Recent research into the construction of concrete pavements

by

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Mr D. R. Sharp (Cement and Concrete Association) said that the summary of research work carried out by the Author and his colleagues was, in one important respect, a model of its kind. In every case, when results were quoted, the Author pointed out the practical importance of the conclusions and showed how, when adopted, they could help in producing better concrete pavements. In many fields, however, the demands of practice had overtaken research and the road field was no exception, as he would demonstrate.

49. The Author had indicated that the density of the concrete was dependent on the amount of work absorbed by it during compaction. The increasing use of cement-stabilized bases under slabs meant that vibrations from compactors were reflected and reabsorbed more completely in the mass of the concrete. The more accurate preparation of bases had also contributed to the more accurate surfaces on slabs now being obtained, and already self-contained machines were available which combined the operation of spreading, grading, and compacting the base material. Some of the machines were precisely guided by sensing fingers riding on stretched piano wires.

50. Many observers, including the Author, had noted that it was essential to avoid stoppages and to proceed reasonably rapidly with the concrete laying if a good surface finish was to be obtained. The large capacity of central mixing plant coupled with new developments in spreading and finishing machinery enabled very large outputs to be achieved. A twin 8-cu. yd mixer arrangement working on the Western Kentucky Parkway in 1963 produced more than 9000 lin. ft of 9-in.-thick, 24-ft-wide reinforced-concrete road in 11½ hours. The current paving record, however, was 12 091 lin. ft of 24-ft-wide reinforced-concrete pavement, 9 in. thick, in a 15-hour working day. These were not mere isolated examples of speed, and perhaps a more impressive figure illustrating the high productivity available was that one contractor in America had produced more than 1 mile of concrete road a day on 40 different days.

51. The Author's work on concrete had led him to stress the importance of choosing the correct workability, which must be maintained to close limits if well-compacted smooth-running pavements were to be obtained. Automation as applied to modern concrete mixing and batching plant was of great assistance in this respect. The latest plant included a meter that automatically measured the moisture content in the aggregates and varied the amounts of added water as necessary. The workability of the concrete in the drum could, in some new plant, be directly assessed by measuring the electric current required to turn the mixer.

52. In introducing his Paper the Author had mentioned that one effect of reinforcement was to reduce the effectiveness of vibrating beams by acting as a blanket. For this reason two-course compaction had very often been necessary. Another difficulty which occurred with reinforcement was that small pockets of air were sometimes found on the underside of the bars where concrete had failed to enter, thus

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reducing bond. The placing of reinforcement by hand had always been a rather untidy operation because it required a certain minimum number of men who were not always continuously available.

53. The placing of steel fabric mechanically was a very recent development in America and its adoption overcame both these problems, and also reduced the likelihood of bond failure when two-course construction would ordinarily be adopted. A fabric carrier was towed by a spreader and was followed by the fabric placer which was sometimes mounted on the front of the finishing machine, this arrangement having the advantage that the mesh placing and finishing operations were controlled by a single operator.

54. A separate machine was also commercially available and this was composed of a series of grids which vibrated and pushed the reinforcement to its proper depth. There were indications that this type of mesh-placing machine might possibly eliminate the need for the normal-type vibrating beams.

55. The Author had stressed the adverse effect on surface regularity of delays between compacting and finishing, particularly in warm drying weather conditions. His results indicated the advantages likely to arise from the use of combination spreading and finishing machines which were now used in America. One such machine was a combination of the ordinary paving train into one machine and consisted of a screw spreader, two transverse beams, and a long wheel-base screed float all combined into a machine operated by one man.

56. The ultimate in combination machines was of course the slip form paver which, moreover, carried out its work without the need for forms. This machine could lay concrete paving at rates of up to 11 ft/min under the guidance of a single operator.

57. Three makes of machine were commercially available at present, one being fully independent of the base upon which it was operated, being controlled electronically by a wire guide to give both line and level of the finished pavement. Twenty States in America had used the slip form paver and one would next year place its thousandth mile of road with this type of machine.

58. He hoped that he had demonstrated that, although the Author's Paper might at first sight seem to point to the need for a large number of rather complicated requirements, the engineer on the site already had available the necessary equipment to comply in many cases.

Mr Archibald Shaw (Consulting Engineer) said that he felt a certain nostalgia in attending the meeting, for it was about six years earlier that his company, when he was a contractor, secured the St Albans By-pass contract, now better known as the reinforced-concrete section of the M1. At that time they had only their experience of concrete pavements gained mainly in the building of aerodromes, and then were suddenly given a £5 million contract for a reinforced-concrete motorway, which had to be completed in 19 months. It had therefore been necessary to make important decisions, and it would have been extremely valuable if the Paper had been available at that time.

60. Some of the decisions taken then were interesting in retrospect. It had been decided to do the job in two-layer construction. It had also been decided to use a heavy screed—a heavy rectangular finishing screed, which was freely supported on articulated bogies. The finishing machine was a robust piece of apparatus which stood no nonsense. The heavy screed floated above the level of the forms. If a stone got in the way, the screed would break it.

