CONCRETE ROAD EXPERIENCE IN GREAT BRITAIN 1969-1975

J. R. Lake, N. W. Lister and P. D. Thompson
Department of Environment
London, England

1. INTRODUCTION

1.1 Historically, concrete for road pavements in Britain has been used for more than 100 years; the first documented example was of an access road to the Inverness (Scotland) freight yard in 1868. However, in spite of a well developed cement industry and the ready availability of suitable aggregates, concrete roads were slow to gain acceptance and by 1919 only a few miles existed in Britain, while 3000 to 4000 miles were in use in the United States.

1.2 The designs and specifications for concrete roads were developed in Great Britain by constructing lengths of road incorporating experimental features, and observing these over periods of time. In the 1920's such aspects as slab thickness, slab length and amount of reinforcement were examined by the Ministry of Transport's Experimental Branch. Most of these pavements were hand laid and a number are still carrying traffic, although most of these have been overlaid with bituminous materials. A few laid in the 1930's are still in use however without overlays.

1.3 Pre-1939 concrete pavements were generally reinforced when used on major roads and unreinforced on minor ones. A variety of load transfer devices was employed, but in some cases they were omitted altogether. After 1946, double-layer reinforcement was replaced by single layer steel of equivalent weight, in order to simplify construction. Expansion joints only were used but in the early 1960's contraction joints were introduced in association with expansion joints and the weight of reinforcement reduced from the range 8-11.5 Kg/m^2 (14-21 lb/sq yd) to 2.5 to 4.8 Kg/m^2 ($4\frac{1}{2}$-$8\frac{1}{2}$ lb/sq yd). Load transfer by dowel bars has been normal practice since 1946. The trend has been away from the earlier dry concrete mixes to a wetter material of higher workability. Air entrainment was not generally accepted practice until after the exceptionally severe winter of 1962-3 which caused widespread spalling.

1.4 Between 1946 and 1966 the Road Research Laboratory carried out more scientifically designed full-scale experiments incorporating a wide range of design variables. Information as accumulated was formulated into the first design recommendations published in 1955 as Road Note No. 19, "The design thicknesses of concrete roads" (1). In this the design thickness was related to subgrade conditions and the intensity of commercial traffic; the recommendations specified the minimum weight of mesh reinforcement and maximum spacing of joint to be used. Later experimental results contributed to successive editions of Road Note No. 29, "A guide to the structural design of flexible and rigid pavements for new roads" in 1960(2), 1965(3) and 1970(4). The last edition was particularly significant as it was followed by a relatively large increase in concrete pavement construction in England.

1.5 Despite continued improvement in design and specification, problems still occur and finished pavements at the present day exhibit undesirable features particularly in riding quality and surface texture.

2. DEVELOPMENT OF DESIGN DETAILS

2.1 The major full-scale concrete road experiments in the Road Research Laboratory's programme are listed in Table 1, which shows site by site the various design aspects investigated. These are discussed in detail below following a description of the

criteria adopted for judging pavement performance.

2.2 Assessment Of Pavement Performance

2.2.1 Assessment of the performance of concrete pavements has been primarily in terms of the length and width of cracks in any slab. Four types of crack are recognised (Fig. 1) ranging from hair cracks, only apparent when the concrete is drying, to wide cracks exceeding 1.2mm (0.05 in) at the surface. Normally failure of the steel in a reinforced pavement is assumed when a crack reaches the worst category.

2.2.2 The life of the pavements for design is defined in terms of the cumulative weight of traffic rather than in terms of time. The weight of traffic is obtained by converting the actual axle loads to equivalent 8.2 Mg (18000 lb) "standard axle" loads using the equivalence factors derived from the AASHO road test.

2.2.3 When the total length of cracking in each 100m (330 ft) of the nearside traffic lane exceeds 250m (830 ft), evidence is that wide cracks are developing at a rate which makes reconstruction or overlaying a cheaper alternative to crack repair. This condition has therefore been adopted to define failure for reinforced concrete pavements. Any crack in an unreinforced concrete pavement will develop relatively rapidly with trapped detritus tending to cause spalling as the concrete expands. Stitching of the cracks or replacement of the slabs is required. The life to failure of unreinforced slabs is therefore fairly sharply defined and the crack length to that moment is considerably less than that associated with failure in a reinforced pavement. Development of the cracking over an 18 year period in reinforced and unreinforced slabs of the Alconbury Hill experiment (See Table 1) is shown in Fig. 1. Using the criterion of 250m of cracking per 100m of carriageway lane the lives of the thinnest reinforced pavements 125mm (5 in) thick would be 2 and $2\frac{1}{2}$ years for the two weights of reinforcement used; these lives correspond to approximately 0.7 and 0.9 million cumulative standard 8.2 Mg (18000 lb) axles. The thinnest unreinforced slabs of 150mm (6 in) thickness failed and stitching was required after 13 years or 7 million standard axles when the total length of cracking was then only 130m per 100m of carriageway lane.

2.3 The Influence of Slab Thickness And Reinforcement On Performance

2.3.1 Fig. 2 shows the relationship between slab thickness and the cumulative number of standard axles carried to failure on the two major road experiments (at Oxton and Alconbury Hill). Results from two further experiments (Great Chertsey Road and Longford - Stanwell Road) are also included. For the two pavements at Oxton and Alconbury the longest lives are based on extrapolation of performance data. Distinction is made in the figure between reinforced and unreinforced pavements where appropriate and the 28 day compressive strengths of the concrete at the various sites is shown at the top of the diagram and values of subgrade CBR are also indicated.

2.3.2 The reinforced slabs at Alconbury Hill were 36m (120 ft) long between joints and experience has shown that a weight of reinforcement of at least 5.8 Kg/m^2 (10.7 lb/sq yd) would be required to control any thermal cracking in slabs of this length. The results from all four sites follow the same pattern but the thickness requirements deduced from the Oxton and Great Chertsey Road experiments are about 25mm (1 in) greater than those from the other two sites. This cannot be explained by differences in subgrade strength. The rather higher crushing strength of cubes prepared with concrete at Alconbury Hill would have a marginal effect on the performance but the most likely explanation is that the Oxton and Great Chertsey experiments were hand laid and this adversely influenced the in-situ strength of the concrete compared with machine laid concrete at the other two sites.

