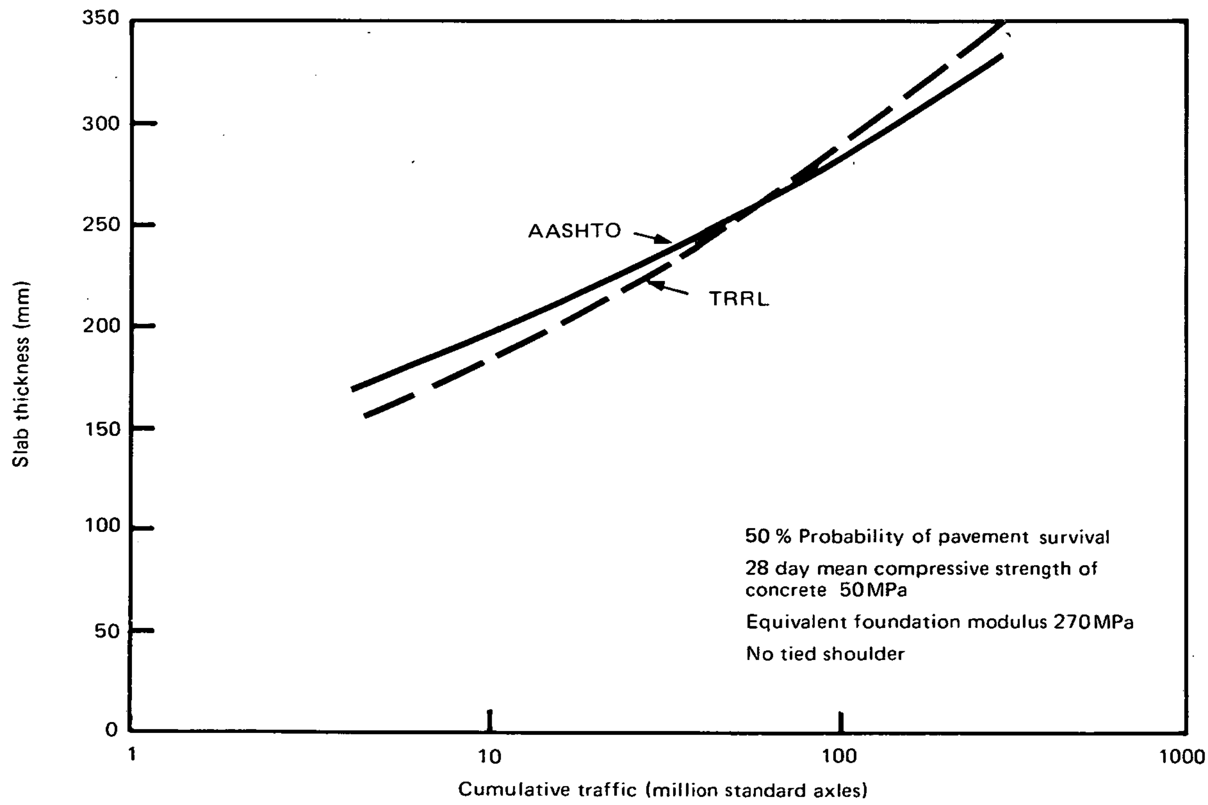

Fig. 6 Comparison of slab thickness versus life characteristic for the AAASHTO design method and TRRL multiple regression equation

The equivalences of a tied shoulder in terms of slab thickness, evaluated using the AASHTO method, are shown in Figure 7 for a pavement with the selected values. The equivalences were not significantly affected by changing the probability of survival from 50 to 85 per cent.

