(3) The new type of distributor developed by the contractors shows considerable promise in providing a concrete which is uniformly spread.
(4) Very good compaction of the concrete is possible throughout the full depth of the slab when concrete is spread in a single layer up to 8 in. thickness.
(5) Manufacturers of forms should give attention to the importance of straightness, so that warped new forms are not sent out. A maximum tolerance of $\frac{1}{16}$ in. in 10 ft should be achieved.
(6) A method of forming expansion joints during the day's work was evolved which had little, if any, effect in producing irregularities.
(7) There is need to develop a method of forming joints at stop ends so as to avoid the formation of surface irregularities.
(8) The placing of reinforcement has been shown to be amenable to mechanical manipulation and need present no problem in future work.
(9) The importance of maintaining a smooth forward progress of plant, with as few stoppages or delays as possible, has been demonstrated. This implies that all construction plant should operate from outside the forms.

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Tables 3, 4, 5, 5a, and Figs 7, 8, and 9 are reproduced by permission of the Director of Road Research. The photographs Figs 3, 4, 5, and 6 are included with the permission of Messrs John Laing & Son Ltd.

The Paper, which was received on 2 December, 1955, is accompanied by five photographs and three sheets of drawings, from which the half-tone page plates and the Figures in the text have been prepared.

Discussion

The Author introduced the Paper with the aid of a film.

Dr W. H. Glanville (Director of Road Research, D.S.I.R.) observed that the essence of concrete-road construction was care and attention to detail, and the Author's experiment in Nottinghamshire was a good example of the great care that was necessary. Despite the machinery employed, it remained a skilled job.

The first Barber-Greene finishing machines for bituminous roads introduced into the United Kingdom had produced results which were not always up to the standard of roads made by hand. With the experience that had now been obtained with Barber-Greene machines over many hundreds and perhaps thousands of miles of roads, a first-class result could be produced which, as the Author had indicated, really set the standard for a concrete road. The concrete road, on the other hand, had not had the same chance—a few miles had been constructed here and there, but the $\frac{3}{4}$ mile described in the Paper was quite a fair-sized job compared with what had been done.

The Author, however, had shown quite definitely that excellent results could be obtained. Given care and experience, the running surface obtained could equal the best roads in

Britain. Results of 25 in/mile and 30 in/mile were shown as the best examples. There was no reason why those figures should not be obtained consistently when there were construction jobs of bigger size and longer lengths to be undertaken.

On the question of formwork, Dr Glanville agreed with the Author that the tolerance of $\frac{1}{8}$ in. was not good enough. There did not seem to be any reason why the forms should ever be a cause of irregularity. He would have thought that the irregularities could well have been as little as the $\frac{1}{16}$ in. which the Author mentioned. Again, it should be possible to set the forms accurately. Therefore, it should be feasible to get rid of the irregularities that arose from the formwork.

With reference to joint construction, Dr Glanville thought the Author had gone farther along the road to solving the problem than he had said, because his method of inducing a crack over the jointing material by the use of a pointed wedge of wood and then cutting it with the machine seemed to have been highly successful once the technique was determined, so successful that in the records the position of the joints in the best cases could hardly be detected. Even if the problem of joint construction was not yet completely solved, it could at least be regarded as possible to eliminate irregularities arising from joints.

One of the most difficult problems was the question of continuity of construction—continuity of uniformity. Laying bituminous roads was a far easier task than concrete; a little more could be added where required and rolled in, but that could not be done with concrete. Concreting had to be a continuous smoothly working process and if it was not so organized the hold-ups would cause the concrete to harden and stiffen, and once that started it was difficult to get rid of the bumps which occurred. The question of continuity needed attention. No doubt on a bigger job it would be possible to organize the work so that the continuity was better maintained.

There were examples of roads in Denmark and other countries where the irregularities were very small indeed, and the riding qualities of those roads were quite as good as the Barber-Greene roads in Britain.

When Dr Glanville had visited Sweden some years ago road constructors there had told him that their way of reducing the number of bumps was to give the men a big bonus and then subtract a given proportion of it for every bump discovered; it was found that the men rapidly acquired a technique for avoiding bumps.

Mr J. M. Fisher (Technical Adviser, John Laing & Son, Ltd, civil engineering contractors, London) remarked that the subject of the Paper was likely in the near future to be of great interest to highway engineers. Presumably the roads which they would be designing and constructing would follow the same general pattern as the road at Oxton, and, therefore, the lessons learned at Oxton would be immediately applicable. It was only a small job, the amount involved being well under £50,000, but the lessons learned from the construction of the road at Oxton might well be applicable to lengths of road many times greater.

Tenders for the construction of the road had been invited from selected contractors with a great deal of experience of airfield construction. One valuable consequence of that procedure was that it had been possible for the client and the contractor to discuss the specification in some detail, so that general agreement had been obtained on the best techniques to employ and how they could best be applied. There was no doubt that the method of having a selected list of contractors was likely to result in better work in the future.

With regard to the forms used, Mr Fisher said most of them were not new but had recently been modified and reconditioned. The major fault in them, a dip between the end of the form and the first stake housing, had apparently been caused during previous use owing to their having a sliding locking plate which had been an imperfect fit; that had led to some deflexion at those points and some distortion had been induced by the heavy loading. Unfortunately, it had not proved possible to eliminate the distortion from the screeding edge of the forms when they were sent for reconditioning, but the incorporation

of a new locking device had prevented any accentuation of the fault during the progress of the work. An inspection of new forms had recently been carried out at the manufacturer's works, and examination of a number of them had shown that the maximum departure from a true straight-edge was a good deal less than $\frac{1}{16}$ in. for a 10-ft length. Therefore, it would seem that new forms when delivered from the manufacturer would, in future, comply with one of the recommendations in the conclusions in the Paper. It was important that every precaution should be taken on the site to ensure that distortion in the forms did not occur because of mishandling there.

It was mentioned in the Paper that a great deal of attention was paid to the levelling of the individual forms and that, with the material available, a high standard of accuracy in form laying was obtained. He felt, however, that an inordinate amount of engineer's time was occupied in setting the forms, and he wondered whether somebody could suggest a device, as easy to use as boning rods, which would give as much precision in setting forms as would a precise levelling.

With regard to the spreading of the concrete and the laying of the reinforcement, the rather novel device used for the positioning and supporting of the reinforcement while the concrete was spread around it was found to be very effective, but it could only be used with the particular type of spreader employed at Oxton where the advancing face of concrete was transverse to the line of the road. Attention should be paid to that point, because in conclusion (8) on p. 224 the Author implied that all the problems relating to the mechanized handling of reinforcement were virtually solved. It was true to say that there were other means of supporting reinforcement while the concrete was spread around it, but they did not appear to be as simple as the method used at Oxton.

