

The Cromwell slip-form paver trials

by

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AUTHORS' PRESENTATION

In introducing a major new item of equipment such as a slip-form paver it was vitally important that its performance and operational characteristics should be evaluated and understood from the outset.

139. The design of a satisfactory dowel bar support system had proved elusive for a number of years, although many arrangements had been tried. The Cromwell trials faced up to the problem, which was more acute with slip-form pavers, and the welded assembly with bent stalk feet in its final form had a substantial claim to general adoption as the standard British joint for use with conventional as well as slip-form construction. This would take much of the uncertainty out of present-day construction.

140. There had been a tendency to identify slip-form pavers with large-scale construction and very high outputs, but this overlooked their singular capacity to perform satisfactorily at lower output levels. The Authors believed that there was a much wider field of operation open to these pavers than had hitherto been contemplated, housing estate roads being one example.

141. The pooling of resources of design, research and contracting interests at Cromwell in mutual consultation and co-operation throughout the planning and execution of the trials resulted in the development of designs and viable techniques in a remarkably short time, and this form of joint effort led to development in pavement construction which could not occur under normal construction processes.

Sir William Glanville (Past-President) said the Authors had been responsible for one of the biggest and most important experiments in mechanized concrete construction which had ever been made in Britain. He had found the Paper particularly valuable because the Authors had described fully the difficulties they had encountered and how they had overcome them, and had pointed out quite frankly that some difficulties still remained.

143. The Authors had shown very considerable ingenuity in overcoming difficulties and had demonstrated that with skill and intelligent supervision the slip-form paver could be made to work, and work well, both for plain concrete and for reinforced concrete. Sir William had no doubt at all that, given further opportunities for experiment, which he hoped that they would have, the Authors would overcome the remaining difficulties which they mentioned and develop still further the potentialities of the machine. The machine had, of course, a voracious appetite for concrete, and the team operating the machine needed to know not only how to operate it in a general sense but how to deal quickly with the ordinary run of problems, such as changing weather conditions and unexpected variations in aggregates. It seemed to him that it was one thing to operate the machine in the predictable weather of California and quite another to operate it in Britain. What was perhaps even more

important, the skill which was developed as a result of experience was essential and the training of a number of teams from different contractors appeared to be almost out of the question. It seemed to him that the machine and the team operating it must be one unit. Had the Authors any thoughts on this?

144. On the question of the thickness of reinforced work compared with plain concrete, the Authors had shown that the greatest economies would occur if the machine could lay unreinforced concrete which would be as good as reinforced concrete. In § 6 it was stated that preliminary findings suggested that for equivalent performance unreinforced pavements should be made 2 in. thicker than reinforced, but that later observations suggested that 2 in. was conservative. There was a distinct danger here that the wish to use the slip-form paver might temper objective judgement. From the evidence available he had found nothing reliable to show that less than 2 in. extra was justifiable. On some grounds the equivalent increase might be expected to increase with thicker slabs almost in proportion to the thickness, and 2 in. on a 6 in. slab might be equivalent to 3 in. on a 9 in. slab. There was no proper comparison with the AASHO experiment, and in the paper on the Alconbury Hill experiment⁷ it was stated that the absence of thinner sections prevented any comparisons between plain and reinforced concrete sections. He would like the Authors to be more specific about the evidence on this point. Was there recent evidence to indicate the true comparison between the two?

145. He had seen a large number of warping joints giving trouble in America and felt that this was something which had to be watched very carefully indeed. He had travelled many miles on one of the most important highways in America, in which there were no proper contraction joints and the joints throughout were virtually warping joints. He had been travelling with the Director of the Highway Research Board and they had inspected many slabs, every one of which had cracked. Sir William felt that before accepting warping joints as a satisfactory solution it was necessary to examine them carefully.

146. On the subject of concrete of different qualities, it was a pity that no figures were given in the Paper for tensile or transverse strength, and he hoped that the Authors could provide some, particularly as more weight was likely to be given in future to such results. He had been a little surprised to see the term 'wet-lean concrete'; he thought that ordinary as distinct from dry-lean concrete was referred to. The use of the word 'wet' might imply that it was wetter than normal, but he did not think that that was intended.

147. In § 87 the Authors referred to early crack development and said that because of the greater stiffness of 'wet-lean' concrete for the same strength it might be expected to crack at an earlier age than dry-lean concrete. Surprise was expressed that that did not occur uniformly, but in fact stiffness was only a part of the story. Cracking depended on shrinkage, creep, bond of the slab with the base, etc., and the bond might depend on the condition of the concrete.

148. On the question of mixes, the Authors referred in § 93 to the better compaction obtainable with richer mixes. He thought that more attention should be given to the richer mixes. They were generally less sensitive to variations in the aggregate and in cement content and possibly, he thought, to the effect of rain during construction. They might also be of some help in getting over some of the difficulties with the sledge. Taking differences in cost and the required slab thicknesses into account, could the Authors give their views on the disadvantages in the use of somewhat richer mixes? The Alconbury Hill experiment had shown that the richer mixes had a considerable advantage in strength.

Mr W. Downie (Ministry of Transport) pointed out that the benefit of the work done at Cromwell had not been confined to concrete roads alone, because it had brought the wire guidance system to the notice of highway engineers, who had been able to see it for themselves at Cromwell. Since the slip-form paver had come to this

country, wire-guided fine graders and base layers had also made their appearance on major road works in Britain. The wire-guidance system was here to stay. It gave closer tolerance limits, and these closer tolerances must inevitably affect the specifications of the future. The Ministry of Transport, in the latest draft of the new specification for concrete roads, allowed for the traditional paving train and the slip-form paver to be used with equal facility. It was likely that the types of joint assemblies shown in Fig. 5 of the Paper, having proved themselves, would be adopted in the Ministry's new specification as standard.

150. The Authors had not mentioned that not only did the slip-form reinforced concrete in one layer make its first appearance at Cromwell, but wet-lean concrete had also made its debut there. An interesting point was made in § 79 about bleeding and erosion of this type of base being possibly corrected by the addition of fine inert material. He would like the Authors to say more about the material which they had in mind. One of the attractions of wet-lean concrete was the excellent surface finish produced when laid by a slip-form paver, which made for economy in the thickness of the pavement above it; but a current doubt about the wet-lean base in bituminous pavements was its rather low strength, so that if a simple and cheap form of filler which also added strength could be chosen, yet another acceptable use of the paver might be found for composite-type pavements.

151. The full investigation at Cromwell into the efficiency of joint assemblies was a very important step forward. Sir William Glanville had referred to the warping joint. Like the Authors, Mr Downie believed that further economies in the cost of unreinforced road construction would follow a specification which incorporated warping joints instead of the universal use of the very good but comparatively expensive Cromwell Mark IV joint.

152. In view of the known difficulties of sawing gravel concrete, a good case could be made for the mandatory use of wet forming on the Cromwell pattern for gravel aggregates. The sawing of joints in other aggregates would be permissible. The Authors did not give comparative costs of the two systems used at Cromwell, but it would be useful to have some idea of these.

153. One point which had perhaps spoilt a great effort at Cromwell had been the failure to achieve a fully satisfactory method of laying a reinforced concrete pavement with the slip-form paver, using mesh reinforcement fed into the machine with the concrete. He was convinced that only time (the by-pass had had to be opened to some kind of schedule) and, more important still, lack of space on the length of the job had been the causes of failure.

154. Independent trials in 1966, sponsored by the CERA, had illustrated that sledge-fed mesh reinforcement was a possibility. The trials had been successful and the Ministry hoped to carry out further work with the slip-form paver, with a CERA sledge, when an opportunity occurred.

155. The Authors had given several costs for paving and these were, of course, applicable to Cromwell, but it was hard to believe that on an ordinary contract the two-layer construction would prove to be less expensive than single-layer work, and he would welcome the Authors' comments on this. In ordinary site conditions rigid surfaces and flexible pavements competed with each other on new major road schemes. The slip-form paver seemed to have an advantage over the conventional train for short distances because of the manoeuvrability of this machine. Could the Authors comment on the minimum length of carriageway along which this versatile machine could be expected to lay concrete competing in price with an asphalt-type surface?

