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**Research and its application to road construction†**

by

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and

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**Dr W. H. Glanville** (Director, Road Research Laboratory) observed that it was rarely possible to isolate the contributions of the practising highway engineer and the research worker; they merged into one result. That was as it should be, for it was very easy inside the laboratory to be led away from practical needs. The research worker who found a fascinating new form of test or who made a new discovery might be tempted, in pressing its claims, to turn a blind eye to the difficulties of engineers. On the other hand, the engineer might try to play safe by turning a blind eye to the potentialities of a new line of thought. Dr Glanville had always tried to bring the two together, because the combination was a healthy one.

102. On the question of pavement design, Dr Glanville said that the difficulties seemed to multiply with experience rather than diminish. He said "seemed to" because he did not believe that they really did; it was merely that an attempt was being made to bring more scientific precision into the use of natural materials, which were very variable in quality and had to be used in Britain under conditions that might change from day to day and even from hour to hour. It was necessary to know a great deal more about these uncertainties and variabilities, and to find means of dealing with the practical difficulties. Methods of design must be resolved into practical rules which could be applied with reasonable hope of success.

103. Dr Glanville recalled that before the 1939-45 war an eminent engineer had said that the roads which were being built were only the foundations of the roads of the future. That was certainly true. Recently, when a length of by-pass road had been opened up and a new section put down it had been necessary to dig through three concrete roads in succession. It was interesting to find that the present answer in Germany, as those who had heard Dr Georner's address a week ago on German motor roads would realize, seemed to be to build three roads on top of one another at the beginning. In that address the great thicknesses of construction used at the present time in Germany had been emphasized. Apparently the Germans did not worry about cost; British engineers had not got so far as that. However, although the Germans were doing so much work they did not use methods of pavement design comparable to those which were being developed in Britain. Some good method of design was urgently needed, and more must be known about the reserve of strength; it would then be possible to build a known reserve of strength into the new roads.

104. Dr Glanville asked if the Authors would give further information concerning

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frost susceptibility and its consequences. That matter ought to be taken more seriously than it had been in the past, because of the great increase in the weight and volume of traffic, which had an effect on the soil and the materials at a much greater depth than had hitherto been normal. It should be borne in mind that about every 10 years Britain had a really bad winter, and unless the precautions taken were adequate the results could be very costly. It was necessary to know more about frost susceptibility, particularly in relation to new materials and crushed stone generally, and the effects of small quantities of cement on them.

105. Another point which had arisen from the Authors' research concerned the question of the continuing deformation of flexible pavements when they had bases of certain types. It was found that there was continuing deformation of the surfaces when bases without much binding material in them, or which had been insufficiently compacted, or which had even been well compacted according to ordinary standards, were used. It seemed that intense traffic might continue to compact materials beyond the point to which it was considered that compaction during construction should be carried. It was important to pay more attention to that.

106. Dr Glanville then referred to the question of the education of highway engineers. There were various methods of educating or improving the knowledge of highway engineers—courses, a special year at a university, etc. It was important that that time should be spent in the most profitable way. Highway engineers could be helped by those who wrote Papers for discussion, but it was very important that that literature should be easy to read and that the short courses which were given by organizations such as the Cement and Concrete Association and the Road Research Laboratory should give just what was needed in a form in which it could be readily assimilated. It was difficult to expect highway engineers to spend a whole year in post-graduate study. Everything depended on the quality of the teaching and on the quality of the guidance which they were likely to get; it was clear that unless the teaching was first class, engineers would be largely wasting their time in studying special branches of engineering. The only people who could impart really up-to-date and first class knowledge were those who were in the business.

107. Dr Lee had mentioned this in connexion with the "Ponts et Chaussées" system. Practising engineers and perhaps research workers, men of distinction, had to take part in university courses if they were to be a success. There had been university courses taken only by a few students from abroad and perhaps a few men from Britain. That was largely due to the quality of the teaching. If the quality of the teaching were raised, and the students felt that they were being brought into touch with people who mattered, the position would be different. Would the Authors say a little more about that? In other countries the professors were often practising engineers of very considerable distinction, who held chairs in the universities and practised at the same time. Unless something of that kind were done in the case of the courses in Britain there would be great difficulty in the courses establishing themselves.

Colonel S. M. Lovell (County Engineer and Surveyor, West Riding of Yorkshire) said that the Authors had provided what had long been needed—an excellent review of the state of current research knowledge. It would be invaluable for quick reference and provided a clue to where details could be found.

109. For more than 10 years the West Riding County Council had been building up a laboratory control system covering soils, concrete, and bituminous materials, and within the expanding limits of its resources it had applied the results of road research to everyday problems. Construction thicknesses for new carriageways had been based on the CBR method of design, which had probably resulted in considerable overall economy and assured complete adequacy for traffic, without excessive depth. By control testing, indigenous materials had been successfully used, and this had resulted in very considerable savings. By using the CBR method and indigenous materials, it had been possible to build roads entirely satisfactorily at less than half the cost of roads constructed by traditional methods and with traditional materials.

110. The quality of single-size roadstone from all his suppliers was now considerably better than the minimum requirements of the British Standard, and that was well worth while. The constant checks for compliance with specification had undoubtedly played a major part in that. Similarly, the average quality of coating materials continued to improve year by year, owing to the improved plant and organization which the suppliers had installed in order to provide consistently good materials, realizing that those materials, when delivered, would be subjected to the normal control testing which had been instituted by the West Riding County Council.

110a. Despite control, some difficulties had inevitably arisen, but in the solving of these many important lessons had been learnt. For example, the checking of sub-base strengths by the plate-bearing test had been found valuable in avoiding weaknesses, particularly where the sub-base had been made of local material. In view of the relatively small cost of general control compared with the savings resulting from smooth and trouble-free construction, it should be a matter of national policy that such control should be the universal tool of the engineer. Unless the control was adequate in both degree and quality it could be dangerously misleading, and therefore within an organization it was necessary to build up a practical minimum to be certain that the materials and methods were being controlled and tested in accordance with the latest research.

111. The Authors had suggested that the contractor might well undertake the soil survey and control of workmanship at the construction stage. Colonel Lovell did not think that that would be advisable. The major contractors in Britain had set up a first-class control organization which was of benefit to all concerned, but from the very nature of control responsibility for it must remain with the engineer in charge of the job, if he was going to do the job properly. The contractor could help considerably by placing the facilities at the engineer's disposal, and the knowledge that the contractor had these facilities behind him would keep the engineer on his toes and would help to ensure that the necessary liaison between them was good. That would result in a good job, which fundamentally was all that mattered.

112. Colonel Lovell hoped that the work of the Laboratory on soil stresses under pavements would soon lead to the publication of some revision of the CBR method such that for given traffic and subsoil conditions the road thicknesses would be related to the strength of the incorporated material and not be a single invariable figure independent of such strengths. He believed that research was tending in that direction. It might well be found that the use of high-stability materials, although more expensive in their initial provision, would prove to be the most economic form of construction. That might be of great value in the execution of contracts, since such materials were generally less weather-susceptible than their lower-stability counterparts. During winter period and in summers such as that of 1958 both contractors and engineers would be encouraged by such a prospect.

113. Dr Glanville had referred to the effect of frost. Would the Authors give their views on the frost susceptibility of materials, in particular the existing materials rather than the materials imported for use in making the road? The existing materials were the most important ones and often caused the trouble so far as frost damage was concerned.

114. The Authors made very little reference to the fact that many of the counties were in fact continually striving to take early advantage of any research findings. Colonel Lovell was confident that in an increasing number of cases laboratory control was the essential link in the application of research to road construction.

**Mr R. L. Fitt** (Partner, Sir Alexander Gibb & Partners, Consulting Engineers) said that the Paper brought out the important point that the work of the Road Research Laboratory was carried out in close collaboration with the side of the industry that was concerned with the practical job of construction—the manufacturers of plant and equipment, the suppliers of roadmaking materials, and civil engineering contractors. The

work of the Laboratory was of the greatest assistance not only in the design and construction of roads, but to those concerned with airfield work and in the construction of dams.