With regard to the results obtained with the spreader, there was little factual evidence that it attained a uniform degree of spreading throughout the whole width of the road, but there was a good deal of circumstantial evidence that it did. The circumstantial evidence was that there was a high degree of accuracy in the surface profile of the road towards the end of it. Given that the form laying was reasonably accurate, the accuracy of spreading made a very great contribution to the attainment of a regular profile.

Another feature of that type of spreader was that the movement of the concrete outwards from the centre of the spreader box to the outside of the road tended to feed it under the reinforcement, and the evidence from the cores was that uniform spreading of the concrete throughout the whole width of the road was achieved. There was good compaction throughout the depth and all round the reinforcement.

He wished, in passing, to mention the wet-surface profilometer supplied by the Road Research Laboratory and operated by its staff. The machine was of very great merit. It was noticed during the construction that the men tended to refer to it whenever they were doing passes with the machine, and it developed in them a great sense of pride in improving on their previous work. He heartily endorsed the Author's recommendation that manufacturers should give some thought to fitting machines with simple versions of the device.

The Author had dealt at length with the construction of joints and their effect on the profile of the road, and quite rightly so, because most of the concrete roads in Britain were characterized by the frequency and bumpiness of joints. Was not the poor reputation of concrete roads largely founded on those two factors?

There was much discussion at the present time regarding expansion-joint spacing, and the general opinion in Britain seemed to be that the joints should be put in at fairly frequent intervals; but engineers in some other countries considered that they should be omitted altogether and that only dummy joints should be used. No doubt the only way to tell which was the right procedure to adopt was to let the joints stand the test of time and so ascertain whether or not they were required. However, the problem of making high-quality running expansion-joints whose presence could not be detected in the profile of the road seemed virtually to have been resolved, so that the spacing of the joints was not particularly important. What was important was the fact that, despite the building of sixteen of the stop-end joints at Oxton, no satisfactory way of making them had yet

been devised. That type of joint had to occur in every concrete road at least once a day, unless a three-shift system was adopted. Therefore, there seemed to be a double incentive to improve them. First of all, it was necessary to perfect them to the greatest extent possible with the machines at present available. Secondly, it was necessary to do as great a length of concreting in a day as was possible. That was not only a function of the rate at which concrete could be produced, but was probably a function of the overall efficiency of the plant and accuracy in all details of construction so that steady forward progress of the whole train of machines could be maintained.

The list of nine conclusions drawn up by the Author as a result of his observations on the work, with the exception of (8), to which reference had already been made, properly reflected the conclusions of the contractors. With particular reference to conclusion (1), might it not be possible to specify that a q value of, say, 50 in/mile should be obtained and that adjustments in the form of a bonus or penalty for results better or worse than that figure should be paid or deducted at the end of the works. Such a scheme would provide an incentive to improve the quality of work and would probably be welcomed by many contractors.

Mr W. F. Adams (a Senior Civil Engineer, Ministry of Transport and Civil Aviation) said he found it a little difficult to reconcile the statement in the synopsis that the strength of the concrete as specified was achieved in 82% of the specimens with the data in Table 2, if that was the information to which reference was made, for it showed that out of the thirty-one tests 26% failed to satisfy the compressive-strength criterion of 5,000 lb/sq. in. and 19% failed to satisfy the flexural-strength criterion of 600 lb/sq. in. However, that was not of practical importance, for he believed that a considerably lower figure than the 5,000 lb/sq. in. specified would have produced a perfectly satisfactory result. That high figure was specified for reasons connected with the experimental nature of the work.

It was also a little puzzling to see from Table 2 that the standard deviation in compressive strength was 847 lb/sq. in., which represented according to Stanton and Walker a good, though not excellent, standard of control, and then to look at the average strength of approximately 5,550 lb/sq. in., which, with the standard deviation, would be expected to result in minimum strengths down to 3,800 lb/sq. in., which was, in fact, realized in one case.

Mr Adams wondered whether sights had been raised high enough in designing the average strength of the mix. In fact, if 5,550 lb/sq. in. was the mean strength aimed at, it would have needed a coefficient of variation of about 5%, representing really well-controlled laboratory tests, to make sure that only one in forty fell below the 5,000-lb/sq. in. mark.

On p. 218, referring to Table 4, the Author said: "It may also be noted that the q values are rather lower near the edges than in the central region." Statistical analysis showed that the q values were very significantly lower nearer the edges. There was less than a 1 in 1,000 chance that that was a false conclusion.

In the same Table there was a highly significant variation along the length of the road for all the lanes concerned—another interesting point having a definite bearing on the prospects for the future.

Table 5 disclosed that there was a highly significant difference between the stop-end joints and the continuous joints—an obvious conclusion, but it was well to have it proved to have a significance of over 1 in 1,000.

It was also clear from Table 5 that the results obtained for the irregularity of the joints varied highly significantly along the length of the road in the case of continuous construction joints and did not vary significantly in the case of stop-end joints, which confirmed the Author's statement that continuous construction joints showed improvement as experience was gained, whilst the stop-end joints did not. That seemed to point to the need for a drastically new form of attack on the stop-end joint problem.

It was stated in conclusion (8) that "The placing of reinforcement has been shown to

be amenable to mechanical manipulation and need present no problem in future work." Mechanically speaking, that was true. However, with reference to Table 3, the number of cores in which the sledging type of placing had been used was not known, but if the depth of reinforcement and the fact that the reinforcement was placed with relation to the bottom of the slab and not the top of it were borne in mind, it remained true that there was a variation of about 2½ in. in the position of the reinforcement in the slab as shown by the cores. That appeared to point to a need for improvement.

Dr R. H. H. Kirkham (Principal Scientific Officer, Road Research Laboratory), referring to the riding quality which had been achieved at Oxton, observed that the irregularity index was the lowest for any considerable length of machine-laid road in the United Kingdom and was of the same order as that of a hand-laid concrete road nearby. Although the riding quality was "good or better" the Author had said that it was not as good as had been expected, and an examination of the profiles taken during the job might be expected to suggest some reasons for some of the remaining irregularities.

Several speakers had mentioned forms. An examination of the profiles showed that there was a regular rise and fall in most of the work of about $\frac{1}{16}$-in. at the end of each 10-ft length; that was almost certainly attributable to the lack of proper shape in the surface of the form. Although the irregularity was small, American experience suggested that a rhythmic roughness, even though of small amount, was one of the most objectionable features of irregularity for a high-speed road, and the comfort of the traveller might best be served by improving the accuracy of the form as manufactured.

A second interesting point about the profile was that there were some good slabs in all sections and some poorer slabs. An examination of the poorer slabs seemed most likely to lead to guidance as to what should be avoided in the future. One of the first things apparent was that a certain amount of uneven filling of the spreading machine had led to irregularities. Once or twice patches were left unfilled by the spreading machine and those later had to be filled by hand; in those places a bump was always left after the first pass of the finishing machine.