156. Mr Maggs had given an excellent example of the value of teamwork at Cromwell and as a comparative outsider Mr Downie endorsed what Mr Maggs had said. He wished to refer in particular to the enthusiasm shown by the Contractor's staff in trying out new and improved ideas of their own, which had helped very much to secure the success obtained.

Dr R. S. Millard (Road Research Laboratory) said that the broad objectives of the work at Cromwell were given in the Paper and were twofold: (a) to establish how well the slip-form paver could be adapted to construct concrete roads following current British practice, and (b) to indicate where practice could be modified so that more effective use could be made of the paver. The work on unreinforced concrete had served both those purposes. The methods adopted for forming dowel joints and sealing grooves in the wet concrete illustrated the adaptation of the machine to follow current practice in Britain, but probably more important were the modifications to which the introduction of the machine had given an incentive.

158. First, there was the impetus which had been given to more consideration of reduction in the thickness of unreinforced concrete. Sir William had suggested that this might be a bad thing. It had already been mooted as a possibility before the slip-form paver was introduced, and the advent of the paver had increased the pressure to see whether it was possible.

159. Similar considerations applied to warping joints. They were easier and cheaper to install. Clearly they could not entirely replace expansion and contraction joints. The issue was to decide what proportion of joints could be made as warping joints. Could the Authors comment on how much light the experience at Cromwell had thrown on this issue? There were also the dowel joint assemblies, which had applications throughout unreinforced concrete practice.

160. He agreed with Mr Burks that with reinforced concrete development was still needed. Of the various methods, the bar-mat and the pick-up had been shown as offering considerable savings, but these methods required further development before they could be used in normal construction. End loading had a clear advantage, and he would like the Authors to comment on the possibility of combining the sledge with longitudinal bar reinforcement.

161. Both the two-layer method and the self-standing reinforcement seemed suitable for use at the present time, but the self-standing reinforcement required improvement to increase its economy. With the self-standing reinforcement at the moment there was need for a firm base such as that provided by lean concrete in order to get a good riding quality. He would like the Authors to comment on this. The two-layer method gave good riding qualities and it seemed that it should offer savings in cost compared with conventional construction. There were still doubts about levels of compaction in the lower layer with two-level construction, but this seemed to be emerging at the moment as the 'best buy' for normal construction.

162. Could the utilization of this machine and its operating team be improved by using the machine to lay other materials? It was applicable only to materials which had low cohesion and which could be made mobile by vibration. Amongst road making materials this meant concrete and lean concrete, and not dry stone or bituminous materials. Although initial trials were with concrete wetter than current practice which must be technically suspect, modifications had now been made to the machine which permitted the customary dry-lean concrete to be used.

163. What, then, was the future of the machine? At its optimum rate of working, the machine could produce 30 miles of dual carriageway in a working year of 35 weeks so that three could cope with the whole of the current motorway programme, all in concrete. The advent of these big machines would put pressure on the authorities to allocate work in such a way as to get the most effective use from the investment in plant. How should that be done? The traditional way would be to strike a balance between the heavy pressures of the various trade interests concerned. Decisions made in that way in the past had worked fairly well, but was it possible to do better? He believed that it was. It should be possible to determine how the costs of concreting and other forms of construction were affected by scale and continuity of work. Although there might well be difficulties in obtaining costs in the detail required, this was the only rational way to reach a wise decision. It was in the national interest

that the investment in roadmaking plant should be related to the work load, and it should also be in the contractor's interest, because it would reduce his risk.

Mr P. Thompson (Resident Engineer for the Cromwell Contract, Nottingham County Council) thanked the Authors for drawing attention to the co-operative spirit shown by the representatives of the several bodies having some part in the experiment described, and said he could confirm that the Paper was a most comprehensive record of all the work which had been carried out in the experiment.

165. The fourth objective of the experiment had been to determine a specification for the general use of the paver, which had been duly accomplished and had been included in the contract documents for the Tuxford by-pass, also in Nottinghamshire, which continued northwards from the Cromwell by-pass. The Authors would no doubt be relieved to hear that further experience of paving on the Tuxford by-pass with the slip-form paver had largely confirmed their conclusions and, although so far paving had been carried out during the months of November and December of 1966, sustained outputs of 200 ft/h had been achieved.

166. The type of joint selected for use had been the one described in the Paper as the welded assembly with bent stalk feet. This type had lent itself to easy fabrication on the site and had proved robust in handling, as the Authors had said it would. Fabrication at a central point on the site also facilitated acceptance checking. Joints were then sampled at random on the site for further checking after fixing. The general alignment and rigidity of the joint had been satisfactory. He would be interested to learn if the Authors had any further evidence of joint movements with particular reference to this type of joint. Fig. 9 indicated that movement at contraction joints was not significantly less than that at expansion joints, when warping joints were provided in a plain concrete slab. More information should be available from the work at Tuxford, where expansion joints were being omitted altogether over approximately one-half of the total length of the scheme.

167. Slight amendments to the bar-mat method of reinforcement had been carried out as a result of further trials and, as the Authors expected, the connexions between the longitudinal and transverse bars had had to be welded with the stools placed 3 ft 6 in. apart. This had produced an average depth of steel in the slab of 2.3 in. with a standard deviation of 0.6 in. Reflexion of the reinforcement in the surface of the slab could be observed, as had been the case during the experiment, but the less frequent transverse supports of the bar-mat method might be partly responsible for the considerable improvement in riding quality which had been recorded at Tuxford.

168. Subsequent experience of the use of wet-lean concrete as a base for a concrete carriageway confirmed the Authors' suggestion that this material seemed satisfactory as a running surface for construction traffic. To date the wet-lean base to one carriageway had been used as a haul road for the construction of 4 miles of pavement to the adjacent carriageway, in addition to its use by other site traffic. The only signs of distress so far noted had been two small localized areas of failure and a certain amount of abrasion to the surface, giving an exposed aggregate finish. On a clay or marl sub-grade, however, it had been found necessary to lay a composite base of 4 in. compacted thickness of crushed rock together with 5 in. of wet-lean concrete, a total of 9 in. altogether, in order to provide a haul road for the delivery of wet-lean concrete to the paver. That composite base had in fact worked out cheaper.

169. The Authors referred to the fine limits of surface tolerance which could be achieved with a slip-formed wet-lean base, with a resulting economy of material. This also had advantages in the fixing of the transverse joint assemblies, in that it guaranteed that there was no danger of the slab locking on joint fixings set either too high or too low. One test which had been carried out in the course of the experiment, and which had not been referred to by the Authors, had been to measure the bond between the pavement slab and the wet-lean concrete base. As a result of those tests, a 500 gauge polythene sliding layer had been specified for the Tuxford contract

between the base and the pavement. The base itself was 32 ft wide, to provide a firm running surface for the tracks of the paver when laying the pavement, because of the tendency of the paver to slew occasionally when working directly on the sub-grade. A refinement in the process of joint fixing had been achieved by forming pockets for the feet of the transverse joint assemblies in the base before the concrete set and by driving wooden dovetailed grounds into the base, also whilst still wet, to which the longitudinal cracking fillet was nailed.

170. Reference had been made to the possibility of adding small quantities of inert fine material to the mix if bleeding occurred from the surface of the wet-lean concrete. In practice, however, this produced batching difficulties and had not been attempted on the Tuxford contract.

171. The most significant improvement in the characteristics of the finished concrete over the results achieved during the experiment was in the riding quality of the pavement. Over the length completed to date at Tuxford an average irregularity index of 36 in./mile had been recorded. Cores had been taken from the pavement, over lengths where the paver had been working up to speeds of 9 ft/min, and these had been checked for density gradient. They tended to confirm the Authors' contention that the present arrangement of vibrators did not compact the concrete fully. The possibility of increasing the number of poker vibrators by 50% for the remainder of the work was being investigated.