116. While he agreed that important work was being carried out by the research and development sections of the leading civil engineering contractors in this country, some qualification of § 91 was necessary. It was suggested that the contractor should undertake both the design and the construction of major road works, but in most circumstances that method could be applied only to a limited extent. In the design of roads both the public authority engineers and the consulting engineers had an important role to play. They provided an essential link between development planning and research on the one hand, and the actual execution of works on the other.

117. The proper role of the consulting engineer, Mr Fitt said, was to supplement and not to supplant the skill and experience of the technical staff of the responsible authority, the client; to relieve them of the peak loads; and to bring his skill and experience to bear on special problems which had not previously been encountered.

118. In most, if not all, major projects the sponsoring authority wished first to establish the alignment of the road, the basic design and specification, and most certainly the probable cost, before awarding the contract for its construction. The task of the responsible technical adviser, whether an employee of the authority or a consulting engineer, was therefore of particular importance during the project-making process, and it was at this stage that the latest developments in technique must be used to determine the route, the specification, and the design. He had to select the route that would be economical in earthworks, bridges, and culverts. In tropical countries in particular he must always be on the lookout for unusual soil properties; was frequently faced with the necessity of using materials of low quality by conventional standards, and with the lack of road stone within economical haulage distance.

119. Many of the newly-developing countries that were intent on opening up communications had slender financial resources, and called for stringent economy in cost of construction. The combination of these physical and financial difficulties required the full utilization of new techniques and the application of new processes. There was an element of research in both the investigation and construction stages, that sometimes meant breaking into fresh territory in advance of research work. Successes in this field and sometimes failures, provided results that were useful to the Road Research Laboratory and were some small recompense for the help and advice which the Laboratory so willingly provided.

120. Once these initial problems had been solved, a reputable contractor might well be given the chance to put forward alternative proposals. That should preferably be done by including alternative forms of construction in the documents issued for tendering. But, as Colonel Lovell had said, the final decision should rest with the engineer.

121. In § 187 the Authors suggested penalties for sub-standard work and bonus payments for high quality workmanship in construction; in practice this might well prove difficult to apply. Difficulties already occurred when the target date had to be met under unfavourable weather conditions, and problems associated with variable subsoil conditions might not have been fully revealed in the investigation stage. If the workmanship was unsatisfactory the employer already had redress under the normal contract conditions, and any reputable contractor would aim at a high standard of finish as the best method of enhancing his reputation.

122. The main problem was arranging under a contract for flexibility of specification during the execution of the work. The co-operation of an experienced engineer and an experienced contractor on the job would ensure that costs were saved and good results achieved. The construction methods employed could be kept under constant review in terms of the weather conditions, the soils, and plant availability, as the work proceeded. To adhere to a rigid design and specification and at the same time play safe must mean assuming the worst conditions, which might occur only in isolated patches.

**Mr E. A. Shaw** (Director and Chief Engineer, Tarmac Civil Engineering Ltd) said

that the contractor had always to deal with the unexpected, for example, some unforeseen physical condition that brought about a change of design. While the contractor might have plenty of enthusiasm to bring to bear on the problem, he also needed the backing of the research worker. Although a contractor might want to undertake research himself, it was often difficult to persuade boards of directors to spend money on research unless they had been awarded a particular contract or had a fair certainty of it. It was not easy, therefore, for a contractor to undertake the rather large-scale programme of research which was envisaged in the Paper, and it was of immense value to know that he had somewhere to go where he could ask questions and get all the latest information.

124. Mr Shaw quoted two examples to show how that worked. When his firm had had a concrete road to construct he had been very much aware of their shortcomings in building concrete roads and very much aware of the difficulties of doing so. They went to the Road Research Laboratory and to the Cement and Concrete Association and so obtained the benefit of all the research that had been undertaken at that time. The information provided had been of immense value in helping his firm to solve some of the problems, notably in regard to riding quality.

125. On another occasion they had been building a road and the sub-base was to have been of crusher run. He had always thought that if rocks were put into a primary crusher the material that came out at the other end was crusher run, but he had been wrong. At that time much attention was being paid to the drainage qualities of the sub-base, and, to ensure free draining, the quarry had at great expense taken out all the fines. The result had been a material which would not compact under the roller, so that eventually it had been necessary to put back the fines. He had been delighted to read in the Paper that there must be fines in order to get a proper locking of the material under the roller, and that the size of the large stones should not exceed 2 in. They had been in trouble because a lot of the stone had been as much as 4 in.

126. The Road Research Laboratory had attained such a position that it had become a national authority, and there was some danger that highway authorities may be inclined to leave a little too much to it. As much research work as possible should be carried out by local highway authorities as well. Some of the problems needed to be tackled on as broad a front as possible. For example, the problem of joints in concrete roads needed a great deal of investigation. Mr Shaw hoped that the solution was in view, but unless much more work was done in a courageous manner the answer would not be obtained for a long time.

127. The Authors had described how the information obtained from research work was disseminated. One of the problems today was the quantity of paper. It was impossible to keep up to date with all the publications that were issued, but it was most important to know where the answer could be obtained, and the spoken word was much more valuable than the written in that respect.

Mr J. S. McNeil (Deputy Chief Engineer, Ministry of Transport) stressed the importance of applying the results of research to practice. He was therefore surprised that the British Standards Institution was not included in the list (§ 95) of bodies concerned with the application of the results of research, since the conclusion of a successful piece of work in research would very often be its incorporation in a B.S. Code of Practice.

129. There was a gap between the full-scale experiment which was controlled at all stages and the ordinary workaday job carried out under normal conditions. It led to difficulties, in that where authorities were obliged to use British Standards wherever they were applicable, they felt hesitant about using new specifications that they felt might have passed the experimental stage but had now "made the grade". Until there had been substantial experience of their use in normal commercial conditions, the B.S.I. were unwilling or reluctant to issue a standard. To try to bridge that gap, his department, in collaboration with the Road Research Laboratory, had been running a series of specification trials in which they tried to use new specifications under normal conditions.

130. Referring to the question of control testing, Mr McNeil said that contractors should have their own testing and control organization, but it was not a substitute for the control and testing that the engineer should do himself, to ensure that his client or employer was getting what was being paid for. In § 70 the Authors said:

“Results of control tests should be available while work is proceeding to anticipate, and prevent, departures from specification, rather than to reveal errors after they have been made.”

There had at times been a tendency to regard tests as something to conduct afterwards, when something had gone wrong and evidence was wanted to fight the contractor. That was altogether a wrong approach to testing.

131. The Authors had referred to the advances made in earth-moving and compacting plant. Considerable advances had been made, but the size and speed of operation of the modern machines brought with them their own problems, especially in the climate of Britain. As Dr Glanville had said in his James Forrest Lecture, some of those problems might well necessitate some re-thinking about the programming of earth works on large-scale works in the British climate.

132. In § 24 there was a suggestion that engineers should under-design flexible pavements and make up afterwards as might become necessary under traffic use. He had understood that all the results of research pointed to the desirability of developing the full strength right from the start, and he was surprised that the Authors had departed from that. Admittedly they had a saving clause in § 26, where they said:

“This procedure is appropriate only on roads where the saving in construction costs more than offsets the cost of any interference to the flow of traffic which the subsequent resurfacing may cause.”

This was a practice in which he had engaged 20–25 years before, when building roads in the West Highlands, but it had been reconstituted solely by shortage of funds and he had always regarded it as a barbarous practice to inflict on the road user.

Mr E. M. Gosschalk (Assistant Engineer, Sir William Halcrow & Partners, Consulting Engineers) said that the published results of the work of research laboratories were a boon to engineers generally and an essential contribution to progress. Nevertheless, the publications of Government organizations often gave an impression of authority beyond their intention, and there was some danger that hard-pressed engineers might apply their contents incautiously. Engineers did not always have time to study antecedents. The extent of the validity of results of research could seldom have been established by widespread practice at the time of publication and adequate provisos were often desirable.

