adjusted to compensate for any obvious changes in the water present in the new material, if it is to be brought into immediate use.

All these points can and should be covered by a skilled "concretor" once the concrete engineer has established his mix on a basis of aggregate supply and site requirement.

With adequate planning of formwork, mechanization, and mix design, high-quality concrete is no more expensive to make and place than inferior material, and will certainly last longer.

ACKNOWLEDGEMENTS

The thanks of the Authors are due to the Director-General of Works for permission to use in this Paper the results of work carried out on Ministry of Works sites.

The Paper, which was received on the 1st September, 1953, is accompanied by four photographs and five sheets of drawings, from some of which the Figures in the text have been prepared.

Discussion

Mr L. R. Creasey (Superintending Structural Engineer, Chief Structural Engineer's Branch, Ministry of Works) said the Authors had referred to a beam-test control of the concreting the value of which, generally, had not perhaps received the recognition which it deserved. The beams which had been used for the work referred to were of 4-inch cross-section by 16 inches long and tested by single-point loading between supports 12 inches apart in the machine shown in Fig. 6, the simplicity of which was notable. The cracking load at which the beam failed in flexure was determined and from that a measure of the crushing strength of the concrete was obtained. The 4-inch beams had been used successfully for both $\frac{3}{4}$-inch and $1\frac{1}{2}$-inch aggregate and were tested at 3 days for early results, on account of which uniformity of curing, preferably by water bath, was an important factor. The machine was a relatively unscientific instrument compared with the laboratory compression-test machine, but the advantages were simplicity, low cost, control on the site, and the early stage at which test results were available; also, experience appeared to confirm that such tests were not less satisfactory than the cubes in predicting the crushing strength of the concrete as actually placed.

The calibration of the beams had called, however, for a special technique. The relative cracking load of the beams and the crushing strength of the cubes for each of the sites given in Table 4 had been plotted on one graph, as shown in Fig. 7. The results fell broadly within an inclined band, the

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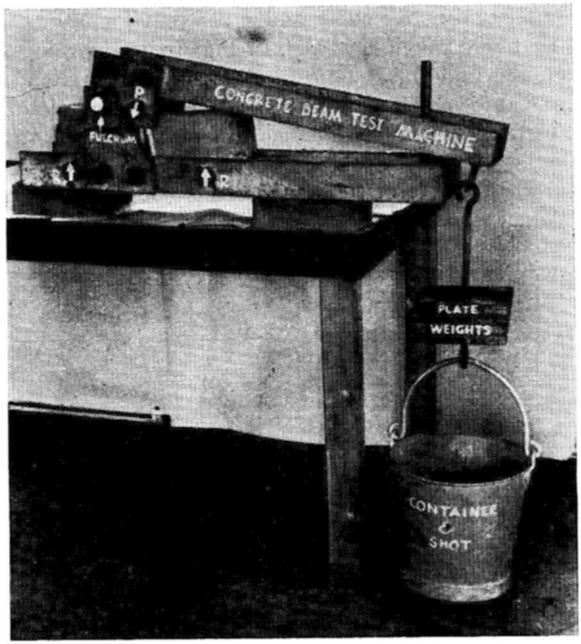

FIG. 6.—CONCRETE BEAM TESTING MACHINE

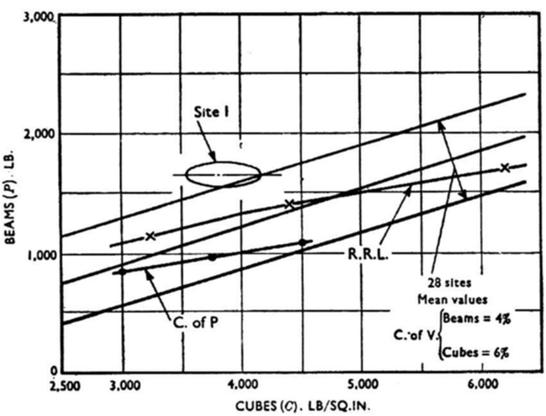

FIG. 7.—CUBE-BEAM SUMMARY

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width of which corresponded to a coefficient of variation from the mean of approximately 6 per cent for cubes and 4 per cent for beams. The sole exception to that rule was indicated. In Fig. 7 certain values were also indicated from the Code of Practice and also from the Road Research Laboratory, and those appeared to fall within the general picture.

From that straight-line relation one might be inclined to deduce a constant value between the crushing strength of a cube and the cracking load of a beam when cast from the same batch of concrete, but the relation between individual results was erratic. Fig. 8 was taken from site B and

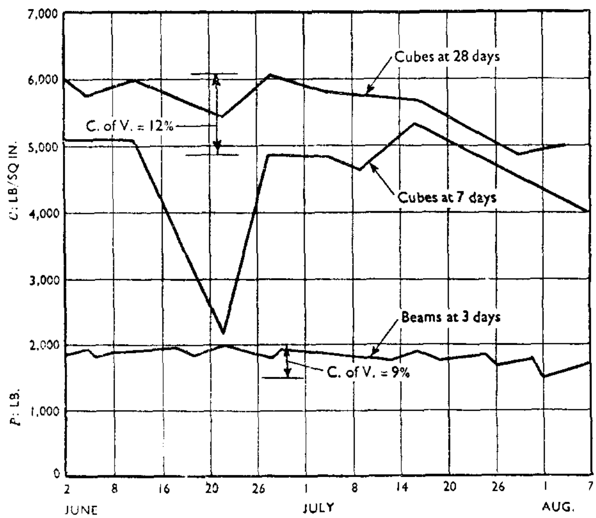

FIG. 8.—CUBE-BEAM RESULTS, SITE B

represented a typical 2-monthly period in which the crushing strengths of cubes at 28 days and at 7 days were shown with the cracking load of the beams at 3 days. It was seen that the general level of the strength of the cubes and the beams corresponded, but closer examination of the curves showed that the individual beam values tended to rise when the cube strengths were falling and *vice versa*, and that appeared to belie any close agreement between individual beam and cube values. It might also be noted, however, that a similar tendency existed between the crushing strength of cubes at 7 and 28 days.

In order to examine that effect more closely for the same site B, the beam cracking loads were plotted vertically to the same scale against the 28-day crushing strength of the cubes (see Fig. 9), and it was seen that the results fell within a grouping of an ellipse shape, of which the major and minor axes corresponded to a coefficient of variation for the cubes and beams of 12 per cent and 9 per cent respectively. Individual beam

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and cube results taken from the same batch of concrete were disposed at random within the ellipse—a high beam value corresponding with a low cube value and *vice versa.* A similar disparity might be expected, however, between individual results of the ultimate strength of the concrete as placed and the corresponding cube when cast from the same batch ; it was

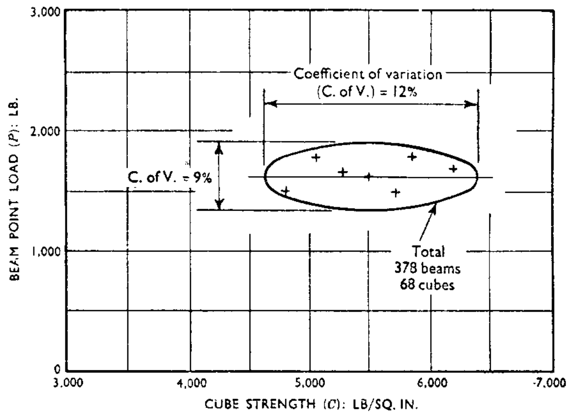

FIG. 9.—CUBE-BEAM RESULTS, SITE B

important to note that the variation in the beam results was less than for the cubes. From that it might be argued either that the beams were a more reliable guide to the strength of concrete in situ or that the beams were much less sensitive than the cubes to variations in the concrete strength.