172. The difficulties encountered with setting-out problems, to which the Authors referred, were very real. They had been overcome to a certain extent by an adaptation of the American system of setting out control points, described by Gillis and Spicklemire.¹ Reference points had been placed in the verges and centre reserve at 50 ft intervals, correct for both line and level, and were used to set the wire supports for each layer in the pavement. They were also used for locating transverse joint assemblies and the longitudinal joint fillet. Since the paver encroached on the central reserve during the laying of the 32 ft wide base, both setting-out control points and centre reserve filter drain had had to be placed on the actual centre line of both carriageways. This had caused a certain amount of instability and the need for re-setting in the case of the centre points.

173. An improvement in the amount of preparatory work required before negotiating a bridge deck with the paver had been effected by providing a transition in the base at the approaches to each bridge over its full width. A stoppage of work at bridge decks was therefore not required if the difference in thickness between the slab over bridge decks and the adjacent pavement was not more than 2 in. This could be accommodated by the paver without a change in headers.

174. The problem of the effect of rain on a newly-laid slab had been solved quite accidentally by the fact that a drainage channel was now conformed by the paver as an integral part of the slab. During wet weather the drainage channel collected water, and provision was made for the water to escape at the nearest wet-formed joint slot. This prevented any of the erosion which the Authors mentioned, and the drainage channel itself appeared to be unaffected by having to come into operation before the concrete had set.

175. Further work had been done on the development of the end-of-day joints with particular reference to the bar-mat system, which by its design was virtually a continuous mat over each bay. This led to difficulties when the end-of-day joints described by the Authors were attempted. A modified method of the skin-patch technique had been tried, but this had been abandoned in favour of a single full-depth joint, very much as described in the Paper except that the end-of-day joint was located four-fifths along a bay and not at an expansion or contraction joint.

176. The potentially high rate of output and the novelty of the techniques described in the Paper produced problems for the Engineer and his representatives on the site. There was the obvious problem that if the paver was to work economically this presumably involved visiting several sites in the course of one concreting season, each

for a relatively short time, so that at each site the paving operations would be supervised by staff completely inexperienced and untrained in the new techniques. In spite of the safety devices on the paver, if faults occurred which did not actually cause the machine to stop but which, for instance, affected the guidance or compaction systems a great deal of uncompacted concrete at the wrong level could be laid unless close supervision was maintained by trained and experienced staff. At Tuxford this supervision was carried out by an assistant resident engineer, one junior engineer and two clerks of works or inspectors. This number of staff compared favourably with that required for the supervision of a conventional paving train, from previous experience in Nottinghamshire. In fact supervision of the paver was somewhat easier because of the more concentrated nature of the work.

177. In addition to providing full-time attendance at the paver, a regular series of routine checks was carried out, covering setting-out control points, thicknesses, transverse profiles and surface tolerances of both base and pavement, rigidity and alignment of transverse joint assemblies, the setting-out of the bar-mats in advance of the paving, and the position of the reinforcement in the slab after paving. The supervisory staff could make a positive contribution to the success of the paving operation and ensure compliance with the specification by close attention to detail in the regularizing of these safety checks by the use of standard forms for each type of check.

Mr D. Raymond Sharp (Cement and Concrete Association) remarked that the Authors had had what in many ways had been a unique opportunity in carrying out such a large and comprehensive full-scale trial. They and their colleagues had responded to the challenge and provided very substantial results which indicated conclusively that the slip-form paver was not only a very impressive piece of equipment but was also capable of producing extremely good results at highly competitive costs. It was necessary, however, to guard against carrying enthusiasm to an extreme.

179. The emphasis in the Paper had rightly been on showing that the slip-form paver could construct concrete roads to the specification now in use in Britain, but it was necessary to guard against the inference that existing methods were rendered obsolescent or produced sub-standard results. There was a substantial pool of concreting equipment in Britain which was just as capable as the slip-form paver of producing good results, and the choice of construction method must for the present, he suggested, be left in the hand of contractors. As Mr Downie had pointed out, it was the intention of the Ministry to do this in the revision of their specification which was designed to permit the use of both the slip-form paver and conventional trains.

180. It should not, however, be inferred from what he had said that he was half-hearted about the slip-form paver. On the contrary, he believed that it had substantial advantages over conventional equipment. In particular, the flexibility of the machine in moving about the site was especially important. Conventional equipment was notoriously immobile, because a concreting train consisted of from four to seven pieces of equipment running on rails, whereas the slip-form paver was a single unit running on tracks and could move about the site under its own power. It could be used to construct quite short lengths satisfactorily, while the conventional train must have substantial lengths if it was to be used to advantage.

181. The increased mobility of the slip-form paver led naturally to the consideration of its use on small sites, but before this could be realized it would be essential to provide batching and mixing plants with a sufficient output, which could be quickly and cheaply erected and dismantled. Bituminous material manufacturers had coped with this problem for many years, but the slip-form paver highlighted the need in the concreting field. He believed that the need could be easily met by the plant industry.

182. Although the slip-form paver had a very large potential output, very large contracts were not necessary in order to realize its advantages. Reference had been

made to American experience. When this was examined it would be found that concrete road contracts in America were substantially of the same length as those in Britain. The point could perhaps be put in another way by saying that continuity and adequate size of contract were desirable in all road work and the slip-form paver was no exception.

183. The fact that the slip-form paver could lay lean concrete and, indeed, benefit from its use as a sub-base to run on, was a happy circumstance. Both wet- and dry-lean concrete could be laid with the slip-form paver, but modifications were necessary before it could lay dry-lean concrete satisfactorily. Interest therefore lay in wet-lean concrete, a new material in Britain, and there was need for a closer evaluation of its properties.

184. It was worth pointing out (§ 86) that the dry-lean concrete had a slightly lower pavement stiffness than the wet-lean concrete with the same cement content, and that of the two sections with the same nominal compressive strength, the wet-lean concrete was considerably stiffer than the corresponding dry-lean concrete. Both seemed to indicate that wet-lean concrete was a satisfactory base material, but perhaps the Authors would give their views on that subject.

185. An important by-product of the trials was the further development of the methods of joint construction pioneered by the contractors on other sites. He had always personally advocated the use of sawing in concrete road slabs mainly because of the very good riding quality which resulted. There were, however, difficulties in sawing some of the flint and quartzite gravel aggregates and clearly when these materials were economically preferable wet forming of joints was cheaper and more effective. The Cromwell by-pass trial had shown once and for all that wet forming methods were economical and effective and he rated this as a very substantial achievement.

Dr R. H. H. Kirkham (Road Research Laboratory), wished first to ask a question concerning Table 10, particularly with regard to the manpower requirements of conventional and slip-form construction. He thought that the Authors might have overestimated the saving in manpower, since their figures did not make allowance for the larger labour force required for setting-out joints for slip-form construction. At Cromwell the force required for reinforced concrete was twice that required for conventional construction, probably because of the more complicated fixing devices used and the increased difficulty of setting-out without the forms in place. In view of this it did not seem likely that there would be a saving of more than 25% of the labour force. In unreinforced concrete, because of the larger number of transverse joints, there would be a further increase in the labour required for setting-out, and also in the labour required for joint sealing, so that the saving in labour costs would not amount to more than about 3% of the direct cost of reinforced concrete construction; for unreinforced concrete the saving would be very small. Some saving might be achieved by increasing output and so reducing overhead costs, but American experience suggested that this depended more on the supply of materials and the amount of work in prospect than on the type of plant.

187. Any major reduction in costs, therefore, seemed likely to be achieved only by changes in techniques, and probably the most useful outcome of the experiment had been the impetus to new thinking on the requirements of concrete construction. For example, the development of warping joints and of rapidly erected contraction and expansion joints might enable unreinforced concrete to be competitive in cost with reinforced concrete, and to be usable where access was only along the carriage-way under construction.

188. The tests on joints, which would be continued, had in fact provided particularly useful information on joint design. The contraction joint which gave the most uniform movement was the bent stalk, which had only a moderate standard of dowel alignment but always cracked in the first seven days. The hoop stalk joint

also always cracked at an early age, but had a poor standard of dowel alignment even before concreting because of distortion under site traffic, and this joint gave the least movement. It seemed, therefore, that a moderate standard of dowel alignment was essential, but that the very high standard achieved by the welded assembly was not in fact completely necessary, since the movements of this joint were as variable as those of cage joints where the standard of alignment was only moderate. It seemed possible, therefore, to consider allowing some small relaxation in the requirements for the alignment of dowel-bars in order to reduce the cost of joints.