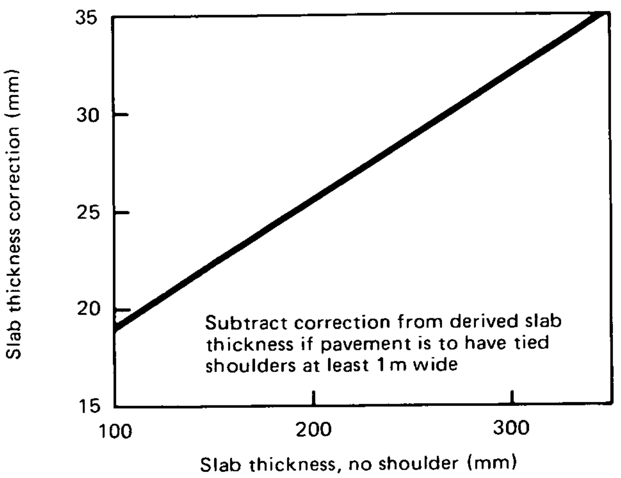

Fig. 7 Contribution of tied shoulder to pavement life in terms of equivalent slab thickness

9 EFFECT OF SLAB THICKNESS ON PROBABILITY OF SURVIVAL

The additional slab thickness required to increase the chances of a pavement's survival from 50 to 85 per cent has been evaluated by averaging the increase demanded by the TRRL unreinforced and reinforced curves of Figures 1 and 4 respectively, and that demanded by the AASHTO design method for pavements with and without tied shoulders. The evaluations, all of which gave a similar set of results, were made using the selected values of the pavement variables. The mean of the four predictions was considered appropriate as it draws equally on all available information; the resulting relationship linking increase in slab thickness with the change from 50 to 85 per cent probability of survival is illustrated in Figure 8.

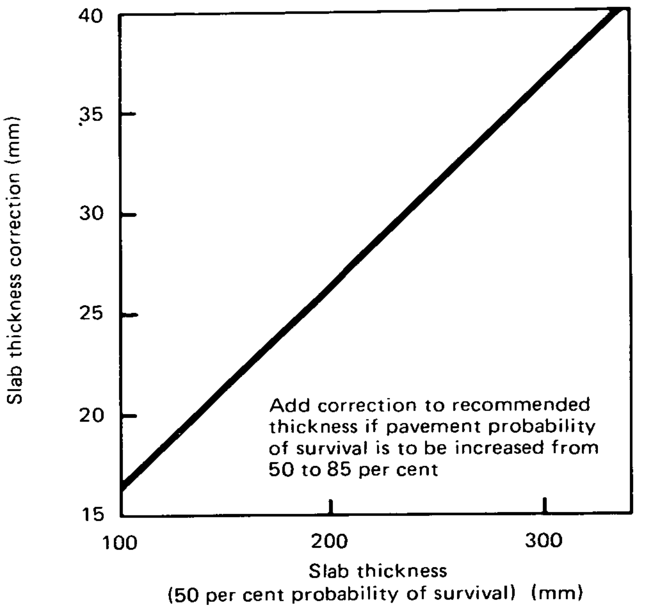

Fig. 8 Increase in slab thickness required to increase probability of pavements survival from 50 to 85 per cent

10 EFFECT OF A DAMAGED SUB-BASE ON PAVEMENT LIFE

Equation 1 has been used to determine the effect on pavement life of micro-cracking in a cemented sub-base; this cracking could be caused by early trafficking of the sub-base during the construction phase. An evaluation has been made assuming that the micro-cracking reduced the sub-base modulus to 350 MPa, which approximately corresponds to the value associated with a bituminous layer. To maintain the same life the thickness of the pavement quality slab would have to be increased by 5 per cent.

However, if it were assumed that the sub-base was severely damaged, and its condition was analogous to an unbound sub-base, the pavement quality slab would have to be increased in thickness by 15 per cent to maintain design life.

11 DESIGNS FOR NEW CONCRETE ROADS

The multiple regression analysis has established equations relating pavement life to the major pavement variables for both unreinforced and reinforced pavements. These relationships, together with the methods described above for accounting for the effects of tied shoulders and variations in the pavement's probability of survival, make it possible to predict the life of a range of different pavements, provided that the variables affecting performance are not significantly different from those covered by the experimental roads.

