*Discussion on Paper No. 6848**

Full-scale pavement design experiment on A.1 at Alconbury Hill, Huntingdonshire

by

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and

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Sir William Glanville (Director of Road Research, Road Research Laboratory) said that the Paper described one of the most important full-scale experiments in road construction that had ever been made anywhere in the world, which was already providing a great deal of very useful information.

116. The experiment was first visualized about 1944, when it was realized that very little was known about road construction. It was found on investigation that practice varied not only throughout Britain but throughout the world. At about this time results of the C.B.R. test had appeared in America and had obtained a measure of acceptance, but more for runway than road design, though there was a certain amount of information to show that they could be applied to the design of roads.

117. The decision to use full-scale experiments was made after considering the theoretical approach and the use of models, but it was decided that these could never produce, without practical proof, really satisfying results.

118. Full-scale experiments could take various forms. The first was with the use of a road machine. There was one at Harmondsworth, consisting of a lorry tethered at the centre, operating on a circle of 110 ft diameter. In the early 1930's it was thought that this would simulate road conditions sufficiently well to enable useful results to be obtained, but it was found that it was not even useful for testing surface dressings.

119. The second type was the controlled, full-scale experiment of the nature of the A.A.S.H.O. test circuit, which had been made by the Americans in the last ten years. This consisted of a number of loops which were trafficked by vehicles with different loads and different axle arrangements. It had cost about £10 million, compared with £150 000 for the Alconbury experiment.

120. The third type was the one produced at Alconbury Hill, in which the normal traffic using the road was utilized, and the road was chosen because it had to be built anyway. The only extra cost involved was that arising from the experimental character of the work.

121. Four or five of these roads had been planned in 1945 to be built on different sub-grades. A start had been made with these experiments, most of them small, but strict economy stopped the work, and it was not until 1957 when the Alconbury Hill site became available that the work went ahead again. They were now getting results which, if the planned programme had continued, might have been available five to ten years ago. The necessary experimental work for motorway construction had been further handicapped because the urge for rapid completion had meant that facilities for comprehensive investigation had been very limited.

122. The Alconbury Hill procedure was advantageous in that the results were immediately applicable to the type of road on which the experiment was done, although it was not possible to sort out variables such as the effect of very heavy axle loads. Some information had been gained from the difference in the two lanes of

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Alconbury Hill, but it was hoped that a series of special road machine trials would provide a useful guide.

123. The Alconbury Hill experiment had had a very big effect on current specifications, and the recommendations given for design in Road Note No. 29 adopted by the Ministry of Transport had depended to a great extent on the results found there.

124. The other experiments had been mentioned by Mr Croney and results had also been obtained from the examination of normal road contracts. These other experiments were small except for the last two which Mr Croney had mentioned, and were not yet yielding results. They were being very carefully examined.

125. The Authors had said that the work had shown up the deficiencies of the C.B.R. method of design and the need for treating the different materials in relation to their own specific qualities. It was necessary to know a great deal more about these in order to be precise, and it was to be hoped that the 1963–64 experiments at the Wheatley and Alconbury by-passes would provide a great deal of information.

126. He thought it wise that the Authors had not attempted to draw conclusions as to the relative merits of flexible and concrete construction. Many people felt that such conclusions were drawn too hastily from the A.A.S.H.O. test. There were fundamental differences in the behaviour of concrete and flexible pavements which only became apparent after a considerable number of years in service. This was one reason why early comparisons could be misleading, and the Americans themselves were very ready to admit that the comparisons made in America of the A.A.S.H.O concrete and flexible pavements might not be valid because the period of test was insufficient to bring out any weaknesses of the concrete.

127. One thing worth considering in more detail was the behaviour of normal and high strength concretes. The results were roughly what would be expected if the performance were in proportion to the strength of the concrete and to the square of the thickness of the slab. Although curling of the slabs owing to temperature and moisture changes was relevant it seemed that the comparison of strength might be sufficient for practical purposes.

128. It was not possible, of course, to experiment with every possible combination of materials and thickness of layer, and it was often necessary to make decisions on newer materials on somewhat slender evidence. There was often insufficient time for full-scale experiment, and decisions had to be made on whatever evidence was available. This was fairly successful in the light of what was now known about the properties of the materials but did not mean that more experimental work should not be done, so as to revise and improve methods of design.

Mr D. R. Sharp (Chief Engineer, Technical Services, Cement and Concrete Association) said that highway engineers and research workers who were interested in the problems of pavement design had been waiting with keen anticipation for the first report on the experimental flexible and concrete sections at Alconbury Hill. The fact that most of the conclusions could have been anticipated, at least in broad terms, indicated merely that the rather arbitrary methods of pavement design used in this country were reasonably correct.

130. He asked the Authors if they would give comparative results of the A.A.S.H.O. and the Alconbury experiments, possibly concentrating on the differences, as he felt that this would be very illuminating.

131. He hoped that soil cement construction would not be condemned simply because at Alconbury Hill the material had not proved very satisfactory. As the Authors pointed out in § 77 the particular soil cement used was made from a single-sized fine sand which would not now be used except for lightly trafficked roads, and which was not only weaker than the 250 lb/sq. in. at 7 days which was specified, but had only about half the strength of soil cement as commonly used. The conclusions in the Paper did not necessarily apply to stronger soil cement roads or to soil cements made from better graded soils.

132. He believed, too, that both the soil cement and lean concrete bases would have performed much better on a different sub-base material. In § 74 the Authors recorded the very interesting experimental conclusion that rolling the sand sub-base material through a thin metal plate was found to result in substantially higher densities. The wet mix and bituminous bound base materials were laid in thinner layers than the soil cement and lean concrete and it was a reasonable assumption that during the laying of the base materials higher densities were obtained due to this 'thin-plate' effect on the fine sand sub-base, under the bituminous bound materials and wet mix than under the cement stabilized materials. This would mean that the former would initially have a greater chance of success.

133. Total deformation appearing at the surface of the flexible pavement was obviously the correct failure criterion. It would be interesting to know whether the Authors had managed to distribute the blame between the surfacing, base, sub-base, and sub-grade. The A.A.S.H.O. had reported that in 51 test sections which were trenched, 32% of the rut depth could be attributed to a reduction in surfacing thickness, 14% to a reduction of base thickness, and 45% to a reduction in sub-base thickness, leaving only 9% attributable to the sub-grade soil, in this case a low embankment.

134. It had been mentioned that the high strength concrete gave a better performance than the lower strength concrete which was specified in accordance with the standard recommendations. The economic importance of this was considerable and it remained to be proved which was correct for the future. It was worth noting however, that the 4000 lb/sq. in. concrete was the lowest used in the world at the present time. As to whether crushed rock material was better than gravel, it was a pity perhaps that a comparison had not been tried at the 4000 lb/sq. in. level.