2.3.3 The design thicknesses shown in Fig. 2 adopted for both reinforced and unreinforced slabs for the lightest traffic conditions of less than about 0.1 million standard axles are seen to be greater than required based on the experimental data. This was primarily to allow for the generally poorer standards of construction associated with lightly trafficked roads, in Britain, normally confined to housing estates. The increased thickness of unreinforced construction required was dictated more by the maintenance problems likely to arise in thin unreinforced pavements constructed to these lower standards rather than by the experimental evidence which

nevertheless does suggest a slightly inferior performance by unreinforced pavements.

2.3.4 The conclusion may also be drawn that the design curves are conservative for pavements well constructed by modern methods. The terminal serviceability index (5) for the curve shown is 2.5; this is considered to be a reasonable approximation to failure conditions in Britain.

2.3.5 For traffic of greater than about 0.1 million standard axles the performance of reinforced slabs has been little, if any, better than that of unreinforced slabs of the same thickness. This led to the significant change in design suggested in the 1970 edition of Road Note No. 29 (4) in which the previously specified 50mm (2 in) differential in thickness between reinforced and unreinforced pavements was eliminated.

2.4 The Relationship Between Weight Of Reinforcement And Length Of Bay Between Sliding Joints

2.4.1 This was investigated in the Grantham Bypass experiment in which various slab lengths, between sliding joints, were used in conjunction with weights of reinforcement between 1.5 and 8.9 Kg/m^2 (2.7 and 16.4 lb/sq yd); the concrete slabs were 225mm (9 in) thick. Results based on a crack survey after 6 years traffic are shown in Fig. 3. Little development in cracking occurred in the preceding 3 years. Calculations of the weight of steel required to resist subgrade restraint forces in slabs of various lengths indicated that the theory was optimistic in relation to road practice but the field evidence nevertheless permitted a relaxation of previous requirements to those shown on Fig. 3.

2.5 Joint Spacing In Unreinforced Concrete

2.5.1 The present spacing of joints in unreinforced pavements was decided on the basis of continuing experience on concrete roads rather than by observation of purpose-built road experiments. For many years a 4.5m (15 ft) spacing was normal practice later changed to 6.0m (20 ft) largely as the result of observation of concrete paving practice on airports. Following some mid-bay cracking on road slabs of this length a 5.0m (16 ft) spacing was adopted in the third edition of Road Note No. 29.

2.6 The Effect Of Omitting Expansion Joints

2.6.1 The omission of expansion joints simplifies concrete pavement construction. Without expansion joints, the compressive stress developed by expansion in hot weather after the contraction joints have closed, also tends to reduce the tensile stress induced by traffic in the bottom of the slab. High temperatures experienced in some parts of the world are known to bring about sufficient thermal expansion to cause buckling in the absence of expansion joints. On the Longford-Stanwell unreinforced concrete road (see Table 1), the expansion joints tended to close after several annual cycles of temperature and subsequently the expansion joints behaved in much the same way as contraction joints.

2.6.2 The magnitude of the compressive stress generated in pavements without expansion joints was investigated by constructing experimental lengths of reinforced concrete pavement 230mm (9 in) thick on the Tuxford Bypass in November 1966 (Table 1). The lengths had contraction joints only, at 25m (80 ft) spacings. Compressive stresses were measured continuously at distances up to 150m (480 ft) from the end of a 300m (1000 ft) section using Glotzl stress gauges cast into the concrete at mid-depth. The maximum compressive stresses measured in five successive summers are shown below:-

Year	Compressive Stress MN/m^2	(lb/sq in)
1970	6.2	900
1971	6.2	900
1972	4.8	700
1973	5.5	800
1974	4.0	600

No buckling has been experienced to date and there therefore appears to be little risk of buckling under the normal temperature conditions in Britain. Road Note No. 29 therefore suggests the omission of expansion joints in concrete pavements laid in the summer period between 21 April and 21 October outside of which the risk of further temperature expansion is very small.

3. PROPORTION OF CONCRETE ROAD PAVEMENTS IN ENGLAND 1969-75

3.1 In 1969 the Ministry of Transport, then directly responsible for all major inter-urban roads, published a fourth edition of their Specification for Road and Bridge Works (6) and circulated Notes for Guidance on the document. At that time, the proportion of new concrete roads being constructed had fallen to approximately 6% and a policy statement was issued to achieve a minimum of 20% new roads constructed in concrete and so provide for a viable concrete road industry to compete with the flexible road industry. Most of the plant used to construct the few concrete roads laid up to that time was acquired by contractors for airfield pavement construction and little, if any, investment in concrete plant was evident solely for highway construction.

3.2 The requirement that alternative tenders for concrete and flexible pavements were to be invited for each road project of length greater than 1 km (0.6 mile), changes in design of concrete roads, in particular the acceptance of unreinforced concrete pavement of the same thickness as reinforced concrete, and relatively thin sub-bases on stronger soil formations were considered to be sufficient incentive to contractors to price concrete competitively and likely lead to an increased number of contracts with concrete pavements without any direct intervention by the central road authority.

3.3 Events showed this to be correct and the proportion of concrete roads increased, associated with increased investment by contractors in paving machines for highway work. The proportions achieved in any one year reached a maximum of 30% in 1972 and 1974 but dropped below 10% in 1973 and to about 1% in 1975. A cyclic variation each two year period may possibly be related to the degree of commitment of plant, the smaller proportion corresponding to those periods where plant was already fully committed. However, little doubt exists but that the average amount of concrete pavement being laid is falling. The low proportion of concrete in the period 1975/76 occurred during the period of severe inflation and the oil crisis, when prices of both bitumen and cement increased very significantly. At that time, it so happened that decisions were taken to increase the thicknesses of sub-base as experience showed that a greater margin of safety was required to offset possible temporary effects of weather on the sub-base and subgrade during and immediately after construction. Added to this was the dissatisfaction with the finish achieved on some concrete road lengths and the degree of remedial work required of Contractors may have affected their attitude to concrete road construction.