134. A case in point, mentioned in § 13, was the method of packing to a density corresponding to a density of not more than 10% air voids. This suggested criterion required some qualification if it was to be applied in conditions overseas, for example, where the moisture content of the soil might change rapidly after the soil had been placed. A reduction in moisture content of, say, 3% would commonly raise the air voids from the 10% specified to perhaps 15%. Compaction that originally satisfied such a specification might rapidly fail to do so, and the contractor's consternation could be imagined.

135. The thesis on air voids contained in reference 6 seemed unconvincing. Seven embankments had been investigated, and in each case the natural moisture content had been equal to or greater than the plastic limit. In the case of the greatest amount of settlement observed since construction the air voids were only 1%. That was hardly a convincing argument.

136. He suggested that, intended or not, the Road Research Laboratory had something of the status of an oracle, and therefore had a responsibility to ensure that any limitations to the conclusions reached were given the same emphasis as the conclusions themselves.

137. The Authors had explained how the Road Research Laboratory disseminated

its knowledge, but they had not referred to the system adopted for deciding what knowledge it aimed to acquire. It was understood that advice on the conduct of investigations was given by the Road Research Board and by committees of the Board, and that the Laboratory co-operated closely with the Ministry of Transport and Civil Aviation, but would the Authors describe how this worked out in practice? Practising engineers, aware of the directions in which their knowledge was limited, could indicate where research could be of most value, but it was not clear how the precise needs of road designers and builders were systematically conveyed to the Road Research Laboratory. In other words, was there any assurance that the capacity of the Laboratory for general investigation was applied to the best overall advantage?

138. There appeared to be many possible studies that would not impose a great strain on the resources of a large laboratory, but that would be of great value in many ways for improvements in road design. Mr Gosschalk suggested that interested firms and Government departments might be invited to submit periodically short lists of subjects for investigation, with reasons, and that these subjects should receive consideration for inclusion in the programme of the Road Research Laboratory. It would, of course, be a condition that the investigation suggested would further the objectives of the Laboratory.

**Mr C. F. Armstrong** (Senior Engineer, Ministry of Transport & Civil Aviation), referring to § 7, pointed out that the British Standard Code of Practice for site investigation, C.P.2001, gave a rather fuller and more recent appraisal of the needs of a soil survey than Road Research Technical Paper No. 15, although both were very useful references.

140. Of the identification of soils and roadmaking materials from aerial survey mentioned in § 10, he said that there was a dearth of people qualified in this branch of survey. There should be encouragement for anyone who contemplated entering this useful field of interpretation. A difficulty was the need for considerable experience in soil mechanics and particularly in geology before this work could usefully be taken up.

141. In § 14, there was not a complete picture of the earthwork difficulties that had been met recently in practice, in particular the problem of a material which was run to spoil mainly because when excavated it was too wet for compaction. If it could be stock-piled temporarily and accepted later it would save the cost of importing materials from borrow-pits, for which a high price was usually charged. This was a matter to which his department was giving attention at the present time and on which discussion would be welcomed.

142. For motorway construction in Britain very little use had been made of rollers for compaction of fill, earth-moving equipment having been relied on very largely for that purpose. Only time would tell whether that had been the right approach, but those directly responsible appeared to be satisfied. He had been disturbed recently to hear a manufacturer complain that he could not sell his vibratory rollers because contractors could not afford to have the fill so well compacted that they had to provide some of it free. If in fact the Ministry of Transport's specification was being interpreted in such a way as to discourage efficient compaction, it would be necessary to reconsider the wording.

143. With regard to Fig. 1, Mr Armstrong understood that a further curve was being considered to cover the range of traffic exceeding 4,500 commercial vehicles per day. With regard to § 22, it was unfortunate that the Authors did not feel able to give in Fig. 2 some results obtained more recently than 1955, or to give some of the first lessons which were being learned from the Alconbury experiment. Although a dense surfacing of good load-spreading capacity was desirable, it might be of more value because it offered an impermeable layer. It might well be that freedom from surface deformation depended more on the nature of the base material than on the nature of the materials of the surfacing layers.

144. In § 25, reference was made to the material becoming stronger. If that occurred the wrong material had been chosen, and it must have been inadequately compacted by

rolling and needed traffic to finish the job. This meant that deformation would occur most extensively in the wheel tracks, a condition that should certainly be avoided now that processes were available that did not require subsequent compaction by traffic.

145. With regard to § 28, although the Ministry of Transport specified compressive strength as the criterion of quality for concrete road slabs, it was open to the engineer to specify flexural strength requirements instead, by means of suitable supplementary clauses for workmanship and testing requirements. In § 29 air entrainment was referred to. The Ministry's specification for road and bridge works did not require the use of air entrainment, but it was open to the engineer to specify it if he wished to do so and could still ensure the minimum strength required.

146. In § 39 the Authors have confirmed Mr Armstrong's view that the dry-bound macadam method of base construction had certain shortcomings.

147. Referring to § 48, Mr Armstrong said that 12 years earlier he had pleaded for the introduction of suitable plant for mix-in-place soil stabilization. Since then the complete single-pass train had been developed, and he understood that they were now well on the way to seeing improved wheeled types, which would be very mobile on site and be able to move readily between jobs under their own power.

148. In § 66 the Authors made a good case for abandoning the use of asphalt on normal concrete in new construction. The Ministry was doing everything possible to see that this line was followed, by advocating bituminous surfacings on jointless flexible bases whenever possible, as an alternative to concrete with a concrete running surface.

149. The Authors had not mentioned the question of temporary and permanent drainage. Disposal of rainfall during large-scale construction did not seem to have been given the attention that it deserved, either by the engineer or by the contractor. In most current specifications the contractor was simply told to keep the site reasonably dry and was left to guess what allowance to make for this in his price for earth-works. Although this might be sound in theory, it was clearly not working out in practice. Would the Authors suggest how the contractor could more effectually be required to prevent a site from lying in a waterlogged condition?

**Mr N. B. Bourne** (Departmental Manager, Geo. Wimpey & Co. Ltd) said that although the purpose of the Government's road research organization was to help all those concerned with roads, the Road Research Laboratory was so well equipped and was doing so much work that it was in danger of losing its status of adviser and of becoming a dictator. That was not a criticism but a warning.

151. It had been made clear that several of the contractors had most efficient laboratories. There was some question whether those laboratories were sufficiently used, and that raised the difficult question who in fact should design the roads. One suggestion had been that the contractors might do it. That had been applied to building quite successfully and it could, with modifications, be applied to road construction. The other question was whether the county surveyor or the consulting engineer should design the road. Would the Authors' give their views on the roles of those three types of engineer?

152. On the question of design, the Authors had rightly stressed the importance of the impervious pavement, but they had, as Mr Armstrong had pointed out, omitted any reference to drainage. The railway engineer was very conversant with drainage, and the road engineer needed to be more so. So far only one kind of drain seemed to be used, something like a French drain, which to Mr Bourne's mind was rather like an Irish bridge.

153. Also on the question of design, he was surprised that the Authors had again published Fig. 2. Surely Fig. 1 made Fig. 2 extinct? It seemed impossible to work straight from Fig. 1 on a CBR value without taking into account what surface was going on top of it. Fig. 2 at least brought hot-rolled asphalt into its own. Not only did it keep the water out and thereby raised the CBR-value, but it also distributed the load considerably and would probably lead to the conclusion that most construction depths were excessive.

154. Mr Bourne disagreed strongly with the Authors when in § 75 they seemed to brush aside the Marshall test. It was a great pity that something better had not been produced in Britain, because the Marshall test was not perfect; but to ignore the properties of stability, flow, and air voids was not good engineering. To talk of an optimum bitumen content without dealing with sand grading was to ignore the whole science of mix design.