135. The old controversy about the relative performances of plain and reinforced pavements had come to the fore because of the recent proposals to use slip form pavers, which could more conveniently lay unreinforced to concrete. The views of the Authors on the probable long-term performance of plain concrete would be helpful, as would their opinion as to the validity of the existing 2-in. difference between plain and reinforced slabs required by Road Note 29.

136. Finally, he wished to emphasize that, useful as they were, results such as those presented must be examined in the cold light of economics. It might be possible to reduce the thickness of a pavement made with a particular material by, say, 30%, but there was little future for its use if the cost of the result was still not comparable with the alternatives.

Dr A. R. Lee (Director, British Slag Federation) said that when pavement design came to be included in the regular syllabus of students of highway engineering he was sure that this experiment would be one of the landmarks of the subject. It might even acquire international fame. He agreed with almost every word the Authors had written, but there were one or two questions he wished to ask.

138. Some reservations had been heard as to whether the results of this experiment could be applied directly to motorways. The traffic on the road was now apparently about 4000 commercial vehicles a day. It would, therefore, be a Chart 1 road, according to the classification of Road Note 29. In view of the remarks by the Authors that the densities of commercial traffic on the nearside lanes of heavily trafficked roads appeared to have reached saturation, and that emphasis was moving towards additional lanes rather than stronger standards, would the Authors agree that the results did apply directly to motorways? If they agreed, could they say what difference, if any, would be required in the application of the results if the permissible weight limitation on vehicles were to be increased?

139. Mr Croney had referred to the difficulty of compacting the top layer of the sub-base and to the problems it caused when compacting the lower layers of the bases. Would he agree that if a better material had been used for the sub-base, one which could be compacted easily and which would give a firm surface, the performance of all

the bases would have been much better, or at least those which required compacting with heavy rollers, such as the asphalt and tarmacadam and the wet mix materials, would have given relatively better results?

140. It was interesting to see that so far no replacements had had to be made of the bases made with rolled asphalt, and it was very reassuring to see the consistency of the results given by this material. Sections 51–54 were particularly interesting: No. 52, with 4 in. of asphalt on 6 in. of asphalt base; No. 53, with $2\frac{3}{4}$ in. of asphalt on 6 in. of asphalt base; No. 54, with $1\frac{1}{2}$ in. of asphalt on 6 in. of asphalt base; and No. 51, with 4 in. of asphalt on 3 in. of asphalt base. In view of the fact that the base course of the surfacing was of the same material as was used in the base, these four sections could be considered as made up of a wearing course of $1\frac{1}{2}$ in. and bases having thicknesses of $8\frac{1}{2}$, $7\frac{1}{2}$, 6, and $5\frac{1}{2}$ in. The experiment had shown that there was less than $\frac{1}{4}$ in. difference in the total deformation given by these sections. He would like to know whether data were available to show where this difference of $\frac{1}{4}$ in. occurred. Was it in the sub-base or in the soil foundation?

141. On the bases of these results, would Mr Croney agree that it should not be necessary to use more than $8\frac{1}{2}$ in. of asphalt base course material as the road base under $1\frac{1}{2}$ in. of wearing course for roads of this category? Furthermore, would he expect equally good results to be given by Chart I roads having a $1\frac{1}{2}$-in. asphalt wearing course on a base made up of $5\frac{1}{2}$ in. base course asphalt and 7 in. of slag wet-mix? A construction of this nature would presumably be classed as one of the stronger type in which the wet mix would become stiffer with time, due to compaction by traffic. Was this increase in stiffness due entirely to compaction? Wet mix slag would develop a slow-cementing action of its own which would increase its stiffness over a long period of time, independent of any compaction effect.

142. Perhaps in this connexion he might refer to a process in which the fines of the wet mix consisted of granulated slag. Mixtures of this type had a marked cementing action and eventually developed strengths equal to those given by Portland cement. Experience on the Continent was promising and would justify its inclusion in a future experiment.

143. The data presented by this Paper had been concentrated from a very large mass of measurements made both during construction and after the road had been carrying traffic. There was no doubt whatever as to the reliability of the results, and it was altogether a most readable Paper.

Mr G. M. Dormon (Senior Technologist, Shell International Petroleum Co.) said that the importance of trials of the type under discussion was very well recognized but it was surprising how difficult it was to interpret the results. The trials of the Road Research Laboratory set a high standard but it should be remembered that the results of any one trial were only applicable to the particular site conditions. The object of a series of trials was to obtain a broad general understanding of the behaviour of the materials concerned, so that it was possible to forecast the behaviour of any road under any conditions, even though there might be no previous experience of such conditions.

145. Three years ago his company had made some proposals concerning the design of flexible pavements, confined at that time to pavements made with dense asphalt layers and unbound granular materials. The basic design approach was to consider the stress distribution through a multi-layered system having the dynamic mechanical properties of the materials concerned, and to design the structure so that permissible strains and stresses in the various layers and in the soil were not exceeded. It might be of interest to see how the 11 relevant sections in this particular trial compared with the expected behaviour as forecast by the theoretical design.

146. The main conclusion from such a comparison was that all the surfacings had behaved rather better than might have been expected. This was not surprising because the calculations were based on a combination of extreme climatic conditions; that is, a very weak sub-grade soil state (such as in a thaw period) occuring at the same

time as a very high asphalt surface temperature (such as in mid-summer). Such conditions were not normally prevalent in the United Kingdom. One section, No. 38, consisting of 4 in. of asphalt on 9 in. of wet mix slag was particularly outstanding.

147. The philosophy (supported by substantial practice data) on which these design recommendations were based, was that the mechanical properties of unbound granular material were limited by their inability to withstand tensile stresses: in other words, the modulus in situ in the road was such that high tensile stresses would not be developed in the material under traffic loads; and a conclusion which could be drawn from this analysis was that the wet mix slag bases were, in effect, not behaving as unbound granular materials. This could be due to some cementitious action. This conclusion and possible explanation was supported by the fact that the behaviour of the wet mix slag sections was comparable to the lean concrete sections of the same base thickness. Could Mr Croney explain to what extent wet mix slag was regarded as a typical material? It would be helpful also if he could say whether in this or in other experiments wet mix slag normally behaved better than wet mix made with crushed rock, from which it had not been differentiated.

148. He understood that in recent proposals made for the revision of Road Note 29 some reduction was allowed for asphalt bases relative to wet mix bases, but here again there appeared to be no differentiation between slag and other materials.

Mr C. F. Armstrong (Superintending Engineer, Ministry of Transport) said that he had a few points to raise on the concrete section of the Paper: they were matters of design and specification to which it was thought the Authors should now give consideration.

150. The design of concrete road pavements differed markedly from that for structural concrete. Over the long lengths of road slab with which they had to deal it was not practicable or economic to use the structural approach of a heavily reinforced beam to achieve strength and prevent cracking. All that could be done with the mixes at present at their disposal was to introduce sufficient longitudinal reinforcement to keep crack widths to within acceptable limits and to introduce joints at sufficient intervals to discourage the random cracking which would otherwise result.