189. However, early cracking seemed to be essential if the movements at joints were to be uniform, and the tests showed that this required a fairly large crack-inducer at the bottom of the slab, such as that provided in the welded angle and bent stalk joints. The design of the welded assembly and warping joints was therefore being modified.

190. The use of the paver to lay the base might also reduce costs. The Paper showed that wet-lean concrete could be laid by the slip-form paver to a high standard of accuracy, which facilitated the setting-up of joint assemblies, but, irrespective of the cement content, there was considerably more cracking than in the dry-lean base. Also, in the more recent work at Tuxford, there had been two small areas of failure under site traffic and several areas of sufficient wear to make it likely that the pavement would adhere to the base. Would the Authors agree that wet-lean concrete was a temporary expedient, since subsequent trials had shown that the slip-form paver could be modified to lay a dry-lean concrete base with the same standard of surface level but with a higher density than the wet-lean concrete? This would be more suitable as the base for a concrete pavement. The results were sufficiently promising for trials to be planned to try to achieve a base with a high enough density for it to be used in flexible construction. Such a development would increase the utilization of the plant and therefore lead to a further saving in cost.

191. Of the three methods of introducing reinforcement tried at Cromwell two were developed to the stage where they might be considered for future use, but some difficulties with compaction and riding quality remained. Two-layer construction, despite its faults, might be the more satisfactory for immediate use, as this would leave only the problem of compaction, which might be overcome, as the Paper indicated, by the use of a special mix. Alternatively a cheap form of slip-form paver might be used to lay the lower course as was sometimes done in America.

192. With self-standing steel, although the compaction was better than for two-layer construction, the density at the bottom of the slab was 2% or 3% less than that generally achieved with conventional plant. It would still be necessary therefore to use a special mix, particularly if the operating speed of the paver was to be increased, unless improved compaction could be obtained by increasing the number and power of the vibrators.

193. Better riding quality was achieved at Cromwell using two-layer construction. When self-standing steel was used the irregularity was increased by reinforcement ripple, particularly when the slab was laid on a base of granular material. A similarly poor riding quality with a high proportion of bumps in the size range of 0.1-0.2 in. had since been obtained at Hamilton, where self-standing steel of the bar-mat type was being used together with a granular base. However, with this type of reinforcement on a wet-lean concrete base at Tuxford, the riding quality was as good as that achieved at Cromwell with two-layer construction. Would the Authors agree therefore that the use of self-standing reinforcement of any type should, for the present, be restricted to sites where an even base was provided and the mix was carefully designed?

194. Probably the difficulties of laying reinforced concrete would be overcome more easily by the development of pick-up methods. If single wires were used they would not be likely to produce reinforcement ripple and compaction could be improved by lowering the vibrators between the wires. The use of single wires was not

likely to affect the performance of the road since overlaps between reinforcing mats were not used at the longitudinal edges, but it could result in a reduction of up to 7% in direct costs while giving a pavement of better quality. While the early tests had not provided a solution, development of this form of construction was certainly worth further consideration.

Mr G. Kinder (Resident Engineer, Contract No. 1, M74 Motorway, Babbie, Shaw & Morton) congratulated the Authors on their Paper. In the summer of 1966 he had had the opportunity as resident engineer to study the paver working on what he believed was its first commercial contract in Britain, a two-mile section of the Hamilton By-pass Motorway M74. This short length of carriageway was experimental, intended to compare the durability of concrete as against the more usual black-top construction under Scottish conditions.

196. The details of the construction adopted had been very similar to those developed as a result of the Cromwell trials, but adapted to suit an 11 in. thick slab. The expansion and contraction joints, of the welded assembly type with bent stalk feet, worked very well when installed properly. The reinforcement system was the bar-mat method described in the Paper, using main steel of $\frac{7}{16}$ in. dia. deformed bars at 6 in. centres supported by deformed $\frac{3}{8}$ in. dia. transverse steel, which was held to level by triangular steel supports. The Authors appeared to be very much in favour of this method of reinforcement, and he would like them to indicate the length of trial slabs laid at Cromwell, using the varying systems of reinforcement, upon which their conclusions had been based. He would also like to know at what intervals the depth to the reinforcement had been checked.

197. Throughout the two-mile section at Hamilton the reinforcement had been a constant source of trouble. It tended to be pushed forward by the concrete in front of the paver, to fall sideways and downhill on the crossfall of the road (which was 1 in 36), and generally to bend and deform, and sometimes to collapse completely. The original 4 ft spacing of transverse steel had been altered, and after various trials a 3 ft spacing had been adopted. The reinforcement had been welded to the trailing edges of the joints and spot-welded where the longitudinal steel and transverse steel crossed and at the laps. Tying wire had also been used to give a more positive anchorage of the steel than had been obtained by the spring clips. To stop the triangular supports from being pushed over by the pressure of concrete in front of the paver they had been nailed down to the sub-base, using 6 in. nails.

198. All the above measures had helped to give a more rigid reinforcement arrangement but, of course, had been poor value economically. The concrete had been blamed for some of the troubles experienced, but generally it had been a workable mix with an average compacting factor of 0.91, giving a slump of about 1½ in. The paver had not had the deflector plate fixed while at Hamilton and this might have caused excessive loads on the reinforcement from the concrete. When plant breakdowns occurred the concrete had stiffened up and this had led to more trouble with the reinforcement. As with most plant, the paver was fine when it was moving, but a breakdown caused tremendous problems and loss of valuable material.

199. From the experience gained at Hamilton it would seem that more thought should be given to developing the design of the triangular steel supports for the reinforcement, and he considered that efforts to reduce the resistance which they offered to the concrete being worked in front of the machine, and also to improve the lateral stability, which was very suspect, were necessary. He was pleased to learn that the Contractors had made some of the necessary amendments and that the bar-mat method was working much better.

200. He assumed that everyone was quite happy about it being correct to have the steel on the top of the slab. Many of the reasons for this appeared to depend on construction problems rather than design. Having the steel on the bottom of the slab would certainly ease the slip-form paver technique of laying reinforced concrete pavements. He would be pleased to have the Authors' observations on that point.

201. So far as the riding quality was concerned he would like to know whether the q values given in the Paper had been taken before or after any remedial work had been carried out. At Hamilton the profilometer had been put over the pavement soon after the laying had been completed and before the joints had been sealed, the bumps at joints cut down, or the general roughness of the pavement taken off by traffic. The q value obtained had varied from 46 to 117, with an average of 84. The values were expected to improve by some 50% once the remedial work had been completed, giving results which would compare favourably with those obtained at Cromwell.

202. There had been a marked difference between the q values for the two lanes, the slow lane value being about 75% of that for the fast lane. Spillage from the side feeder on the fast-lane side of the paver could have caused the guidance wire to vibrate and the paver to dance, and this spillage would also have made the wheel tracks for the brush carriage uneven, which would lead to different pressures from the brushes. Both these possible reasons would have a more noticeable effect on the fast lane than on the slow lane. He was pleased to learn that a wire guided brush had been developed and that the spillage from the side feeder had been stopped.

203. The average speed of laying (taking the whole day into account rather than the time when the paver was in fact moving) varied from 28 ft/h to a maximum of 92 ft/h. Reinforcement ripple had been found in only one section of the slab, that which had been laid at the fastest speed. This strengthened the view that the ripple was due to more work being put into the concrete by vibration along the reinforcement, since the faster the paver moved, the more alive would be the concrete behind the paver and therefore the more susceptible to further compaction. The reinforcement ripple was at 3 ft centres, comparable to the 3 ft centres of the transverse steel.

204. On other days average speeds of laying of 88 ft/h had been recorded, and on other sections more than 70 ft/h. It was of interest to note that on these days the relative humidity had been low, so helping the concrete to stiffen up, whereas on the day on which the reinforcement ripple occurred the weather had been generally damp, with a high humidity which kept the concrete workable. He would be pleased to know whether the reinforcement ripple recorded on other contracts had been correlated to weather conditions or to speeds of laying. It appeared likely that the necessary control would have to be applied not only to the workability of the concrete, the arrangement of the steel and the mode of vibrations, but also to the weather.