To examine that question more closely, a laboratory analysis had been made in which four beams had been cast from each of three identical batches of concrete from each of sixteen different variations in cement/aggregate and water/cement ratios. For every beam the cracking load at 3 days and the crushing strength at 28 days for the two broken halves of the beam had been obtained. Typical results for two of the mixes, obtained from plotting the 3 days' cracking load against the mean 28 days' crushing strength of the two ends of the beam to the same scale, were shown in Fig. 10. In each case the variation in the cracking load was more uniform than for the mean of the crushed ends of the beams and the results fell within an elliptical shape of the form shown. In each group, also, the variation between the crushing strengths of the two ends of the beams corresponded to the variation between the mean of the crushing strengths of the beams within the group, which appeared to confirm that the beams were less erratic than the cubes and were, therefore, more reliable indicators of the strength of the concrete as placed.

It appeared that the beams might be employed as an Izod type of test in which the cracking load might be empirically used as a direct indicator

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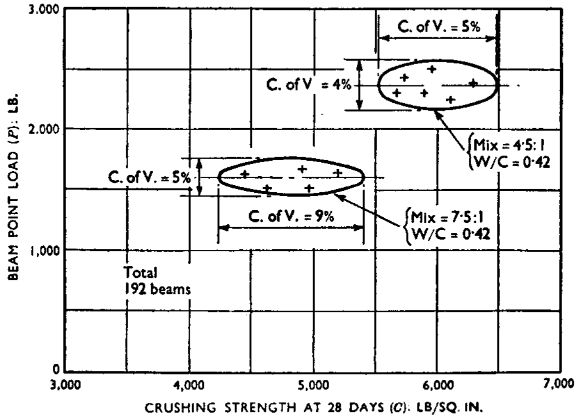

FIG. 10.—BEAM ENDS

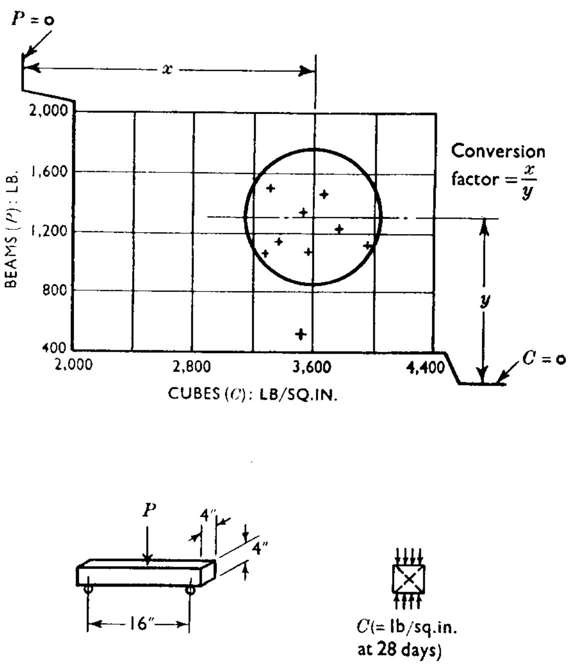

FIG. 11.—BEAM-CUBE FACTOR

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of the crushing strength without delving too deeply into the philosophical argument as to the relation between the strength of concrete in flexure and compression. The suggested procedure for the calibration of such a test was shown in Fig. 11, in which the conversion factor was determined from beams and cubes cast in the usual way from identical preliminary batches of concrete of the proposed mix. P denoted the mean cracking load of the beams at 3 days and C the mean crushing strength of the cubes at 28 days, from which the conversion factor $(F) = C/P$. Alternatively, C could be determined from the average crushing strength of the two halves of the cracked beam. During the running of the contract the cracking load of the test beams would then be converted into the probable crushing strength of the concrete in situ by multiplying by the factor F, and there seemed no reason to suppose that that beam procedure would give a less satisfactory answer than that imposed by the inconsistency of the concrete as placed.

Mr G. P. Manning (Consulting Engineer) remarked that the Authors had described how they thought concrete should be made and how it should behave after they had made it, but the proof of the pudding was in the eating, and it was of interest to look at the facts. Mr Manning showed a slide of a column where the weather had reached the steel, which had rusted and blown off its covering concrete. That was a typical and depressingly common sight. Probably much of the reinforcement in the prestressed post-tensioned work which was now being built would be in a similar state within 10 or 15 years. A second slide showed a view of the underside of a decking. The soffit of the external beam was split throughout its length, and the soffit of the internal beam had cracked and fallen away, exposing the main steel. That job had not been designed by a beginner and had not been built by a small firm of local contractors. There were in Britain quite a number of firms of some size who specialized in repairing defective concrete work, and there were many general contractors who undertook such work among their other activities. Mr Manning did not know the exact cost of that repair work, but it was probably not less than £1,000,000 per annum.

That was not all. Not only were new methods of repairing defective concrete being developed, but apparently the number of firms taking up such work was actually increasing. Did that mean that despite their research organizations and despite their post-graduate education in Britain their concrete technique was actually deteriorating ? Did it, in fact, mean that because of their research organizations and because of their post-graduate education their concrete technique was actually deteriorating ?

Who was responsible for that shocking waste of money every year on repairing defective concrete ? The fashionable answer was, of course, that it was the contractors' fault ; but Mr Manning maintained that the blame must be borne by all branches of the concrete industry. Considering first the academic branch, far too much literature was published which

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applied only to small quantities of concrete made under artificial conditions, and not enough literature which was really helpful in dealing with large quantities of concrete under site conditions. If there was to be any improvement in concrete technique in Britain, 75 per cent of the research workers must be taken out of the laboratories and placed on contracts, particularly medium-size and very small contracts, and in the various quarries and gravel pits.

Coming next to the "professional" section, he had started his career in the office of a firm of consulting engineers, but he had soon realized that there were many things about concrete which could not possibly be learnt in a consulting engineer's office, and that if he were ever to know anything about concrete he would have to join a firm of contractors. He had always maintained that no man should set up as a consulting engineer in reinforced concrete unless he had had at least 5 years, and preferably 10, as an active member of a firm of contractors. However, on the one hand he could not see any of the professional bodies insisting on such a stipulation, and on the other he could not see any improvement in concrete technique unless they would do so.

Dealing next with the contractor, Mr Manning maintained that he was more sinned against than sinning, and cited the following case. The contractor was invited to tender on a reinforced concrete job, and with the invitation he received a bill of quantities, a specification, and a few small-scale preliminary drawings. He took a quick look through the documents and a quick look at the site, rushed out a price and found that he had landed the contract. If it was a "modern" design he would find that he was expected to use a lean, dry, harsh mix of concrete, with the reinforcement in very small sections, inadequately covered, with no proper spacing between the bars to get the concrete down. The steel would be a lot of short rods with inadequate anchorage and no stirrups or bent rods to tie them together. The contractor knew that if he built the job in accordance with the design and specification in a few years time it would look deplorable. If at his own expense he substituted a rich workable mix of concrete, increased the sections and gave adequate cover and clearance between the rods, redesigned the reinforcement and substituted long rods with proper end hooks and bent-up rods, and provided asbestos-cement spacers to make sure that the steel stayed where it should, what happened? He went bankrupt and had to go out of business.