A set of designs has been produced for a pavement with the selected values of the variables. The practical choice of foundation was restricted by the need to provide a sub-base/subgrade combination that was non-erodable and provided an all-weather working platform for the road construction, whilst remaining stable through the predicted life of the pavement. The cemented sub-base foundations given in Table 2 meet these criteria and yield a minimum value of equivalent foundation modulus of 270 MPa. Concrete with a 28-day mean compressive strength of 50 MPa was chosen for the pavement slabs as material of this strength approximates to the currently adopted C40 specification of the

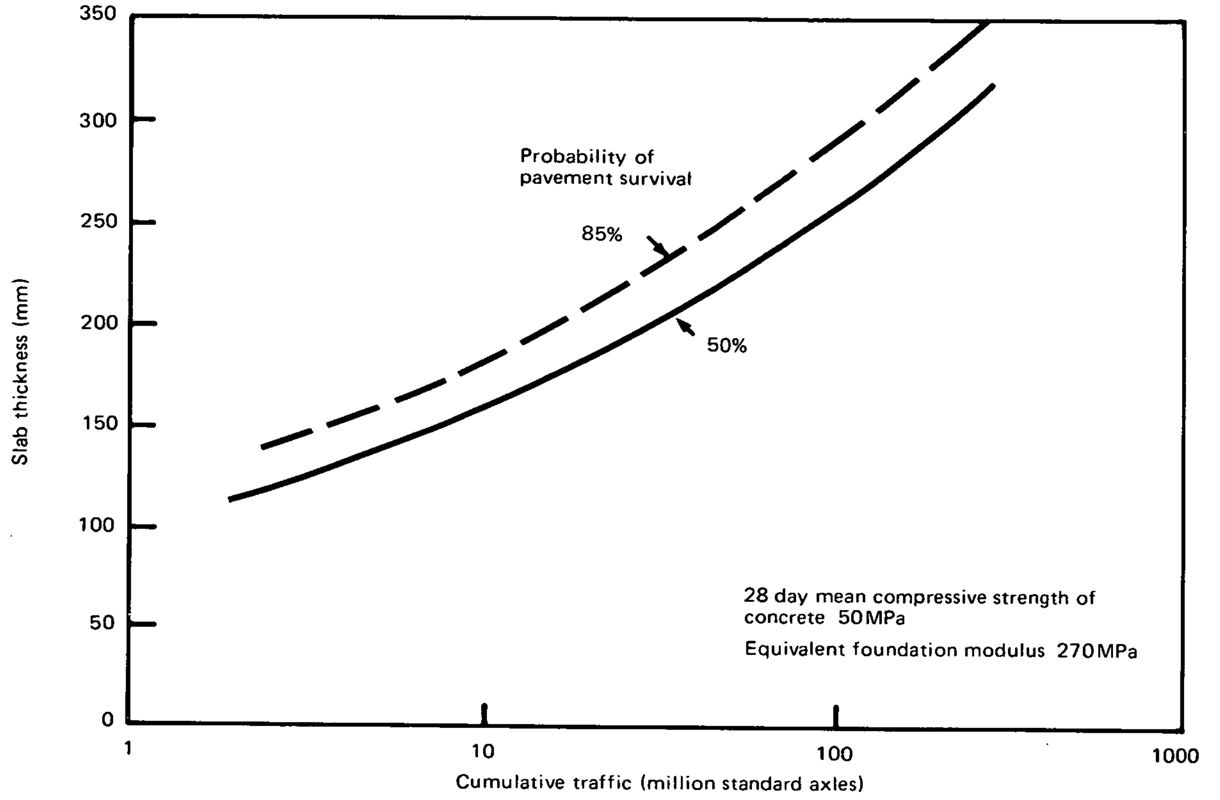

Fig. 9 Designs for unreinforced concrete pavements with a tied shoulder

Department of Transport (1985); it has a longer structural life than the lower strength material previously specified and should exhibit less deterioration at joints and edges. The designs resulting from this approach for unreinforced concrete are illustrated in Figure 9. The curves have been extrapolated beyond the range of the data used to derive the regression equation in order to provide designs for roads where very heavy traffic, up to 300 msa, is predicted.

A set of designs for reinforced concrete slabs has been obtained using the same method but in conjunction with the multiple regression Equation 3. These designs are illustrated in Figures 10 and 11; the increased life resulting from additional reinforcement is clearly shown.