151. It was stated that the 6-in. and 7-in. slabs at Alconbury Hill were expected to last only 15 to 20 years, but that it was thought probable that slabs not less than 8 in. in thickness would have a satisfactory long-term performance—presumably a life without re-surfacing of some 30 to 40 years. This suggested that by some modification of the design of the concrete itself it might be possible to make even these thinner slabs as acceptable as those of 8 in. or more in thickness. Thus, any modification which would further inhibit the propensity of carriageway slabs to crack—and which designers of structures might consider themselves able to combat by reinforcement alone—might well offer definite economies if applied to road design.

152. In research into the design of asphalt and coated macadam polymers, additives such as rubber were freely mentioned as a means of modifying the properties of the binder and thus reducing any tendency of the surfacing to crack. Yet cracking of concrete road slabs was accepted as inevitable; it was one of the measures used to compare experimental sections. Many additives were available for concrete but the search for those which might alter its characteristics so as to prevent cracking altogether might merit the Authors' attention. Perhaps some compound in the fields of rubber or plastics might provide the answer.

153. To turn to two other points of design—the period for withholding constructional traffic from new road slabs and the length of time before side forms were struck—any reduction in the times currently required clearly had a money value. The period now accepted for withholding traffic from road slabs was 20 days for normal Portland cement concrete and 10 days for rapidly hardening cement concrete, but it could be that some other period would be equally sound from the design point of view. After the periods of prohibition, constructional traffic often used the slab

freely, and it was also admitted after seven days onto weaker and thinner lean concrete. This suggested that the choice of the number of days was not scientifically based. Controlled trafficking of surfaces was a comparatively simple form of full-scale experiment, and it would be well worth while seeking a solution to this problem.

154. Although there were advantages in using edge beams in concrete slab design, many roads would continue to be built using steel side forms. At present side forms were kept in position for not less than 12 hours, and even longer where arrises had to be protected. Yet it was known that if the mix and type of vibration were appropriate, slab sides would stand vertically of their own accord behind a slip form paver. This again suggested that for normal construction an appreciable reduction on the figure of 12 hours could well be tolerated, but again trials were needed to establish what this figure should be.

155. Finally, now that it was customary to provide a substantial layer below the concrete slab to serve construction traffic, it should be established whether or not dowels were still necessary. At Alconbury Hill the undowelled slabs had only a 3-in. layer beneath them.

Mr J. M. Fisher (John Laing Research and Development Ltd) said that he wished to discuss a section of the Paper which gave results which were available some five weeks rather than the usual five years after the event. He referred to the information given in Table 11 of the Paper. He wished to comment on the wide disparity between the results of core tests and cube tests, not so much as to strength (for by suitable choice of correction factors one could make average 'equivalent cube strengths' of cores exactly equal to average laboratory cube strengths), but to variations measured on cores and on cubes.

157. In the case of the normal strength concrete, cores cut from the actual slab had a standard deviation of 1220 lb/sq. in. at 28 days and a coefficient of variation of 20%. According to Stanton Walker[9] this was 'poor minus' control. However, test cubes had a standard deviation of only 740 lb/sq. in. and a coefficient of variation of 12%, which, according to Walker, indicated 'excellent' control. For high strength concrete, cores had a standard deviation of 500 lb/sq. in. and a C.V. of 5%, whilst cubes had a standard deviation of 200 lb/sq. in. and a C.V. of 2·2%—a remarkable result, but on a small number of specimens only. Thus there seemed to have been quite a wide disparity between the control over the high quality concrete and its placing as compared with that over the gravel concrete. Could the Authors give any explanation for these results, and in particular say why the lowering of the standard from laboratory samples to cores had been so much greater with the gravel concrete than the granite concrete, when the equipment used was exactly the same?

158. Another interesting feature of these figures was the relationship between strengths of samples taken in the form of laboratory cubes and those of cores cut from the actual work. It was quite different from that of Graham and Martin[10] who quoted a list of some 30 core tests and related cube tests and found that the average strength of cores was marginally superior to that of cubes. Correction factors were the same in those days as now, but possibly testing techniques, particularly in regard to the form of end capping, were now better. The odd point was that the variation in strength of cores was only marginally inferior to that of cubes, which seemed to indicate that very little could have gone wrong between the making of the cubes and placing them in position. He believed that this state of affairs should persist. One had a right to expect that the strength of concrete in the work was fairly well represented by that of test cubes.

159. In his view the question of differing standards in laboratory samples and finished work was a matter for considerable concern to engineers who used concrete as one of their main structural media. If the answer could be found it might be possible to effect very considerable economies in structures, including road slabs. There would then be little justification for such a comment as was made by the Authors in conclusion (*b*) (§ 112).

160. Regarding the use of granite aggregate in concrete, he wondered if the effect of the bond between a concrete aggregate and the surrounding cement mortar matrix had ever been studied. Simple observation on a number of both concrete and asphalt roads would show that the bond between a binder and flint gravel was not nearly as good as the bond between the same binder and crushed rock. Was there not a lesson to be learned from this when pursuing the question of the skid resistance of concrete?

161. With regard to the general plan of the experiment, it would have been a good idea if granite aggregate of normal strength could have been used in the series. Whilst it was good to know that a very rich granite mix performed so excellently it was important to ensure that this excellent performance did not lead to extravagance in design and hence in cost. Could the Authors hazard a guess at what the performance of a granite concrete of normal strength, as compared with that of a flint gravel, would have been at this particular site?

162. He would finish with one or two comments on the Authors' conclusions as they affected the economics of construction. It was found that under the conditions applying at Alconbury, 8-in. slabs were satisfactory, but as a bonus strength they should be 10 in., an increase of 25% in the volume of concrete used to cover a contingency which should not, and now rarely did, exist. Secondly, it was found that 7·88 lb/sq. yd of reinforcement had proved adequate. Present designs called for not less than 8·5 lb/sq. yd, which turned out to be 9·32 lb/sq. yd, an increase of 1·44 lb, or 18%. There was, however, the qualification that the heavier reinforcement might be better over a long period of years. Could the Authors indicate their reasons for this conclusion? Thirdly, with this weight of reinforcement a 120-ft spacing for joints was satisfactory, provided slabs were not under-designed—presumably not less than 8 in. The present requirement was that joints (either expansion or contraction) should be at 80-ft intervals—a 50% increase in the number of joints. From a weighted collection of all these factors it would be seen that the cost of road slabs designed in accordance with Road Note 29 would be about 23% higher than the cost of those which according to the Alconbury experiment should prove satisfactory for a long period of years. This was particularly important when the budgeted amount for road construction was likely to be constant and it was desirable to get as many miles of road as possible for the money spent.