It was clear that the contractor was forced by financial considerations to supply only the minimum construction which would comply with the specification and the design, however bad those might be. If he turned out an unsatisfactory job apparently the legal responsibility rested on him, but the moral responsibility rested on the designer.

The Authors had mentioned the Code of Practice. Mr Manning had criticized that document in the past, and in his view there would be no progress in concrete technique until it was completely scrapped and

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rewritten from a newer and more practical standpoint. The committee which wrote the new code ought to include at least two experienced general foremen.

Mr F. N. Sparkes (Head of the Concrete Section, Road Research Laboratory, D.S.I.R.) said he had been associated with the Authors for many years and was familiar with the background of the work which they had described, but he would like to ask them some questions, the replies to which should help the practical engineer who was not a specialist concrete technologist to apply the information given in the Paper a little more readily than was perhaps possible at the moment.

The Authors discussed the theoretical aspects of the design of concrete mixes and then proceeded to deal with the practical implications. Mr Sparkes felt that no clear relation had been shown in the Paper between the theoretical aspects and the practical conclusions. The Authors had made certain theoretical assumptions in developing their theory, which he thought were not always valid. Why should there be any relation, for example, between the rhombohedral packing of spheres and the arrangement of the particles of, say, a crushed-rock aggregate in a concrete mix? In the Paper the theory dealt essentially with the packing of spheres but the application seemed to apply to the use of all types of aggregate—rounded, irregular, and crushed.

Another theoretical point was that the spheres were all touching each other. If they were then surrounded with a matrix there would be, in effect, a series of points in that structure which were not bound together by any cement film. That might be unimportant in the case of spheres so far as the development of strength was concerned, but it might be of more importance when dealing with non-spherical aggregates and when there might be area contact instead of point contact. The important thing from a theoretical point of view was that there must be a film of cement paste between the particles of aggregate and that seemed to upset the relation which the Authors had tried to establish between what they called major spheres, major occupational spheres, minor occupational spheres, and admittance spheres. It seemed to him that those values would have to be increased, depending on the thickness of the film of matrix surrounding the particles. He did not know what that thickness was, but the Authors must have had some difficulty with that because both had mentioned in introducing the Paper that they had found it necessary to increase either the sand content or the mortar content a little. The reason might be that the theory dealt with the condition when the aggregate particles touched each other, which in practice they did not do.

He was always a little doubtful about the desirability of applying theoretical considerations to the design of concrete mixes. It was always necessary to make certain assumptions such as perfect geometrical forms for the aggregates and certain conditions of packing. In the Paper the

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Authors also required that the value of the bulk density should be determined. The value obtained from a bulk density test depended largely on the way in which the test was done, and Mr Sparkes did not consider that it bore much relation to the bulk density of the aggregate when that aggregate was surrounded by a cement paste.

Another point was that the theoretical part of the Paper did not seem to take into account sufficiently the effect of workability of the concrete. It dealt essentially with the strength requirements, but the workability was just as important as the strength. It was no use designing a mix which would give an adequate strength if it was not possible to compact it because its workability was too low, or if there was segregation because it was too high. If the Authors could give more information about the aspect of workability in their mix-design method it would be helpful.

Mr Sparkes was not questioning the Authors' personal ability to apply their theoretical methods. The potentialities of gap-graded concrete could be fully realized only if somebody with the Authors' experience and knowledge supervised the job closely to get it started properly. It might lead to trouble if inexperienced people tried to apply the theories which the Authors had propounded.

Mr Sparkes observed that on p. 591 a number of technical advantages of leaner and drier mixes were mentioned, but all those technical advantages did not operate at the same time. For example, it was possible to obtain either a higher strength or a saving of cement, but generally not both.

In discussing the theory, it would be useful if the Authors would define the terms which they used on p. 594 for the various spheres which were mentioned. "Major occupational sphere," "minor occupational sphere," and "admittance sphere" were new terms to most people, and it was important to define them if the statement on p. 595 were to be accepted that "It is evident, therefore, from consideration of the processes of making a mix that only two particle sizes are of practical importance, the major and the admittance spheres." The other spheres must be known if that was to be accepted.

It was stated on p. 595 that "In general, the maximum size of aggregate should not exceed one-sixth of the distance between vertical shutter faces or between the base and surface of a slab." At the Road Research Laboratory they had found, in making test specimens as distinct from an actual structure, that they could work on a figure of 0·25, and it might be that in mass work, as distinct from reinforced work, such a higher figure could be used. In other words, the maximum size of the aggregate should not be more than one-quarter of the minimum dimension, and good compaction could normally be obtained under those conditions.

In paragraph (5) on p. 596 it was stated that the compressive strength of the cement should be known before the mix was designed. That implied that the cement which was going to be used through the work would not

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vary. It would be of interest to know the Authors' experience in that regard, because most engineers had practical experience of cements tested up to 28 days showing considerable variations on the site, and it would be useful to know how that affected the theoretical aspect of their mix-design procedure.

There was one point which he wished to make in connexion with the reference on p. 596 to Road Note No. 4. He did not propose to enter into an argument with the Authors on the relative merits of continuous and gap-graded concrete, chiefly because he thought that there was room for both methods, and that the method used should depend on the availability of local aggregates ; but in the past few years the Road Research Laboratory had had a number of results of concrete strength, from their own laboratory and others and from sites, which suggested that the figures given by the family of curves relating the water/cement ratio to strength in Road Note No. 4 were rather too low. The reason, they felt, was that modern cements were ground more finely than those used before the 1939–45 war. They were at present collecting information with a view to modifying those curves a little, if in fact it was shown to be desirable to do so.

Referring again to p. 596, the Authors in the example which they gave had chosen two single sizes for their coarse aggregate, but in the requirements for the job they said that the grading available was " $1\frac{1}{2}$ inch down to $\frac{3}{16}$ inch or in single sizes." They had chosen the single sizes, but they did not say why. It was extremely important, in order to get a proper view of continuous and gap-graded concrete, to know why with the choice open to them the Authors had chosen the single sizes. It would have been useful if they had compared the mix proportions of the continuously graded aggregate concrete and the gap-graded, to afford some comparison between the two.

It was important to know how the figures in Table 1 had been derived. Mr Sparkes presumed that they were for $1\frac{1}{2}$-inch aggregates, but the Authors did not say so. Unless it was known how those figures had been obtained the reliance to be placed on them in designing the concrete mix could not be assessed. He had no doubt that the Authors had based them on many years of experience ; if so that should be stated.