61. Another aim had been workability; it had been thought desirable to ensure that this was adequate. They had wished to do this by adding more cement and by using more water. There were two difficulties from the point of view of the contractor. The first was that in those days people frowned on the practice of putting extra water in the concrete and if more cement were used, how could one get paid for it?

62. Another point from those days, to which the Author had referred, was that it had been found possible to get a much better finish by eliminating the $\frac{3}{8}$ -in. aggregate from the mix. It had been the $\frac{3}{8}$ -in. aggregate that had been inclined to be caught up by the finishing screed and to tear the surface. This might have had an effect on skidding resistance. In those days it had been thought that what was wanted was a sandpaper finish. It would be interesting if the Author would give the latest thinking on the subject of skidding resistance. What sort of surface was being sought? It used to be the fashion to have a sandpaper finish; nobody had objected to the $\frac{3}{8}$ -in. aggregate being cut out and it had made finishing easier.

63. He was a little puzzled, however, about air-entrainment. They were told that it was highly desirable from the point of view of frost resistance and the use of salt, and it seemed to him to be a splendid thing to use, but he had found it most unpopular with the men. It required a different technique in finishing, and the usual skills in laying paving concrete did not always work with air-entrainment. There had been the greatest difficulty in getting the men to like it. It seemed to be unpopular. But if there were advantages, it should be used, and the slight loss of strength did not matter.

64. It was gratifying to find that so many of the major decisions which had been taken in those days were supported in such an authoritative Paper as that before the meeting. The reinforced-concrete road still had some difficulties to overcome, but he hoped that more would be heard about skidding resistance, joints, and costs, so that more progress would be made with it.

Mr J. M. Fisher (Technical Adviser, John Laing & Son Ltd) said that he was pleased to be able to speak about a Paper by a former colleague from the Road Research Laboratory who had chosen to remain there and to continue with his research. Mr Fisher, on the other hand, had chosen to be a contractor's engineer whose main object had been dealing with high-quality concrete and producing roads as economically as possible. In doing this work he had been fortunate to continue a close liaison with the Author and his team at the Road Research Laboratory. He believed it essential that the closest possible liaison should exist.

66. The reader of the Paper must have been impressed by the vast amount of research work which had gone into its production—work which had led to the recommendations at the end of the Paper, which could be looked on as a code of practice for concrete paving.

67. In the Paper there was all the information which, in theory, was needed for the construction of concrete roads, but anyone who travelled along concrete roads in Britain must be aware that in some cases they had faults which announced themselves. If he were observant he would notice that many had other minor faults which might or might not prejudice their future performance. On the other hand, it was possible to travel hundreds of miles on concrete roads in the U.S.A. and Germany and hardly ever to notice a fault which in any way detracted from the quality of the road or the stability of the structure.

68. One was justified in asking why this was so, and in his opinion the answer was very simple. The besetting problem of concrete roads in Britain was that we had not enough of them. The meagre portion of the road construction programme which since the war had been carried out in concrete had resulted in inadequate scope and facilities for the proper development of plant and techniques for their most efficient and economical construction. He particularly emphasized 'economical construction' because the guiding rule at the moment was that they should be more economical in first cost. While concrete road construction in the U.S.A. was measured in terms of hundreds of miles a year, in Britain it was measured in units.

69. This was not the forum for considering why concrete roads had so much higher a proportion of available construction in the U.S.A. and Germany, but clearly the attitude of mind towards first costs and total costs during the lifetime of the roads

had much bearing on it. German construction methods suggested that first costs might be quite high, but on American roads the very speeds of construction achieved in the United States—up to about two miles a day had been quoted and Mr Sharp had used even higher figures—suggested that even first costs might compare very favourably with those for other forms of construction.

70. He was not necessarily an advocate of the adoption of American road construction techniques here, but he could not fail to observe that they seemed to have been so simplified and geared to high production rates that it was difficult to avoid some admiration of them, particularly as the standard seemed, on the whole, to be adequately high. Perhaps there had been a tendency to over-simplify, because one saw evidence of the introduction of items of equipment such as hopper spreaders—which the Author had shown—presumably because they required these to meet the increasingly tight specifications which were coming into vogue.

71. The advent of the slip form paver in America and on the Continent of Europe, thereby eliminating the use of static formwork, was claimed to have brought about very substantial reductions in construction costs, but it would seem from admittedly rather superficial examination of the economics of paving construction, that no overwhelming case could be made out for it. Coupled with this, it had to be borne in mind that this sort of equipment could not yet be made to produce the type of reinforced, dowel-jointed concrete slabs which long investigation here and in other countries had shown to be necessary. German methods had long been looked upon as being the standard at which we should aim, but it appeared that they might tend to be unnecessarily elaborate.

72. The construction of flexible roads in Britain, using basically the same type of machine—a bituminous paver—for every structural layer must have a great deal of appeal to contractors, particularly when uncertain weather conditions were the rule rather than the exception. He believed that this inherent simplicity of flexible construction weighed in no small measure against concrete construction with its multiplicity of different types of equipment ranged out for, sometimes, hundreds of feet along the road.

73. Sooner or later we should have to start thinking about ways of so modifying concrete construction methods that they would have the same appeal as those used in flexible construction—and here, surely, was ample scope for ingenuity.