Mr W. Downie (Ministry of Transport) said that if highway engineers studied the Paper and considered the various conditions applicable to the sites it might enable them to make economies in construction and in ultimate cost. He had in mind one or two improvement schemes round London where the highway engineer concerned had elected to use a lean mix concrete as the base. A bitumen bound base would have been much quicker to cover with the final surfacing and would have allowed traffic to use the base during construction.

164. With regard to the last conclusion from the flexible pavement experiment, he had been a little surprised and disappointed to find that the C.B.R. was rather run down. Could the Authors give some guidance on the use of the C.B.R. in respect of the various materials used?

165. He hoped that the Authors might be able to say what would be the economic designs for the various materials they had put forward. It would be helpful if some idea could be given of the economic design the Authors had in mind for the 4-in. asphalt base as opposed to the conventional concrete pavement.

Mr L. S. Blake (Cement and Concrete Association) said that the main point that worried him about the flexible construction experiment was the variation in dry density of the sand sub-base. This amounted to something like 7%, which meant that subsequent compaction by traffic could, on some sections, result in a deflexion approximately ¾ in. greater than on other sections where better compaction had been achieved. Would not this have a considerable effect on the relative performance of the various sections? One would anticipate that some of the materials might be affected more adversely than others by such a large amount of compaction due to traffic.

167. Clearly this was a Paper prepared by two Authors and between the two sections there was a difference in the criterion of failure adopted. On the one hand the criterion for concrete was by extrapolation of the crack pattern, and sections predicted as having less than twenty years' life were considered to be unsatisfactory. On the other hand, the criterion for failure on flexible sections was a deflexion of 1 in.; but flexible sections which had a deflexion of ½ in. after only six years were described as having performed well. Would the Authors comment on this difference in approach?

The following contributions were received in writing:

Mr F. L. D. Wooltorton (Senior Engineer (Roads), Howard Humphreys and Sons) wrote that the objects of the experiment, as listed in § 8, suggest that the endeavour to determine the validity of the C.B.R. method of design, when applied to the forms of flexible construction used, was an afterthought. Whether this was true or not, it appeared that insufficient consideration had been given to this object, and it was doubtful whether the broad condemnation of the C.B.R. method of design was justified by the results of this particular experiment.

169. It did not require much experience of materials and design in the U.K. to suspect that the C.B.R. method of design, in any of its modifications, might not always be suitable, for reasons very similar to those which caused the California Division of Highways to abandon it many years ago.

170. Some change in procedure, or indeed, in method, would appear essential if only to avoid a panic reversion to something similar to the old Public Roads Administration's correlationship between pavement thickness and soil type, which would be an admission that designers had failed in their duty to understand the properties of British soils and in their task to design roads to carry loads. Nevertheless, it was only right to consider, before condemning the C.B.R. method of design *in toto*, whether it was, in fact, given a fair chance. If it was, then it would be reasonable to condemn it on the basis of failure but it hardly seemed logical to condemn it because some under-designed pavement thicknesses successfully carried rather more than the designed volume of traffic for the restricted period of only six years or because of deformation occurring as a result of subsequent consolidation of the sub-base under traffic.

171. The Paper contained scant reference to design assumptions and laboratory data so that it was dangerous to criticize the design approach. It would, however, appear reasonable to assume that the assumptions and procedures outlined in Road Note 29 (1960) were very much in mind when the design was finalized in 1957. On this assumption, it was perhaps permissible for a colonial cousin to defend his belief that it was Road Note 29 and the specifications which were found to be invalid, and not necessarily the C.B.R. method of design.

172. Pavement design under Road Note 29 was seemingly based on a C.B.R. value assessed from unsoaked C.B.R. data obtained for samples compacted by static compaction at the believed ultimate moisture content to approximately 5% air voids content. There were reservations pertaining to the practicability of achieving such an air voids content but none when lower values are attainable.

173. If this was a correct interpretation, then the following objections to Road Note 29 might be made.

174. (a) *Factor of safety*. Design on the basis of Road Note 29 would seem to be based on a factor of safety of only one, which might explain why the Authors had apparently expected more failures than experienced.

175. This value of unity contrasted with the higher, though indeterminate, value generally to be anticipated when the C.B.R. was determined for the soaked condition, where this higher value increased with improvement in the quality of the materials used in the various layers as compared with those used when the C.B.R. values were first correlated with performance, the efficiency of internal and external drainage, the efficiency of control, a run of good luck as regards weather and the absence of any unanticipated incidents. A factor of safety of unity assumed drainage, control and membranes to be 100% efficient and that incidents could be avoided. It was as much a factor of danger as one of safety and it implied that a percentage of a carriageway might fail where such failures could not be tolerated financially or politically on present day highly trafficked motorways.

176. (b) *Use of unsoaked C.B.R.* Because of the difficulty in predicting ultimate moisture content under an impermeable pavement and, presumably, because of the susceptibility of some soils to a rapid loss in stability with small increases in moisture content, the 'Accepted procedure for the C.B.R. test'[11] provided that 'For this reason it was stipulated that the C.B.R. design penetration test should be performed on soaked specimens'. It was true that the text continued: 'However, provisions were made to reduce the total pavement thickness 20% for ideal sub-grade conditions and for sub-grades with low moisture' but from the context it would appear that the excepted sub-grades in mind were those which were free-draining.

177. It was pertinent to add that recent publications showed how C.B.R. values used in successive contracts in the U.K. over apparently similar sub-grade materials tended to drop with acquired experience until the designers were now using values corresponding very closely to the soaked values.

178. (c) *Design stability not adequately tied to site stability.* If design was based on a C.B.R. value obtained for samples compacted to about 5% air voids content at a believed ultimate moisture content which might be reached on site within a few months or conceivably only after a number of years, was any firm relationship to be expected between this value and that achieved initially or finally for construction in accordance with the present Specifications which permitted compaction over a wide range of moisture content?

179. A scraper had no respect for the designer. As long as the material was 'suitable', it engulfed indiscriminately from, say, a sedimentary profile soil which might be 'overconsolidated' at very low moisture content together with weathered, or less consolidated material, at a very much higher moisture content, and such a mixture of moisture and density conditions went into the sub-grade in the form of clods and finer material.

180. Apart from the possibility that one area of sub-grade might require more effort to achieve 5% air-voids content than another, the finished product would be variable in moisture content, density, and in free energy (potential swelling pressure) where any such variations, even though small, might produce a differential in the initial and final stabilities, and where the ultimate stabilities would not, in general, be expected to be identical with the design value.

181. It could well be that under such conditions, the irresponsible British climate was the greatest friend the tax payer had by virtue of its tendency to provide, through cycles of wetting and drying, uniformity of moisture content, density, and energy. This thought was inherent in the formerly used principles of 'ponding' and 'stage construction', which might have operated along the Alconbury Hill experiment if the earthworks constructed in 1939 had stopped at formation level instead of from 1 to 2 feet above.