Mr R. David (Robert McGregor & Sons Ltd) said that the contractor, among his many talents, had to be an eternal optimist. In purchasing the slip-form paver his firm had shown their faith in this machine and its potential; at the same time they were aware of certain problem areas. Since acquiring the machine they had made continuous, and mainly successful, efforts to solve the problems involved:

- (a) they now had a reliable side feeder, which had been developed since the Cromwell trials;
- (b) trials were at present being carried out which he considered would ensure full compaction throughout the thickness of the slab and over the whole width, and would also help considerably in the elimination of reinforcement ripple;
- (c) they were well aware that edge slump, though of no great moment on road construction, was of great importance on airfields;
- (d) successful experiments had been carried out on varying the edge profile and, combined with the stiffer mix which could be adopted with the more efficient compaction they were optimistic that edge slump would be completely eliminated;
- (e) their ultimate aim was to use this machine at all levels of construction, from the sub-grade upwards; experiments were about to start on the spreading and compaction of dry-lean concrete and this should open up the field more widely for the continuous use of the slip-form paver; further studies were

proposed on the laying of bituminous materials and sub-base; the finished surface of the paving could be laid to any camber and channels and up-stands could be formed to any section.

206. A previous speaker had mentioned the problem of the batcher and in this connexion it was hoped soon to acquire a batching plant which would match the slip-form paver in output, mobility and ease of erection. He felt, therefore, that they were well on the way to solving the problem areas thrown up by the Cromwell experiment.

207. For the future, the economic use of this machine would obviously require considerable forward planning, but it should be possible to fix a target quantity of concrete for a year (to be reviewed at the end of the year) so that, with the aid of the mobile batching plant previously mentioned, it would enable small jobs to be carried out as economically as large ones. From the cost investigations to date it appeared feasible to carry out paving of under a mile in length and still remain competitive against black-top.

208. Still on the aspect of cost, comparable tenders worked out for slip-form paving against the use of conventional equipment, demonstrated the fact that savings could be made of about 10% over the operation as a whole.

209. There was still the question of where the work was to come from. They felt that *they* had done their part in acquiring the paver and in eradicating, or being well on the way to eradicating, most of its idiosyncrasies.

210. In the Lofthouse Committee, of which he was a member, one of the main arguments for a more select list of contractors was that sufficient experience had now been gained on motorway construction, and the time had now come to reap the benefit by using only those contractors who had the experience. If this applied over the wide field of motorway construction, he felt that it applied even more strongly to a specialist operation such as paving. He would suggest that concrete paving should be dealt with on a functional basis, either as a separate contract or a nominated sub-contract, since it was not an operation which essentially had to be integrated with other operations. In one recent instance his firm had quoted for a trunk road contract and their quotation for the paving element had been lower than that of the successful tenderer; thus, in this case a functional contract would have given the best outcome from the point of view of the Ministry.

211. This led to the question of serial contracting, on which the Ministry were carrying out investigations at the present time. They seemed to be somewhat mesmerized by its application to large motorway contracts. However, here serial contracting could lead to serious difficulties, since no one contract was the same as the previous one, and this could lead to protracted arguments on rates and claims. This did not apply to paving where the variables were reduced to a minimum and continuity could be achieved, not necessarily on adjoining contracts, but, due to the high degree of mobility of this equipment, on contracts in different parts of the country.

212. In conclusion it was his hope that the money and effort which had been put into the work at Cromwell would not be wasted and that the faith shown by his firm in acquiring the slip-form paver would be justified.

Mr C. F. Armstrong (Ministry of Transport) suggested that it was necessary to look carefully at the French use of the slip-form paver. Many miles of autoroute of very simple design had been constructed with it using 10 in. of paving on about 10 in. of lean concrete base, with plain contraction joints at 5 m intervals. The only conclusion was that either this method was very wrong, or the base was acting as an efficient dowel, in which case the French were right and design in Britain had been over-elaborate.

214. Soon after the inception of the paver, those concerned in Britain had been under strong pressure to accept French designs, so that the paver could be used with-

out modification. This would be impracticable at present with the British traditional design. That had not been seen as a desirable change, but, as the Authors had pointed out, we had gone some of the way with an unreinforced slab on a lean concrete base, though not accepting, as the French must have done, that the cemented base was a massive dowel.

215. If the French were proved to be right they would have solved, by a process of omission, many of the problems raised at Cromwell. For this reason the future performance of the autoroutes would be of very great interest.

Written contributions:

Mr F. H. P. Williams (Road Research Laboratory) referred to § 86 in which the Authors suggested that the wet-lean concrete was stiffer than the dry-lean concrete on the evidence of the figures given in columns 7 and 8 of Table 6. He understood that these sections were laid in pairs on the approaches to an overbridge. The repeatability of the main deflexions for the same construction appeared to be about 0.3×10^{-3} in. This, taken in conjunction with the figures given for the range of deflexions in each section, suggested that there was little if any significant difference between them. This could be checked if figures were available for the standard deviations and numbers of results.

217. In Figs 12-15, the density gradients suggested that in many cases more than 100% of theoretical density was achieved, which was of course impossible. Although not stated in the Paper, he understood that an air-entraining agent was used and the mix designed to have 5% voids. If this was so it should be stated, and the compaction target should be 95% of the maximum theoretical density with zero air voids, and not 98% of the theoretical density, assuming 5% voids.

Mr A. Jefferson (Robert McGregor & Sons, Ltd.) considered that the objectives of the experiment as set down by the Authors in many respects covered a considerable portion of current engineering thought on concrete pavements, regardless of the type of plant used. Many of the aspects of the work, particularly work on the joints, were carried out bearing in mind the considerable pressures involved with the slip-form paver, but were generally applicable to all forms of construction. However, he was particularly interested in the performance of the slip-form paver and the conclusions reached.

219. In more general terms, the quality of ride appeared to be acceptable within the context of current specifications. Where considerably more information was needed appeared to be on the question of compaction of the concrete. In particular, § 135 stated that the 'present arrangement of vibrators is not entirely effective in producing full compaction'. Would the Authors care to expand on this particular topic, as the spacing of vibrators appeared to be an arbitrary arrangement, i.e. a 2 ft module across the width of the paver?

220. In the light of further work carried out since the Cromwell experiment, would the Authors care to comment on the merits of closer spacing of the pokers and also possible adjustment of the position of the pokers in relation to base height?

221. Present experience appeared to suggest that closer spacing of the pokers could give appreciably better compaction than that achieved at Cromwell, but more precise experimental work on this aspect was lacking, and perhaps the Authors would like to indicate work which had been done elsewhere into this aspect.

Dr J. P. Stott (Road Research Laboratory) mentioned that he had been closely concerned with the design of the transverse joints.⁹ The welded assembly type of joint had the advantages that its accuracy was built-in under 'factory' conditions by welding, it was also easily fixed, and this might lead to its wide-scale adoption. When the manufacture of a welded joint was first proposed, initial estimates of cost were high, due to lack of experience and unfounded fears of excessive welding distortion. Considerable attention was paid to persuading manufacturers to reduce

costs by discussion and advice on details of manufacture. In consequence, the 'as-delivered' prices of the joint assemblies fell by about 60% for the expansion joints and 70% for the contraction joints during the first weeks of the experiment. Indeed, the Contractor took over the work, which had been farmed out to engineering workshops, and made the assemblies in a simple jig on the site.

223. However, there was need for contractors to have freedom to use an alternative joint despite the attractions of the welded assembly joint. Cage joints appeared to be satisfactory—and, of course, cheaper—than welded assembly joints provided that there was sufficient time to fix them in advance of construction and that the fixing was carefully done. It was thought that the best method of fixing was by the use of a mortar-bed and the following drill was suggested:

- (a) the joint assembly should be made up in a jig in the carpenter's shop;
- (b) the site of the joint should be checked for level and all high spots in the base removed (this work must be restricted to a minimum to allow the assembly to sit down on its correct level, and the base must *not* be trenched);
- (c) the site of the joint should be brushed free of loose material;
- (d) if a sliding layer or separating layer—e.g. of polythene sheet—was used under the road slab, this should be placed on the site of the joint;
- (e) a suitable jig to position the dowel-bars accurately should be erected and levelled on the site of the joint;
- (f) the joint assembly should be placed in the jig and gaps at the sides and bottoms of filler-boards stuffed (the fit of the assembly into the jig should be checked, as a mismatch could result in subsequent misalignment of the dowel-bars);
- (g) liquid mortar should then be poured around the assembly so as to form a level bed to about the mid-height of the bottom bars (the aim being to 'fix' the bottom bars of the assembly with a minimum depth of mortar).
- (h) after the mortar had set hard, the jigs should be removed.