74. The paragraph which interested him most was § 46 of the Paper. If the type of equipment suggested by the Author had to be used, then he would be in general agreement with most of the recommendations. But from observation of the performance of hopper spreaders of the type described, he would feel it an obligation to contrive to eliminate them, particularly if their proper operation called for such procedures as described in (b) (iv). So far as he could see, such a recommendation would increase, by at least one-third to one-half, the time required for spreading; and even then, he felt sure, some of the objections would remain.

75. He could not see the reason for the recommendation in (d) that a separate finishing machine should not be used. It had often been found advisable to have one finishing machine compacting concrete and another giving a final truing-up to the surface by means of a freely suspended smoothing beam. This at least had the major advantage that in the event of failure of one of these so-vital machines, work could often carry on, albeit at a reduced rate. The breakdown of a single machine would completely stop the job. Nevertheless, one machine of known high availability in place of two led to a substantial saving.

76. The Author's implied suggestion that the smoothing beam on a finisher might sometimes need an approach angle of about 10° was, he submitted, never likely to be realized in practice. The consequence of using such an angle of feed-in would, he was sure, be that almost the same longitudinal profile on the concrete as had been present before the passage of the smoothing plate remained. However, since it

probably cost no more to have the beams tiltable through 10° rather than through 2° or 3° , the recommendation could be accepted.

77. Observation of the performance of equipment in which compaction was achieved by a combination of pressure and vibration as in a vibratory roller, or impact as in a plate compactor, led him to suggest that a good deal more attention should be paid to the potential value of such equipment. Fig. 7 dealt with impact pressures and was directly related to the depth of compaction achieved, which was an indication that the use of vibrators of this sort with high unit pressure or high impact pressure might be of considerable value in improving the efficiency of the compacting equipment. The use of such equipment had been found satisfactory on concrete mixes of workability lower than that of those proposed, and in this direction lay the prospect of worth-while savings in costs of materials—by far the major proportion of concrete road costs. Concrete of the consistency suited to this technique could readily be laid by bituminous paver, but an overlay of more workable concrete would be necessary for finishing to acceptable surface tolerances.

78. He was glad to note that the Author had referred in (f) (i) to the need for as high a speed as possible. He agreed with this, but thought that there was probably a limit—perhaps four or five feet a minute, or it might go slightly beyond that. He also noted that the Author mentioned reducing stoppages to a minimum. No one wanted any more than the minimum number of stoppages, but surely the way to ensure this was to use the minimum number of the simplest and most readily maintained machines for the work. No effort should be spared to make concrete paving a less complex operation than it was in Britain at present.

79. Regarding the design of equipment he asked the Author whether he had observed the operation of angled smoothing beams on the final articulated finishing machines, and whether he was prepared to make any firm recommendation that such a beam be used, and if so, what angle should be adopted.

Mr W. H. Spencer (Assistant Chief Engineer, Motorways Branch, Ministry of Transport) congratulated Dr Kirkham not only on the research which had gone into the Paper, but also on the excellent way in which the results of the research had been documented.

81. In the Ministry he was responsible to a degree for the drafting of specifications and for the acceptance of the end product. After reading the Paper and, to refresh his memory, looking at the specifications of the Ministry, it seemed to him that it would be very difficult to ensure that the findings of the Paper were enforced in the building of a concrete road. The reason was that we aimed at the end product and all we could specify was the measure of workability or riding quality and the density of compaction. Had the Author given any thought to the application of this research to the Ministry standard specification in the way of writing it more tightly, without perhaps departing from the general concept of writing an end specification?

82. On reading the Paper he had been forced to the view that some of the processes described as giving the best riding quality at the end would probably be restrictive of the rate of progress. For instance, the double-spreading operation by the loaded hopper must be rather time-consuming in a machine which had to be moving forward at several feet a minute to produce the necessary riding quality. He wondered whether contractors would be able to use such methods as this to produce the riding surfaces which the Author's researches said could be obtained if properly used. He recalled that when he had been associated with the Author and others in the construction of a road in the North Midlands, they had found it necessary to use the method of double compaction from two separate trains of machinery to obtain the specification of riding quality. It was interesting to note—if he were reading the Paper correctly—that since the Ministry always called for a depth of concrete greater than 8 in. it should also specify that compaction must be in two definite layers.

83. Mr Shaw had mentioned a point in one context which he would mention in

another: the research would lead to improved strength, density, and riding quality of the road, and yet there was a disturbing tendency coming to notice that these improved concrete roads were developing early in their life low sideways force coefficient.

84. In the end this was an even greater problem than obtaining density and good riding quality because if the road became dangerously slippery it must be surfaced, and if this were necessary one had lost all the effort put into producing this excellent running surface. In any of the research which he had done, at the Road Research Laboratory or elsewhere, had the Author made any investigation into methods of building-in this satisfactory sideways force coefficient and retaining it in the concrete? There were methods of construction other than concrete which to some degree suffered from this effect but with age they seemed to show up rather better than the concrete surfaces provided in the motorway era.