182. The suggestion from the above was that not only should the design C.B.R. be based on the soaked condition but that the task (not always so difficult as anticipated) should be attempted to bring the moisture content up to some more-or-less uniform value, approaching the maximum permissible value or better still the ultimate value, at compaction. Apart from its beneficial effect on uniformity of stability, it would

produce a compacted material with near minimum swelling properties where sub-grade swelling appeared to have been a problem in some sections of the Alconbury experiment.

183. (d) *Static compaction in the laboratory might lead to underdesign.* Road Note 29 apparently recommended that the samples required for C.B.R. testing should be compacted by static compaction.

184. American experience as published from the time of the C.B.R. Symposium in 1950, strongly suggested that:

(i) compaction by kneading and dynamic methods produced stabilities more closely representing those achieved in the field than did static compaction;
(ii) static compaction might give stabilities greatly in excess of the field values.

In view of this he wondered why Road Note 29 recommended static compaction and reserved dynamic compaction for those occasions where the static compaction apparatus was not readily available.

185. (e) *5% air voids might lead to underdesign.* The Paper did not appear to record the air voids content achieved during compaction but did record that in subsequent measurements air contents of as low as 0% were obtained. This suggested not only that compaction might have occurred under traffic but that 5% (approximately) of air voids might be a wrong assumption in design.

186. It also suggested that if the material was one whose stability depreciated with over-compaction, then a C.B.R. based on a 5% air void content might result in under-design and failure. For such materials, which appeared to be common, design should presumably be based on a lower air voids content of perhaps 3% or less.

Dr K. R. Peattie (Esso Petroleum Ltd) wrote that the Authors were to be congratulated on presenting so ably such a large amount of data of value in relation to pavement design.

188. The results of the investigation into the validity of applying the California Bearing Ratio method of pavement design to the flexible sections used at Alconbury Hill were interesting but not so very surprising when the type of pavement for which this was developed was considered. At the time the C.B.R. method was developed[12] the type of pavement considered consisted of 2–4 in. of bituminous surface and a thickness of granular base determined by the quality of the sub-grade and the intensity of the traffic. Subsequently, further work was carried out by others, notably the U.S. Corps of Engineers, which led to the production of additional design curves for different loading conditions. However, so far as was known no attempt had ever been made to take into account the different load-spreading abilities of various base materials. C.B.R.-type design curves, therefore, although up-dated so far as traffic loading and intensity were concerned, only remained valid for roads with essentially granular bases. This limitation on the use of C.B.R. design curves had previously been emphasized by the writer[13] in the development of a theoretical analysis of the behaviour of flexible pavements.

189. The problem of extending the results of full-scale trials to designs for pavements appropriate to other conditions of sub-grade, climate, and traffic was a difficult one. Since it was not usually possible to include sub-grade material as a variable in addition to the materials in the other layers, it was desirable that the sub-grade materials should be sufficiently common and well defined to allow the test results to be as widely applied as possible.

190. The climate at a test site could not be controlled: it was therefore desirable to choose a location with a reasonably representative climate. The fact that the climate at Ottawa, Illinois, was considered to be somewhat extreme caused difficulties in extending the A.A.S.H.O. road test. (This aspect of the test was discussed at some length at the International Conference on the Structural Design of Asphalt Pavements held at Ann Arbor, Michigan, in 1962.) The Highway Research Board was now engaged in planning 'satellite' tests in order to extend the results of the A.A.S.H.O.

test to other locations. While the climate and conditions at Alconbury Hill were undoubtedly reasonably representative of those existing over much of a small country like England, he wondered how far it was justifiable to extend the results to, say, the north of England or Scotland.

191. Other problems arose in the choice of traffic to which the test sections were subjected. The Authors had commented on this in their introduction and suggested that there were unlikely to be further increases in wheel loads. This might well be true. However, it was not only the weight of the heaviest vehicles that must be taken into account, but also the composition of the traffic in terms of the numbers of each wheel load which were applied. As a result of the counting and weighing of vehicles at Alconbury Hill, the composition of the traffic there was well defined. So far as the comparative behaviour of the various sections was concerned the composition of the traffic was relatively unimportant. There might, however, be difficulties in applying the results of such a test to the design of pavements where different traffic was to be expected. For example, how did the composition of traffic on main trunk roads, such as the A.4, A.5, A.6, and motorways, compare with that on the A.1 at Alconbury Hill?

192. In the A.A.S.H.O. road test each section carried traffic of only one wheel load and one axle configuration. It was undoubtedly difficult to apply the results of tests subjected to traffic of this type to the design of pavements to carry conventional traffic. Nevertheless, information obtained from such tests would appear to be more readily applicable to the design of pavements carrying traffic of any type and configuration, once a fundamental analysis of pavement behaviour had been developed, than would be possible with the results of tests in which mixed traffic was used. The Authors' views on this would be appreciated.

193. Dr Peattie noted with great interest the measurement of stresses, deformations and deflexions which had been made on the A.1 at Alconbury Hill. Many theoretical analyses of flexible pavement behaviour had been made, but one of the great difficulties had been the obtaining of experimental data with which to test the theories. These theoretical treatments could provide much useful guidance on the effect of using different materials and methods of constructions, but their acceptance as a basic means of pavement design was to a large extent conditional on the correlation between calculated and measured data of the type obtained at Alconbury Hill. It would, therefore, be of great interest to know when the data referred to in § 54 were to be published.

Mr H. G. Clapham (Manager, Ground Engineering Ltd) wrote that the Authors had produced an extremely interesting Paper which would be very useful for rationalizing pavement design in the future. He would be grateful for comments from the Authors on the following points.

195. Why was the fine sand used for the sub-base in the full experiment, when it was found to be a difficult material to compact in the preliminary work prior to starting the full scale experiment? Surely placing thin metal sheets on the sand and then rolling over them was not a reasonable method to use in order to get a sub-base compacted to the correct density.

196. Drainage from the base and sub-base could only take place through holes in the continuous concrete edge beam at points corresponding to low areas of the sub-grade where surface water was likely to accumulate during construction. In the light of information obtained on pavement failures which had taken place due to poor drainage since this experimental road was constructed, the drainage would appear to be very inadequate. In addition, the water table was high at the site, measurements made over a period of 12 months before the road was built showing that it would be close to formation level in winter and only about 2 ft below in summer. Would the Authors like to comment as to whether, in their opinion, the poor drainage in conjunction with the height of the water table contributed to the poor performance of the soil cement bases?

197. Since the C.B.R. method of design was not applicable to flexible pavements of the type used in the experiment, did the Authors suggest any amendment to the design procedure given in Road Note No. 29, or could they give a lead to some other method which might be applicable in the future for the design of this type of flexible pavement?

Mr D. B. Herbert (Design Engineer, Ministry of Works, Auckland) wrote that he was interested to read that the tests showed that the 6-in. and 7-in. thick reinforced concrete slabs were expected to have a useful life of only 15 to 20 years.