224. The first samples on any new site should be tested for rigidity. The main danger in the method of fixing was that of locking the slab to the base. This danger should not arise provided the base was not 'trenched' in the joint and the same treatment with regard to a separating layer was applied to the joint as elsewhere along the road (see (d) above). Tests at Cromwell showed that a mortar bed used on a lean concrete base would have satisfactory 'frangibility' provided the mortar was between 12 and 36 h old. Older mortar might have sufficient strength to lock a slab to a lean concrete base although there had been no evidence of this happening. Fears had been expressed that such a mortar bed might deteriorate and weaken the ends of slabs by a loss of support. However, no evidence of such trouble was known and it was not thought likely to be serious.

225. As indicated in the Paper, the warping joints were designed on the assumption that they would behave in a manner similar to 'satisfactory cracks' in a reinforced concrete road. Two types of joint were used; in one the steel bars were painted with bitumen over a length of 8 in. to prevent bond between steel and concrete, and help the warping joint to crack and to articulate freely; and in the other, the bitumen covered a length of 24 in. Further measurements had indicated an average opening between summer and winter conditions of 0.014 in. with a maximum of 0.020 in. for the 8 in. length of painted bar and 0.022 in. with a maximum of 0.030 in. for the 24 in. length of painted bar. Such openings would class the joints as fine to medium cracks and there was no reason to suppose that they would not continue to behave satisfactorily indefinitely. None of the slabs had cracked between warping joints.

226. It was important to see that the slip-form paver did not lead to unjustifiable changes in pavement design. Thus, it might be more convenient to lay steel in fewer, larger bars. However, although the weight of steel and the cross-sectional area might

be the same as that normally used, the external surface area might be less. A transfer of tension from concrete to steel by bond occurred at a crack, and this required a certain bond area in order to be effective. This bond area was a function of the external surface area and a length of steel, called the transfer length. If the external surface area was reduced, then the transfer length would be increased. The widths of cracks were a function of transfer length, so that a concentration of steel reinforcement into fewer, larger bars was likely to lead to wider cracks and eventually to loss of 'crack control'. Two criticisms of the slip-form paver were made for the Authors' comments. First, the machine could not run backwards over placed concrete so that it was difficult to correct errors, e.g. if the concrete was badly compacted due to a dry mix. Secondly, the slip-form paver appeared to be less versatile than form-running plant as regards speed of laying. It could not run slowly without either over-compacting the concrete or stopping frequently, when it was liable to ridge the surface. In America, form-running plant of conventional vibrating-plate type laid concrete roads at a rate of 500 ft/h or 5000 ft/day. Could the slip-form paver do better?

Mr P. Smith (Department of Highways, Ontario) wrote that he was pleased to see that the striving for perfection in concrete pavement construction in Great Britain, which he recalled from his own experience some years before, still prevailed. For this reason and because nowhere else had the introduction of the slip-form method been accompanied by such a far-reaching and systematic evaluation of its potential, the Paper was particularly welcome.

228. Certain of the findings, in particular those relating to the design and installation of joint assemblies, had implications which applied also to conventionally laid pavements. Joints in general remained the weak link in concrete pavements and it was at joints that most of the problems developed during the service life of the pavement and these required costly and bothersome maintenance work to correct. Since the elimination of joints by the use of continuously reinforced or prestressed concrete had not proved, as yet, to be a good engineering solution (bearing cost also in mind) it was apparent that very great emphasis should be placed in any future work on the development of better joint systems.

229. Other findings, for example those related to the position of reinforcing steel and density of the concrete, while of value in evaluating one particular type of slip-form paver, were not of such lasting importance. Experience had already established that, provided the reinforcing steel had adequate cover, it hardly mattered from the performance viewpoint if it was at the top or bottom of the slab, let alone within $\frac{1}{2}$ in. of the specified position. Similarly with density, a normal workable mix, required in any case by the slip-form paver to produce a smooth riding pavement, would not display noticeable differences in performance under traffic.

230. The selection of the type of pavement most suitable for a particular project involved factors other than structural design and first cost. If concrete was to compete effectively it must display a long service life, be initially smooth riding in order to gain driver acceptance and also so that the natural deterioration with time in riding quality would not lead to a premature clamour by the public for resurfacing, and at the same time it must retain a durable non-skid surface. It therefore appeared that for at least two parameters, adequate air entrainment and smoothness, the results achieved at Cromwell were either not fully documented or were unsatisfactory by standards found necessary elsewhere. This might impose an unnecessary burden on the later full acceptance of the slip-form method if deterioration developed on the initial work.

231. The Authors commented that the two principal mixes were air-entrained. Though full details were not given of the concrete mixes used, it appeared that at or below the specified mean air content of $4\frac{1}{2} \pm 1\frac{1}{2}\%$ with a $\frac{3}{8}$ in. nominal maximum size of coarse aggregate and 40% sand content, the air void system in the hardened concrete might be marginal in providing adequate air-entrained protection to the concrete,

in particular when de-icing chemicals were used. Were determinations made of the air void structure in the hardened concrete, in particular at or close to the surface? If so, were there any noticeable differences in the entrained (not entrapped) air which related to the compaction and finishing methods used?

232. Though it was noticed that the slump used was $1\frac{1}{2}$ in. at Cromwell, it appeared from a distance that concrete strength and full compaction were still regarded as of paramount importance in British practice, whereas experience in North America showed that, taking all factors into consideration, the best riding and most durable pavements (which were still of adequate strength) could be most easily and economically produced by using air-entrained concrete at about 6% air content and $2\frac{1}{2}$ in. slump. For example, the average irregularity index of conventionally laid concrete pavements in Ontario¹⁰ had been 17 in./mile, and 30, the lowest value recorded at Cromwell, would generally be considered as unacceptable. The general experience in the United States was that the smoothness of slip-formed pavements (measured however by other not directly relatable criteria) could be at least as good as, if not better than, those laid conventionally. It might therefore seem that in future work, greater emphasis should be placed on improving the characteristics of the slip-form paver operation which controlled smoothness.

233. In view of the Authors' findings that pavements built by two-layer construction were smoother than those built with self-standing steel, and since this was also found to be a cheaper method, was it to be assumed that British practice would standardize on the former technique, which from experience in the United States since 1963 also appeared to be the best and most economical method?

234. Because of the small scale of the Cromwell trial and relatively low production rate dictated in part by the experimental work undertaken, the Authors' estimate of the potential savings as about 5% might be conservative. Indeed, would a 5% saving be worth the upheaval involved in the industry, since the pavement produced by the slip-form method was not noticeably superior in any structural or surface respect? However, if the savings could turn out to be 20% or even 10%, the answer must then be emphatically that a complete and immediate switch to the slip-form method should be made. Experience in the United States, such as that reported from California, Iowa and Colorado, suggested that ultimately savings would be of the order of 20% with large-scale use. This would involve production at a much faster pace than appeared to be envisaged in British conditions. Zulian,¹¹ for example, reported that in Colorado, 16.7 miles of a four-lane divided highway were completed in 40 working days. Mile-a-day paving, by both conventional and slip-form methods was now commonplace, and two miles a day had been achieved exceptionally.

235. It was pertinent to observe that the slip-form method had to undergo 20 years of development in the United States, admittedly largely by trial and error on the part of contractors, to reach its present acceptance as a proven technique for laying economically all designs of concrete pavement. This acceptance might be judged by recalling that by the end of 1964, immediately prior to the Cromwell trial, 4000 miles of pavement had already been slip-formed¹² and that currently about 1000 miles were being so constructed each year.