Mr D. A. Stewart (Partner, Cowdell & Stewart) said that the Paper had been of great interest, and he congratulated the Author on his work. He had been particularly interested in the reference to gap-graded concrete and had noticed with pleasure that the Author found that he could get a more compactible concrete by removing the $\frac{3}{8}$ -in. to $\frac{3}{16}$ -in. aggregate.

86. He had found this many years ago and had committed himself forcibly on gap-grading. At the same time as the Paper had reached him, he had received two papers from India dealing with work carried out in 1958. In that case sands of the usually acceptable grading, zone 2, had not been available except at considerable expense, and they had been forced to investigate the possibility of making concrete with local sands. They had investigated whether, with the apparently unsuitable coarse or fine sands found locally, and the use of gap-grading, they could still get satisfactory results. The results had been so satisfactory that even when they could get zone 2 sand they preferred to use gap-grading, which would save £400/mile on a road 24 ft wide and 6 in. thick.

87. He was sure that this could be done in Britain. We should not save quite as much because the cost of cement was lower than in India. If we were to have serious accidents as a result of skidding, then obviously gap-grading was out of the question, but he could not believe that the stones between $\frac{3}{8}$ in. and $\frac{3}{16}$ in. were the only materials which stopped traffic sliding on a concrete road.

88. Some of the roads with the best skidding resistance, in his view if not in that of the Road Research Laboratory, were black-top roads in which the stone was to a considerable extent gap-graded between 1 in. and $\frac{1}{2}$ in. in size.

Mr Fisher asked whether the Author would raise any objection to the use of higher aggregate-cement ratios in the concrete than current specifications allowed, provided all the requirements regarding compressive and flexural strength were met, that the cores showed the concrete to be satisfactorily compacted, and that the surface profiles complied with the tolerances laid down.

Mr R. David (Robert McGregor & Sons Ltd) expressed admiration of the Author for his very concise Paper, which clearly covered a number of years' hard work. He hoped that his colleague, Mr Carter, would speak on the rather more detailed technical points, so he would speak on the broad aspect.

91. Having seen the slip form paver at work in France, he added his voice to those who deplored the multiplicity of machines which were being used and which seemed to be proliferating, making this operation very awkward and inflexible in all senses of the word.

92. For instance there could now be a train of machines up to 400 ft long, which meant that on any contract one must have all obstacles, such as the bridge works, completed before starting the reinforced-concrete paving.

93. He felt that everybody—Government departments, the Road Research

Laboratory, local authorities, and manufacturers—should direct their thoughts towards the use of a single machine for doing the work, to be comparable with flexible construction.

94. The main problems in the use of a slip form paver were reinforcement and joints. In dealing with joints, his firm considered that they had produced a load-transfer unit which would be suitable with a slip form paver. But the problem of reinforcement had still to be solved. Nevertheless, thoughts must be turned more in that direction rather than to producing another machine to put into the circus. He almost said 'three-ring circus', but it was probably better described as a two-layer circus.

95. He offered the rather sobering thought that after all this magnificent machinery had passed they still needed the true virtuoso, i.e. the man with the brush who added the final texture to the concrete.

Mr P. A. Fitzpatrick (Fitzpatrick & Son Ltd) asked the Author to enlarge on Mr Stewart's remarks about gap-grading and the sideways force coefficient. Had he reached any definite conclusion whether the skidding resistance was dependent solely on the minus $\frac{3}{16}$ -in. elements?

Mr Shaw pointed out that the Author had emphasized the importance of working accurately to levels. While he agreed that this was desirable, he felt that there was also a hazard as the work became expensive. He would like to see some relaxation and greater tolerances in concrete roads. Much could be learned from the black-top road. In that case, engineers did not work slavishly to levels; perhaps there was a chance for the same to apply to the concrete road. He was talking not about riding qualities but about levels. It was important to maintain a high standard of riding quality. He had been told on good authority that the slip form paver could cope with steel reinforcement and with dowelled joints. As some speakers had suggested that this was not so, he thought that the point should be brought to the notice of the meeting.

Mr F. G. Carter (Robert McGregor & Sons Ltd), commenting on the slip form paver, said that the problem was that of introducing a load-transfer dowelled joint. He had never been happy with the specified method of making a load-transfer dowelled joint in concrete roads. The current Ministry of Transport specification did not produce the answer and it seemed to him impossible to put a dowel joint in a road using the slip form paver with some sort of cradle. His firm had developed and proved a method which could do this work and which also, he thought, improved construction of the joint in the type of concrete road built to the present specification. He knew that steel could be put in using the slip form paver, but to do so restricted the ability of the machine to lay large quantities of concrete in a day. Introducing steel into the pavement would slow it down.

99. This raised a contentious issue—how much good did reinforcement do in a road? Would the Author enlarge on this point? Introducing steel affected rideability, and reflexion of the ripple of reinforcement could be noticeable, especially where air-entrained concrete was used.