12 CONCLUSIONS

1. Regression equations have been developed for the design of both reinforced and unreinforced concrete pavements. The design equations are based on the systematic observation over more than 30 years of the performance of numerous sections of experimental road; they quantitatively account for the major factors generally thought to control concrete pavement performance.

2. Design life has been defined as the traffic carried to a well defined condition of pavement deterioration for both reinforced and unreinforced concrete.

3. A straightforward and simple method based on equivalent thickness elastic analysis has been used to evaluate pavement foundation support.

4. The life of both unreinforced and reinforced pavements was sensitive, in order of significance, to changes in slab thickness, concrete strength and foundation support. In reinforced pavements the amount of steel also had a considerable effect on life and was second in significance only to slab thickness.

5. Stresses predicted by multi-layer elastic analysis for a wide range of pavement designs developed from the regression equation for unreinforced concrete, gave a unique relationship between design life and the ratio of concrete strength to combined traffic and thermal stresses within the slab. This suggests a possible criterion for design in terms of this ratio and supports the realism of the regression equation by indicating a credible mechanism of pavement deterioration.

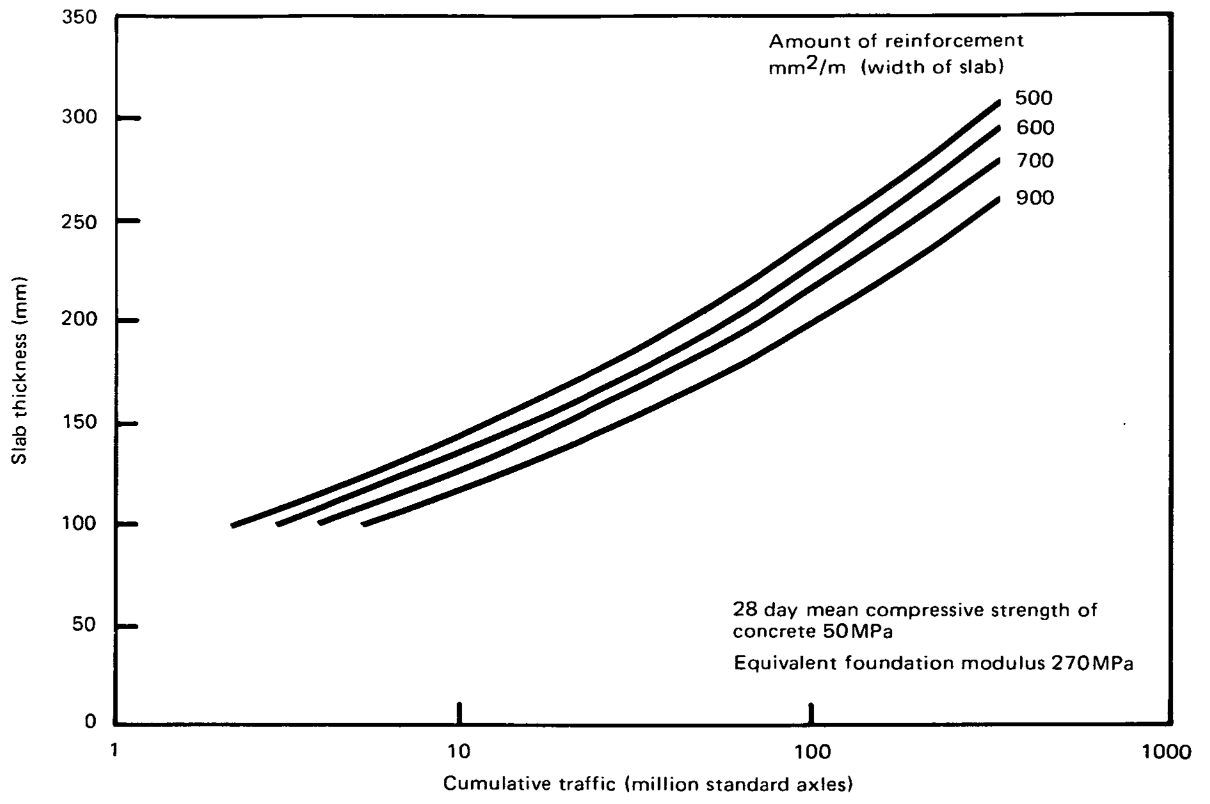

Fig. 10 Designs for reinforced concrete pavements with a tied shoulder and 50 per cent probability of survival