236. Could the foresight displayed in bringing over a slip-form paver and setting up such a searching trial as that conducted at Cromwell make up for lost time and lack of opportunity to experiment on hundreds of miles of road a year? Unfortunately it still appeared that some of the fundamental weaknesses which had plagued the British approach to innovations in concrete and other matters of road construction ever since the Oxtou By-pass experiment¹³ prevailed. Too much appeared to depend on the findings from a small experiment and there were obvious dangers in basing future policy solely on the conclusions that could be drawn therefrom. Account must be taken of the process of natural selection by the contractors and full appreciation of the potential of slip-form paving (and any other new method of road building for that matter) would only be achieved if it was allowed to find its own place within

an overall and continuing programme of volume construction based on the engineering results and economics attained.

237. The Paper by the Writer already mentioned¹² concluded with an observation by Phil Fordyce of the Portland Cement Association following an inspection of the first reinforced concrete pavement laid by the slip-form method in Iowa to the effect that 'it's goodbye forms within five years'. Mr Smith wondered if the Cromwell trial and subsequent experience at Tuxford had led the Authors to the same prognostication.

The Authors, in reply, said that Sir William Glanville had asked for more specific evidence on the question of the thickness of reinforced versus unreinforced construction. The Authors were unable to add anything to what they had said, but they understood that at the present time the Ministry of Transport was considering the up-to-date evidence jointly with the Research Committee on Concrete Roads, and their conclusions would be made known in due course. Warping joints needed some time to prove their performance and the Authors would endorse Sir William Glanville's comment that these needed watching. They were grateful for his remarks on the stiffness of lean concrete and agreed that cracking depended on more than stiffness.

239. Regarding the strength of the pavement quality concrete used, routine direct and indirect tensile testing was carried out simultaneously with the standard cube compression testing and the latter was noticeably more variable than the other forms. A number of cases of apparent failure shown by the cubes were not substantiated by the tensile tests which remained perfectly satisfactory. The term 'wet-lean' had been used deliberately to avoid confusion from the fact that dry-lean concrete' was often referred to as lean-mix; the more usual contraction 'dry-lean' led naturally to 'wet-lean' for the material used. With regard to richer mixes, the Authors suspected that sometimes these could raise the more cohesive properties in the mix, which with the bar-mat method could lead to difficulties in stabilizing the steel. A cohesive mix might be helpful in the sledge method because the steel would be kept at a more uniform height by the increased tension caused by the dragging force, provided the anchorage problem had been solved. A richer mix must, however, go with lesser thickness if it was to be justified economically.

240. The Authors agreed with Mr Downie that single layer construction should prove to be more economical than two-layer work. At Cromwell single-layer work was more expensive because of the high cost of the cradles required to support the mesh, but the bar-mat method of single layer work reduced the amount of steel required and was therefore cheaper than two-layer construction. The Authors expected slip-formed concrete to be competitive with black-top on lengths less than one mile; if suitable support facilities were developed this limit might become as low as $\frac{1}{2}$ mile. They were pleased to have Mr David's confirmation of their view. Mr Downie's question on the addition of fine inert material had in part been answered by Mr Thompson, who pointed out the difficulty. Some addition to the batching equipment would be needed to make it viable. The Authors agreed with Mr Downie that wet forming might be made mandatory on gravel concretes, especially in certain weather conditions.

241. In reply to Dr Millard's question (§ 159) about the proportion of warping joints to contraction joints, one might consider designs using warping joints as essentially reinforced construction in which the steel was provided only where the cracks occurred. It would therefore be logical to propose a spacing of the accompanying contraction and expansion joints similar to that used on normal reinforced construction, i.e. at 80 ft and 240 ft intervals respectively. The intermediate warping joints could then be conveniently spaced at average intervals of 16 ft. Concerning the suggestion in § 160, the Authors regarded the pick-up method as essentially an adaptation of the sledge principle to the use of longitudinal bar reinforcement. Mr Thompson had observed that expansion and contraction joints had similar movements

when warping joints were used. Once the expansion joint had accommodated the initial expansion of the slabs, the movements at both types of joint would be much the same, on the basis that each length of concrete was then expanding and contracting about a stationary centre. He had made a useful point about thickness over bridges. Either one changed the thickness, as he suggested, or one tried to develop a header (a sliding form) which could accommodate over-large variations.

242. Dr Millard and Dr Kirkham had advocated two-layer construction, even though the method gave lower density at the bottom of the slab, largely because it was economical in comparison to cradle-supported mesh and resulted in better riding quality on irregular bases. Mr Smith had also confirmed that in America two-layer construction using two slip-form pavers had been considered the best and most economical solution since 1963. The question of the comparative attractiveness of two-layer construction had a number of facets. With two-layer construction the advantages of having the concrete fed into the machine and dealt with over a length of only 6 ft were lost, so increasing the vulnerability to bad weather conditions. With regard to self-standing steel, the Paper showed that better results could be expected with level bases, and for other reasons there were advantages in using a wet- or dry-lean base laid by the slip-form paver itself. The need for a level base was not necessarily a disadvantage.

243. One of the reasons why single-layer construction had not been used more in the USA was suggested by Burke and Mascunana¹⁴ commenting on the Illinois experiment that the Rex slip-form paver had insufficient traction when fitted with the sledge used. It would appear that a successful method of single-layer construction with dowelled joints had not yet been devised in America, and with the greater availability of plant which existed in the USA, there was less incentive to use single-layer construction. From illustrations of some of the recent two-layer construction there, it appeared that the two pavers and ancillary equipment were spaced out over a length bearing comparison with the growing lengths of conventional trains of machines which had been causing concern in Britain in recent years.

244. The Authors believed that one of the most important advantages offered by the Guntert and Zimmerman slip-form paver was the way in which the process of forming the slab was condensed into the operation of a single machine. This was not a theoretical advantage: it reduced the amount of concrete exposed to weather risk, it provided the maximum plant utilization, and it made for the greatest degree of mobility and flexibility, having the least demand for *running on and running off* lengths. When considering the case for and against two-layer construction, account must be taken of the fact that these important assets were discarded when this method was used. In the Authors' view, abandonment of these assets could be justified only where the available aggregate resources were such that the concrete mix provided for the top of the pavement differed in materials content from that of the lower portion.

245. The present 8 mile dual carriageway construction at Tuxford had established the technical and economic viability of single-layer construction using the bar-mat method; Mr Downie had also mentioned (§ 154) that the trials carried out by CERA had shown how the problems left unsolved at Cromwell, in respect of sledge-fed fabric reinforcement, could be overcome. It therefore appeared to the Authors that, barring any requirement for two differing mixes, there were no compelling arguments to support a preference for two-layer construction.

246. Dr Kirkham had questioned (§ 186) the Authors' estimate of the saving in manpower for slip-form construction. In arriving at their conclusion (§ 30) that the total cost of welded assembly joints was no more than that for cage joints, the labour element had been taken into account, and the costs of joints, if taken into Table 10, would have been shown as equal for both forms of construction; it now appeared that there was a margin of cost advantage to the slip-form construction. Mr David's claim of a 10% overall saving was interesting. In many ways the contractor's view

was more persuasive than anything the Authors could say. It was difficult for an outsider to attach the right weight to the various factors and different contractors would not necessarily arrive at the same conclusions.

247. Questions of early cracking, freedom of movement and standard of dowel bar alignment had been raised by Dr Kirkham (§§ 188 and 189) and Mr Thompson had asked whether any further information was available (§ 166). The Authors had stated in § 29 that data on early cracking and freedom of movement for the final design of the welded assembly had not been obtained at Cromwell. These joints had, however, been observed at Tuxford and of 100 joints examined all were found to have cracked within 24 h; measurements of movement were being made but were not yet available. These observations, which were of particular importance in view of the comments made by Dr Kirkham, suggested that the design, as it emerged from Cromwell, was in fact satisfactory without further modification.