The following contributions were received in writing:

Mr P. A. R. Hodge and **Mr F. C. Stott** (Taylor Woodrow Wilkins Davies, Auckland International Airport) wrote that one fault common in spreader hoppers, but not mentioned in the Paper, was excessive deflexion when loaded. This allowed a loaded hopper to sink into concrete previously spread with a partially emptied hopper, causing bulldozing. This displaced the spread concrete, often spilling it over the road forms, upsetting the differential surcharge, and putting an additional strain on the

machine. Thus, even with bottom doors on the hopper closed, the machine often had insufficient power to overpass spread concrete. Hoppers should be made strong enough to avoid this.

101. Regarding compaction, no regard was taken in the Paper of the quality of the sub-base upon which the concrete was poured. In a slab of infinite thickness the effect of surface vibration would die away with depth, but given a dense sub-base such as was normally the case, the vibration was reflected. This necessitated a stiffer concrete mix which avoided excessive heave behind and in front of the beam, but in turn retained the vibration energy in the working zone between the beam and the sub-base. The effect of this vibration could be seen in Fig. 9, which gave results from a 14-in.-thick slab compacted in one layer by two vibrating-plate machines on a crushed-stone sub-base with a *K*-value of 500. It would be noted that the densities at the bottom were slightly higher than those at the top. This pattern was also obtained consistently with slabs 12 in. and 16 in. thick. All this concrete was laid and compacted in one layer on a polythene underlay which retained the moisture in the mix, and may have enhanced the reflexion from the sub-base.

FIG. 9: CORE DENSITY—14-IN. CONCRETE

102. The Author had suggested a lower limit of 0.86 compacting factor for thick slabs. Surely this depended on vibrating equipment, aggregate shape and grading, and cement fineness, and should be decided on each site after trials. The concrete in the 14-in.-thick slab referred to above was made with an angular gap-graded basalt aggregate, a water/cement ratio of 0.42, and 2.9% entrained air. When dropped through a compacting factor apparatus it gave a factor of only 0.75 to 0.78, but when trapped under a vibrating beam and mechanically taken apart and reorganized it proved adequately workable.

103. It appeared then, that a recommended compacting factor could only be applied to concrete using similar materials and compacted with similar plant. For different materials and plant an optimum compacting factor must be found by trials, and it could then be used as a control.

104. In practice, however, the best 'compacting factor apparatus' was the compacting machine itself. An experienced concrete foreman could detect small changes in mix consistency by eye and by its performance under his machines. It had been

found essential to put him in radio contact with the mixer so that small adjustments, often of the order of $\frac{1}{2}$ gal of water in a 3-cu. yd mix, could be made immediately.

105. In addition to this, however, some measure of laboratory control was essential, but related more particularly to low-workability pavement concrete, perhaps in the form of a 'vibratability factor'. This would give some idea of cross flow to be expected across crossfalls and it might even be possible to arrive at an ideal 'vibratability factor' for any given thickness, crossfall, beam vibration, and sub-base reaction. With this in mind, trials were at present being carried out with an apparatus to simulate the conditions under which the concrete was placed in the pavement.

106. It had been noticed that better results were obtained when the speed of laying was uniform and when there were no stoppages. When using two vibrating-plate compacting machines in tandem, as was common on thick slabs, this usually meant that the two machines were close together. Could it be that the two machines, say 15 ft apart, acted in concert, and if so, had the Author any details of this interaction or knowledge of machines where this effect was used?

107. Regarding speed of laying, the high outputs of up to 10 ft/min on 25-ft bays obtained in the U.S.A., had generally been obtained with gangs of immersion vibrators in a much more workable mix than was usable with top-plate vibrators. Did the Author consider that such outputs could be obtained with plate vibrators, or was the answer a stiff mix, a plate vibrator, and a gang of immersion vibrators just ahead of and below the plate and working in conjunction with it?

108. In this context, could the Author give any comparison of the surfaces obtained with plate vibrators and immersion vibrators working at comparable speeds? Was surface regularity sacrificed when high laying speeds were attained?

Mr R. F. Legget and Mr E. G. Swenson (Division of Building Research, National Research Council, Ottawa) wrote that they had studied Dr Kirkham's Paper with interest and appreciation. The factual evidence that it presented in support of sound concreting practice was a valuable addition to the literature. The Author's Conclusions (§ 46) could usefully be widely distributed as a succinct guide to the construction of good concrete pavements.

110. The comments on the use of air-entraining agents presented in the Paper would be emphasized by the writers, in the light of some Canadian experience that might soon also be the lot of British engineers. This related to the phenomenal increase in Canada within recent years of the use of chemicals for 'de-icing' roadway surfaces during winter weather.

111. At a recent conference in Ottawa on snow clearing and ice removal, sponsored by the Associate Committee on Soil and Snow Mechanics of Canada's National Research Council, it was revealed that approximately one million tons of 'salt' were going to be used in Great Britain during the current winter season for the amelioration of winter road conditions, following the severe trials of the winter of 1962/63. If Canadian experience were any guide, British motorists would demand the continuation and extension of this service, when once started, even though concurrent deterioration of some concrete pavements, due to chemical action, might also be experienced.