155. On the question of analysis (§ 75), the chemical analysis referred to was merely a sort of post mortem on the contractor. The obvious solution lay in vibrational testing methods.

156. It had been suggested that asphalt could be laid on lean concrete; but it must be lean enough, or there would be cracks through contraction, or blowing up through expansion. The solution was to have a concrete so lean that it had no cement in it at all—the material now known as “wet-mix”.

Mr E. E. Morgan (Road Materials Testing Laboratory) referred to the question of the factor of safety raised by Dr Glanville and said that, in their design of roads in rural areas, highway authorities based their estimates for future traffic volumes on 75% in excess of the average daily traffic flow in 1954. Applying this to the CBR curves in Fig. 1 meant that the road was designed with a greater depth of construction than the actual traffic would warrant. It might be suggested that there was little advantage in increasing the census figures by 75% if at the same time there was a possibility of some of this increase being diverted to cope with a possible reduction in the strength of the soil. On the other hand, by the time the traffic had reached its increased intensity, the soil might have become more consolidated without having reached the stage of gradual weakening mentioned by Dr Glanville.

158. In § 67 the Authors had said: “Where for any reason a bituminous surface is required over concrete it appears that it must be at least 3½–4 in. thick. . . .” Probably they were referring to hot-rolled asphalt, because it was shown that two-course bitumen macadam having a total thickness of 4 in. was not immune from reflexion cracking.

159. It was recognized that at the Road Research Laboratory much research on lean concrete had been carried out, a type of construction which was being used to an increasing extent, but Mr Morgan would like to know what method of control they had found to be the most satisfactory. Cube strength was one method, density of the wet concrete was another. Dealing with the former first, the making of cubes was desirable (otherwise there would be no check on the quality of the material being used) but, like cubes for reinforced concrete carriageways, their strengths had mainly a “post-mortem” value, indicating that the lean concrete was not too strong or it would have undesirable shrinkage cracks, neither was it too weak otherwise it would deform under the traffic loading. It was necessary to specify two cube strengths, a maximum of 2,000 lb/sq. in. and a minimum of 500 lb/sq. in. had been suggested, but the results obtained depended to some extent upon the strength of the man who made the cubes and there was no certainty that the lean concrete after being rolled had the same density as the cubes.

160. The other method of control was a density test to ensure that the concrete had been sufficiently rolled. To obtain a representative average density at least three sand-replacement tests were essential, but each took about half-an-hour to complete. By the time these densities had been obtained the concrete had started to harden and could not be rolled again, consequently any corrections that had been found to be necessary were either too late to be used or were applied to the next area of concrete that was laid.

161. Mr Morgan believed that the basis of control should lie within the manufacturing procedure, such as the grading of the aggregate, the proportioning of the materials, water-cement ratio, time of mixing, haulage distance, and placing and rolling of the lean concrete. Some uniformity of the grading was essential. With an all-in “as-raised” material this would be difficult to ensure. In the Thames Valley area highway authorities had on some occasions in the past been fortunate in obtaining a gravel having a fairly uniform grading with about 35% fine aggregate and a much closer grading than

the B.S.882 requirements for 1½-in. all-in aggregate. Could the Authors suggest any better methods?

162. In his desire to use lean concrete economically, one of Mr Morgan's problems was the selection of a suitable reduction factor to be applied to that part of the thickness of flexible paving for which it was desired to substitute lean concrete, the total thickness having been found by means of the CBR apparatus. He had used two-thirds as being a reasonable figure to adopt but, although he had modified this factor when he considered the site conditions to be exceptional, his choice was a matter of opinion based on the fact that roads for the design of which he had used this reduction factor had not up to the present time shown any signs of failure. Something more than an arbitrary choice was essential because even 1 in. too much in the thickness of the lean concrete would raise the price per square yard by about 1s. 6d. In § 22 the Authors had mentioned that full-scale road experiments had been carried out to obtain data on the performance of flexible pavements made with different materials and in § 23 they had indicated that the purpose of these experiments was to economize in construction costs by suitable reductions in thickness. Whether lean concrete could be classed as a flexible material or not he hoped that the experiments had included or would include this material. Although some highway authorities had testing apparatus and undertook experimental work, the special apparatus and accompanying techniques needed to solve this problem were probably beyond their reach and certainly beyond his. The properties of lean concrete when placed under the carriageway might make it impractical for a definite reduction factor to be recommended but it would still be helpful if limiting values could be suggested. He thought that the matter had sufficient general interest to justify his request for information.

**Dr A. R. Collins** (Director of Research, Cement and Concrete Association) said that it was usually assumed, and had been assumed so far in the present discussion, that research was in advance of practice. This was certainly so in matters of detail, but was it so general? Just after the 1939-45 war prestressed concrete had been introduced in Britain, and there had been an almost indecent scramble among research organizations to enter the new field. Yet at the time that the first prestressed concrete structure had been erected no research at all had been done. He believed in research, and the Cement and Concrete Association spent a very large proportion of its income on doing it; but one of the great problems was to keep research up to date with practice, to foresee a new development and to obtain basic information on it before it became widely used.

164. Sometimes a method of road construction came into being through practical experience. Research was then carried out to evolve the best design for that type of road. But by the time the results were available, the method of construction might be superseded by another. The most important road in Britain was being built in lean-mix concrete, yet the results of experiments to determine how thick the concrete should be would not be available for 3 years.

165. Perhaps the best solution to this problem would be to undertake more basic research. That would provide a fundamental understanding of the materials used as distinct from the mere information provided by applied research or testing work. With that understanding and perhaps a few tests, it would be possible to predict what would happen as a result of a change in practice. Without understanding, research had to be begun again every time a new method of construction appeared.

**Mr Pitt H. Jones** (Ministry of Supply) referring to the problems of constructing roads in wet conditions, said that the Authors appeared to have reached the conclusion that it was easier to use plant mix under these conditions. Would they reconsider whether this conclusion was always right. Plant mix had the disadvantage that, while easy to control at optimum moisture content, it had, in spreading, to be carried over an already softened subgrade, which might be further churned up in the process, whereas material spread on the subgrade for mix-in-place stabilization would protect the subgrade, allow adequate compaction, and serve to carry construction traffic prior to stabilization. The choice appeared to be between placing a good base on a dubious subgrade with plant

mix, or sometimes having to stop stabilizing with mix-in-place because of too high a moisture content. This likelihood would be lessened by adequate drainage.

The following contributions were received in writing.

**Mr Sidney Rosenak** (Senior Engineer, Terresearch Ltd) said that the Authors had drawn attention to the potentialities of soil stabilization in tropical countries, where many suitable soils were to be found. The soils compacted and stabilized in various forms had been used for centuries in many parts of the tropics as a walling material. That ancient technique had been revived by the application of modern principles of soil stabilization, and by the use of cement and lime as the main stabilizers. Much development work had been carried out in parts of Africa, India, Australia, and South America, and the results had been described in various technical publications.

168. The suitability criteria of soils to be used for walling were generally similar to those of soils to be used for road construction. The results of tests on soil walling could therefore be taken as a guide to the probable behaviour of such soils for use in road construction.

169. In 1955 and 1956 Mr Rosenak had carried out some work on stabilized soil walling in Burma. He had found that sandy soils with a plasticity index below about 37 could be very well compacted and stabilized with low percentages of cement. The cement content of the soil was not to exceed 5%, but depending on the compactive effort very high crushing strengths could be obtained. Suitable soils containing 5% cement and compacted into blocks in a machine operating at a compacting pressure of about 1,000 lb/sq. in. had crushing strengths at 90 days of between 2,000 and 3,000 lb/sq. in., in the dry state. Similar soils compacted at lower compacting pressures, at compactive efforts similar to the B.S. compaction test, had final crushing strengths of between 400 and 800 lb/sq. in.