On p. 600 there were certain comments on road work with which Mr Sparkes did not entirely agree. It was stated that in the case of the concrete road " it has been found that, despite a very high degree of mechanization, the riding quality compares unfavourably with hand-placed work although, where mix control has improved, the durability of the concrete has been greatly increased." The riding quality of concrete roads laid by mechanical methods in Britain had not been so good as with the old hand-placed work, but he attributed that not to the introduction of mechanization but to the fact that in Britain there had been up to now few opportunities to use modern machinery in road work. On the Continent,

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where such opportunities were available, concrete roads were being produced with a riding quality which was second to none. He had recently been in Denmark and had driven over newly constructed roads which had an excellent riding quality. He thought that was because they used an experienced contractor and techniques of construction which lent themselves to good riding quality so far as the mechanization of road work was concerned.

Mr Sparkes did not see why improvement in mix control should improve durability. He thought that it led to more economical mixes and made for easier working on the job and good compaction.

Table 3 gave the results of a large number of tests from various jobs and might give a somewhat misleading impression of the nature of the variations which had to be dealt with in concrete work. For example, with a water/cement ratio of 0·50 the average compressive strength at 28 days varied from 4,597 (say, 4,600) lb. per square inch to 6,840 lb. per square inch, the latter figure being 1·5 times the former, which seemed a very large variation, even from job to job. With a water/cement ratio of 0·45 the variation was from 4,398 (say 4,400) to 7,459 (say 7,500) lb. per square inch, a ratio of 1·7. It would be useful to know to what the Authors attributed that variation. It was also noted that with a water/cement ratio of 0·5 design strengths of both 3,000 and 4,000 lb. per square inch were specified, and some explanation of that apparent inconsistency would be useful. Was the variation due to the use of different cements, different curing temperatures and so on, and were the cubes always made in accordance with B.S. 1881 ? He was not surprised that no appreciable relation had been discovered between the 3-day beam and the 28-day cube-test results. Mr Creasy's Figures were interesting, since they showed in all cases a much lower variation in the beam test than in the cube test. That might mean that the beam test was less sensitive than the cube test, and it might not mean that the concrete measured in that way was in fact more uniform.

Finally, if the Authors could give some information on the differences between the gap-graded-concrete method which they favoured and that normally used in Road Note No. 4, it would be very useful.

Mr C. K. Haswell (a Senior Engineer, Sir William Halcrow and Partners, Consulting Engineers, London) described the Paper as both interesting and controversial. It was controversial even to the title, which suggested a very wide field of view. That was not really the case since the Authors were, in general, putting forward a particular modern concrete technique, namely the use of a single-sized coarse aggregate, also referred to as gap-grading. As Mr Stewart had pointed out in introducing the Paper, one of the features of that was that the large stones were in contact with each other enabling the formwork to be removed very early in the life of the concrete. Bearing that in mind gap-graded concrete appeared to be a

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logical development, albeit in miniature, of the times when walls and arches had been formed of stone blocks set adjacent to one another without any cementing medium, as in prehistoric megalithic construction and in cyclopean masonry. The other modern development was, of course, colloidal concrete.

The conflicting requirements of the client and of the contractor were discussed by the Authors, as well as the sources of trouble which might be expected owing to, for example, the inconsistency of aggregates or human deficiencies. Even assuming that the technical ability, satisfactory materials and plant were all available, Mr Haswell was convinced that in the end the quality of concrete was largely dependent upon knowing the minimum requirement and accepting nothing less from the contractor. He thought that that was most important. The principle was, of course, not confined to the making of concrete. Indeed, it should be extended to placing emphasis upon the need for properly qualified concrete technicians, which was referred to at the end of the Paper. The contractor would thereby be forced to employ those skilled men in order to deliver the right quality end-product.

The Authors' mix design seemed to be based on the use of a single-sized coarse aggregate for all classes of concrete, because the basic idea sprang from the packing of single-sized spheres, as illustrated in Fig. 1. There were, however, several objections which seemed to outweigh the saving in cement possibly due to the richer mortar fraction available. To omit the smaller sizes of coarse aggregate must, when considering large quantities, tend to raise the unit price of the aggregate. Secondly, there must be extra costs in compacting concrete with reduced workability. Thirdly, with the volume of concrete being exactly equal to the displaced volume of coarse aggregate there remained no margin for any error in compaction. Except under very favourable conditions some segregation must occur. Indeed, that seemed to be confirmed by the Authors' remark on p. 603 that " it is possible and indeed desirable to strip away the form-work from walls and columns immediately placing has been completed in order to allow any faulty work to be seen . . ."

The Authors had rightly drawn attention to the advisability of studying the reinforcement in relation to its effect on the compaction of concrete. All too often that point was neglected by the reinforced concrete designer, who rarely appeared to be well versed in concrete technology.

Little mention was made in the Paper of cement as a variable, a point which had already been touched on by Mr Sparkes, yet wide differences existed between Portland cement from different sources. That could be significant, especially when the cement only just complied with B.S. 12, and other conditions were adverse for making good-quality concrete. A case could certainly be made out for having Portland cement divided into two classes ; that would at least reduce the range of one of the variables. Figs 12 and 13, which might be of some interest, showed differences in

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cement from the same source. Fig. 12 showed the variation in crushing strengths of cubes made from ordinary Portland cement delivered at the same time upon the same site and from the same manufacturer, the only difference being that part of the cement had been delivered in bulk and part in bags. The results showed quite a significant advantage in the strength properties of bulk cement as opposed to cement in bags, at any rate in that instance. Fig. 13 showed the relevant results of crushing tests on the concrete made with those consignments of cement. The same trend as that shown in Fig. 12 would be expected, but that was not the case.

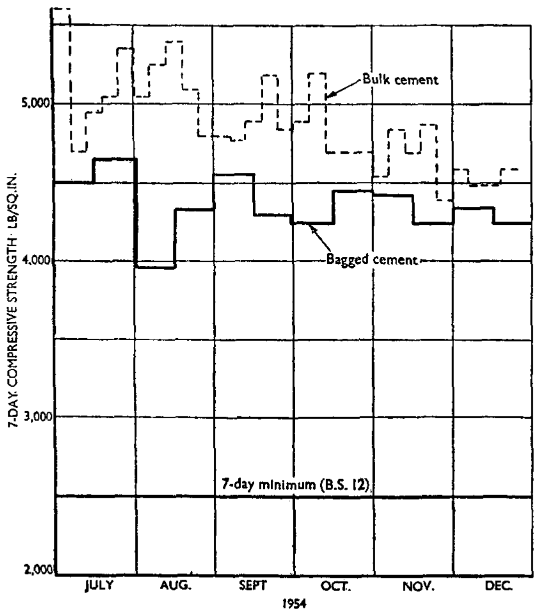

FIG. 12.—ORDINARY PORTLAND-CEMENT TEST-CUBE RESULTS FOR DIFFERENT CONSIGNMENTS FROM SAME SOURCE TO SAME SITE

The results shown were 28-day compressive-strength results and were similar in pattern to the corresponding 7-day test results.

In connexion with concrete surface finishes, the Authors referred to the washing down of the surface by means of a fine water jet shortly after casting. Mr Haswell had seen that performed in the laboratory. It certainly resulted in a very pleasing appearance and one which obviously had an application in the architectural field. The weathering properties of that surface finish, however, might well be doubtful, especially when considering possible damage due to frost action. In any event it was obviously worth a trial in practice.

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The Authors mentioned the reduction in heat evolution and shrinkage when using a leaner gap-graded concrete. Whilst the first part of the statement was obviously correct, it would be useful if the Authors were able to give some results of tests on the shrinkage of that type of concrete. Any appreciable reduction in the setting and drying shrinkages would obviously be of great advantage to the engineer.