There was greater irregularity at the centre of the slab than at the edges although the shape of the profile was similar. The spreading machine which was used was a good deal better than any previously used in Britain but, unfortunately, it was loaded at the middle. Any uneven filling of the machine would therefore have a greater effect on the pre-compaction of the concrete at the middle of the slab than at the edges, and the increased irregularities at the centre probably arose from the type of spreading machine.

Turning to stoppages, Dr Kirkham said that once or twice, for various reasons, the spreading machine had been stopped for periods of ½ to 1 hour and some concrete which had been spread was therefore left uncompacted. In those regions there was always a bump and repeated finishing attempts did not manage to remove the whole of it. Other bumps could also be attributed to stopping and starting the finishing machine.

Changes in workability of the concrete seemed also to have affected the profile. Generally, when the concrete became more workable there was a slight rise in the surface above form level, which made finishing to form level more difficult than elsewhere.

Dr Kirkham thought the use of the wet-surface profilometer led rapidly to a reduction in surface irregularities and he was pleased to find that both the Author and Mr Fisher had found it of value. The Road Research Laboratory were at present considering further development of the recording instrument so that it could be fitted to any finishing machine, in the hope that it would prove of even more value.

The irregularities of joints were also of interest. Although the Author had classified some of them as bad in relation to the other joints at Oxton, it was not fair to say that any of the joints at Oxton was a bad joint. If they considered the average step at a joint after the first passage of the compacting machine as a measure of the irregularity—a very useful measure, since it was not affected by hand finishing—the joints at the end of the day's work at Oxton gave an average step of only a little more than 0·2 in., whilst joints formed during the day's work gave an average of 0·19 in. On an experimental

road some years ago the figures for stop-ends and joints formed during the day's work were almost exactly the same.

Both at Oxton and on the experimental road there was a certain amount of hand compaction around the dowel bars near the joint, but on another experimental road, where there was no pre-compaction around the dowel bars, the step at the stop-end joint was as high as 0·4 in. and that on a joint during the day's work as high as 0·3 in Contrary to expectation, therefore, a certain amount of pre-compaction of the concrete near the joint seemed to have led to less irregularity.

The difference measured after the first passage of the finishing machine between stop-ends and joints formed during a day's work was much less than the figure measured on the hardened surface. Dr Kirkham suspected that that was probably because of the difficulty in estimating the line of the next slab when hand finishing at the stop-end.

Could the stop-end joints have been improved, at least to the level of the other joints if a batten had been placed across the road at form level 2 ft clear of the joint so that the men forming the arris had some guidance about the level of the next slab?

The most important conclusion, on joints, was that cutting joints reduced the irregularity after the first pass to about half that with the formed joint, and that amount of irregularity was small enough for most of it to be removed during the finishing operation.

Dr A. R. Collins (Technical Director of the Cement and Concrete Association) remarked that like Dr Glanville he was a little worried about forms, although for rather different reasons. While the work was in progress the site had been visited by one of the most experienced American road engineers, who expressed surprise at the amount of care being taken with form setting. He commented that nothing like the same care was taken in the United States and expressed the view that the riding quality of American roads was quite satisfactory. He attributed that to the fact that in America the longitudinal float was almost invariably used for finishing, and with that machine riding quality was much less affected by the form setting than with the transverse finisher used in Britain.

Dr Collins thought, however, that the longitudinal float was not necessarily the only means of obtaining good riding quality, because from figures obtained by the Road Research Laboratory it seemed that the Danish concrete roads were at least as good as the best results ever obtained in Britain with any type of construction and yet, when seeing the Danish roads under construction recently he had been struck by the seeming lack of care given to the setting of the forms. Although he would be the last to suggest that roads should not be laid carefully, Dr Collins thought that taking more and more care was not necessarily the correct method of making progress; in fact, it was desirable, if possible, to reduce the amount of skill and care required in order to obtain good results, and he thought that an investigation into the precise effect of inaccuracies of form setting on the riding quality of concrete roads might give useful results.

Dr Collins said that he was interested in the results which had been obtained at Oxton in showing that making joints by the sawing process substantially eliminated their effects on riding quality, and that the only remaining problem seemed to be that of obtaining a good joint at the end of a day's work. The results of experimental work made by the Cement and Concrete Association on methods of sawing joints indicated that cutting at an age earlier than that used at Oxton would be preferable. If that were done granite aggregate could be cut with a silicon-carbide blade, which resulted in lower costs.

Dealing with a minor point in regard to the joint sawn with a diamond blade, Dr Collins asked whether the Author had encountered any trouble in sealing the joint.

Mr G. C. Ollerhead (Civil Engineer, A. Monk & Co. Ltd) made a few comments following the headings laid down by Dr Kirkham.

With regard to the machinery used, in Mr Ollerhead's experience the present vibrating machines of 20-ft span or more being used in Britain appeared incapable of producing a true plane surface between forms. That experience was obviously shared by the contractors at Oxton since they had utilized the expedient of placing extra weights on the finishing beam and, as shown by the profilometer readings, the results near the centre

of the bay were less satisfactory than those nearer the forms. He therefore wished to query the Author's contention that full-width construction eliminated possible causes of surface irregularities since machines of 10 to 15-ft span could be relied upon to give a truer finish between forms and should therefore give a better riding surface in the longitudinal direction. Irregularities caused by longitudinal construction joints would be parallel to the flow of traffic and should not materially affect riding quality. However, since it was undoubtedly better practice to have full-width construction, he felt that there was an urgent need for heavier equipment capable of finishing the concrete in 20-ft or greater widths to the very exacting specifications now being considered.

Dr Kirkham had suggested that irregularities in the centre of the slab were caused by the particular type of spreader employed at Oxton, but in Mr Ollerhead's experience with the hopper-type spreader, where loading was from the side of the forms, the same problem of inaccuracies along the bay centre had been encountered. It had been found that the finishing beam tended to hump upwards and thereby not completely remove the irregularities left behind the vibrating beam.

To obtain the high standard of surface finish required it was necessary to have a "workability" which allowed the elimination of surface irregularities shown up by the wet-surface profilometers. It appeared, at Oxton, that once that mix was found, further attempts to reduce the water and sand content resulted in the surface becoming unworkable. In spite of the aggregate/cement ratio being reduced to 6·25:1, Table 2 showed that 20% of the test beams failed, from which it could be argued that the concrete did not attain the flexual and compressive strength specified.

Would the Author agree, therefore, that in using that mix to attain the desired q value, strength had to be sacrificed to workability? Would he agree, in the light of his experience at Oxton, that more cement was necessary in the concrete to obtain fully both the required *strength and riding quality*?