170. In areas with a monsoon climate, where soils might become fully saturated during the rainy season, it might be useful to measure the "wet" strength of stabilized soil samples. The "wet" strength of stabilized soils in Burma was found to be about 35 to 50% of the "dry" strength, depending on the initial compaction and density of the soil. A useful test was the accelerated weathering test described in the American standard specifications<sup>60</sup> to observe the behaviour of soil samples under repeated cycles of wetting, drying, and abrading. Suitable soils mixed with 5% lime and allowed to stand for several days before compaction were found to behave very well under the accelerated weathering test in comparison with cement stabilized samples. Details of this work had been described in a report<sup>61</sup> to the United Nations Technical Assistance Administration, who had sponsored the work.

171. The results of the tests, although primarily meant for the use of stabilized soil walling, could equally well be applied to soil stabilization for road construction.

**Mr S. W. F. Morum** (Director, Taylor Woodrow Overseas Ltd) asked whether the Authors could provide any information on the economics of compacting the dry, silty clays in Iraq and Iran at the head of the Persian Gulf. If these clays were placed in embankments during the dry season they were usually well below optimum moisture content. Because clays had low permeability, additional water added during construction did not penetrate the nodules properly, and tended to be lost by evaporation. Further, if the water were applied as a spray on a filled embankment, the surface layer would be considerably above optimum moisture content and difficult to compact, because the soil adhered to the machinery.

173. In Mr Morum's experience, because compaction at optimum moisture content appeared uneconomical and difficult, it was preferable to accept the maximum compaction possible with the soil in its normal condition and, if necessary, to apply a temporary road surface for a season or so.

174. The Authors had stated that bitumen stabilization could only be used with sandy soil. While agreeing that this was generally true, Mr Morum drew the Authors' 30+

attention to the work on clay soils which had been done in the Middle East; some early work on this had been described by Mr Morum in 1942<sup>62</sup>. Tests carried out by the Road Research Laboratory had shown that that stabilization of clay was, perhaps, not a true soil stabilization, because the shear strength of the bitumen/clay mix was less than that of the clay compacted at optimum moisture content; but its value lay in the following:—

- (a) Waterproofing the clay, so that the clay was not affected by moisture changes due to rain, floodwater, or capillary.
- (b) Providing a dust-free surface on which a thin carpet of surface dressing could be laid.

175. The technique employed to stabilize the clays was to break the soil down with a disk harrow and to spray the broken clay with alternative water and bitumen cutback sprays, thereafter mixing with a disk harrow. It was found that if the clay was broken down too finely by the use of machinery like pulvi-mixers it became intractable and did not dry out properly.

Mr N. F. Richards (Public Works Department, Nyasaland) said that the position referred to in § 3 occurred frequently in the Public Works Departments of those overseas territories that did not possess large financial reserves; consequently, any upward revisions of preliminary estimates which had been written into the development plans could be effected only by directing limited funds from other projects. One solution, which was of great assistance to highway engineers was the inclusion in the development plans of a block sum of all capital road projects, accompanied by a list of those projects in order of priority but without individual estimates of cost; each project could be authorized separately. A firm estimate based on adequate site investigations and design could then be submitted.

177. In view of his experience of Public Works Departments in British overseas territories, Mr Richards agreed with the Authors' description in § 93 of the situation regarding engineers. There was an acute shortage of properly trained highway engineers in many of those Departments, and he strongly supported the Authors' recommendation in § 99 that engineers who had some practical experience of highway engineering should be encouraged to take comprehensive post-graduate courses. The need for properly conceived courses covering all aspects of the subject was real and urgent, but it was essential that employers should then make it possible for selected engineers to attend such courses without suffering financial loss.

Mr R. L. Mitchell (Materials Engineer, Division of Roads and Road Traffic, Southern Rhodesia Government), observed that the Authors had referred to the use of aerial photography in the assessment of sub-grade soils in Central Africa. Most Central African soils were of residual formation, and little work had been done on such formations. Mr Mitchell used aerial photography exclusively for the location of constructional materials, both as an aid to the prospector, and to confirm prospectors' reports. Laterites could be expected to follow contours and to impede drainage, and the shade that the moisture created indicated their location and extent. Unfortunately rock bars showed similar properties. "Gravels", which were invariably decomposed rock, often showed lighter colouring, and occasionally a different erosion pattern; but it was difficult to distinguish the usable zones between rock and soil.

179. Mr Mitchell used 1/20,000 scale black-and-white photographs, but was shortly to experiment with 1/10,000 scale, both in black and white, and in colour, although the latter was very expensive. Another difficulty was the change in moisture, shade, and colour throughout the marked wet and dry seasons. Aerial photography was an art to be developed locally, but in Central Africa all photographs should be taken in a fixed month of the year; that called for long-term planning.

180. Mr Mitchell said that he had great faith in geophysical prospecting, provided that it was used in conjunction with geological experience. Holden<sup>63</sup> had reviewed its application in Southern Rhodesia. He had used it for all bridge site investigations,

drilling only to give a "scale" to the work—to identify layers—and for estimating rocks in deep cut. Only A.C. resistivity methods were used, because the depths of horizons could be estimated more accurately than with drilling. Drilling gave depths at one point, which in residual country was invariably isolated, whereas resistivity gave mean depths.

181. Fifty-ton compactors were increasingly used in Rhodesia, but large field trials had indicated that they were limited to sands—if only because they compacted in depth, and only open-graded sands could be watered in depth. Such sands sheared beneath high tire pressures, and Mr Mitchell had had difficulty in obtaining heavy rollers that could be used with pressures not exceeding 50 lb/sq. in.

182. The stress distributions illustrated in Fig. 2 were of fundamental interest; it would be interesting if the original California study of road failures were repeated with a view to deducing different curves for different types of pavement construction. In many countries tar, if not bitumen, was cheap, and it might be cheaper to use rolled "tar asphalt" instead of the more traditional gravel base with a bitumen surface treatment. Such studies should be continued to include cement stabilized bases. Mr Mitchell hoped to continue this work to study the effect of temperature on stress distribution, because in Rhodesia surface temperatures ranged from 30–160°F.

183. He could not unreservedly accept the thesis in § 25. Most soils showed an increasing CBR-value (and presumably bearing capacity) with increasing density—at least for densities of the order of 100% (B.S.); but that was by no means general, presumably since pore pressures were set up, and not all roads would show a progressive reduction in deformation with time. He believed that soils could "fatigue"; if an under-designed road were fatigued, it might be necessary to rip it up and to re-compact it before adding the extra cover material. A 20% initial reduction in thickness was all that could safely be considered; perhaps a surface treatment could be employed instead of a rolled asphalt, but the postponement of a 4- or 6-in. base should not be considered, save for a short period.

184. Probably 3,000,000 sq. yd of cement- or lime-stabilized bases had been laid in Southern Rhodesia, at least 90% of which had been in cement. Very seldom had more than 2% of cement been used, and the only base failure that Mr Mitchell could recall was at a construction joint where the cement had been forgotten between 2 days' work. However, as a general rule, only gravels were cement-stabilized, and bases were required to have CBR-values of about 80, with maximum P.I.-values of 8 before stabilization, and of about 150 afterwards. Frost being no problem, the unconfined-compression-test requirement of 250 lb/sq. in. was not adhered to. As the Authors had remarked, coarse material mitigated against the use of rotary mixers, the grader and the disk being used to obtain a mix, which was probably not very efficient. Apart from the difficulty of rotor maintenance, single-pass stabilizers were not favoured, owing to the difficulty of compaction. On one sandy soil, Mr Mitchell had obtained 105% Proctor density with road mixing and pneumatic (and also with vibratory) compaction, while a similar soil in Mozambique was said to give only 95% with an impact compactor. A single-pass stabilizer would be suitable if it were rugged enough and if a towed vibrator could give sufficient compaction.