4. 1969 SPECIFICATION FOR ROAD AND BRIDGE WORKS

4.1 The 1969 Specification is based partly on performance testing and partly on method of construction. For example, the minimum strength, air voids, limits of workability, position and alignment of dowel bars and reinforcement, alignment of joints and surface regularity are all clearly defined and the engineer can test or measure to ensure conformity. However, instructions on the formation of grooves at joints, the alignment and setting of side forms, the operation of machinery working in paving trains, guidance system for slip form pavers, the delivery, storage and batching of concrete materials, spreading of concrete, are specified by method of construction and the Contract requires the Contractor to undertake laboratory tests in the presence of the engineer to satisfactorily obtain the mix proportions to be used in the Contract. The Contractor also has to lay a trial slab to demonstrate that the methods he proposes will produce the required result. Principal points in this Specification are as follows.

4.1.1 The quality and type of the cement is controlled by British Standard Specification. The aggregates, both coarse and fine, are controlled in terms of grading as is the proportion of calcium carbonate in the fine material. If limestone coarse aggregate is used within 50mm (2 in) of the road surface, accelerated wear testing on laboratory speciments of the concrete mix must indicate minimum skid resistance properties. The

water/cement ratio for the surface dry aggregate is related to the strength requirements. The concrete within at least 50mm (2 in) of surface is required to have an air content from the use of air-entraining agents of $4\frac{1}{2} \pm 1\frac{1}{2}\%$.

4.1.2 The strength of concrete measured by crushing cubes must not be less than 28 MN/m^2 (4000 lbs per sq in) at 28 days. Provision is also made for testing some of the cubes after 7 days curing to provide an early indication of any changes in the quality of concrete and of corrective action needed. Additionally, provision is made for the Contractor to cut cores from the finished concrete slab if the crushing strength of 28 MN/m^2 (4000 lbs force per sq in) is not obtained, and the results from compressive tests done on these cores take precedence over cube strengths in determining the acceptability of the concrete in the pavement.

4.1.3 Concrete workability is determined in accordance with a British Standard test for compaction factor and the Specification lays down tolerances of ± 0.03 from its optimum value. Where higher workability mixes are used, a slump test is permitted with a tolerance of ± 25mm (± 1 in) on an optimum value which is normally greater than 40mm ($1\frac{1}{2}$ in).

4.1.4 Steel reinforcement in reinforced concrete construction is required to be 60 ± 10mm ($2\frac{1}{2} \pm \frac{1}{2}$ in) below finished surface of the slab and to terminate between 40 and 80mm ($1\frac{1}{2}$ and 3 in) from the edges of slabs and all joints. Either steel fabrics or steel deformed bars are permitted, the latter being introduced because it was considered to be more convenient and economical for use with slip form pavers and permits full depth construction in one operation with conventional paving trains.

Dowel bars are required at transverse joints whether expansion or contraction, and criteria are given for their position and alignment. They are normally placed at mid-depth of slab and in line with the longitudinal run of the road pavement; small deviations are permitted on a few bars, the object being to minimise corner slab cracking. In contraction joints a fillet of wood, metal or synthetic material is fixed to the surface underneath the concrete slab and aligned vertically with the groove in the surface. The fillet may be omitted if the grooves in the concrete slab are sawn in concrete made with crushed stone coarse aggregate, but in this case the depth of the groove is increased. Warping joints may be used in place of some contraction joints. They consist of a reinforcing mesh or tie-bars with a crack inducer cast into the bottom of the slab and a sealing groove on the surface, the centre 200mm (8 in) of the bars across the joint being painted with a bond breaking compound.

At longitudinal joints 12mm (0.5 in) diameter tie bars are required at the mid-depth of the slabs. Approved timber or synthetic crack-inducing fillets are required to be fixed securely to the surface underlying the slab along the line of the joint. The fillet is not, however, required if the grooves are sawn, in which case the depth of the sawn groove shall be not less than one-third of the slab depth.

Construction joints are not required in unreinforced concrete and are only permitted in reinforced concrete carriageways in the event of mechanical breakdown or adverse weather, while end-of-day joints are to be constructed at positions corresponding to the ends of slabs of bay lengths. All joints are to be formed in a straight line at right angles to the longitudinal axis of the carriageway except at road junctions and roundabouts.

Grooves in the concrete surface may either be formed in the plastic concrete or sawn after the concrete has set. Forming is presently the most economic method. In forming, the Contractor has to demonstrate in the trial length his ability to do the work and still produce a surface finish across the joint with the appropriate surface tolerance. When sawing, the work must be done within 8 and 18 hours of final compaction depending on whether the slab was laid before or after mid-day.

4.1.5 Permanent sealing of joints is required not less than 28 days after the laying of the concrete. Sealing compounds may be either hot poured or two-component cold poured. In addition, pre-formed compression sealing strips are permitted providing their design is such that they remain in compression at all times.

4.1.6 Machinery for mixing concrete may be either the batch type, or continuous mixer and must be in accordance with the appropriate British Standard Specification. The Specification and the various British Standard Specifications state the required mixing performance and the standards of maintenance of the machines. Concrete is permitted to be delivered in truck mixers or in truck agitators providing the concrete has first been mixed in stationary mixers and providing the truck mixer and its mixing performance has been manufactured in accordance with the appropriate British Standard Specification. The Specification is written in a form to include paving trains such as ABG and SGME and also G & Z Slip-form pavers. Instruction is given on the machinery used to distribute the concrete uniformly, to avoid pre-compaction and to reduce segregation to a minimum. Concrete in reinforced slabs may be spread in one or two layers and constraints are placed in relation to the placing and support of reinforcement. With paving trains, compaction of the concrete must be carried out by vibrating beams travelling on the surface or by a combination of mechanical tamping and surface vibration. The finishing screeds are also described and have a minimum weight.

Slip-form pavers rely on internal vibration for compaction and the Specification gives the minimum energy output for the vibrators related to the width of slab and speed of paving. The Contractor is required to demonstrate during the construction of the trial length referred to later that the machine he proposes to use will compact the distributed concrete to the full specified depth and produce the required surface levels.

Table 2 indicates that both paving trains and slip form pavers have been used in United Kingdom during the past 6 years to lay and construct concrete road pavements. While every effort is made to encourage the use of modern paving machinery, the Specification recognises that where slabs are small or irregular or the site is very restricted, hand finish or other means may be inevitable. With hand working the Specification requires vibrating beams to be used for compaction and surface regulation.

4.1.7 The Specification requires that after the final pass of the finishing beam on the completion of joints and before the application of the curing membrane, the surface of the concrete carriageways shall be brushed in a direction at right angles to the centre of the carriageway with a wire broom of defined construction. The average texture depth measured by a set of tests shall not be less than 0.76mm (0.03 in).