It was noted that the top of the triangular timber fillet on the expansion joints was left $\frac{3}{4}$ in. below the surface to reduce the surge of the concrete. Was that $\frac{3}{4}$-in. dimension *dictated by the maximum size of aggregate* used? If $1\frac{1}{2}$-in. aggregate were used, would the fillet be left $1\frac{1}{2}$ in. down? Did the Author consider it likely that the expansion joint might close up with an increase in temperature, before the joint was sawn, thus causing the slabs adjacent to the joint to spall? Mr Ollerhead had experienced that happening in unreinforced pavements when the joint filler was left $\frac{1}{4}$ in. below the surface, with a result that the concrete spalled off up to 6 in. from the joint.

Was it a necessity for work to be stopped at expansion joints? Surely a suitable stop-end could have been put in between joints, allowing the reinforcement to run through. On a long road—say, 10 miles—that would reduce the number of stop-ends required, since being limited to 100-ft bays must reduce the length of pavement a contractor could construct in a day and indirectly, therefore, increase the cost of the road.

It was possible that the use of stop-ends, fitted flush to the top of the screeds, would have eliminated the falling away experienced when finishing up to expansion joints. He surmised that those were $\frac{3}{4}$ in. below screed level and were possibly not robust enough to withstand the full forward pressure of the vibrator without moving slightly and thus accentuating the falling away. Surge bumps, which would possibly have been left by the flush stop-end, could be removed by manual devices before a final pass with the machine.

He was interested in the construction of a 4-in.-thick lean-mix base on which to bed the screeds. Was that specified and was its primary object to fix the screed pins securely or to prevent settlement of the screeds under the load of the machines?

Mr Ollerhead had had some experience with compacted burnt shale and had found that it possessed a certain resilience; but although it generally seemed to return to original level after the passage of machines, it could not always be relied on to do so.

On the subject of formation, it appeared that some appreciable variation in level was encountered, as indicated by the varying depths of cores cut. That in itself was not conducive to good riding quality since it entailed varying adjustments of the spreader

to give the required surcharge, thus tending to disrupt the even flow of the machinery so necessary for an accurate surface.

On the subject of curing, he congratulated all concerned on their ability to prevent sun and wind crazing by spraying a water-proof membrane on to concrete laid up to 2 hours previously. Mr Ollerhead's experience had been that under adverse conditions it was essential to spray the concrete within 1 hour of placing and immediately to cover up behind with hessian covers. That meant that the concrete trains had to move forward at a rate of between 80 and 100 ft/hour, which seemed to be about double the speeds attained on the Oxton contract.

He could only assume that the differences in experiences of curing were caused by, first, the use of bag cement instead of the quicker-setting bulk cement which, under present circumstances, often arrived on site in a "hot" condition; secondly, more humid conditions prevailing, as well as the possible lower temperature in September and October than in, say, June and July; thirdly, the surface of the concrete being disturbed less owing to the smaller number of joints; and fourthly, the use of reinforcement in the slab.

Mr A. A. Osborne (Resident Engineer, Messrs Wilson & Mason) said the Author had made it quite clear that it was at expansion joints and stop-ends that the fairly high q factor had been experienced. The Author had travelled on the Continent and studied Continental methods, and it would be interesting to know what he thought of the method used in Belgium, where they had dispensed with dowel bars. Mr Osborne had always considered them essential, but now that it was necessary to construct roads at great speed and of long length it might be worthwhile, economically, to change that view.

There was now a type of expansion joint where the expansion jointing was vibrated down into the concrete to form a joint. In order that there should be no movement between two slabs in such a joint, which was usually stopped by the use of dowel bars, there was a bearing slab at the bottom of the joint. That type of construction had been tried as long ago as 1925–30 but eventually had been dropped, Mr Osborne thought correctly, in favour of dowel bars. Now that trouble was being experienced with machines, expansion joints, and stop-ends, the other system might be worth considering. What was the Author's view of that alternative type of joint?

Mr Osborne did not foresee any trouble with the stop-end, even if the work was reinforced, because the reinforcement could be cut off where it was intended to finish in, say, half-an-hour's time. As additional reinforcement a special short mat could be placed at the end of the joint to allow for any stresses arising from the absence of dowel bars. The Author had, it appeared, obtained a good result with the normal dowel joint, but why had he decided to use it and what were his views on the alternative joint? Had he considered using a slab underneath, and vibrating some suitable material down?

Why had the Author chosen slab lengths of 97 ft and 113 ft? Mr Osborne had made a rough calculation of the amount of work done per day, based on information in the Paper, and the average seemed to be about 230 ft per day. What were the average and maximum lengths of slab concreted per day?

Mr B. G. Combridge (Assistant Engineer, Surrey County Council) asked, first, whether the longitudinal joint was necessary, since several speakers had made it obvious that overcoming joint trouble was a difficult problem. Would the Author elaborate on the reasons for cutting an additional joint for a slab width of only 24 ft, apparently reinforced right across?

The Author had mentioned that he had departed from the British Standard for reinforcing mats in making the longitudinal wires 4-in. spacing instead of 3-in. spacing as specified in B.S.1221. Was that purely to get the concrete through the reinforcement more easily or in order to gain full compaction? Had the size of aggregate any influence on the spacing? Did he consider that he would be justified in future in departing from B.S.1221 or did his action foreshadow a coming amendment to that standard?

What was the method in the contract of specifying the concrete? Was it specified only by flexural or compressive strength, or was it also specified by a compaction factor?

The Author had mentioned alterations in the mixes; had those been left entirely to the contractor's discretion or imposed by the Author?

On p. 215 it was stated that the white edging strip was ramped down every 10 ft to slab level, but Fig. 2 suggested that it was dished into the slab. Mr Combridge was not clear about the method; was it tapered from ½ in. to zero thickness or was the slab underneath the edging strip dished in the manner indicated in Fig. 2?

*** **Mr T. S. Sinclair** (London Director, Robert M. Douglas (Contractors) Ltd) agreed with Dr Collins that the profilometer readings in the centre were much worse than those at the sides of the carriageway and that that would lead to the conclusion that there was deflexion and vibration in the machines themselves. Bearing in mind speakers' remarks on the excellent results obtained in Denmark and Belgium where the placing of road forms was much less exact than at Oxton, the fact that the Oxton forms were set on concrete, and also Mr Fisher's admission that those road forms were not by any means new, Mr Sinclair considered that the Author's remark "that the major fault in the formwork was the dip between the end of the forms and the first stake housing" was a particular criticism of the forms used on the Oxton job and not a criticism of forms in general. In the circumstances "initial inaccuracies in the forms" could not be objected to since the forms were, in effect, second-hand and not designed for the job on which they were being used.