185. The exception to the cement or lime stabilization of coarse gravels in Rhodesia was the stabilization of a close-graded aeolian sand. Mr Mitchell stabilized this, as a road mix, with a specially developed tar. The Authors had said that in most countries bitumen was imported and was expensive; but that criticism often did not apply to tar. Were there often cases where the stabilization with tar could be justified?

186. The Authors had said that bitumen stabilization was not successful with soils containing silt or clay. While he agreed with this, Mr Mitchell had stabilized such materials with emulsion to form running surfaces which did not dust. That work should have a certain, though limited, future.

**Mr Henry Grace** (Partner, Messrs Scott & Wilson, Kirkpatrick & Partners, Consulting Engineers) said that it was interesting that a high proportion of the results had been

obtained from full-scale experiments in the field, or from a study of how actual roads behaved in practice. Research of that type was in general likely to yield more valuable results than laboratory investigations. Professor Terzaghi had stated as long ago as 1936 in his address<sup>64</sup> to the First Soils Conference that "the center of gravity of research has shifted from the study and the laboratory into the construction camp where it will remain." Although research had a most vital contribution to make, the only way to find out how to build roads was by building roads.

188. In § 12 the suggestion had been made that soil surveys might, with advantage, be undertaken by testing consultants. Mr Grace considered that an understanding of the behaviour of soils was as essential to the engineer as his knowledge of the behaviour of steel, concrete, or water. In a modern motorway a very substantial proportion of the cost was accounted for by earthworks; the engineer responsible should therefore be fully qualified to make decisions affecting that vital part of the work. Apart from the physical operation of digging the trial pits of drilling holes, the soil survey should be undertaken by the engineers responsible for the work. The routine testing could be undertaken by the testing consultant; but because the interpretation of the test results depended on a thorough knowledge of the methods of testing employed, Mr Grace had always preferred to use his own laboratory and staff for carrying out this work. The interpretation of soil survey was such a vital part of the work of the road designer that it would be wrong for the engineer to rely on an interpretation provided by any organization other than his own.

189. In order that the results of research should be applied to engineering practice it was essential that the findings be incorporated in specifications. The work of drafting specifications was difficult. Although that work was normally considered the responsibility of the engineer it could at times with advantage be undertaken with the assistance of the research worker and the contractor. Present specifications—especially those dealing with earthworks—left much to be desired. In many cases it was found that they could not be complied with in practice. The resident engineer was often told to use his judgement in enforcing the specifications and to obtain compliance as far as was practical in the circumstances. That was an unsatisfactory state of affairs for all concerned. A single standard specification for earthworks could not be evolved to cover all conditions that would be met with in practice. In Mr Grace's experience, a new specification incorporating all that had been learned from the soil survey and the other investigations had to be prepared for each job. Did the Authors agree with this?

190. Site control was probably the most difficult step in the application of research to practice. Constant and adequate supervision was required, and it was often difficult to obtain the clients' agreement to the expenditure of funds on this vital aspect of the work. Methods of testing were still relatively crude and time consuming, and any developments to speed up those processes would be most welcome. Mr Grace had at times employed heavy pneumatic-tired rollers for the load testing of foundations and pavements. In an airfield which had recently been completed it was found that layers of soft silt had been formed in the sand subgrade during the reclamation process. The layers were usually only about 1 in. in thickness and were difficult to locate by the normal testing procedure. In order to ensure the stability of the pavement it had been essential that they should all be removed. The subgrade had therefore been rolled with an 80-ton pneumatic-tired roller, and the presence of the silt layers had been easily detected by the deflexion of the surface. Probably no other method of testing would have proved as effective and economical. Before the runway had been handed over to the client its whole area had been subjected to eight passes of a 100-ton roller with tire pressures of 150 lb/sq. in., and certain limited areas had been subjected to fifty passes of the roller. That had generally subjected the pavement to stresses in excess of the maximum design load. Apart from a small area where the surfacing had incorporated too much bitumen, the pavement had withstood the test without any indications of distress. In that case it had been known that the subgrade was most unlikely to lose strength with time, and the completed runway, after the replacement of the defective surfacing, had been handed over with confidence.

191. The foregoing method of testing had to be used with a knowledge of what change in the strength of the subgrade and pavement might take place in the future. However, it had its place with the other methods of testing commonly used. Could that method of test loading be applied to roadworks? From a knowledge of the stress distribution beneath the pavement it might be possible to calculate the weight and the tire pressure of the roller which the subgrade, sub-base, and base should support without deformation. Testing in that way would be quick, thorough, and comparatively cheap. Such a test would undoubtedly show up any areas that were defective at the time of construction.

192. In § 91, it had been suggested that contractors should be invited to submit competitive tenders for the design and construction of roads. In general, it would follow that the cheaper and more meagre the initial design the higher would be the maintenance costs. Such tenders would therefore have limited values unless they were accompanied by an undertaking by the contractor that he would maintain the road to a given standard for a period of 5 or possibly 10 years. Would any contractor be prepared to give such a guarantee, and would any competent highway authority call for tenders on this basis?

193. During his travels abroad since the war Mr Grace had met several design authorities who had set up their own road construction organizations, and contractors who had set up their own design organizations. Each believed that he could do the other man's job more satisfactorily. In Mr Grace's experience those attempts to fill the dual role had rarely met with even a limited degree of success, and in many cases the organizations had failed. Although it was essential that the engineer and contractor should appreciate each other's activities, the best results were obtained when engineers limited their activities to engineering and contractors limited their activities to contracting.

**Mr J. K. B. Willis** (Ministry of Works, Nairobi) said that in § 11 reference had been made to geophysical methods where speed of investigation was more important than accuracy. Such use must be very rare; he had always associated both the seismic and resistivity approaches with hydrological studies, although they had been used in tunnel location as the geologist's tool.

195. In their reference to crusher-run bases the Authors had made no mention of the recent introduction of grid rollers which, it was claimed, would break down a stone base imported direct from the quarry face to give a surface layer of crusher-run type material.

196. Experience in Kenya with pre-mix surfaces (B.S.1621) had been disappointing owing to stripping of the binder. That fact was now generally recognized, because all aggregates had a greater affinity for water than binders. The effect was to bring the binder to the surface while stability was held solely by mechanical interlock of the aggregate. That weakness, unless the addition of hydrated lime or Portland cement fillers could improve adhesion, appeared to render pre-mix unsuitable for strengthening deformed roads.

197. Mention had been made of the rate of deformation decreasing with time; that was not always the case, for the spring frequency of vehicles could considerably increase the load in a depression, the load increasing progressively with depth. In view of the rising importance overseas of resuscitating deformed surfaces, would the Authors give their views on methods of dealing with those deformed surfaces that, having been built with multi seals (surface dressings) had very "fatty" surfaces? The following difficulties were apparent:—

- (a) Resurfacing required the use of a levelling course to reduce the differential compaction always present when materials of different thickness were rolled.
- (b) The depressions in the old surface might hold water, which could reproduce the stripping referred to above.

- (c) That difficulty could be overcome by previously heating and planing the old surface. However, because that had been known to cause the failure of well established road bases in Britain the risk overseas with marginal bases would be greater.

198. Where asphalt containing low-penetration binders was used for levelling and resurfacing, the increase in rigidity demonstrated in § 22 would appear to increase the possibility of cracking, should deformation of the base continue.

199. The importance of rapid control testing even with semi-automatic plant had been demonstrated by a recent occurrence. Dampness on the enclosed hopper of a batching plant had caused clogging on the hopper of cement, which had been weighed at every cycle but not discharged. The resultant sub-standard concrete was produced for 7 days before being revealed by the 7-day test cubes.

200. Mr Willis considered that the caution exercised by local authorities in accepting new methods of construction for housing estate roads and private streets was fully justified if the methods had not been proved by the central authority. Many local authorities were anxious to adopt those economical methods of construction, but the price of failure to a small authority (with its political implications) was too high.