199. In the Auckland area there were some miles of concrete road laid during the period between the first and second world wars, which were generally speaking still in good condition. Considerable distances might be driven along them without any cracks being evident. Deterioration had usually occurred only in areas which had been developed industrially since the last war, and in roads now carrying loads such as trolley buses and articulated trucks with heavy trailers far in excess of those in use at the time of construction. In most of the latter cases the slabs had not suffered excessive damage, and with a bituminous running coat added were still in use.

200. Most of these slabs were similar in construction to the Illinois P.W.D. Standard Concrete Highway of those days. They had a nominal thickness of 6 in., except at the edges which were stiffened, tapering for a width of 2 ft to a depth of 9 in. One $\frac{3}{4}$-in. diameter reinforcing bar was provided continuously round the perimeter, $4\frac{1}{2}$ in. from the top and bottom and 6 in. in from the edge and lapped 2 ft at joints. Contraction and longitudinal joints were keyed and dowelled. The sub-base was generally a 2-in. to 3-in. thickness of rolled 'scoria', a local porous volcanic basaltic material, on clay sub-grades. Usually field tile underdrains were provided.

201. Before and after the 1939–45 war a considerable mileage of reinforced concrete road was constructed in Australia using the stiffened edge principle. The nominal slab thickness varied from 4 in. to 6 in. with edges half as thick again tapering in for a distance of about 2 ft. Two continuous perimeter bars $\frac{1}{2}$ in. to $\frac{3}{4}$ in. in diameter were used with a layer of steel mesh reinforcement near the top surface. In addition a 'hair-pin' bar, top and bottom, was provided at each corner to resist 'curling' moments. The latter were made sufficiently long to provide full bond length beyond the assumed cracking planes where the highest bending moments generally occurred (Fig. 18). The slabs were laid on a compacted sub-base of sand, gravel or metal on clay sub-grades. Longitudinal joints were usually keyed and transverse joints dowelled.

202. When the writer was in Australia in 1953 he had observed few transverse or corner cracks in spite of extremes of temperature in many areas. Latterly slabs of constant thickness, but still retaining the perimeter and hair pin bars top and bottom with temperature reinforcement near the upper face had been constructed.

203. From the writer's observation and experience of reinforced concrete roads, some of them over 40 years old, slabs were not adequately reinforced by providing the usual single layer of mesh reinforcement near the top face, nor by using steel mesh top and bottom. The edges were subject to much higher bending stresses from wheel loads than the interior of the slab. In the case of the corners, the bending stress along the 45° line caused by a wheel on the corner of the slab was greater than any wheel load stresses on the edges. Both these stresses became even more severe if for any reason the joints were bad and could deflect, so causing high impact forces. Lastly, the corners could also be subject to temperature warping.

204. It would appear, therefore, that however firm the sub-grade, the ideal reinforced concrete road slab designed to carry heavy traffic, with possibly millions of repetitions and reversals of stress, should be efficiently reinforced along all edges and at all corners. On doubtful sub-grades, a bottom layer of mesh reinforcement should be provided in addition to that at the top.

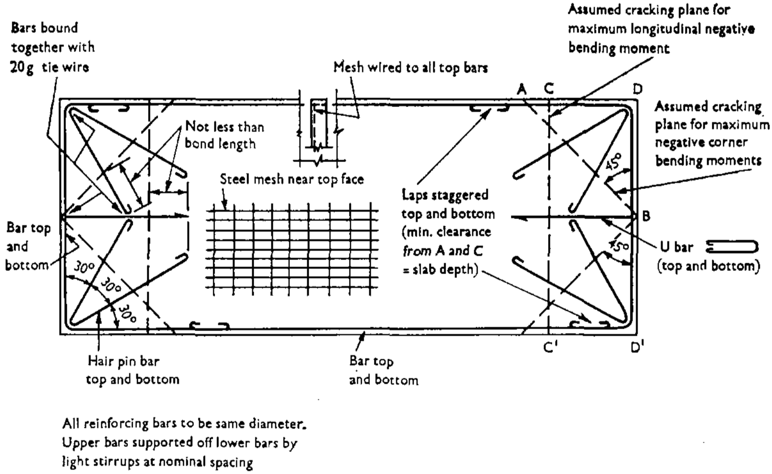

FIG. 18: REINFORCED CONCRETE ROAD SLAB (BASED ON QUEENSLAND MAIN ROADS COMMISSION STANDARDS). Assuming maximum wheel load W at D produces maximum B.M. per ft width on plane AB, maximum axle load $= 2W$ along DD′ and symmetrical with B (C.L.) will produce an equal B.M./ft width along plane CC′. CD = 3/8 DD′ (for a prismatic unreinforced slab).

205. In the matter of shrinkage, temperature and creep stresses the perimeter bars also perform useful functions to supplement those of the steel mesh. Longitudinally they are an important factor in preventing the formation of transverse cracks, which invariably start at the edges of slabs, and they also obviate or reduce the use of dummy joints between expansion joints.

206. The possibility of local overloading and failure of the sub-base near the expansion joint is reduced by the end perimeter bars which distribute the wheel loads over the weakest area of the slab to the longitudinal, hairpin, and U-bars. They also spread the loads more uniformly along any transverse dowelled or keyed joints which may be provided.

207. Could the Authors please state their experience of and opinions on edge-stiffened and corner-reinforced reinforced concrete road slabs similar to those described above?

Mr David Croney, in reply, mentioned Sir William Glanville's reference to the application of theory to pavement design. He was aware that experiments such as the one described offered an excellent proving ground for theoretical methods based on multi-layer elastic theory. Although in the present Paper it had not been possible to deal with this aspect it was hoped to do so in a later publication.

209. He agreed with Mr Sharp that soil cement as a material for construction should not be condemned solely on the results of the Alconbury Hill experience. The term soil cement embraced a very wide variety of materials and it was the type made from a single-size sand which had performed so badly in the experiment. He did not agree that a different sub-base would have materially altered the relative performance of the sections and instanced another experiment at Ashford by-pass where bases of wet-mix stone, open-textured tarmacadam, and a soil cement made with single-size sand, had performed in the same manner as at Alconbury Hill, on a very different foundation. With regard to where within the construction permanent

deformation had occurred information on this matter was obtained in only seven of the flexible sections using permanent deformation gauges recording at different depths. The results given in Fig. 12 of the Paper showed that the proportion of the total deformation which occurred in the sub-grade varied, as might be expected with the stiffness of the construction. It could be as much as 50% or even lower than the 9% quoted by Mr Sharp. Mr Croney did not feel that it would be wise at this stage, for the reasons referred to by Sir William Glanville, to publish any comparison between the Alconbury Hill and A.A.S.H.O. test results, since the former used normal mixed traffic and the latter selected wheel loads. However, the Authors had given the wheel-load spectrum at Alconbury Hill so that anyone interested could make his own comparison based on the axle-load equivalence factors already published in connexion with the A.A.S.H.O. test.