With reference to conclusion (5) on p. 224, probably manufacturers would agree that any firm of repute did not send out road forms which were in any way warped. In fact, a maximum tolerance of ⅛ in. in 10 ft was the usual criterion.

It would be appreciated that road forms were made to a specification which assured maximum strength at the cheapest possible price. The type of road form used was designed to withstand the weight and vibrations of the normal machine concreting widths up to 18 or 20 ft; if wider machines were to be used, with their consequent increase in weight necessary to overcome the vibrations referred to, those who used the machines should advise the manufacturers of their new requirements and so obtain road forms which would stand up to the new weights without deflexion. No doubt the manufacturers would be pleased to give the County Councils, Ministry of Transport, and the Road Research Laboratory the forms they required—at a price!

Mr W. J. O. Scott (Principal Scientific Officer, Road Research Laboratory, D.S.I.R.) remarked that there was no doubt about the desirability of the best possible riding-surface quality on all roads, particularly trunk roads and the motor roads which were now within sight, and on which the Paper had a bearing. The fact that irregularity-index values had enabled a target to be set up and aimed at in the important work which had been described in the Paper, and that a leading representative of the road engineering industry had suggested their use as a means of attracting a bonus for improving on the target (and presumably for invoking a penalty for falling short of it), encouraged a belief that they had served, and would continue to serve, a useful purpose.

Mr Scott said he was now able to give a few additional figures which might serve to emphasize the Author's conclusions (6) and (7) in regard to joints. Considering the surface irregularity data for the four lanes in the aggregate, the overall mean value of the irregularity index q was 61 in/mile. Further analysis had shown that irregularities associated with the joints were responsible for about 11% of that total and of that proportion much the greater share, about 8%, was associated with irregularities at the stop-end joints. In justice it must be acknowledged that the introduction of a joint was liable to affect an appreciable length of the surface on either side, a length which, in the absence of the joint, would presumably have included a limited amount of irregularity, proportional to that found on the majority of the surfaces. If that length was taken as being up to 1½ ft on either side of a joint (those considerations were introduced on a

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*** This and the following contributions were received in writing upon the closure of the oral discussion.—SEC.

previous occasion[3]), it amounted to approximately 3% of the total length in that case. So although the low order of overall irregularity at Oxton emphasized the proportion associated with the joints, the disparity between 3% and 8% or 11% did underline the fact that some further improvements in joint construction technique were desirable in order to match the higher standards of surface quality which were evidently attainable on a concrete road of that type as a whole. Nevertheless, although the Author quite properly expressed his dissatisfaction with the stop-end joints, the fairly considerable interval between joints at Oxton diminished their influence so that the total irregularity associated with them was small and need give road users no cause for serious concern.

Although a number of very creditable concrete-road surfaces existed (mostly pre-war and hand-finished), it was true, as had already been mentioned, that criticism had frequently been directed at concrete roads, both post-war and pre-war, on account of unsatisfactory riding-surface quality for which the joints were usually blamed. Even though an analysis of relevant surface irregularity data had shown that in a number of post-war cases the joints were not responsible for an undue proportion of irregularity[3] (mostly cases, however, in which the overall standard of riding-surface quality was not very good), joints often attracted undue attention; they not only made an unfavourable visual impression but also an audible impression, which together led road users to infer that joints were the main source of irregularity when it was very seldom the truth. That was unjust but often unavoidable. Mr Scott suggested, therefore, that that should be countered so far as possible by efficient and tidy maintenance, including the use of modern sealing materials, the repair of spalled edges, and generally making the joints as unobtrusive as possible. Incidentally, road users almost invariably approved the lighter colour of concrete surfaces, and Mr Scott was glad for that reason that it had been decided not to darken the main concrete at Oxton, apart from the consideration that a darker colour would have engendered greater heat absorption in fine weather with consequently increased stresses.

It might be of interest to present certain considerations which arose in connexion with the possible use of longitudinal finishers such as were often employed in America, as Dr Collins had mentioned. Contours at small intervals on concrete-road surfaces tended, not unnaturally, to lie in directions roughly parallel to the length of the finishing screed, tamper, or beam. In consequence, there tended to be fewer short-length minor irregularities in a direction parallel to the length of the finishing tool than at right-angles to it. Although very good riding-surface quality had been achieved on both transversely and longitudinally finished surfaces (hand-finished), the wide variations found on different examples of both types of work precluded any valid deductions as to their relative merits. Only instances in which some work of both types had been included in the same job could afford a valid comparison, and such cases were rare; but the limited data available suggested that appreciably less overall irregularity characterized the longitudinally finished work where both types existed in comparable circumstances. Apart from the short-length minor irregularities just referred to, concrete-road surfaces might also include a number of smaller very short irregularities of small amplitude (less than 0·1 in.) which, if classified according to their shape and length, would lie in a sort of no-man's-land between the shortest genuine irregularities which gave rise to appreciable disturbing motion and the most prominent asperities which were associated with a rugous non-skid coarse surface texture. Whilst it was common knowledge that surfaces of the latter type tended to "growl" at the average modern car, those very small and minor irregularities on a concrete surface could also give rise to a "rumble" or irregular vibration, and resulted in the allegations of harsh running which were sometimes made in regard to concrete roads. In one or two cases, by virtue of the existence of cross-roads, it was possible to drive over certain slabs in directions mutually at right-angles; the usual forms of construction entailed transverse finishing and consequently vehicles normally travelled at right-angles to most of the minor contours, but when the surface was traversed in a direction

[3] Arthur Floyd, "The Trend of Road Construction" (Introductory Note), Road Division. Instn Civ. Engrs, 1950.

parallel to the minor contours (i.e., to the direction of the length of the finishing tool) a noticeable diminution of vibration and/or harshness resulted. Although the actual physical motion associated with those types of disturbance might be very slight or almost unappreciable, they were objectionable riding-surface characteristics when present. The foregoing considerations suggested that, though the resulting advantage might be less when the overall order of irregularity was low, longitudinal finishers, employed with due care, might confer a worthwhile improvement in riding-surface quality.

Mr W. P. Andrews (Roads Consultant, Cement and Concrete Association) observed that there had been little experience of concrete-road construction in recent years, though, notwithstanding the ban on the use of cement, there had been an average mileage of more than 180 during the past 5 years although very little of that work had been mechanized.

The Author had taken great care to prepare a good base on which to lay the concrete and the value of that could not be over-emphasized. Nearly all concrete road failures were caused by subgrade failures and it was interesting that the C.B.R. in that case was raised from approximately 6% to an average of well above 30%.