201. Although the Road Research Laboratory provided engineers overseas with the results of their work, there was need for a more positive lead from a central organization, which could disseminate to underdeveloped areas information on the practical results of modern research. The engineer struggling with limited finances could then more readily adopt proved research to his particular conditions. Such an organization could also provide for the interchange of ideas presented against a standard background.

202. Most engineers overseas could draw on the resources of a testing laboratory. Kenya was fortunate in possessing an extremely well equipped and staffed laboratory. There was little to prevent the simultaneous development of identical research in different territories. Taking a long view, construction standards should ideally be developed on a continental or zonal basis, rather than for individual countries.

203. Britain was well to the fore with road surfacing techniques, and could be of great assistance to overseas territories. However, owing to differences of climate and materials, that was not the case in base construction, and should Britain wish to contribute to that field, the present policy of seconding teams to undertake research overseas must be extended.

Mr J. C. King (Principal Engineer, Queensland Branch, Commonwealth Department of Works, Australia) said that pavement engineers in Australia had obtained valuable information from publications of the British Road Research Laboratory. Funds and personnel available in Australia for research into matters concerned with pavements were very much limited, so that Australian pavement engineers were forced to take considerable interest in research and practices in the United States, Britain, other Dominions, and elsewhere.

205. There was no central road research authority in Australia, but since the 1939-45 war there had been a very close liaison between each of the road authorities of the six States, together with the Commonwealth Department of Works, which constructed major airfields and was responsible for the roads in the Mainland territory and the Island Territories of Australia. Local government authorities generally had very limited research facilities.

206. A section of the Paper of particular interest to Australians was that dealing with crushed stone bases.

207. In Australia it had been necessary to make extensive use of low cost construction in order to develop a good road system over large areas having sparse population. Until the 1920s, waterbound macadam and penetration macadam had been the more common forms of pavement construction, but at that time much of the road system was not constructed or was earth formation. After the 1914-18 war, motor transport had increased rapidly, causing a need to improve a large total length of highways, main roads, and rural roads; the major proportion of road pavements constructed since had

been of low cost, naturally occurring gravel. When bituminous surfacing could be justified on economic grounds, or because of the volume of traffic, a single- or double-coat sprayed surfacing was applied.

208. On some roads where good quality natural gravels were not obtainable from pits close to the work and the traffic intensity required a good quality pavement, an artificial gravel was used, produced by crushing quarried stone or coarse gravel. Crusher-run was preferred, rather than re-combination of screenings. This crushed material graded down to dust was known in Australia as "fine crushed rock". Fine crushed rock base with seal coat was successfully carrying high traffic intensities and large axle loads.

TABLE 2

	Road pavement (max. axle load 18,000 lb.)	Aerodrome pavement for planes of 50,000 to 150,000 lb. A.U.W.	
Passing $1\frac{1}{2}$ " B.S. sieve . . . . .		100%	
" 1" " " " . . . . .	100%	80 to 100%	Grading of fraction passing $\frac{3}{4}$ " B.S. sieve.
" $\frac{3}{4}$ " " " " . . . . .	90 to 100%	70 to 100%	100%
" $\frac{3}{8}$ " " " " " " . . . . .	60 to 80%		50 to 75%
" $\frac{1}{8}$ " " " " " " " . . . . .	38 to 60%		35 to 55%
" No. 7, " " " " . . . . .	25 to 45%		25 to 42%
" No. 14 " " " " . . . . .	15 to 32%		
" No. 36 " " " " . . . . .			10 to 22
" No. 200 " " " " . . . . .	4 to 12		(Not less than 5%, not more than half of % passing No. 36)
Plastic limit . . . . .		If to be bitumen surfaced: up to 25 Not " " " " " " 35	
Plasticity index . . . . .		If to be bitumen surfaced: up to 6 Not " " " " " " 2 to 9	

The grading may be designed by use of the formula:—

$$\left(\frac{P_2}{P_1} = \frac{D_2}{D_1}\right)^n$$

where  $P$  is the percentage passing a square mesh sieve of clear opening  $D$ . The upper and lower limits of the gradings are obtained by using  $n=1/3$  and  $n=1/2$ .

209. A large proportion of town streets had been constructed of natural gravel or fine crushed rock since these had been introduced for inter-town and rural roads; but many local government authorities still prefer red macadam when flexible pavements were to be constructed for the more heavily trafficked streets.

210. In 1937, Mr King said, the process known as "slurried crushed rock" was introduced from the United States. Fine crushed rock was watered before or while being loaded into the motor trucks, so that the fines were very wet. The wet crushed rock was tipped direct on to the road bed, spread by drag spreader or motor grader to a uniform depth, and rolled before it dried out appreciably. The cost of cartage was increased because of the presence of a considerable quantity of water, so that the slurried crushed rock process had not been used as extensively as it could have been.

211. In Australia, traffic was usually allowed to run on a gravel or fine crushed rock pavement as soon as the pavement material had received preliminary rolling. The

pavement was kept moist and the traffic assisted in compacting it. In some cases traffic could not be utilized to assist in the compaction of fine crushed rock (for example, hard-standing in a new factory area), and the slurried crushed rock process was then very suitable. Compaction was usually carried out with pneumatic-tired rollers.

212. Fine crushed rock base on a sub-base of natural gravel, sand-clay, or cement-stabilized material, had been used for most of the pavements on major airfields constructed during recent years in Australia. Especially for airfield pavement construction, the crushed rock was delivered to a stockpile, built up in layers 1–2 ft in thickness. The material from the stockpile was loaded to trucks by a shovel or front-end loader, care being taken to load from a full face. By this procedure, variations occurring in day-to-day deliveries were averaged. The crushed rock was watered to a moist condition in the stockpile before loading, and was spread by plant such as the "Jersey Spreader", or by graders, and was immediately compacted by extra-heavy pneumatic-tired rollers.

213. Investigations had shown that sheepfoot rollers ground crushed rock to some extent, and could produce sufficient additional fines to jeopardize stability.

214. The water content of the fine crushed rock during compaction was adjusted to suit the compacting plant and the nature of the binding material in the fine crushed rock. Usually moisture content was in the vicinity of modified A.A.S.H.O. moisture content, but in a few cases watering the fine crushed rock to slurry-wet had facilitated compaction.

215. When traffic was utilized to assist in compaction, the surface of the crushed rock was kept in a condition suitable for priming and sealing by regular watering and trimming with a motor grader. If compaction had to be done without traffic it was often difficult to produce a surface of low rugosity. In such a case the common practice was to lay wetted crushed rock to a depth that would compact to slightly above the finished level. After compaction, the surface was watered, the surplus thickness cut off by motor grader, and the surface rolled with both steel-wheeled and pneumatic-tired rollers. Typical gradings specified for fine crushed rock were shown in Table 2.

**The Authors, in reply, agreed with Dr Glanville that the subject of the frost-susceptibility of road-making materials must be taken much more seriously than it had been in the past. The great increase in traffic and the use of motor roads meant that special care must be taken to exclude from the frost-affected zones of the road, materials that were weakened when subjected to frost. It was clear from the results of the Laboratory's investigations into the effects of the frost in 1947 that many roads were damaged by that agency and that, in the United Kingdom, precautions ought to be taken, even though the problems might not be so serious as those on the Continent; perhaps the recent run of relatively mild winters had implanted an unjustified feeling of security.**

217. The action of frost was not just the freezing of the base and sub-base material which contained water; more important was the fact that freezing took place from the top surface downwards, and was accompanied by migration of water upwards from some available supply below. There was, consequently, the creation of large ice-lenses which burst the material asunder and reduced its strength very considerably. Obviously, to keep the risk of frost damage to the minimum, precautions must be taken in the first place to prevent the ingress of water to the road and to its foundations. Sealing of the soil formation and the use of strong impervious surfacings helped in that connexion. In the selection of granular materials for sub-bases and bases, it was known that certain gradings were particularly prone to encourage frost-susceptibility. The grading of the fine aggregate was particularly important. It was well known that several limestones were very susceptible, and laboratory tests at present in hand suggested that other aggregates, when densely graded, were also affected by frost. The mixing of small quantities of Portland cement and of tar and bitumen with such materials would substantially reduce the frost heave, however, and it was important to find out what was the economic limit for such additives that would ensure freedom from frost troubles.