210. With regard to the points raised by Dr Lee, Mr Croney felt that the results from this experiment could be applied to motorway pavements There were few motorways likely to carry more commercial vehicles in the slow traffic lane than was the case at Alconbury Hill. It was difficult to estimate what effect an increase in maximum permitted wheel load would have on pavement performance. Measurements showed that a significant proportion of wheel loads at Alconbury Hill were already in excess of the maximum. He doubted, therefore, if a small increase in the permitted maximum would influence the present position very much. He agreed that the results showed that where asphalt base course material was used as a base a thickness of 8½ in. of this material had been adequate. Although reducing this thickness to 7½, 6, or 5½ in. increased the deformation by only ¼ in., this was a significant difference, reflected in the general appearance of the four sections concerned. The results did not prove whether or not a composite base using a combination of asphalt base course material and wet-mix slag of the type suggested by Dr Lee would be satisfactory because the combination was not used, but they suggested that such a composite base would have performed satisfactorily. Deflexion measurements made with the Benkelman beam indicated a tendency for the wet-mix bases to increase in strength when adequate thicknesses were used, but it was not clear whether this was due to compaction or to a cementing action.

211. Mr Croney felt that Mr Dormon's comments illustrated the difficulty of applying elastic theory to the results at what might be too early a stage. Tests to determine the elastic moduli of the soil foundation and of the other layers of the pavement had been made during construction and at intervals since the road was opened to traffic. Once this data had been analysed it should be possible to make a more realistic theoretical evaluation of the experimental results. Mr Dormon implied that he had probably underestimated the modulus of the foundation. This would have accounted for the fact that the flexible sections had performed better than Mr Dormon's calculations would suggest. With regard to the wet-mix base materials, Mr Croney felt that Mr Dormon might have assumed too low a value of modulus for this material. Wave velocity techniques might well underestimate the E value and a value based on repeated loading triaxial measurements might be more realistic. He did not agree that well-compacted mechanically stable materials could not accept some tensile stress. At the same time the ability to accept tensile stress would be much enhanced by any cementing action. In this connexion wet-mix slag bases did appear to have behaved marginally better than comparable bases composed of other aggregates.

212. Mr Blake's point regarding compaction of the sub-base was an important one but it had really been dealt with in § 74. There was little doubt from the measurements made during investigations on failed sections and from the permanent deformation gauges that the process of compacting the bases produced a much more uniform density condition in the sub-base than was suggested by Table 3. The two different methods of assessing conditions of the flexible and concrete pavements were traditional for the two forms of construction and the Authors could see no alternative. The

methods adopted in the A.A.S.H.O. test were basically very similar to those adopted in the present experiment. The rate of development of deformation or of cracking at any given time could be taken as an indication of future performance. Where the deformation/time curves had levelled off before the six-year life had been reached it seemed reasonable to assume that the sections would have a substantially longer life.

Mr J. A. Loe thanked Sir William Glanville for drawing attention to the simple approximate relationship between the performance of the experimental sections at Alconbury Hill and the thickness and strength of the concrete. It was hoped that data relating performance to all the design variables would eventually be obtained from the experimental roads built by the Road Research Laboratory and that from this data it should be possible to evolve empirical formulae for the design of concrete roads for any conditions. It was unfortunate that full-scale experiments usually required at least several years to produce results because these experiments had proved to be the only satisfactory method of obtaining reliable design data for roads.

214. Mr Sharp had asked if the results from the A.A.S.H.O. and Alconbury Hill experiments could be compared. A quantitative comparison of the results was not possible because of several important differences between the two experiments. In the A.A.S.H.O. experiment only one type of loading was applied to each lane of the five trafficked loops and these loadings were concentrated into a period of just over two years, by which time about 25% of the sections had failed. At Alconbury Hill the loadings were those of ordinary mixed traffic and the Paper reported results obtained over a period of six years during which time less than 1% of the area of the slabs had to be replaced. In the A.A.S.H.O. experiment severe pumping of both sub-grade and base material, mainly from the edges of the slab, occurred in the thinnest and next thinnest slabs in each of the loops except for the sections carrying the lightest (2000 lb axle-load) traffic. A survival curve for the test sections given in the A.A.S.H.O. Road Test Report 5[14] showed that pumping was a very important factor in the performance of the concrete sections. At Alconbury Hill pumping had been negligible and had not influenced performance; the development of cracks had been a direct result of trafficking.

215. The results from the A.A.S.H.O. test could not yet be expressed in terms of performance under ordinary traffic so that any comparison with the Alconbury Hill results was difficult, quite apart from the differences in type of failure and other differences in climate, materials, etc. Only general trends could be compared, such as the better performance of thicker slabs and the small effect of bases shown by both experiments. No comparison between plain and reinforced concrete could yet be drawn from Alconbury Hill and more information was needed to explain why in Great Britain reinforcement was usually found to be beneficial in improving performance whereas the A.A.S.H.O. experiment showed that it did not have a significant effect on performance.

216. With regard to the strength of the concrete, Mr Sharp mentioned that the 4000 lb/sq. in. minimum crushing strength was the lowest used in the world at the present time. The effect of strength was a matter which needed further consideration and it was hoped that an experimental road near Swansea, where the strength of the concrete and the type of aggregate had been varied, would yield some information. This should enable a better assessment to be made as to the advantages of using higher strengths and relatively more expensive crushed rock aggregates.

217. Since the unreinforced slabs were in a satisfactory condition it was difficult to predict their likely long-term performance or to compare them with reinforced construction. It would be necessary therefore to wait for further evidence before it would be possible to relate the performance of the road at Alconbury to the Road Note No. 29 requirement for an extra 2 in. for unreinforced construction.

218. In reply to Mr Armstrong's suggestion that the properties of concrete might be modified to reduce the likelihood of cracking, Mr Loe said that while rubber

or bituminous additives reduced the modulus of elasticity of concrete, they also reduced its strength, so that the strain capacity was not changed by any appreciable amount. The Alconbury Hill experiment had shown that cracking could be reduced by the change in concrete properties resulting from the use of crushed rock and a higher cement content (§ 112(c)) but methods were needed which would be economically more attractive.

219. With regard to a reduction in the period during which construction traffic was prohibited from using freshly laid slabs, this needed to be treated with some caution. Overstressing of the concrete at an early age could initiate cracks which would not develop and become evident until some months after the road was opened to traffic. However, the high rates of output now being achieved in concrete road construction could result in long lengths of carriageway being unavailable for construction traffic, and there might now be a case for a scientific re-examination of this restriction. With regard to the earlier removal of side forms, it was desirable to avoid any disturbance to the concrete during the first few hours after setting had commenced. It would seem preferable therefore to use either the slip-form principle, where the forms slid away before setting began, or to use fixed side forms with the present restriction of 12 hours before removal.