With regard to surface finish, whilst it was a matter of great disappointment that the q value of 40 was not obtained throughout the job, the Paper showed that it could be obtained when the engineers and the labour, both skilled and unskilled, were more familiar with the work. On the Continent, where the large scale of construction had given the necessary training and experience, q values of 40 were being obtained consistently. The Oxton job lasted only 17 days and improvement in the finish and in joint construction had been noticeable as it proceeded.

If two-course construction had been adopted better results might have been obtained. With a relatively thin top course errors in spreading and pre-compaction and ultimate finish would have been minimized, and it was interesting that that two-course construction was adopted in Holland, Germany, and Denmark, even where the road was not reinforced.

Meticulous care was taken by the contractors in the bedding of the forms, yet irregularities had occurred owing to faults in the forms themselves. A finishing machine or a finishing method which would not be so dependent on the trueness of the formwork was desirable and the German method, which eliminated forms might be considered.

An American engineer who visited the work during construction was amazed at the expense involved in the careful laying of the forms and he suggested that the American method of using a longitudinal float to finish the surface might be adopted although it was questionable if that would function satisfactorily with British very dry concrete.

Perhaps one of the most valuable features of the Paper was that it showed that the bogy of joints had been laid. The Author pointed out on p. 216 that such improvements had been made that it was virtually impossible to determine the position of the joints on the profile. The one exception was at the end of a day's run and it seemed that the difficulty there could be overcome by hand compaction, possibly using the compactor in a longitudinal direction.

Mr Andrews considered that the crossfall of 1 in 48 (see p. 203), was too steep for present-day requirements. On runways a crossfall of 1 in 80 or even 1 in 100 was accepted.

Referring to concrete strength he said the requirement of 5,000 lb/sq. in. at 28 days was too high; he thought 4,000 lb/sq. in. would be adequate. In Belgium and other Continental countries higher strengths were required, but that was where the concrete was not reinforced. A concrete strength of 4,000 lb/sq. in. reinforced was preferable to one of 6,000 or 7,000 lb/sq. in. unreinforced.

It was mentioned on p. 206 that specially made reinforcement was used which served as a tie across the longitudinal joint. It would have been more economical to use tie-bars in that case, with standard types of reinforcement.

Fig. 2c indicated that the joints were cut after 14 days. The concrete aggregate was granite and Mr Andrews considered that it should have been possible to have cut that

joint after 48 hours. In that case a silicon-carbide saw could have been used whereas with the older concrete it was necessary to use the much more expensive diamond saw. Had any difficulty been experienced in sealing the narrow cut thus obtained?

On p. 214 the Author rightly endorsed the importance of the first pass in getting good riding qualities, and that again raised the question of whether one-course or two-course work should be adopted.

The Author, in reply, said that the earlier experimental road at Oxton had been of great value, as had been shown in the Paper [4] by Mr Loe, for it had established many points in connexion with concrete road design and construction. Some parts had been designed to fail and others to last a very long time and the point between success and failure had been found. In addition, many other factors had been evaluated such as the value of reinforcement and the function of the base.

He was glad that Dr Glanville agreed with his own conclusions from the work on the Oxton extension, namely, that there was no reason why concrete roads could not be constructed with a first-class riding quality, and also that more attention to the accuracy of manufacture of forms would help considerably in obtaining that quality more easily. It seemed from Mr Fisher's and Mr Sinclair's observations on that point that at least some manufacturers were aware of the importance of it, although the Author knew of other cases within the past few years where new forms had had to be rejected because they were not straight. It seemed to him that the discussion had crystallized the essential needs in formwork: (1) that manufacturers could make straight forms to less than 1/16 in. tolerance and it was therefore to be hoped that that would become common practice with all manufacturers in future; and (2) that users of forms should handle them with greater care to ensure that no distortion occurred through rough-and-ready methods of handling. Dr Kirkham's observations on the profilometer records further emphasized the importance of accurate forms. As Mr Sinclair had stated, consideration had to be given to the ability of road forms to stand up to very heavy machines, but whatever the difficulties, the forms still had to be straight and true to line if good riding quality was to be obtained on concrete roads.

Dr Glanville had pin-pointed one of the important lessons learned from the work described in the Paper, namely, the importance of continuity of construction. It would be well worth while in future jobs, especially those of some magnitude, to give careful consideration to the layout and type of plant and to the organization of the work, having regard particularly to maintaining that continuity of construction. Thought might also be given to the overlapping of meal-breaks and to the continued presence of a maintenance man or men to deal quickly with mechanical troubles. Dr Glanville had also underlined one point which could be expressed as the slogan "Bonus for no bumps." It was unlikely that we could deal with the bonus question as easily as the Swedes but it was an idea. Mr Fisher had mentioned a measurement of the "q" value and a bonus in relation to it when considering the setting of the forms and in that respect something might be done.

The Author fully concurred with Mr Fisher's comments on the value of the detailed discussions between the engineer and the contractor on a draft specification. It ensured that full advantage was taken of the contractor's experience to meet the engineering requirements and that engendered a helpful spirit of co-operation from the very beginning. It could not be said that it would be possible to adopt that technique on an ordinary road job where a larger number of experienced contractors would normally be asked to tender, but he thought that the success of the experiment certainly demonstrated the advantages of such a procedure if it could be worked. He was grateful to Mr Fisher for the qualification he applied to Conclusion (8) in the Paper. It was quite true that the mechanical placing of the reinforcement could only be effected at present with a set-up similar to that used at Oxton. He also agreed with Mr Fisher's comments on the value of the wet-surface profilometer and was pleased to hear from Dr Kirkham that the Road Research

[4] See reference 1 on p. 202.

Laboratory was, in fact, at present considering the design of such an instrument for attachment to the commercial finishing machines.

The Author was obliged to Mr Adams for his critical examination of all the Tables and was delighted that he had found something of merit in at least one of them! It might be as well to explain the reasons why the figures of 5,000 lb/sq. in. and 600 lb/sq. in. were adopted for the minimum compressive and flexural strengths respectively. It had been the Author's original idea to use a very strong concrete, since Belgian experience had demonstrated its value in preventing cracks in relatively long unreinforced slabs. Upon reflexion, however, it seemed that the use of the richer and more workable mix involved, might present problems in mixing and placing with British machines and in British conditions which could not be completely solved during the progress of the work. Since the prime object of the experiment was to see how good a road could be built it had been thought better to use the sort of mix to which experienced contractors had been accustomed. Thus a mix of 1 : 6 to 1 : 6·5 was indicated and that would normally be expected to give an average strength of about 5,500 lb/sq. in. In preliminary trials the average strengths obtained had in fact been well over 6,000 lb/sq. in. and it had therefore been decided to raise the specified minimum crushing strength from 4,000 to 5,000 lb/sq. in. Thus, while still using a mix with which the contractor was familiar, an attempt had been made to work to higher strength figures. The strength results showed that a fair measure of success had been obtained in achieving the specified minima although the number of results falling below the specified values was larger than would normally be accepted on non-experimental work.