248. Dr Kirkham had asked (§ 190) whether the Authors agreed that wet-lean concrete was a temporary expedient pending the development of a method for laying dry-lean concrete using the slip-form paver. Experience to date suggested that, while it might prove possible to lay fully compacted dry-lean concrete to surface tolerances comparable with those of wet-lean concrete, it would not be possible to lay it at comparable speeds simply because of the extra effort required to compact it. Wet-lean concrete was therefore likely to remain the more economical unless the cement content was significantly increased. The impression gained at Cromwell that the wet-lean concrete had appreciably greater resistance to attrition under site traffic than dry-lean concrete had been confirmed at Tuxford as Mr Thompson had pointed out. It was also significant that there had been no evidence of surface spalling at the cracks under site traffic. Far from continuing to regard the wet-lean concrete as an expedient, the Authors now believed that it warranted a thorough investigation of its range of application, including its use in flexible construction under heavy traffic. It might well be found that this material possessed performance attributes that were unrelated to previous experience with lean concrete. The economic advantages to be gained from a wider use of this material were ample justification for such an investigation.

249. If the Authors' belief that the provision of an even base was in any case worthwhile was accepted, then the question of restricting the use of self-standing reinforcement to bases of this type, as suggested by Dr Millard and Dr Kirkham, did not arise. As far as compaction was concerned (and this applied to all methods of construction) the Authors preferred to see improved methods of compaction developed rather than the imposition of restrictions on the use of the paver through the necessity of special mix design. In fact such developments were in progress already.

250. In this connexion, Mr Jefferson commented upon the arbitrary spacing of the poker vibrators. The chosen spacing was the one commonly used in American practice. In view of the results at Cromwell, it would seem likely that putting the pokers closer together would increase the density of concrete between the pokers but would not affect the density variations near the pokers. The Authors believed that the differences between surface vibrated concrete and the mode of the slip-form paver should not be overlooked. In the latter case the flow of the concrete introduced a special problem. It was possible for the concrete to be flowing down towards the conforming plate too fast for the air to escape. The compacting devices should be so placed that they intercepted all the concrete flow at a point which would give the air time to escape. Further work on compaction with the slip-form paver should take this dynamic aspect into consideration to determine the type and amount of energy required, and at what position or positions and level it was best applied.

251. The Authors were indebted to Dr Stott for the further information towards the performance of the warping joints. However, they felt less enthusiastic towards the cage joints than Dr Stott, especially in view of the latest reports on the performance of the welded assembly contraction joints mentioned elsewhere in the

discussion, and they felt that the accuracy of laying the mortar bed required in item (g) would be very difficult to achieve on site.

252. With regard to Dr Stott's first point of criticism, the Authors saw no serious disadvantage in the paver not being able to run backwards to correct errors. Most engineers on concrete road construction would agree that in order to achieve the required surface profile the ideal way of operating conventional plant was to move it steadily forward without any backtracking, but this had seldom proved possible in the Authors' experience. With the slip-form paver it became possible to do this because the required profile was produced the first time, with some qualification concerning reinforcement ripple. They had not related reinforcement ripple to weather as suggested by Mr Kinder and it would also be interesting to examine whether there was any correlation with speed of working; the Authors were grateful for these suggestions.

253. In relation to Dr Stott's second point about the speed of laying, the Authors believed that the paver could run steadily at low speeds, i.e. at $1\frac{1}{2}$ ft/min or less, without difficulty, provided the compactive effort was correspondingly reduced, and they could not see any advantage in laying full-width paving at high speeds merely for the sake of doing so. The road programme in Britain hardly warranted competition with American outputs of 5000 ft/day, whether laid by conventional or slip-form methods. The logistics problems associated with very high laying rates could easily nullify any possible savings.

254. Unfortunately some of the criticisms made by Mr Smith were due to his not being fully acquainted with the road building situation in Britain. The Authors ought, perhaps, to point out that the annual mileage of new major concrete roads was seldom more than 30 miles. It followed that in order to make the greatest use for the future of the relatively small amount that was constructed it was necessary to take every opportunity to incorporate experimental features. It was on the performance of full-scale experiments such as the Oxton by-pass and the Alconbury by-pass that designs were now based. The observation of these roads, which formed part of the road system proper, provided evidence of behaviour that must be valid because the time and traffic factors were the actual ones normally experienced. Sooner or later the road programme would have to be accelerated and when it was it would benefit from the experiments because these would make it possible to choose the most economical designs based on sound evidence.

255. Before the Cromwell experiment was undertaken a careful study was made of American experience and, in fact, one of the Authors attended the 44th Annual Meeting of the Highway Research Board in Washington in January 1965. Here, at the session devoted to the slip-form paver, when Mr Smith was chairman, Mr Burks made a public appeal for information on such matters as concrete density. A great deal of general advice was obtained, which proved helpful in the conduct of the experiment, but little information was available on some detailed matters which they regarded as important.

256. The difference in view between the Authors and Mr Smith concerning the importance of checking the density of the concrete might be due to the greater stress on least cost which existed in Britain. The Authors agreed with Mr Smith that concrete must display a long service life if it was to be competitive, and while they also agreed that its strength was not the only criterion, they believed that it was the major factor in determining the structural life of the pavement. They therefore considered that it was illogical not to demand a density which ensured that the design strength was reached. The Authors showed that with a mix whose workability was within the normal range for the slip-form paver there was some lack of compaction. It was important to find this out and to consider how the compactive effort of the paver might be improved. The undesirable alternative was to use such a rich mix that the loss of strength was of no account, accepting the extra cost.

257. The Authors had placed less stress on detailed measurement of air content

than Mr Smith, again because of different experience. The risk of frost damage was a good deal less in Great Britain than in North America, and indeed it was not until the comparatively severe winter of 1962/63 that any of our major roads suffered serious surface damage, even though up to that time very little air-entrained concrete had been used. The mix details had been given in the Paper in Figs 12-14.

258. While the Authors agreed that the exact position of the reinforcement was not critical, they considered that it was advisable to ensure that it remained fairly parallel to the surface. Otherwise there was a risk of it lying too near the surface or even coming through it, as could happen especially with air-entrained concrete. It was for this reason that the Authors had placed emphasis on the standard deviation of the reinforcement rather than on its depth. As Mr Kinder had said, it might be easier to place reinforcement at the bottom of the slab but there was no evidence to justify doing so. The pre-war experiments by the Ministry of Transport showed in one instance that there was very little difference between steel at the top and at the bottom, while in the other, steel at the top gave better crack control; this was the basis of the current specification.

259. With regard to riding quality, the Authors wondered if Mr Smith's irregularity index was measured on exactly the same basis as at Cromwell since there was a wide variety in this type of measurement. It was of interest to record that the Cromwell profiles were at one time assessed in terms of the Californian Profile Index as defined by Gillis and Spicklemire¹ and they were found to be well under 3 in./mile. This was a good deal better than the Californian acceptance limit of 7 in./mile. The riding qualities for the Cromwell by-pass had been obtained before remedial treatment; there had been no remedial treatment of any significance.

260. Mr Smith referred to savings of the order of 20% with the slip-form paver in the United States. The Authors had looked at these cases but would like to point out that, due to differences in the ratio of labour costs to material costs between the United States and Great Britain such savings would be impossible here. Labour costs in Britain were only 20% of the total paving cost and so there was not the same room for economy, even allowing for the saving in side forms.

261. With regard to Mr Armstrong's comments on the French design, if this was right for a slip-form paver, it would be equally right for conventional plant. Why, then, had it not been used in Britain before the introduction of the paver? It seemed there had not been great confidence in the French method since even in America whence it had been derived it had not always been successful. Probably the nearest approach in Britain had been the Alconbury Hill experiment, where plain concrete had been laid on a 3 in. granular base.

262. On the question of nominated subcontractors, these would be useful in the present situation, whether as a temporary measure or a permanent feature. The Authors envisaged having a pavement sub-contractor nominated for any of the types of pavement covered by Road Note 29, being invited to tender at the same time as the main contractor. In that case, the pavement sub-contractor could be nominated at the same time as the main contractor was appointed. Possibly this might lead to cheaper overall costs. The slip-form paver called for continuity of experience in that a trained team should always go with the machine, though this could also apply to conventional trains. The resident engineer had also an important part to play in supervising and integrating his work with that of the contractor.

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