112. The deterioration that was causing such concern to many city engineers in Canada took the form of excessive scaling of the surface of concrete slabs used as sidewalks or pavements. The most serious trouble had naturally made itself evident in the pavements of busy streets where the intensity of traffic had had the effect of quickly removing the products of deterioration, leaving coarse aggregate exposed with a correspondingly rough surface which was objectionable to motorists. If the concrete so exposed was not itself of good quality, the deterioration might continue, as individual pieces of coarse aggregate were 'plucked' out of their matrix by the action of traffic, leading in extreme cases to almost complete failure of the concrete slab.

113. That the resulting troubles were not peculiar to Canada was shown by the

published records of research work on this problem that had been conducted by well-known concrete research laboratories in other countries. In Sweden, for example, the problem had been recognized as so serious that the use of de-icing salts had been prohibited for some years. Study of the problems created by the use of de-icing materials had been carried out at the Swedish Cement and Concrete Research Institute in Stockholm. A report on this work had recently been published.⁹

114. In North America, intensive work on the same problems had been in progress at the research laboratories of the Portland Cement Association at Skokie, near Chicago. In a notable paper to the Highway Research Board at its 35th annual meeting, Verbeck and Klieger presented a report on their investigation of the action of de-icing materials upon concrete.¹⁰ This was not in any sense a final report but a progress statement which showed conclusively that all the commonly used de-icing materials were capable of producing serious deterioration under laboratory freezing and thawing conditions. Deterioration was not, however, produced in any sound concrete in which proper air-entrainment was used. Work at the P.C.A. laboratories was continuing. The widespread interest in this problem was shown by the number and scope of the papers presented at the 1962 symposium sponsored by the Highway Research Board.¹¹ Other research studies had also been reported.¹²⁻¹⁴

115. The evidence that the use of salts was closely allied with current difficulties was too strong to be ignored. Difficulties had increased concurrently with the greatly increased use of salts. It had been shown in the laboratory that salts could produce serious scaling. The field failures in the main tended to follow closely the use of salt but there were some anomalies in the pattern, such as some observed failures with concrete in which air-entrainment had been used. None of this negative evidence contradicted the main conclusion that the use of salts was involved, but it did suggest that other factors might be involved in a minor way. There was, for example, some evidence to suggest that concrete which was not performing well despite the use of air-entrainment might not have the proper distribution of air bubbles essential for good performance.

116. The exact mechanism by which de-icing salts produced scaling of concrete pavements and sidewalks was not known. Some authorities considered that it was a physical rather than a chemical reaction. This opinion was based on the fact that the same result was produced by chemicals which differed widely in properties, e.g. calcium chloride and urea. The destructive action of these de-icing materials occurred in conjunction with freezing and thawing of the concrete. In general, the factors that promoted resistance to freeze-thaw deterioration also promoted resistance to de-icer scaling. It was therefore probable that the role of the salt was to 'trigger' or accentuate the destructive action of freeze-thaw cycling.

117. Resistance of concrete to de-icing 'salt' action could be greatly increased by attention to the following points. It must be kept in mind that disregard of only one of these factors might nullify the benefits to be expected from others:

(a) The aggregates and cement must be of good quality. They should meet standard specifications for such materials.

(b) A good mix design should be developed for the particular aggregates and cement to be used. This was important in order to ensure a dense, impermeable concrete, rigid control of proportioning being necessary.

(c) Water/cement ratios should be kept to a minimum consistent with good workability; rigid control was particularly important here. An increase in water-cement ratios would reduce resistance to frost action and salt action, owing largely to the increase in capillary voids. The tendency to bleeding and formation of laitance material caused by excessive water would promote scaling.

(d) Air-entrainment was absolutely necessary. The air-entraining agent selected should be one generally accepted as having a good performance record. The amount of air might vary from 4% to 7% in the concrete and this air must be

properly distributed throughout the concrete as evenly spaced bubbles. Air contents should be checked at the job and any concrete that did not meet the air requirements should be rejected.

(e) Any admixture other than a plain air-entraining agent was preferably to be avoided unless its performance record had proved it to be advantageous. It should be emphasized that any extra ingredient, although it might be potentially beneficial, added to the difficulty of mix design and control.

118. In addition to these points which the writers took the liberty of stressing in support of the Author's recommendations, his other conclusions would also naturally assist in protecting concrete pavements against chemical deterioration. The writers naturally hoped that city engineers in Great Britain would not experience the same troubles from this cause that many of their Canadian confrères had had to deal with in the past decade. This note of warning in support of the Author's thesis might, however, be warranted in view of the apparent after-effects in the U.K. of the winter of 1962-63, of which all Canadians read with such concern.

The Author, in reply, said that he would deal first with one or two general points. The first concerned the problems arising from the use of the slip form paver. The Paper had been written at a time when there were new thoughts on the types of plant which should be used. The slip form paver was being considered and also the suggestion that 36-ft-wide roads should be laid in one width, whereas ten years ago few contractors were prepared to consider laying even 24-ft-wide pavements in one width.

120. In considering the slip form paver and American experience it had to be realized that it was very difficult to generalize about America. Different States had different techniques. Different States had different specifications. Different States basically often used different types of plant. The slip form paver had primarily been used for laying unreinforced concrete pavements with undowelled joints. A few pavements had been laid with reinforcement and dowelled-contraction joints, but in these pavements the reinforcement, or some of it, had to be continuous through the joints to prevent the reinforcement moving as the machine went forward. This was providing a tied joint, rather than a free-moving joint, and this was likely to increase considerably the risk of cracking between joints.