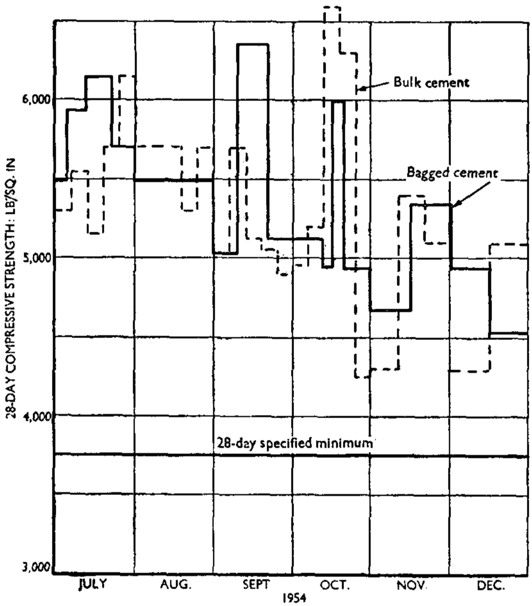

FIG. 13.—6-INCH CONCRETE-CUBE RESULTS FROM SAME MIX AND MATERIALS OBTAINED BY DIFFERENT CONTRACTS WITHIN SAME SITE

One problem which remained was that the results of concrete cube crushing tests were not available until the structure had hardened so much that it often involved considerable effort to have it destroyed. One possible way out of that difficulty was to employ non-destructive tests, but that technique did not appear to have reached the point where it could be used in practice. Another alternative appeared to be by autoclaving the cubes. That was known to hasten greatly the curing of concrete, but unfortunately the strengths for steam-cured concrete were not necessarily comparable to the ultimate strengths of normally cured concrete. However, it was possible to obtain a quick qualitative answer in that way and it might allow the engineer to decide whether the structure, or part of the structure, should be rejected when it was relatively green. Inferior work had often been accepted because the quality of the concrete had been found out so late that removal of the faulty work had become a major operation.

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Mr R. J. Hamilton (Supervising Engineer, W. & C. French Ltd, Contractors) observed that having had some unfortunate experiences with gap-graded concrete recently, he felt that there were difficulties which had been over-simplified in the Paper. It was true that under laboratory conditions it was possible to produce a strong and lean mix of concrete in which the sand content might be as low as 26 per cent of the total aggregate and in which the cement/aggregate ratio was as low as 1 : 9 or even 1 : 10. Under site conditions, however, various other factors caused difficulties which made concrete of that type extraordinarily difficult to work. On p. 594 the Authors dealt with the packing of spheres from a theoretical aspect, and then applied the theory to bulk concrete. It was noteworthy that in spite of the perfection of the packing conditions which were envisaged hand packing was to be used when material of the size to which the Authors referred as " minor occupational spheres " was present. The whole of the grading would be completely upset by the presence of such material in excess of $2\frac{1}{2}$ per cent by weight of the coarse aggregate.

That meant in practice that using a $1\frac{1}{2}$-inch rounded aggregate with sand to the extent of 30 per cent of the total aggregate, if there was 6 per cent of the material in that sand which exceeded $\frac{3}{16}$ inch, or alternatively if there was 4 per cent of stone which was under $\frac{3}{8}$ inch, there would be very considerable difficulty because the whole of the packing of the $1\frac{1}{2}$-inch stone would be upset. It was by no means exceptional to receive material from suppliers with those proportions of undesirable gradings present and whenever that happened there would be trouble.

When spheres were packed against a plane surface, the void content of the spheres which had eventually to be filled with mortar was over double the void content in mass work. That surface condition extended over a thickness which was about three-quarters of the diameter of the sphere. If that were applied to $1\frac{1}{2}$-inch aggregate then the volume of voids in the stone at a surface was very great and very different from that in mass work. The voids in the $1\frac{1}{2}$-inch stone in mass work were about 26 per cent, but in a wall 1 foot thick the voids would go up to 35 or 40 per cent. That meant either that the mix must be varied with every variation of section which was being poured or some average must be agreed on the concrete, so that in one place it would work easily whilst in another it would work with far more difficulty.

The Authors admitted on p. 591 that the effects of variation in grading and moisture content of the aggregate were reduced in the case of normal concrete. Mr Hamilton took that to mean that when comparing gap-graded concrete with normal concrete it could be said that the effect of variations with gap-grading were much greater than in the case of normal concrete. He agreed strongly with that statement. A gap-graded concrete was so sensitive that very minor discrepancies in grading, in batching, or in water content would set up difficulties and troubles which were out of all propor-

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tion to the errors creating them, and which would never have been suspected nor have arisen with an ordinary graded concrete.

The contracting firm with which Mr Hamilton was connected had approached gap-grading with an open mind and considerable enthusiasm. It had been hoped that it would be possible to produce a concrete of adequate strength and sound finish without unduly increasing the expenditure on labour in placing and consolidating. There were certain restrictions on the choice of stone and sand. After 4 months' experiment, however, no concrete had yet been placed without an expenditure of labour in placing and in vibration at least double that on similar contracts where continuous graded aggregate had been used, and the surface finish was in many places the poorest ever produced under his supervision. Any saving in cost through economy in cement had been far outweighed by the increased expenditure on labour and by the general loss of progress. All the plant used had been new; it included a three-bin hopper and weigh-batcher, an open paddle-type mixer, and internal vibrators operating at a frequency of 10,000. All those types of plant had been extensively used by them for the production of high quality concrete with water/cement ratios down to 0·35 and had given excellent results elsewhere. The labour force had also been changed to make sure that the trouble was not caused by faulty workmanship, but the change had had no effect whatever.

Mr Hamilton had had considerable discussion with other contractors, in view of the difficulties which his firm had experienced; and, whilst it was possible that his approaches had been unfortunate or to the wrong people, he had yet to find one contractor who showed any enthusiasm for gap-graded concrete or who would not be prepared to change to normal continuous graded material and bear the additional cost of the cement himself.

Dr L. J. Murdock (Manager, Central Laboratory, and member of the Board of Management, George Wimpey & Co. Ltd) gathered from the Paper that the Authors felt that concrete should be made only from gap-graded aggregate, which, assuming a maximum size of $1\frac{1}{2}$ inch or $\frac{3}{4}$ inch, appeared to exclude the use of all material between $\frac{3}{8}$ inch and No. 7 mesh in reinforced concrete work. If that was so, it would presumably be necessary for the producer to regard that material as waste and, hence, to raise the prices charged for the other sizes. The effect of such an increase in cost of aggregate was important since the aggregate was considerably the larger constituent of concrete.

The Authors complained of a wide variation in grading and bulk density of coarse and fine aggregates, and whilst Dr Murdock agreed that improvements could be made by many of the suppliers he doubted whether it would be economically practicable to reduce the variation in grading to the extent the Authors apparently desired. In his view the finer particles of the aggregate had far more influence on the workability of the concrete than

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the larger sizes, the effect decreasing roughly in geometrical progression. He thought that the greater effort should therefore be made to provide sand of constant grading by means of the classifiers which were now being introduced, rather than in efforts to produce more or less single-sized coarse and fine aggregate to satisfy gap-grading requirements.