4.1.8 The surface level of a concrete slab in relation to the true pavement surface must not deviate vertically at any point by more than 6mm ($\pm \frac{1}{4}$ in). A grid of points, both longitudinally and transversely is specified at which measurements are to be made. Tolerances from true level are given for the sub-base thus constraining the thickness of concrete pavement. For example, a concrete pavement of 280mm (11 in) thickness must be laid within a tolerance 19mm ($\pm \frac{3}{4}$ in) while with the subgrade, which may extend to 450mm to 600mm (18 to 24 in) from the true road level, a tolerance of 25mm ($\pm$ 1 in) is permitted.

4.1.9 The longitudinal regularity required of the surfaces of the constructed concrete wearing course is given in terms of the maximum number of permitted surface regularities exceeding 3 and 6mm ($\frac{1}{8}$ and $\frac{1}{4}$ in) as measured by a rolling straight edge of the type designed by the Transport and Road Research Laboratory and operated parallel to the centre line of the carriageway, 1.2m (4 ft) from the nearside edge of each carriageway. Lengths for test of 300 or 75m (1000 or 250 ft) are specified.

4.1.10 An important single feature of the Specification is the requirement that prior to the commencement of paving, the Contractor shall construct a trial length of the main carriageway at least 60m (200 ft) and not more than 300m (1000 ft) long, using the plant and equipment to be employed on the works and with concrete having proportions expected to be suitable as determined by the laboratory trial mixes. In the trial length the Contractor has to demonstrate the method he proposes to use for the construction of joints and for the laying of reinforcement, the joint construction later being investigated by digging out the wet concrete from around the joints. The Contractor may proceed with normal working 10 calendar days after the completion of the trial length unless he is advised of any deficiencies. In the event of deficiencies the Contractor is required to construct a second trial length.

5. DEVELOPMENT 1969-1975

5.1 Since the Specification for Road and Bridge Works was published in 1969 (6), several major changes and developments have taken place in both pavement design for concrete roads and specification for construction. The changes in pavement design are referred to in Section 2 of this paper. During this period, trials have been made with machines for inserting dowel bars and tie bars in plastic concrete and developments have taken place in the forming of joints. Experience has shown that with subgrades of intermediate and low strengths the sub-base thicknesses used have sometimes been inadequate and affected performance both during and immediately after construction. Perhaps the biggest single development has taken place in texturing methods for concrete roads. In 1969 all new concrete roads were brushed transversely to provide a non-skid finish. Since then the advantages of deeper texture in maintaining high speed skid resistance have become apparent and much research and development has gone into the production of machines for grooving concrete both in the plastic and hardened state. These machines have been used on a number of major road projects in the United Kingdom and while very satisfactory results were obtained from the technological aspect, major problems arose because of the increased levels of surface/tyre noise on such surfacings. A solution to this problem is thought to have been found and is described in Section 7.

6. THE ADVISORY PANEL ON CONCRETE ROAD CONSTRUCTION

6.1 Because of the run down in concrete road construction the situation was reached in the middle 1960's when few engineers were available with any practical experience in concrete road technology. What experience existed was mainly concentrated in the Cement and Concrete Association (C & CA) and the Transport and Road Research Laboratory (TRRL) and Directorate General of Highways (DGH) of the Department of the Environment. As referred to earlier, changes in design, particularly the inclusion of unreinforced concrete slabs of thickness similar to reinforced concrete slabs used previously were thought likely to increase the competitiveness and therefore use of concrete, and the decision was taken to form an Advisory Panel on Concrete Road Construction to advise both engineer and contractor engaged on concrete road contracts on latest concreting techniques. Composed of representatives of the C & CA, TRRL and DGH the Panel also aimed to collate feedback from practical experience to assist re-appraisal of the Specification.

6.2 The Panel held some 30 meetings a year between 1972 and 1975, the meetings being attended by both engineers and contractors to encourage a frank interchange of information on problems. Early apprehension that these meetings might affect and possibly upset contractual positions was not confirmed. In total the Panel has examined and commented on the works at 28 contracts.

6.3 Reports prepared annually describe the Panel's experiences in the particular year and draw attention to design and construction problems, in most cases proposing solutions. For example, detailed advice has been given on the formation of joints, remedial work and riding qualities. The work of the Panel has undoubtedly speeded up the implementation of improvements in the Specification.

7. PROBLEMS EXPERIENCED 1969-1975 WITH CONCRETE PAVEMENT CONSTRUCTION

7.1 In this Section problems encountered in the period 1969-1975 are described. Those concerned with surface finish and surface regularity were the most difficult and indeed have not yet been resolved completely.

7.1.1 Few problems have been experienced with the quality of concrete. On only one contract did the material fail to meet the specified strength requirements. This occurred at the peak of the energy crisis when under the conditions then prevailing and with difficulties of cement production the Contractor accepted cement from several sources to maintain his construction programme. This increased his and the client's control problems. It was unfortunate that trial mixes were not undertaken with each new cement used. If this had been done the problems may not have arisen. A more frequent problem was that of variable workability of the concrete. Even experienced contractors appear to devote insufficient attention to the control of mixing and batching plants, and in several cases the operation of plant at the limits of its

production capabilities to keep up with paving operations resulted in a variable product. This particular feature may have been a contributory factor in affecting the riding quality referred to later.

7.1.2 Reinforced concrete pavements have not been laid on major roads for 5 or 6 years. Of those laid earlier, such problems as existed were usually related to the laying of the steel reinforcement. On contracts where the concrete was laid in two layers and where the reinforcing was laid on the lower layer of concrete which was then compacted through the steel, few problems arose, whereas on other contracts where the lower layer of concrete was compacted before laying the steel, the subsequent compaction of the upper concrete layer appeared to induce a ripple in the surface of the finished road thought to be related to the movement of the reinforcement. Although not affecting the performance of the concrete pavement as a structural element, the riding quality was affected.

7.1.3 Up until a few years ago most dowel bars were held in place by cages. More recently, however, dowel bars have been inserted into the wet concrete using dowel bar placers. With cages, problems have been largely concerned with the fixings to the sub-base, particularly with unbound material and also with obtaining a balance between rigidity to withstand the concreting machinery and the facility of movement during the life of the road. On one contract the cage assembly as laid initially was so rigid as to prevent any movement of the joint.