121. It would be simpler to consider the use of a slip form paver with unreinforced concrete and with dowelled joints and this step forward could be made. But unreinforced slabs would need to be thicker than the reinforced slabs being used at present, and it might, therefore, be found that the economy to be expected from the use of a slip form paver was not nearly as great as American experience might suggest. The reports suggested a 10 to 15% economy, but these figures had been obtained in States which had used unreinforced, undowelled construction.

122. Gap-grading needed careful consideration. While it was true that using the coarser sands and eliminating the $\frac{3}{8}$ -in. size led to easier compaction, this was not universally true and mixes made with finer sands could accommodate a percentage of the $\frac{3}{8}$ -in. size without difficulty.

123. It was also important to consider what effect this $\frac{3}{8}$ -in. size had on skidding resistance. The German mix design for roads required a high percentage of material between the $\frac{3}{8}$ -in. and No. 7 sieve, so that a coarse sand with some $\frac{3}{8}$ -in. material was used and he had been led to believe that this type of mix had been designed particularly with skidding problems in mind.

124. For high-speed skidding resistance it seemed that the road needed a rather greater texture depth than most concrete engineers had been prepared to provide. Some years ago an experiment had been carried out in which the surface had been treated with a number of different types of brush. A soft broom had made the surface rather less skid-resistant than no treatment at all. But a severe brushing with a wire brush had given a texture which on that road had survived heavy traffic for seven

years, after which, unfortunately, the road had been surfaced for reasons not connected with skidding resistance.

125. In considering skidding resistance, it seemed to be necessary, therefore, to look for much greater texture depth than had been accepted in the past. This texture depth should be great enough for the coarse aggregate and finer particles to be in the surface when the texture depth itself had been worn away. There would therefore be some danger at the moment in omitting too much of the coarse sand or finer coarse aggregate.

126. It was desirable to reduce the number of machines. A multiplicity of machines was likely to lead to delays because of minor breakdowns and short-term stops and there was an advantage in concentrating the work on one or two machines. But there was some difficulty in deciding which machines to combine. Personally I preferred to have a separate spreading machine and would combine the compactor and finisher, but obviously not everyone would agree with this choice. The choice seemed reasonable because the spreading was an intermittent operation whereas compaction and finishing should be a smooth-running operation. There was an advantage in a finisher which ran smoothly forward, and there was some advantage in the German practice of some years ago where there was so much equipment behind the compactor-finishing machine that there was no chance to turn back. It was important to try to produce a machine which gave the required surface in one pass. No one wanted a separate finishing machine which reversed and did a second pass.

127. The angle of tilt of 10° suggested in the Paper was deliberately made high, and he had never used this angle. There was, however, a need to tilt the screed to different angles. With a crushed rock aggregate rather more tilt was often required than with a round aggregate. The degree of tilt also depended on the percentage of $\frac{3}{8}$ -in. material in the mix. The figure of 10° had been suggested as the largest angle which any engineer would want to use and it was possibly larger than it need be.

128. Unfortunately, there had been no opportunity to test an angled finisher. This was a very old idea; it had been in German reports at least 20 years ago, but it was only in the past year or two that it had been manufactured. In choosing the angle it seemed desirable to try to keep the finishing screed approximately level in relation to the gradient and crossfall. With this arrangement the screed would not be moving across the slope and the crossfall would be countered by the angle of the finishing screed. This would be difficult to adhere to in practice because it would be necessary to alter the angle for a change in gradient and to reverse the screed for super-elevation, and a compromise was necessary.

129. It had been suggested that the better bases which were being produced had led to improved compaction, but most of the tests on compaction had been carried out on a very well compacted base. The thicknesses which were given in the Paper were the maximum which would be expected on a sound base and took account of reflexion of vibration from the base. The thickness would be reduced if a poor base were used. Slightly lower densities were often obtained at the top of the slab than below. This was thought to be due to some small amount of segregation by which the concrete at the top had a slightly higher mortar content than that in the rest of the slab.

130. The compacting factor could, of course, only be used as a guide to the suitability of a mix for compaction by vibration. The compacting factor test measured the compaction achieved under a standard amount of work, but it was more important to know the amount of work required to obtain full compaction. The compacting factor test, in fact, favoured coarse sand and it would certainly be reasonable to expect to use concrete of a lower compacting factor if a very fine sand was used, particularly if this was used in a gap-graded mix. Work was in hand at the Road Research Laboratory to examine the possibility of using a vibrating test for mix design in place of the compacting factor test. The vibrating test was designed to assess with a particular type of vibration the minimum water content necessary for full compaction for a given grading of material.