The Authors also complained that lack of skill on the part of the labour employed was a source of trouble but did not state clearly how they would improve matters. Dr Murdock was convinced that the greatest benefit would accrue from more training of the supervisory staffs, as for instance, foremen and chargehands, and that every encouragement should be given to the men in those categories to attend training courses, such as those for City and Guilds certificates in Concrete Practice now being held in many technical colleges.

The Authors listed a number of technical advantages to be gained from the use of leaner and drier mixes, and, whilst he would agree that a reduction in shrinkage was an advantage, he doubted whether that attributable to a change from continuous grading to gap-grading was of practical importance. A reduction in creep might be a disadvantage, since creep tended not only to offset cracking and other troubles due to shrinkage, but also to relieve high stresses which might be set up in a structure owing to foundation movements, temperature stresses, etc. He also doubted the claim of better weathering for leaner mixes and he could not understand the argument concerning the possibility of higher working strength, since the major factor governing strength was water/cement ratio and not the leanness or otherwise of the mix. He could not agree with the Authors, therefore, that such technical advantages as might be gained by the use of leaner and drier mixes were of sufficient importance to offset the undoubted increase in cost of mixing, handling, and placing in reinforced concrete structures. He agreed, however, that the leaner and drier mixes though not necessarily gap-graded were advantageous in road work for which heavy vibrating machinery was practicable and in mass concrete, particularly dams, for which the reduction in heat evolution with leaner mixes was of importance.

It was normally considered desirable that not more than 1 or perhaps 2 per cent of cubes failed to comply with the minimum strength required. That appeared to be a lower proportion of cube failures than was indicated by a statistical analysis of the results given in Table 3 of the Paper as being acceptable to the Authors. Judging from the mean strengths and the coefficient of variation, on only one-third of the sites were the cube failures likely to amount to less than 1 per cent of the cubes tested. On sites 19 and 27 Dr Murdock estimated cube failures to amount to about 15 per cent, and on site 4(*a*) to as many as 35 per cent of the cubes tested. Further examples were sites 3(*a*), 3(*b*), and 4(*b*) with more than 100 cubes tested on each, so that a statistical analysis could be expected to give quite an accurate assessment, and yet the estimated number of cube failures was

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4 to 6 per cent. In view of that analysis the saving in cost of cement quoted in the last column of Table 3 was in many cases false, since the concrete was not fulfilling the specified requirements.

On the site it was rarely practicable to obtain a sand which varied less than was indicated by the limits of one of the four zones in the new B.S., and with such low proportions of sand as those suggested by the Authors he felt sure that should the sand become appreciably coarser than that for which the mix was designed, then it would become unworkable and honeycombing would result. It was quite impracticable on the site to keep changing mix proportions with every new load of sand which arrived, and Table 6 gave the mix proportions he would use to produce workable

TABLE 6.—RECOMMENDED MIX PROPORTIONS TO MEET STRENGTH REQUIREMENTS OF 3,000 LB/SQ. IN. AT 28 DAYS, USING LONDON RIVER GRAVEL AGGREGATE

Workability		Mix proportions by weight			
Slump: in.	Compacting factor	Weigh-batching using sand from		Volume-batching using sand from	
		zone 2	zone 3	zone 2	zone 3
½	0·81	1 : 2·6 : 4·3	1 : 2·3 : 4·3	1 : 2·5 : 4·0	1 : 2·2 : 4·0
1½	0·90	1 : 2·2 : 3·7	1 : 2·0 : 3·7	1 : 2·1 : 3·4	1 : 1·9 : 3·5
4	0·94	1 : 2·3 : 3·1	1 : 2·1 : 3·2	1 : 2·1 : 3·0	1 : 1·9 : 3·0
Over 6	0·98	1 : 1·9 : 2·7	1 : 1·8 : 2·3	1 : 1·8 : 2·5	1 : 1·6 : 2·6

The effective water/cement ratio should not exceed 0·55 when volume batching and 0·58 when weigh-batching.

concrete with a minimum compressive strength at 28 days of 3,000 lb. per square inch suitable for all sands falling either in zone 2 or zone 3 of B.S. 882. The mix proportions given were for London area gravel aggregate only, and it should be noted that all mixes with slumps of 1½ inch or more were richer than the nominal 1 : 2 : 4 mix required by the British Standard Code of Practice.

Table 2 gave limits of aggregate/cement ratios from the latest Ministry of Works specification. Dr Murdock would go so far as to suggest that if those ratios were adhered to and no more than 1 per cent of cubes were allowed to fall below the minimum specified, then the mix required would be so dry and stiff for structural purposes that the finished concrete would cost more than more workable richer concrete, for the reasons already given.

He disagreed with the statement of the Authors on p. 598 that it was only with vibrators that it was possible to obtain uniform and approximately

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complete compaction of concrete. Good compaction was largely dependent on the use of concrete having a workability which was suited to the method of compaction adopted, whether by hand or by vibration. He disagreed also with the Authors' claim that the use of vibrators necessarily resulted in practice in a denser, stronger, and more durable concrete permitting some concession on the cover to the reinforcement. The cover to the reinforcement for structures exposed to the weather was all too often too small already, and there was insufficient regard to the working tolerance necessary in the bending and fixing of reinforcing bars, particularly of the larger sizes.

Concrete from which the shuttering could be removed immediately could as readily be made with a continuous grading as with a gap-grading, and that practice had been in common use in the cast-concrete-products industry for at least 30 years. In building and civil engineering the shuttering could only be removed immediately in a limited range of structural members, and casting cycles were likely to limit further the usefulness of that attribute of vibrated dry mixes.

He disagreed entirely with the belief that the only method of producing good concrete was by the use of gap-grading, low proportions of sand, lean mixes, and vibration. The civil engineer was required to produce a satisfactory structure as economically as possible and to do that it was necessary for him to make the best use of local materials readily available.

Concrete mixes which would fulfil that object could be designed with continuous as well as gap-gradings and Dr Murdock suggested that the tendency should be to over-sand a mix rather than to risk honeycombing, with the accompanying serious loss in strength and high permeability due to the presence of insufficient fine material adequately to fill the voids between the coarse aggregate. Further, he would suggest that the emphasis on lean gap-graded mixes for structural reinforced concrete in the Paper was misplaced and that any saving in the cost of cement was more than offset by the extra cost of handling, placing, and compacting.

Mr I. S. S. Greeves, (Superintending Engineer in charge of dock works, John Mowlem & Co. Ltd, London), commenting on the Authors' statement that contractors preferred to use high cement contents and wet mixes because they were easy to place and compact, said that a contractor was seldom able to have things his own way. On occasions the structure which the contractor was called upon to build might have been designed by someone of high technical ability but of very little practical experience. On a recent contract the reinforcing bars had been so numerous and closely spaced that it had been necessary to use a mix of $\frac{3}{8}$-inch aggregate with a high slump. It had been impossible to get a vibrator between the bars, or between the bars and the shuttering, and the only way to place the concrete had been to have it sufficiently fluid so that it flowed and then to prod it where it was possible to do so.

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Contractors might go to the other extreme and use very stiff mixes, particularly where prestressed concrete was employed, because when making precast members the increased use of shuttering obtainable through stressing the units at a quicker rate might well pay for the extra cost of placing the concrete.