Misaligned dowel bars appear to occur more frequently when dowel bar placers are used. As a result some corner cracking on a number of contracts and some transverse cracking has occurred. Correctly used, and possibly subject to further development, dowel bar placers are probably a logical development but further work is needed to control the operation of placing and maintaining the bars in the correct position and alignment and to ensure adequate recompaction of the concrete above and around the bars. The development of equipment for the non-destructive detection of the dowel bars in the slab would assist greatly the degree of confidence in the method.

7.1.4 Most transverse joints have been formed in situ in the wet concrete and contractors have generally developed their own equipment for this operation, particularly with slip form paving. The only problem has been inadequate recompaction of the concrete after forming the joints which has occurred in some contracts. Forming transverse joints by ploughing has not been particularly successful and this method is discouraged in favour of the insertion of a temporary former or compression seal vibrated vertically into position. More stringent control of recompaction at joints will most likely result in ploughing being discontinued.

Displacement of the crack inducers at the base of the slabs sometimes results in transverse cracks off the line of the joint. On the rare occasions when joint grooves are sawn, the Specification has not permitted the use of a crack inducer in an effort to avoid this problem. The crack inducer is now optional for work carried out in the summer period, providing the depth of the top groove is increased when the inducer has been omitted. This relaxation has been allowed because theoretical consideration showed that early cracking at the underneath side of the slab is only likely in cold weather.

Trials have been carried out on the use of narrow unsealed and, usually sawn, joints. Encouraging results have been obtained but the evidence is not available so far to permit narrow unsealed joints to be specified with confidence.

7.1.5 Few problems have occurred with longitudinal joints. Generally tie bars are inserted in the wet concrete across these joints but as alignment is less important than in transverse joints, no problems have occurred. On occasions the longitudinal seal has accidentally been inserted at an angle to the vertical or displacement of bottom crack inducer has occurred, but these have not adversely affected the slab. Difficulties have arisen where the transverse seal crosses the longitudinal one. While these can be overcome by cutting the one seal to allow the uninterrupted insertion of the other, care has been taken when elastomeric transverse seals are used and are under tension. Cutting of these after insertion could result in unacceptable shrinkage.

7.1.6 The use of modern machinery for laying concrete pavements, whether train or slip form, can provide pavements within the tolerances specified, providing the machinery is adequately maintained and operated correctly with the proper materials. However a significant proportion of the length of concrete pavement laid in the past 5 or 6 years is considered unlikely to have conformed with the Specification for surface regularity. The demonstration of a trial slab is no guarantee that the remainder of the contract will be constructed satisfactorily. Indeed, until recently the Contractor has been permitted to repeat trial lengths 6 or 7 times occupying a considerable length of a contract, in an attempt to demonstrate acceptable work. Sub-standard work, where detected, has not been cut out and replaced; therefore a considerable amount of surface remedial work has been required in an attempt to improve surface regularity. Experience has indicated that such remedial work did not produce surface regularities which conformed with the Specification, and at best merely improved the parts of the surface considerably out of Specification. Much tighter control of the operation of machinery is proposed in the new Specification issued in 1976.

7.1.7 Two hours is presently the current maximum time allowed between mixing of the concrete and final finishing, except when the temperature of the concrete is over 30°C when operations must cease. Contractors have had problems meeting this requirement and where two-course construction has been used, separation of the layers is known to have occurred occasionally. A more flexible approach to maximum permissible time has been incorporated in the new Specification.

7.1.8 While the bulk of the concrete pavements laid in England since 1969 have been of good quality concrete, structurally sound, and, apart from a few difficulties, in accordance with the Specification, their riding quality has not matched this performance. Probably the relatively small amount of concrete laid before 1969 has resulted in a lack of experience which has been partly to blame. This is particularly unfortunate as some engineers and members of the public are known to prefer asphaltic rather than concrete pavements and any concrete of poor rideability raises further questions on the use of concrete pavements. Indeed, Government Ministers responsible for transport have received correspondence on the subject. The Department of the Environment, the central road authority, formed a Working Party to study this problem; its first aim was to consider whether the facts confirmed opinion and judgements. Recently constructed flexible and unreinforced concrete roads were surveyed to determine their surface regularity measured by means of a TRRL bump integrator. Results showed that the riding quality of unreinforced concrete roads in England was less good than that of flexible pavements laid in the same period and also that a significant proportion of the concrete paving in any contract was unlikely to be in accordance with the specification for surface regularity. The survey also showed that the unreinforced concrete pavements recently constructed had a poorer riding quality than reinforced concrete pavements constructed several years ago. The possible causes of this unfortunate state of affairs were examined further. Included among the variables considered were type and thickness of sub-base, paving machinery, supply, spreading and possible variability of concrete, contractor, whether the joints were sawn or pre-formed, surface texture. Although all these factors undoubtedly contribute to the final riding surface, no clear conclusions could be drawn, probably because of the small number of contracts which included each of the particular variables considered. A common factor to emerge from the study was the need for closer site supervision and control. One facet of particular interest was whether or not the deeper texture now required on English concrete roads for skid resistance purposes was perhaps a factor contributing to indifferent surface regularity. Early reinforced concrete roads were lightly brushed transversely. The investigation provided a clearer understanding of investigations needed to improve the riding quality of concrete roads.

7.1.9 The trend since 1969 is towards surfacings of coarse texture produced either by heavy brushing or more recently by grooving to give adequate skid resistance on high speed roads. Earlier fine textured surfacings were shown to have a skid resistance at 130 km/h of only 50-70% of that at 50 km/h in broad terms. Grooving was developed jointly by the C & CA, a private firm and the DOE, and machines built capable of grooving plastic concrete during construction and of grooving hardened concrete for remedial purposes after construction. Early trials with grooves spaced at regular intervals produced surface/tyre noise with an unacceptable pure tone sound (a whine) but later developments using irregularly spaced grooves produced a more irregular sound

frequency spectrum. However, public criticism of even the irregularly spaced grooves (6mm wide and 6mm deep) caused the Department to restrict the use of grooving to non-noise sensitive areas on motorway and trunk road contracts. This effectively meant that grooving was largely abandoned for two to three years. Recent research by TRRL has, however, shown a relationship between cross sectional area of the groove and the surface/tyre noise generated and from this it has been possible to devise a 3mm wide x 5mm deep groove which, spaced irregularly, does not produce any more noise than a heavily brushed concrete pavement and yet gives a zero fall-off in skidding resistance from 50 to 130 km/h. Practical construction trials are presently being undertaken to investigate the grooves on a motorway contract, and, if successful, are likely to lead to this form of grooving being standard practice for concrete roads in England.