220. Many of the troubles which had occurred in earlier concrete roads had been avoided by the use of properly dowelled joints. With the increasing intensity of heavy axle loads on most roads, dowel bars should always be used, even where a substantial base was provided. Some support to this view was given by a road where slabs with undowelled joints were laid on a very substantial gravel base. After 16 years of traffic varying between 1000 and 2000 commercial vehicles/day settlements of up to nearly 0·2 in. were occurring at some of the joints.

221. Mr Fisher had commented upon the variability in the strengths of cores cut from the road, particularly from the concrete of normal strength. It should be remembered that these cores were obtained from plain and reinforced slabs having a total range of thickness from 5 in. to 11 in. The results had been corrected for the different heights of core but there still appeared to be some variation of strength with height which tended to give lower results for the thicker slabs. The normal strength concrete was laid first, commencing with the thicker slabs, and it might be noted that the four lowest core results were obtained from the first three slabs which were 10 or 11 in. thick. The three highest results were obtained from 5 in. and 6 in. slabs concreted during the second half of the work. The use of concrete laying machinery, which was of a type not used before in Great Britain for full-width road construction, might have contributed to the variability of the cores. The points mentioned above would introduce variations in the core results which would not appear in the cube results; they would also not appear in construction work where a uniform thickness of concrete was being laid over a period of much longer than the 12 days of concreting at Alconbury Hill.

222. The two qualities of concrete used in the experiment were included to compare a concrete fairly typical of those used for roads in Great Britain (normal-strength, gravel concrete) with a type of concrete used in some West European countries (high-strength, crushed rock concrete). Space did not permit the inclusion of slabs of normal-strength concrete made with crushed rock aggregate but the performance of slabs might be expected to bear some relationship to their relative flexural strength. On this basis normal-strength crushed rock concrete should show an improvement over normal-strength gravel concrete of about one-third of the improvement given by high-strength crushed rock concrete.

223. Mr Loe felt he could not agree with Mr Fisher that the Alconbury Hill experiment had shown that roads built to Road Note No. 29 designs were unnecessarily costly. However carefully the quality of concrete might be controlled, the roads still had to be built on a foundation of natural soil. At Alconbury Hill sub-grade preparation had been carried out only under conditions suitable for obtain-

ing the uniformity needed for the experiment. This would not be possible on a normal site and weather alone might cause considerable variations. The pattern of traffic loading was unlikely to remain static and its damaging effect might increase. Against this background the margin suggested in § 112(b) did not appear to be excessive and any reduction might well result in failures which were difficult and costly to repair and which everyone would wish to avoid.

224. Dealing with written comments, Mr Croney found some difficulty in understanding the contribution of Mr Wooltorton. It was not clear whether Mr Wooltorton was supporting or condemning the C.B.R. method of design or indeed what particular variant of the C.B.R. method he was talking about. Where three objectives were quoted it seemed obvious that one would perforce be last. It was not clear, therefore, why Mr Wooltorton had suggested that the last was in the nature of an afterthought. If he meant that it was regarded by the Authors as the least important objective, he was correct. The C.B.R. method tested was, of course, that which had been in use in Great Britain for the last 12 years. The results showed that the method was conservative for the stiff sections laid at Alconbury Hill, a conclusion not unexpected to those conversant with current thinking in the field of pavement design.

225. Mr Croney wished to make it clear that the conclusions in the Paper did not apply to the C.B.R. method as developed in the United States for flexible airfield pavements with crushed stone bases. The method had been highly developed for this application, in which the wheel-load ratings ascribed to the various curves had experimentally proved significance.

226. Mr Croney fully agreed with Dr Peattie that it was important to know more about the wheel-load spectrum associated with the heavy traffic before the results from any one site could be exactly applied to another site. The present assumption, based on a limited survey, was that the spectrum was similar on all heavily trafficked roads although the actual numbers of commercial vehicles might vary within wide limits. At all the sites of current full-scale experiments, on such roads as A.1, A.40, A.30, and A.38, automatic weighbridges had been installed so that more precise information on the constitution of traffic could be obtained.

227. The reasons for using the fine sand sub-base requested by Mr Clapham, were really given in §§ 14 and 27 of the Paper. The alternative material available in the area was a well-graded gravel, which although a better sub-base material did not meet the requirement for an intermediate C.B.R. value. The preliminary trials to which Mr Clapham referred showed that a satisfactory density would be obtained in the material when it was rolled under the restraint such as that provided by the lower layer of the base above. It was this finding which finally caused the Authors to use the material. Although they would not use a similar material again, given choice, there was no evidence that the sand had materially affected the results. Indeed, there was a very satisfactory correlation between the results of Alconbury Hill and those from later experiments where similar base and surfacing materials had been laid on a gravel sub-base. The solid edge beams used at the site did provide potential drainage barriers and on later experiments an edge beam incorporating a 'no-fines' concrete base to give continuous drainage had been used.

228. However, at Alconbury Hill, which was situated in the Fen District of England, the general level of the water table was only a matter of inches below ground level and drainage was not feasible. Borings had shown that the level of the water table was identical on both sides of the edge beam. Undoubtedly with a lower water table the strength of the soil would have been greater than the figures quoted in the Paper and the sections would have performed better. It seemed unlikely however that the relative performance of the soil-cement bases would have been affected.

229. With regard to the recommendations of Road Note No. 29, it was not proposed at present to make changes relating to the overall thickness requirements. Although the experiments showed that this would lead to conservative design, parti-

cularly when stiff bases and surfacings were used, the additional thickness would be of relatively cheap sub-base material and was regarded as providing some further safety factor against possible construction shortcomings. This matter would be reviewed again at a later revision of the Road Note. The results from this and other full-scale experiments had enabled reductions to be made in base thickness leading to substantial monetary savings.

230. Mr Herbert had given an interesting account of the design and performance of concrete roads in New Zealand and Australia. Mr Loe thought that the difference in performance of 6- and 7-in. slabs at Alconbury, where a life of 15 to 20 years was expected, and Auckland, where considerable lengths built between the two world wars were still satisfactory, were almost certainly accounted for by differences in traffic intensity. He agreed with Mr Herbert's comments on the use of reinforcement and said that tests on slabs instrumented with strain gauges had shown that the highest stresses were parallel to the edge at the bottom of the slab and across the bisector of the corner angle at the top of the slab. From the aspect of performance alone the ideal distribution of reinforcement steel would be in two layers with extra steel at the corners and the edges. The use of machines capable of large outputs of concrete carriageway, however, demanded simplification of the reinforcement and the use of a single layer of reinforcement fabric with steel dowels at the joints was a compromise between the two requirements. An experiment was now in progress to see whether improved performance could be obtained with a varied distribution of steel across a single layer of fabric.

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