218. On the question of pavement design, Mr Bourne had asked if the information given in Fig. 2 did not, in fact, contradict that of Fig. 1. The object of the work

illustrated in Fig. 2 had been to get a more rational method of design than was indicated in Fig. 1. Perhaps the reference to that design had not been made very clear; the idea behind the suggestion was really that advantage might be taken of the increase in strength that occurred when a certain deformation had taken place in the surface of the flexible road. The slowing down of the rate of deformation, as deformation proceeded, implied that there was an increase in resistance to deformation; so that, if the road was somewhat under-designed and the finishing surfacing was applied after some deformation had occurred, provided the stage of shear failure was not reached, it might be possible to economize in the total thickness of construction. This procedure could not, of course, be used on those very heavily-trafficked roads where traffic hold-ups could not be tolerated.

219. Several speakers had referred to the relation between practising engineers and the research worker. One of the main purposes in preparing the Paper was to stimulate thinking on that point, and those contributors must be thanked for giving their opinion in such a straightforward way. Mr Shaw had given the warning that the local authority engineers should not leave the Road Research Laboratory to do all the research. His comment had been echoed by Mr Bourne and Mr Gosschalk. Both were concerned about the construction which practising engineers put upon conclusions and recommendations issued by the Road Research Laboratory. Behind those comments there lay a principle which the Authors felt to be of great importance. The practising engineer must use his judgement as to when and how the particular results of a particular piece of research work could be applied to his own problems. It was important to everyone concerned that this should be so, but it carried with it the necessity that the engineer should understand the basic nature of his problems and should himself have at his disposal the means of assessing the technical data pertaining to them. There was no doubt that there were many ways in which help could be given to practising engineers to enable them to obtain a working familiarity with all the new knowledge now available in highway engineering.

220. Some form of post-graduate instruction was needed to complement experience gained in the field. British highway engineers showed no reluctance to come forward for short courses. Longer courses of several months' duration were also needed. For those to succeed there were three essentials:—

- (1) The instruction must be given by engineers and research workers who, in their daily work, were in the forefront of the business. That point had been emphasized by Dr Glanville.
- (2) Engineers attending such courses should have had at least 2 years' practical experience in road engineering. The Authors concurred with Mr Richards that it should be made possible for selected engineers to attend such courses without financial loss. Industry was already helping with scholarships and bursaries; more help could be given from national and local government resources.
- (3) Successful completion of the courses should carry some professional recognition.

221. There had been a great deal of comment, some of it adverse, on the suggestion in the Paper that contractors could undertake a larger share of the design and control of road construction. Undoubtedly many contractors employed staff with the experience and ability to do such work, and many now had design and research departments with all the equipment available for soil survey and soil testing, and for control testing during construction. Only good could come from increasing the co-operation between supervising engineer and contractor in control testing, and it was an increasing practice for the contractor to be required to provide testing facilities as part of a contract. Although the suggestion was made in the Paper that a number of contractors be invited to submit tenders for design and construction, the engineer might be faced with some difficulty in deciding whether the alternative designs would, in fact, meet his requirements. The really important point the Authors wished to bring out, however, was that the engineers' design should always be in such broad terms as to allow the maximum

use of ingenuity and knowledge of the subject by the contractor. In other words the basic specification should not be so restrictive as to prevent the maximum utilization of the experience of the contractor who had research and development facilities such as those described.

222. In commenting on § 87, Mr Fitt had questioned the feasibility of operating a bonus-and-penalty clause for the quality of the surface finish of the carriageway. Apart from the desirability of making incentive payments for good work, it was well known that under the present arrangements, particularly with concrete surfacings, it was seldom that the extreme penalty of complete removal of substandard work was ever enforced. It remained as a permanent reminder of bad workmanship and poor supervision. Perhaps, however, the short answer to the comment was that the principle stated was, in fact, operated without difficulty in some countries abroad. How far the reputation of the contractor was prejudiced by relatively poor work was difficult to assess, but there could be no doubt that a great deal of justification could be found for introducing such a clause as that mentioned.

223. Mr Shaw had referred to the difficulty of making joints in concrete roads. The problem had not been satisfactorily resolved anywhere in the world. Now that contraction joints could be made easily by sawing the set concrete, it might well be that the best attack on the problem would be to leave out the expansion joints altogether, especially if concreting were done in the warmer half of the year. This boldness had been shown in some parts with apparently no ill effects, and it was interesting to note that the Road Research Laboratory were proposing to lay some slabs up to 4,000 ft long without expansion joints, other than those at the end of each day's work.

224. Mr Armstrong, in framing that part of his contribution which dealt with drainage and waterlogged ground, clearly had in mind what had transpired in 1958 and early 1959. While it was difficult to see how the effects of such exceptional weather could be completely eliminated, it would seem reasonable to require contractors to make wider use of graders in the construction of earthworks. It should be obvious that to work in bad weather in isolated areas, which might easily become sump holes, was asking for trouble.

225. Like Mr Armstrong, Mr Bourne had mentioned the problem of drainage of roads. There was no doubt that the provision of adequate facilities for drainage and for areas of cut and fill should be provided in all earthwork constructions. It would appear desirable that the need for shaping and trimming areas of cut and fill to speed drainage should be more widely appreciated by all parties concerned. Much could be done by shaping the formation, so that drainage was more effective than at present.

226. Mr Morgan had raised the question of control over the production of lean concrete. It seemed to the Authors that it should lie in the direction of stating what cement was required, how the concrete should be mixed, and what density would be required in the field. Compression tests on small cube samples might well bear little relation to the in-situ strength of the concrete. With reference to the comment on the need for uniformity in the grading of all-in as-dug aggregate, the Authors experience had been that from any particular source the grading had been remarkably uniform. It had been found that the uniformity of the lean concrete was improved by the use of continuous weight-proportioning equipment, and of efficient mixers.

227. The Authors had no first-hand experience with which to help Mr Morum with the economics of compacting silty clays in the Persian Gulf. They knew from data obtained from Habbaniyah airfield that in that dry climate, with water-tables not far below the surface of the ground, the provision of an impervious bituminous surfacing, by cutting off evaporation, caused an increase in moisture content in the soil below roads or airfields. They knew that this ultimate moisture condition could be predicted, using the method referred to in § 18. If the soils were compacted in embankments in a dry condition, then the increases in moisture content would bring settlement with soils which were poorly compacted. Reasonable estimates of settlement could be made in the laboratory if they were needed. Similarly, estimates could be made—and indeed had been made—of the ultimate strength of those soils.

228. But the important consideration was surely to ensure that any settlement which took place was uniform. The Authors agreed with Mr Morum that the most practical approach was to make the best job possible of compacting those soils in a dry condition. It was with such dry soils that sheepsfoot rollers found their best use. Grid rollers would be useful with such soils (as well as with the crushed stone bases to which Mr Willis had referred). If the soils were uniformly compacted in thin layers, then the effects of subsequent settlement might well not be at all serious.

229. The Authors agreed with Mr Morum and Mr Mitchell that it was possible to stabilize cohesive soils with bitumen and tar, and that the stabilizing effect was derived mainly from preventing the entry of water to weaken the soil. There were circumstances where bituminous stabilization of cohesive soils was worth while, but generally stabilization with cement or lime would be preferred, both on the grounds of cost and from the added strength they gave to the soil.

230. Mr Rosenak had mentioned the use of soil stabilization in walling. Soil stabilization had been practised for different uses in many countries for centuries. For a long time the Chinese had been mixing sandy clays with lime to produce a plaster, "chunan", used in building and in lining canals. Indeed, the farmer, in liming heavy soils to improve their texture, was employing a form of the process now used by the road engineer.

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