The difference between the proportion of results in Table 2 which did not meet the specification, and the figure quoted in the synopsis arose because the former referred to the averages for pairs of specimens and the latter to individual specimens. Of the 61 flexural specimens tested, 12 had failed to give the required strength and of the 122 half-beams tested for crushing strength 25 had failed to give the required strength. That represented 20% of failures in each case.

Regarding the average crushing strength and standard deviation, the former was lower than it had been hoped to obtain on the basis of trial mixes, namely, about 6,000 lb/sq. in. That might have been the result of using, for the trial mixes, a batch of cement which, by chance, gave higher than average strengths. The standard deviation achieved corresponded to what Sparkes[5] and Himsworth[6] had classified as "average" or "fair." It had been hoped that on the Oxton contract a value nearer 500 lb/sq. in. ("excellent" or "very good") would have been achieved and that together with an average of 6,000 lb/sq. in. would have corresponded with a minimum of about 5,000 lb/sq. in. One point which had contributed to relatively high standard deviation concerned the variations made in the mix proportions in the early part of the work, as noted in the Paper. It was thought likely that had the work lasted longer the standard deviation of the later strengths would have been considerably reduced.

Dr Kirkham's observations on the records obtained at the site helpfully amplified some of the points in the Paper. His suggested explanations for some of the small irregularities remaining, such as the uneven filling of the spreading machine, discontinuity of processes, small changes in workability of the concrete and methods of making joints, were most useful in indicating the direction in which further progress could be made. With regard to Dr Kirkham's specific suggestions about an improvement in the surface at the stop-end, it seemed a good idea to carry forward some datum on the succeeding slab as the concreting machines approached the stop-end. He could not at the moment see how it would work in practice because it should be borne in mind that the machines finishing off the slab up to the stop-end were governed in operation by the forms on which they ran and it

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[5] F. N. Sparkes, "The control of concrete quality: a review of the present position." Proc. Symposium on Mix Design and Quality Control of Concrete. C.A.C.A., London, 1954.

[6] F. R. Himsworth, "The application of statistics to concrete quality." *Loc. cit.*

was not certain that there would be time for an adjustment, as they approached the stop-end in relation to some datum set out in advance. It was an idea which might be followed up.

It might be, as Dr Collins and Mr Scott had suggested, that the use of a longitudinal float would help to overcome errors in form alignment and straightness. It was true that the Americans used that type of float successfully on their wetter concretes, as indicated by Mr Andrews, but it was doubtful whether it would be sufficiently powerful to improve the surface of the dry concretes used in Britain and might in any case cause some tearing in the surface. That was another idea which could easily be tried out on an actual construction job and lent point to the expressed views of the Author and others that if only engineers were given the opportunity to build some concrete roads, most of the problems would be quickly solved. In the absence of special equipment such as a longitudinal float, the Author could not agree with Dr Collins that too much care was being taken in setting forms. No doubt the contractors on the Oxton job spent a lot of time and energy in setting the forms to the best of their ability and if forms were always manufactured to the high standard referred to by Mr Fisher a lot of that time and energy could be saved, but, having regard to the very high standard which should be set, meticulous care should be given to form setting. That was the datum for all machine operations.

He had seen the records of measurements with the bump integrator in Denmark and had been amazed by the results produced, having regard to a description of their methods; he hoped that Dr Glanville and the Road Research Laboratory engineers would be able to make further investigations. Was it possible to analyse the Danish methods in some way to find out how they achieved relatively good riding qualities, notwithstanding their apparent indifference in form setting?

Dr Collins had asked whether there was any difficulty in sealing the groove cut by the diamond saw. The Author had watched it closely and spent a lot of time with those doing it, and to his surprise the joint had been perfectly filled. The filler was heated to such a temperature that it flowed evenly and the man had become expert in the job. One could see the filler running along the bottom of the joint in advance of the pouring. That was the method adopted: so long as the filler could be seen flowing in the bottom of the joint in advance then the joint was perfectly sealed.

The first point raised by Mr Ollerhead concerned the effect of full-width construction on riding quality. It might be true, as he had remarked, that the use of half-width construction facilitated the production of a plane surface and that would certainly apply in the first lane. The Author felt, however, that in constructing the second lane, any irregularities in the surface of the first lane (on which the machines would run) would be reproduced in the second lane and added to those irregularities normally produced. It seemed likely therefore that a relatively poor riding surface would be obtained in the second lane. He fully agreed with Mr Ollerhead that there was an urgent need for heavier equipment capable of finishing very wide slabs to the present exacting specifications. There would seem to be no doubt that such machinery could and would be produced when the demand arose and the experience at Oxton had demonstrated its importance. It might be pertinent to note that runway specifications were now much more stringent than formerly in regard to riding quality and, with the large amount of work in hand, the necessary machines might be developed for that purpose and subsequently used in full-width road construction. Dr Kirkham [7] had previously described the advantages and disadvantages of the different types of spreading machines. The spreader used at Oxton was of a new kind developed by the contractors and was considered by the Author and others to be better than any spreader used hitherto. Whilst it was probably correct that differences occurred in the precompaction of the concrete across the width of the bay, that disadvantage was not, in the Author's view, as serious as the variation in precompaction obtained with orthodox spreading machines.

The Author did not agree with the suggestion that strength should be sacrificed to workability to achieve the desired riding quality. If the workability were too high, it

[7] See reference 2 on p. 205.

would be difficult to control variable flow of the concrete under the vibrating beam on a slab having a gradient or crossfall: that would result in poorer riding quality. If the cement content were increased there was the greater possibility of laitance being produced on the surface which might give both a slippery surface and scaling from frost action. It was noticeable that in Belgium, where a mix of about 1 : 5 was used, parts of the Ostend-Brussels motor road were labelled "Danger de glisser". Also as referred to previously, in replying to Mr Adams, it should be noted that the target figures for strength had been raised by about 25% above what was normally considered adequate. The Author was grateful to Mr Ollerhead for referring to the possibility of spalling at the expansion joint before sawing the groove at the top. It had not happened at Oxton, where the temperature had been rather high throughout the work but it was easy to visualize that such a defect might arise should the concrete be subjected to a large rise in temperature between the times of laying the concrete and sawing the joint.