Mr Greeves felt that Mr Manning had not been quite fair in the slide which he had shown of the deterioration in the column, first because Mr Greeves believed that it was an example from a gas works, and secondly —a much more important point—the work being done now on repairing concrete was on structure about 30 or 40 years old, for which their predecessors had used all-in ballast and very little cover. In most of the cases which he had seen recently the bars were very near the surface and weather had penetrated, or there had been honeycombing. Probably in another 30 years, with the concrete now being used and with the knowledge that was being gained, the firms which repaired defective concrete, the number of which Mr Manning said was increasing, would be out of work.

It was not possible to generalize on how rich the mix should be and whether gap-grading should be used or not. There was, however, a point which was sometimes missed, particularly where very stiff mixes were in fashion. It was that with reinforced concrete there was a danger that the concrete might be very good but that the bond between it and the reinforcement might not be so good.

Mr Greeves regretted that the last section had been included in the Paper, because he would have thought that a discussion on rates of pay would be much better left to the Conciliation Board of the Federation of Civil Engineering Contractors. However, as it had been included, there were one or two points which he would like to make. Possibly the Authors had not had a vast amount of experience of the control of site labour. Judging by the results in other industries, higher wages did not necessarily guarantee greater effort or higher skill. The introduction of the trade of concretor could cause many problems. For instance, what happened to the tradesmen on days when no concrete work was being done ? Did they sit down and refuse to " muck in " with the rest of the gang on excavation, drain laying and other day-to-day jobs which normally the concrete gang had to do, or did they revert to their basic labour wage ? If the latter, the time-keeper's job with P.A.Y.E. would become still more complicated, because he would have to keep a tally of the days on which the men had their concreting money and those on which they did not. The Authors said that weigh-batching was a trade, but in Mr Greeves's opinion it was no more difficult for a man on a weigh-batching plant to use the correct weights than for a porter to weigh luggage at a railway station. In fact the porter had a more difficult task because he was weighing different weights each time, whereas the weigh-batcher applied the same weight. What would happen if the concretor were absent from the gang ? Would it be permissible to upgrade a labourer, or would the job be stopped

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because there was no man with the required union ticket to fill the gap ?

Mr Greeves believed that a better way to get really good concrete was to employ a contractor who took a pride in his work and who had a high reputation to uphold and who maintained a permanent staff of engineers, foremen, and gangers skilled in the art of concreting. All that the Authors' suggestion would do would be to force up the cost of concrete without necessarily improving the final result. It was the contractor's site engineers and foremen who were responsible for the quality of the concrete on any job.

Mr Roderick Cameron (a Civil Engineer, Ministry of Works) said that as one of the Ministry of Works engineers referred to in the Paper he wished to make a few observations on the use of the formula in practice. He did not agree with Mr Greeves's suggestion that the Ministry's methods were instrumental in raising costs. On at least one site in London last year their advice had been accepted by Mr Greeves's firm in producing a 7 : 1 concrete for 4,000 lb. per square inch. Mr Cameron had often spoken to the ganger and site engineer concerned, and there had been no objections whatever from them to the use of the mix.

Reference had been made to the increase required in the sand beyond the amount laid down in the formula. Whatever theoretical reasons might be given, Mr Cameron regarded that increase as a factor of safety against segregation and variation in the aggregate grading. When using the formula it was important to have suitable aggregates, because if the aggregates were not suitable—in other words, if they were continuously graded aggregates—then the answer given by the formula was useless, even as a rough guide. He would prefer to say that if the aggregates were suitable then the answer given by the formula was useful as a guide. Anyone who tried to design concrete on a site using a formula, getting a mathematical answer and adding certain percentages and leaving it at that, was courting disaster. It might work, but equally it might not.

As a matter of interest he had analysed a number of mixes which they had used in the past 3 years and he found that 75 per cent of those mixes used a gap-graded concrete. By " gap-graded " he meant a mix with the coarse aggregate stopping at $\frac{3}{8}$ inch, or with a fine sand. Mr Cameron agreed that workability could not be calculated and he knew of no practical method of measuring it on the site. Fortunately the reaction of a well-proportioned mix to vibration was quite a sensitive guide, and was in his opinion the best way of measuring workability. What did the Authors consider a workable concrete ? Mr Cameron suggested that for most cases, except in high-strength prestressed work, a workable concrete was one which could be compacted by one modern high-frequency vibrator at the rate of not less than 5 cubic yards per hour. Some speakers, particularly from the contractors' side, who had condemned the Authors' methods outright,

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might be interested in that figure because it was what the Ministry expected to achieve. It meant one vibrator to the output of a 14/10 mixer.

The Authors inferred on p. 601 that vibrated mixes never had more than 30 per cent of sand. That might be generally true, but he had known cases where mixes designed by the methods described had needed 32 and 33 per cent.

Referring to the Tables in the second half of the Paper, Mr Cameron suggested that the use of statistics in concrete control on small sites could easily be over-rated, especially bearing in mind that on few sites of that type were as many as fifty cubes made and tested at a given age. What it amounted to on Ministry of Works sites was an increase of 1,500 lb. per square inch for trial mixes, which meant that for 3,000-lb.-per-square-inch concrete they seldom went beyond a 0·55 water/cement ratio. However, Mr Cameron considered that the time had come when the average strength should be considered when specifying concrete, not in place of but in addition to the minimum strength. If the average was specified at 4,000 lb. per square inch for the 3,000-lb. mix which he had mentioned, a more intelligent interest on the part of the site control might follow. He did not suggest than an average of 4,000 lb. per square inch would always be sufficient to prevent not more than 1 per cent of cubes failing, but it would be a step in the right direction.

Table 4 contained sites where quality control was not enforced and the average in at least six cases was too low. It was stretching a point to call any of the first three mixes a 3,000-lb. concrete, he agreed ; but Table 3, which referred to quality controlled jobs, seemed to show that, by keeping the average more than 4,000 lb. per square inch for 3,000-lb. concrete, they had achieved their purpose, except perhaps in one case where a cube was obtained as low as 2,335 lb. per square inch. In effect, that meant that in nearly every case the average had been the criterion. In Table 5, job 1, in which quality control had been enforced, the average was still too low and quite a number of cubes could be expected to fail. Specifying an average of at least 4,000 lb. per square inch would have obviated that, and it was quite a practical proposition and well worthy of consideration.

Mr A. G. Hall (Director, Alexander Hall & Son (Builders) Ltd, building contractors, Aberdeen) said that during the past 3 years the mixes for the concrete required for a number of contracts which his firm had carried out in Scotland had been designed by Mr Stewart. Those contracts had been mainly for the three-or-four-storey-and-basement type of building, some of them for the Ministry of Works, where a guaranteed strength was specified, and others for engineers whose specifications called for concrete in accordance with the Code of Practice, and which had been later altered by agreement to guaranteed-strength concrete, leaving the mix design to Mr Stewart and Mr Hall's firm. It might be of some interest, therefore, to describe how they had tried to translate the theories and mathematics in

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the Paper into terms and techniques which could be readily understood and put into practice by the average general foreman.