131. The use of two compacting machines in tandem often enabled better results to be obtained, as had been suggested, because speed of laying was generally more uniform and there were fewer stoppages. It was unlikely, however, that the two machines about 15 ft apart would act in concert. Measurements of the vibrations in the fresh concrete under the vibrating machine had shown that the vibration was generally transmitted for about 2 ft in front of and about 2 ft behind the vibrating beam, and outside this area the vibration had little effect. The high speeds of laying in the U.S.A. had been obtained using much more workable concretes than those generally used in Great Britain and certainly more workable than those used in the tests reported in the Paper. While these more workable concretes had enabled gangs of immersion vibrators to be used since this type of plant required a more workable mix than surface vibrators, the high output was achieved because a satisfactory surface finish could be obtained easily even when the concrete was spread unevenly. There was, however, no reason why high outputs should not be obtained with the normal vibrating beam. The main problems were to design methods of spreading the concrete sufficiently uniformly at a sufficiently high rate, and to design a suitable finishing machine and it was hoped that the data given in the Paper would enable these problems to be solved.

132. With most existing equipment it would generally be desirable to use compaction in two layers for concrete slabs more than 8 in. thick. With some of the more powerful plant, however, it might be possible to get full compaction in one layer with a slab up to about 10 in. thick and the specification might therefore require a slab of more than 8 in. to be compacted in two layers unless it could be shown in trials that the full depth could be compacted satisfactorily in one layer.

133. More research was required into the use of rollers and vibrating rollers for the compaction of both concrete and lean concrete. Although, as had been shown in the Paper, the pressures applied were directly related to the depth of compaction achieved, experience suggested that there might be a maximum pressure and that if this was exceeded some disturbance of the surface layers of the concrete took place. Rollers seemed to be suitable only for very dry mixes where this disturbance could be limited. On wetter mixes it was generally necessary for the vibrating roller to be driven forward at a high speed in order to prevent it from sinking into the concrete. With this arrangement, there was a high pressure, but very few vibrations were transmitted and it was not likely that the total depth of compaction would be much better than that achieved by a vibrating beam moving forward more slowly.

134. The automatic measuring of the moisture content in the aggregates or of the workability of the concrete in the mixer drum was of course most desirable. Unfortunately all the methods of measurement which had been proposed up to the present suffered from some disadvantages and they needed further testing to show that they were sufficiently accurate for practical purposes. This was particularly necessary where the equipment had been developed to deal with wetter concrete since it was not always suitable with a drier mix.

135. The use of air-entrainment could increase the difficulties associated with the construction of a concrete road. Variation in air content was an extra cause of variability in the concrete and for this reason it had not been well liked in Britain. It was, however, certain that there was going to be an increasing use of salt for clearing ice and snow from British roads, and experience in the severe winter of 1962/63 had shown that random damage occurred in many concretes which did not contain entrained air but there had been no damage in any of the air-entrained concrete inspected. It was therefore necessary to include air-entrainment in concrete for road surfaces at the present time. The use of air-entrained concrete was not by itself, however, sufficient and the rules of good concrete practice must always be borne in mind as had been emphasized. For this reason it was doubtful whether leaner mixes than those at present specified would be acceptable unless it could be shown that there would be no increase in capillary voids.

136. The suggestion that reinforcement should be vibrated into place was interesting. This might get the reinforcement well surrounded by concrete, but it could have unfortunate effects on the finished surface unless the finishing screed was sufficiently far away from where the vibration was applied for the reinforcement to have stopped vibrating. Such an arrangement would have to be tried before it would be possible to be sure that it would be satisfactory.

137. The greatest difficulty in the development of new plant and techniques was that the tests by which the efficiency of plant was measured had been relatively poor. This was the difficulty which arose in considering the preparation of the specification. It would be possible to prepare a specification requiring the equipment to meet certain standards, if the methods of testing the equipment were laid down fairly carefully, and more progress had been made with this type of specification on the Continent than in Great Britain. In Germany spreading machines and compacting machines were tested in accordance with a standard test procedure so that their general efficiency was known. If new equipment was to be developed, this type of test would be essential. In the meantime, the only thing to do was to use the results of research when developing any new type of plant to assess the problems which were likely to be serious. Essentially, to improve specifications better testing techniques were required.

138. Sometimes the best product was produced by what appeared to be the most complicated method but the method could often be made simpler by alterations to plant. For example, spreading was a difficulty only if the plant were relatively slow moving. There was not much difficulty with a fast-moving spreading machine which could accept material at any point and transport it quickly to where it was wanted. The difficulties of spreading, therefore, could be taken care of by designing the plant to have sufficient power and sufficient speed to make the movements rapidly enough to avoid delay to the other equipment.

139. It was also important, as had been suggested, for the spreading machine to be sufficiently rigid to avoid excessive deflexion when loaded. Even if the spreading machine had sufficient power to overpass spread concrete, if there was excessive deflexion when the hopper was loaded, the spreading was less even than that given by a rigid hopper and consequently the surface was less regular. This was an important point to consider in the design of this type of machine.

140. It was often asserted that in many ways the laying of a bituminous-surfaced road was a simpler problem. But here again separate spreading and compacting machines were used. Although the bituminous paver did some compaction, the bulk of the compaction and finishing was done separately by the roller behind it. Similarly for concrete construction, if one had to have two machines rather than one, it would be preferable to think in terms of one machine to do the spreading and one to do the compacting and finishing.

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