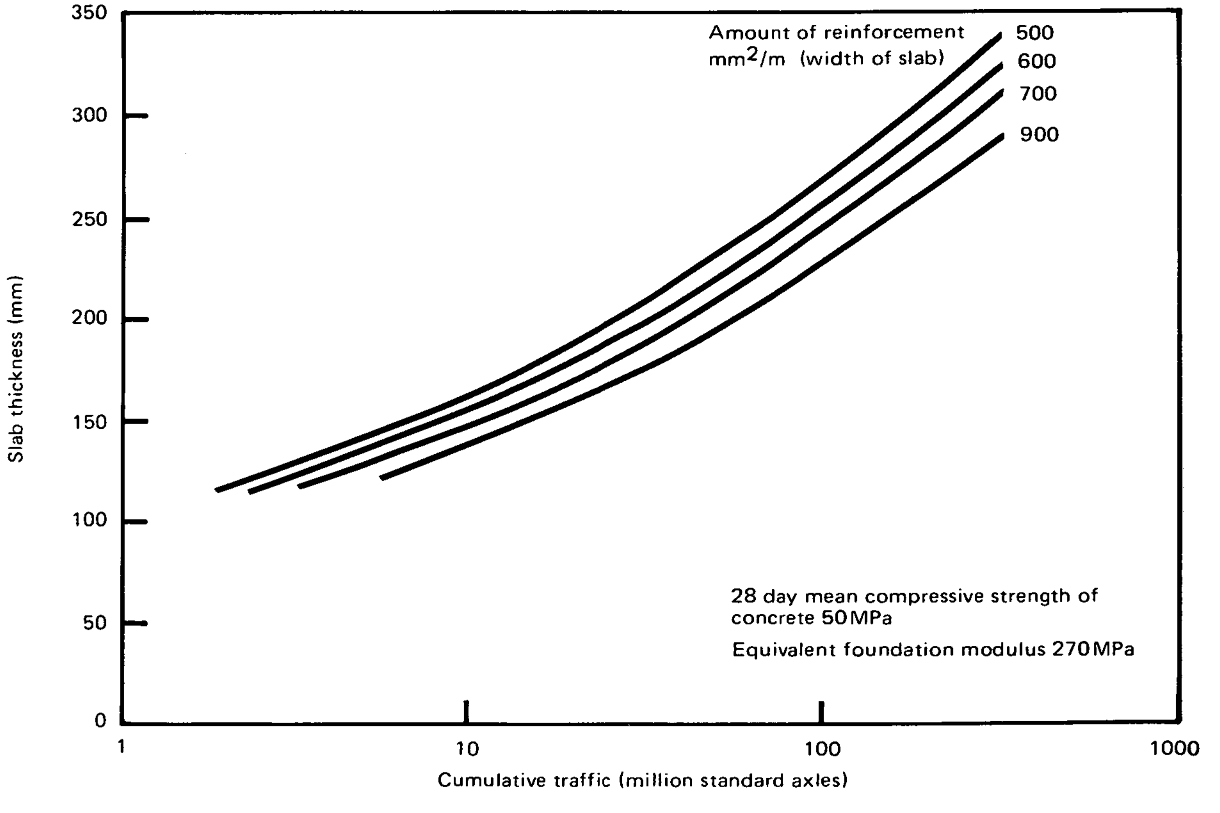

Fig. 11 Designs for reinforced concrete pavements with a tied shoulder and 85 per cent probability of survival

6. The regression equation for unreinforced concrete pavements gave similar results to those obtained from the proposed AASHTO Design Method (1985) when designing substantial pavements on good foundations. The two methods also predict a similar relationship between slab thickness and the pavement's probability of survival. This agreement between the two methods has enabled account to be taken in the present work of the effect on performance of pavements with tied shoulders.

7. Increasing the strength of the concrete forming the road slab not only improved structural performance but also reduced slab surface deterioration. The resulting reduction in maintenance was important because of the unsatisfactory performance of local repairs.

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