8. METRIC SPECIFICATION 1976

8.1 The main changes made in the Specification for Road and Bridge Works since 1969 and introduced into the 1976 Edition are as follows.

8.1.1 The surface tolerances of sub-bases under concrete pavements with warping joints have been reduced to improve slippage between slab and sub-base. A thick polythene layer is required under the concrete to assist slippage.

8.1.2 An indirect tensile strength test has replaced the cube crushing test for compliance purposes of pavement quality concrete.

8.1.3 The thicknesses of sub-bases under concrete pavements have been increased for certain subgrade strengths.

8.1.4 Plasticisers or water-reducing agents may exceptionally be permitted in certain circumstances eg when paving with difficult aggregates, slip form paving or paving in winter.

8.1.5 In contraction joints constructed in the summer the bottom crack inducer may be omitted, provided the slab discontinuity at the top is between one-quarter and one-third of the depth of the slab. This extends the provision already allowed with sawn joints.

8.1.6 The minimum width of slab laid in one operation is increased to 4.65m (15.5 ft) to permit the construction of the standard two-lane all-purpose trunk road with 1m hardstrips at either side without a longitudinal joint between hardstrip and the adjacent lane.

8.1.7 The time allowed for mixing and finishing of concrete has been altered to between 2 and 3 hours, the value depending on the temperature of the concrete.

8.1.8 A separate transverse or oblique oscillating finishing screed must be provided after any transverse wet formed joint to improve surface regularity.

8.1.9 Restrictions in pavement level tolerances are imposed to avoid unacceptable reductions in concrete slab thicknesses.

8.1.10 Clauses on paving plant are intended to allow the inclusion of other available slip form pavers eg CMI.

8.1.11 Wet lean concrete sub-base is permitted which is intended to be laid by concrete paving machinery.

8.1.12 The most important single change has been the requirements for the trial bay. The Contractor is no longer permitted to undertake trial after trial while taking remedial action to bring defective concrete pavement laid within the Specification. In the 1976 edition only 3 trial lengths are permitted as part of the pavement. If these are not successful in indicating an ability to lay in accordance with the Specification in all respects, then further trials must be off-site or below the level of the pavement quality concrete.

8.1.13 The Specification encourages the use of grooving as a finish for concrete pavements in those areas where noise is unlikely to be a sensitive issue and the Contractor's choice of working makes it possible for grooving to be undertaken with available machines. In this context, encouragement is being given to industry to develop machines to groove slip form paved lengths in addition to those laid by paving train and trials with groove configuration now thought to be best, namely 3mm x 5mm deep, may result soon in grooving being required as the only form of surface treatment for concrete roads on all contracts.

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TABLE 1 Details of major full-scale pavement design experiments using concrete construction

Year of Construction & Location	Main objectives and construction details	Subgrade Type	Commercial Traffic		
			Initial Daily Flow	Annual Growth Rate %	Damaging Effect (Standard Axles/ 100 Axles)
1930 A316 Great Chertsey Road, Middlesex	To obtain information on the design of joints and load transfer devices Slab thickness - 230 mm (reinforced) Compressive strength - (28 days) 21.4 MN/m^2 Sub-base - Clinker - 75 mm thick Slab length - 6.1 m	Silty clay and gravel	500	4	20 (average)
1946 A6097 at Oxton, Nottinghamshire	To study the effect on performance of: 1. Thickness of slab (100-200 mm) 2. Thickness of sand-cement sub-base (50-150 mm) Compressive strength - 37 MN/m^2 Slab length - 4.5 m (unreinforced) 9.0 m (reinforced)	Sandy	200	10 (average)	25
1948 B379 Longford to Stanwell Rd, Middlesex	1. Performance of unreinforced slabs 2. Effect of spacing of expansion joints in unreinforced pavements on joint movements Slab thickness - 200 mm Compressive strength - 39 MN/m^2 Slab length - 4.6 m Sub-base - None	Gravel embankment	500	4	20
1955 A48 Llangyfelach, Glamorganshire	The influence of strength on the performance of a reinforced pavement Slab thickness - 200 mm Slab length - 37 m Reinforcement - 3.5 Kg/m^2 Sub-base - Clinker - 150 mm thick	Gravel	450	5	25

TABLE 1 continued

1957 A1 Alconbury Hill, Cambridgeshire	The effect on performance of: 1. Slab thickness for reinforced and unreinforced slabs 2. Strength of concrete 3. Weight of reinforcement when one slab length was used 4. Thickness and type of sub-base Slab thickness - 125-200 mm Slab length - 4.5 m (unreinforced) 37 m (reinforced) Compressive strength - (28 days) 44 MN/m^2 and 66 MN/m^2 Sub-base - Gravel and lean concrete 76 mm and 230 mm thick	Silty clay	1400	5	25
1961 A46 Winthorpe (3 km east of Newark), Nottinghamshire	The effect on performance of pre-stressing thin slabs Slab thickness - 125 mm and 178 mm Compressive strength - (28 days) 48 MN/m^2 Sub-base - Lean concrete - 100 mm thick	Imported granular material	500	4	20
1962 A1 Grantham By-pass, Lincolnshire	The effect on performance of: 1. Type and weight of reinforcement in relation to slab length (including continuously reinforced concrete) 2. Using a sliding layer between the slabs and the sub-base Slab thickness - 230 mm, increased to 254 mm on embankments Compressive strength - (28 days) 38 MN/m^2 Sub-base - Lean concrete - 75 mm thick	Various - ranging from silty clay to limestone brash	1200	5	30
1966 A1 Tuxford By-pass, Nottinghamshire	The compressive stresses generated in slabs without expansion joints Slab thickness - 230 mm Compressive strength - (28 days) 30 MN/m^2 Sub-base - Lean concrete - 125 mm thick on crushed rock - 100 mm thick	Silty clay	1500	0	30

TABLE 2 Lengths of Road Paved by Different Pavers Since 1969 (km)