The Author did not view with favour the inclusion of construction joints at the end of a day's work, to avoid finishing always at an expansion joint. It seemed to him that that would introduce an additional cause of irregularity since there was almost bound to be a bump at such a joint. It should be noted also that the contractor had had some latitude in organizing his day's work since the slab lengths had been specified to be between 97 and 113 ft, and if he had been doubtful of completing a given number of slabs of the longer length he could reduce his slab length to the lower value. The Author could assure Mr Ollerhead that the stop ends had always been right up to the finished level: the irregularity had been formed not at the actual joint itself but some little distance back and that had been due to lack of forward movement of the machine. It was the secondary effect which in some cases was more serious than the difficulty at the stop-end itself. The 4-in.-thick lean-concrete base on which the forms had been bedded had been provided to ensure full support for the forms. It was possible that the compacted colliery shale might, itself, have been strong enough but it was thought better at Oxton to be quite satisfied that forms were fully supported. Mr Ollerhead was not correct in deducing, from the data on cores, that there were considerable variations in level of the colliery shale base. The figures for the heights of the cores were normally subject to rather wide variations owing to quite small and local depressions or bumps—the sort of minor defect which could easily occur between rolling the base and laying the concrete, especially if the men were allowed to walk or wheel barrows over the prepared formation. It was of interest to note that the average value of the heights given in the Table was 8·2 in., which was quite close to the specified value.

In reply to Mr Osborne, the Author considered it would be a mistake to omit the dowel-bars at expansion joints. Experience on motor roads in Germany and Belgium had shown that where dowel-bars had been omitted in roads carrying heavy traffic, serious faulting sometimes occurred. Some slabs on the German motor roads, for example, were up to 1 in. out of vertical alignment on each side of a joint. It was true that the sleeper beam referred to by Mr Osborne, was used in Holland and, at any rate after a few years, appeared to be satisfactory. In view of pre-war experience in Britain, however, the Author did not feel that they were a satisfactory answer to the problem of load transfer; they were relatively useless, of course, when the slabs were warping upwards at the ends and their insertion caused a disturbance in the carefully prepared base just in the areas where the stability of the base was very important. Before substituting sleeper beams for dowel-bars, the effect of the Dutch type should be observed after a longer period under traffic. It was only fair also, to point out that the construction of dowelled expansion joints during the day's run did not prevent the production of a first-class riding quality in their vicinity. The only objection to dowel-bars that the Author could see was in preventing the use of the vibrating plate to form the expansion joint in the freshly laid concrete. In his view the advantages of effective load-transfer under all conditions of warping, freedom from subsequent differential settlement, and uniformity in consolidation of the base more than outweighed the passing advantage of allowing the use of a special machine for their formation.

Mr Osborne had raised a point which the Author had fully expected—the length of the slab. The slab-lengths ranged from 97 to 113 ft with an average of about 100 ft. The idea had been to have an irregular length, in case some rhythmic disturbance might be created, and 100 ft had been selected after certain observations on the Continent, after discussion with the Germans on the length they were using, and after consideration of the desirability of minimizing the number of joints, of the decision to eliminate contraction joints, of the whole design of the slab, thickness, weight, reinforcement, and so on; and the conclusion had been reached that 100 ft, more or less, was a reasonably safe unit to adopt with little possibility of cracking.

As for the output on the job, the machines had not been tested to full capacity for various reasons; on some days two slabs, each about 100 ft, had been laid and on some days three slabs, but so far as he could recollect, there had never been more than three slabs laid in one day.

Mr Combridge had asked why a longitudinal joint had been considered necessary in view of the troubles known to be attendant upon joints generally. The Author replied that a longitudinal joint was very desirable with a view to minimizing the possibility of longitudinal cracking, having regard to the comparatively long bay adopted. No irregularity whatever had been introduced by the cutting of that joint and although there had been a small expense and the question of the machine operation, he did not look upon that as trouble and felt that there was no trouble at all with surface irregularity.

On the question of the mesh of the reinforcing fabric, the spacing of the longitudinal bars had been increased to 4 in. instead of the 3 in. in B.S.1221, since it had been thought that that might assist in getting good compaction of the concrete. It was possible, of course, that a spacing of 3 in. would have been satisfactory and, presumably, if any change were contemplated in the Standard, that would only be made as a result of more experience than had been obtained at Oxton and possibly the carrying-out of a comprehensive experiment. The concrete itself had been specified in relation to minimum compressive and flexural strengths and the workability of the concrete had been based on contractor's experience. The amendments to the mix proportions had been made by agreement with the contractor.

The white edging strip had been ramped down so far as the surface was concerned but not floated out to a feather edge. There was a thickness of concrete underneath. The man doing the work had scratched out rather more of the concrete there than elsewhere, the whole idea being to get a proper bond between the white edging strip and the concrete slab and to have a reasonable thickness the whole way and not work to a feathered edge, which might well spall off.

The Author was grateful to Mr Scott for his amplification of the results of the multi-wheel profilometer records. It was very useful to have the factual confirmation of many of the impressions gained as a result of examining the early records. Mr Scott's views on the importance of neat and tidy maintenance of joints were apt. It seemed a fact that because concrete roads required a very small amount of maintenance they often received none at all, which sometimes led to the development of faults which were easily and cheaply preventable.

The question of two-course construction advocated by Mr Andrews was a debatable one, and the fact that it had been adopted in Holland, Germany, and Denmark did not necessarily mean that it contributed in major degree to a good riding quality. So far as the Author knew, Denmark was the only country which had produced better results than at Oxton, and the Danish roads were designed without reinforcement and with very few, if any, expansion joints—both factors which would help considerably in improving the surface quality. The use of two-course construction would, of course, involve a second train of machines and the Author felt that better comparisons between single- and two-course work were required before the latter could be recommended for general adoption. With regard to crossfall, there was a tendency to decrease the amount of crossfall with the introduction of smoother running surfaces; a very good reason for not going below 1 in 48 was that the steeper slope allowed the water to get away reasonably readily to the channels,

particularly during periods of alternate frost, snow and thaw, and, as a practising highway engineer with responsibilities beyond initial construction, the Author could not consider adopting a flatter crossfall. He did not agree with Mr Andrews that the provision of tie-bars across the longitudinal joint would have been more economical than the use of fabric with increased transverse reinforcement. The reinforcement manufacturers could readily change the wire-size and spacing of their welded mesh fabrics, whereas the inclusion of the tie-bars would have involved considerable difficulty in placing and fixing especially when the paver was operating between the forms. The delay of 14 days in joint cutting suited the convenience of the contractors since the experienced workmen necessary for setting out and cutting the joints had been engaged in other work during concreting. Schönberg[8] had stated that: "The operation of cutting the joint in the concrete when it is only three days old, oddly enough takes more time than cutting a joint in older concrete". That was at variance with Mr Andrews's comment and it might well be as he had implied, that the difference might be due to the use of different types of saw-blade. Any information Mr Andrews might have on that subject would be very welcome and helpful to engineers if it could be published.

[8] W. Schönberg, "Beobachtungen bei dem Bau von Betonfahrbahndecken". Strasse u. Autobahn, vol. 8, 1955, p. 278.