Type of Road	Dual 2	Dual 3	Dual 3	Dual 3 + HS	Dual 3 or Dual 2 + HS	Concrete HS	1 m strip	Single 3	Single 2	Single 2
Width in one pass	2 lanes	2 lanes + 1 lane	3 x 1 lane	2 x 2 lanes	3 lanes or 2 lanes + HS	alone	alone	1 lane	1 lane	2 lanes
PLANT										
Trains										
SGME	9 Reinf. 32	39	3	27						
ABG	31.4	11	-	5	39.3	3.4				1.8
Hand Laying							18		1.4	
Slip Formers										
G & Z large	2 Reinf. 4			65.5						
G & Z small						9				
CMI	13.6			8	4.8	2.6				
CPP 60								2		2

NB. All are unreinforced unless stated

HS = Hardshoulder

Width of 1 lane = 3.65m (12 ft)

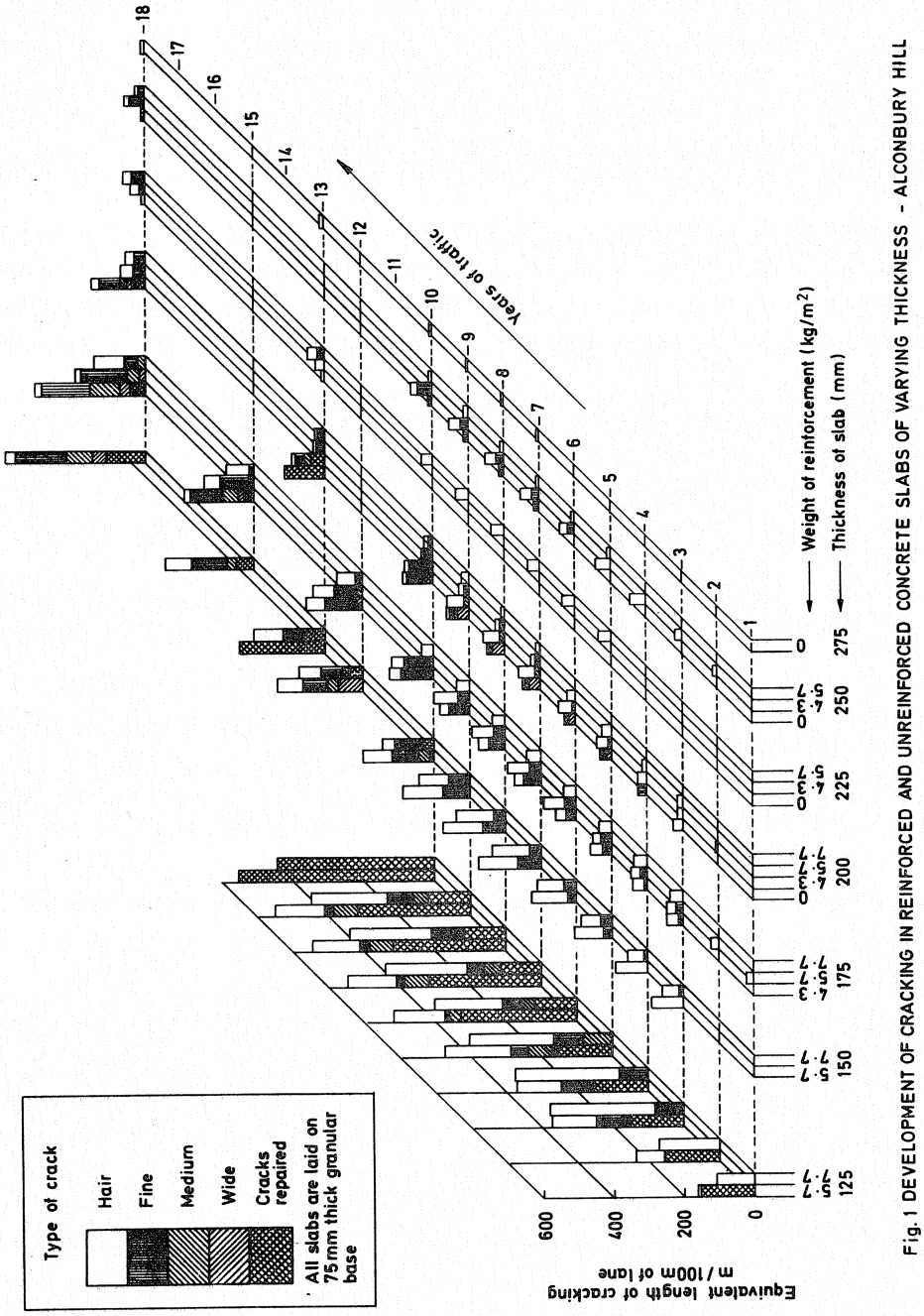


Fig. 1 DEVELOPMENT OF CRACKING IN REINFORCED AND UNREINFORCED CONCRETE SLABS OF VARYING THICKNESS - ALCONBURY HILL

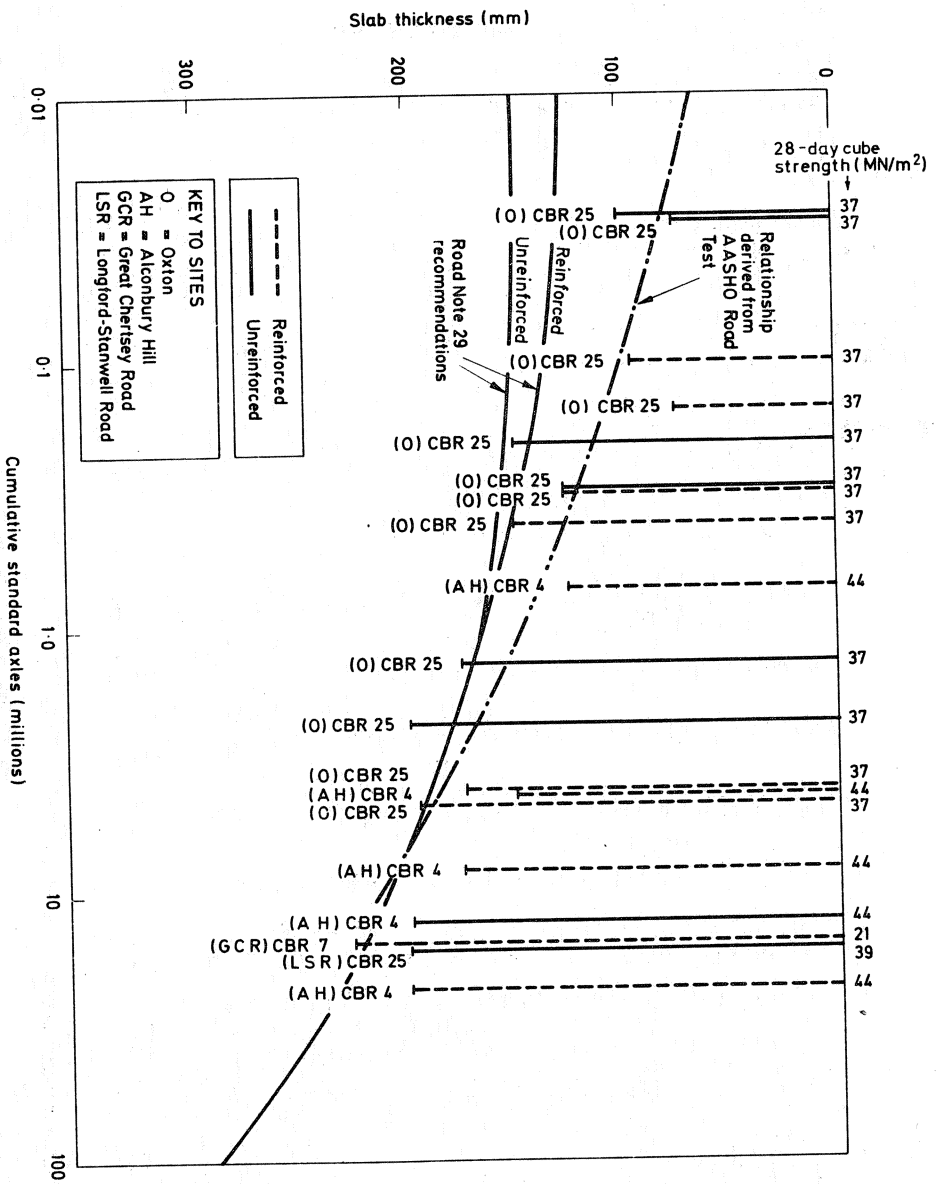


Fig.2 PERFORMANCE OF EXPERIMENTAL CONCRETE PAVEMENTS

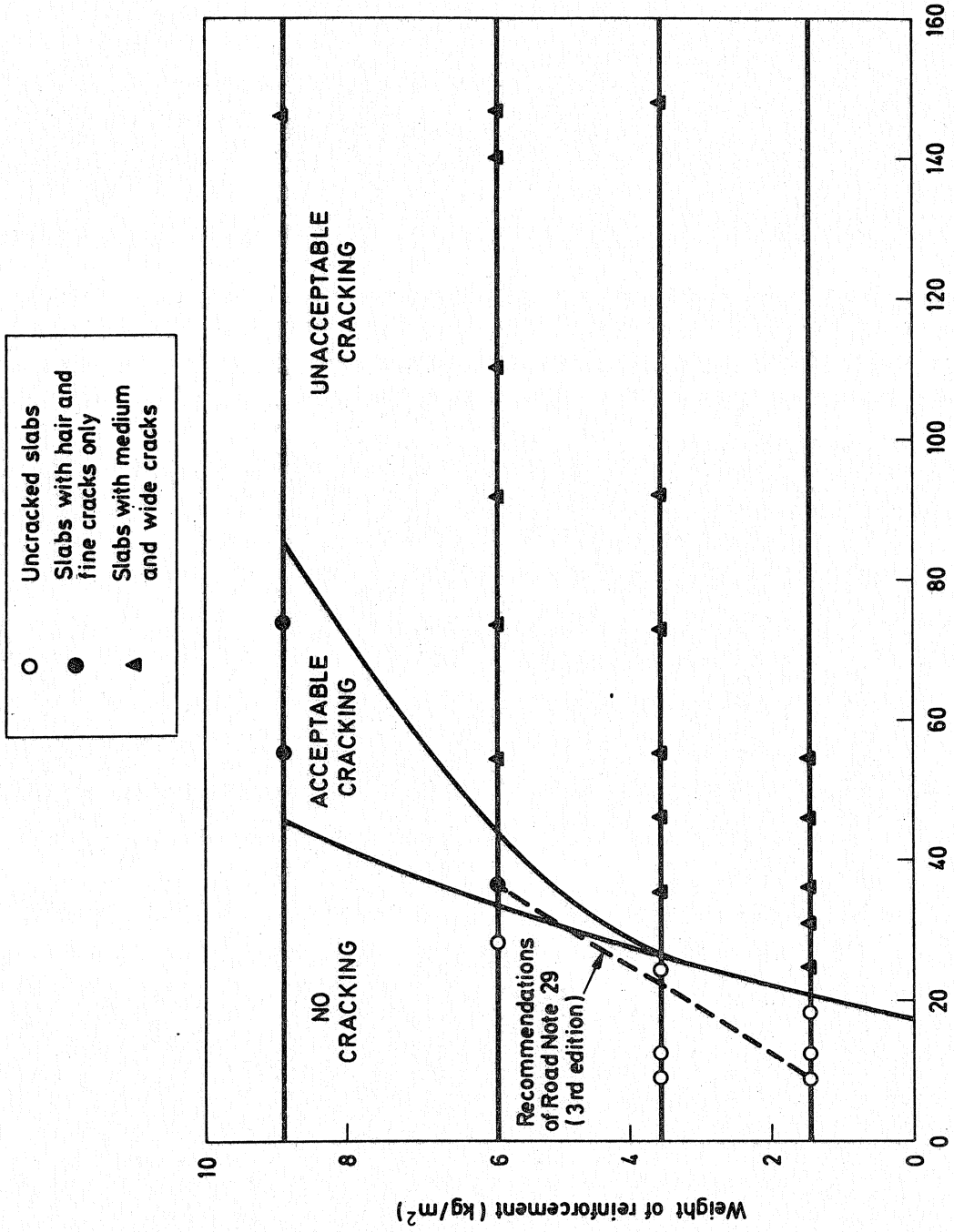


Fig.3 GRANTHAM BY-PASS - CRACKING RELATED TO SLAB LENGTH AND WEIGHT OF REINFORCEMENT