Their approach to the matter of gap-graded concrete was conditioned by the fact that they had ample and cheap supplies of all grades of aggregates in the north east of Scotland, both rounded and crushed, and they had therefore been able to experiment freely. When the gap-graded mix had been designed they had found that site control was relatively simple. They had used a single-sized aggregate, mainly 1 inch, and a fine sand; fortunately deliveries to that specification were obtainable without a great deal of trouble. They had impressed on the site foreman that he must watch the sand to see that he at no time got a coarse grading which would force the coarse aggregate particles apart, causing voids and the appearance of under-sanding. The other point of control which was important was to impress on the foreman the necessity to adjust the gross weights of the aggregates and the added water in order to take into account the water content in the aggregates themselves. They had found that the placing ganger soon learnt the technique; a good understanding between him and the mixer operator was essential. Those two were the key men, and it had been found that their enthusiasm and co-operation were improved if it was explained to them that their job was at least as important as that of any of the building craftsmen; and, in spite of what had been said by Mr Greeves, Mr Hall's firm paid them accordingly.

With gap-graded mixes designed for vibrators they had experienced a good deal of trouble with plant. The sand content was critical and they had found, from experiments which they had made with the ordinary tilting-drum type of mixer, that 15 per cent of the sand of the first batch stuck inside the drum when the batch was discharged, and similarly with the second batch. The third batch got indigestion and all the sand came out, so that there were two batches under-sanded and one grossly over-sanded. That applied to some extent to rotary-drum mixers also. They had made some improvement by taking out half the paddles, but the rotary-drum mixers had to be set dead level or the water, when put in the drum, tended to run towards one half of the drum resulting in half the batch being too wet and the other half too dry. The most satisfactory type of mixer was the flat pan type, but it was cumbersome and expensive to buy; also they had found that it needed excessive maintenance. None of the mixers on the market which they had seen provided an instant and accurate means of adjusting the water from batch to batch, and they regarded that as important. They had found that the best arrangement was to set the mixer to discharge a fixed amount of water and to top up with a separate arrangement through a petrol-pump type of meter, which was instantly adjustable and accurate to within 1 lb.

A good deal of trouble had occurred with vibrators, mainly from breakages of the flexible shaft, and they had found that for every three vibrators in use one was needed as a standby, which seemed excessive. If

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the full advantages of gap-graded vibrated concrete were to be obtained, considerable improvements were needed in the mechanical equipment involved. One serious difficulty was the consolidation of thin slabs, where vibrators could not conveniently be used. In those circumstances they had found that the only answer was to consolidate by hand, lowering the aggregate/cement ratio to give greater workability while maintaining the water/cement ratio to preserve the strength.

With regard to the economics of gap-graded guaranteed-strength concrete they found it impossible to be precise since it was difficult to get two precisely similar jobs from which to take accurate time studies. The saving in cement, which would appear to be even greater where higher strengths were required, was offset by the additional cost of equipment (vibrators, weigh-batchers, and water meters) and laboratory tests, as well as the additional cost of the materials themselves. They found that a gap-graded concrete weighed about 5 per cent more than that made from aggregates to B.S. 882. There was, however, an appreciable saving in shuttering costs. The shuttering could be stripped more quickly and therefore it could be re-used more frequently, thus reducing the total quantity and the total capital expenditure required. After experimenting with most types they had found that the factory-made standardized strong timber frame, with renewable plywood faces, was the most economical and adaptable. High-strength concretes of 5,000 to 6,000 lb. per square inch could be made reasonably easily and relatively cheaply. It might well be that the real economies of gap-graded concrete would come from designs using those higher strengths with more use of manipulated and high-tensile steels and smaller concrete sections; that would result in a reduced area of shuttering, which on a building job normally cost more than the concrete itself.

Mr J. D. McIntosh (Section Leader, Concrete and Construction Research Sections of the Research Division, Cement and Concrete Association) referred to the Authors' statement that they did not propose to discuss the question of workability and said that the Cement and Concrete Association had examined experimentally the compressive strength and workability of gap-graded and continuously-graded mixes. Fig. 14 showed sets of curves of compressive strength plotted against compacting factor for three types of aggregate; the mixes had a cement/aggregate ratio of 1 : 6 by weight. The compacting factor was taken as the measure of workability, but they had also checked against values of slump, values of time taken to compact the concrete in ordinary cube moulds, and visual observation by the people handling the concrete; so far as they could tell, all the methods of assessing workability seemed to agree.

Each little group of points on a curve represented a particular water/cement ratio; within the groups were circles representing continuously

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graded mixes and crosses gap-graded mixes, and there were four or five points of each type in a group, representing different proportions of sand. The curve was an envelope line which represented the highest strength for the highest compacting factor, and therefore the optimum mix from the point of view of the contractor. It could be seen that there was a similar number of crosses and circles approaching the curve indicating that, for any particular richness, the same workability and the same strength could be obtained for both gap-graded and continuously graded mixes, provided the optimum sand content was used for each. Mr McIntosh suggested that there was therefore no particular advantage, if thinking primarily of compressive strength and workability, in using either a gap-graded or a continuously graded mix. Whether the aggregates available gave gapped or

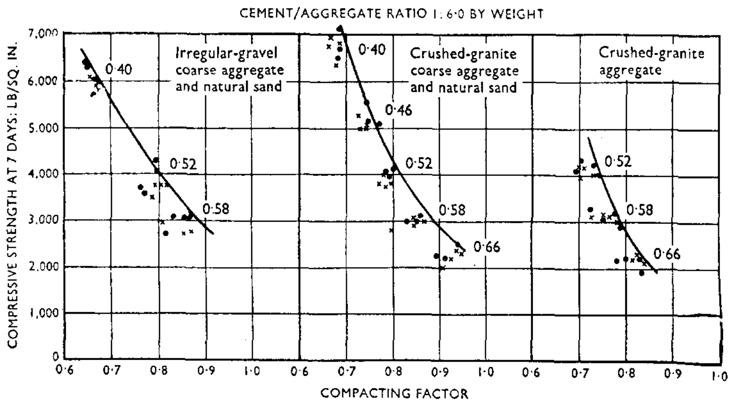

Fig. 14

continuous gradings they felt that it was technically possible to get concrete of similar quality.

It was sometimes said that the coarse aggregate particles in gap-graded mixes were touching each other and that therefore a specimen of concrete would not shrink as a whole because there was a continuous skeleton of coarse aggregate. Even if that were so the cement would not stop shrinking so that the mortar between the particles would contract and tend to break away from the particles. However, they had made some tests with gap-graded and continuously graded mixes, with equivalent gradings as indicated in Fig. 14, and they had found that the drying shrinkage and moisture movement of the two types of concrete were not significantly different. The average shrinkage and moisture movement were slightly less for the gap-graded mixes, but the difference was negligible for practical purposes.

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*** **Professor A. A. L. Baker** (Professor of Concrete Technology, Imperial College of Science and Technology) observed that the Authors made no reference to making adjustments to the mortar content during the process of concreting. The influence of the shape of the mould and the degree of concentration of reinforcement were mentioned as factors which affected the proportion of mortar required to fill the voids. Thus, in structures in which the section of the mould and the reinforcement varied, there would arise the need to vary the mortar content slightly during the process of concreting, and the amount of variation could not be satisfactorily predicted.

How did the Authors propose to deal with that difficulty ? Should not the practice of the skilled and experienced concreting foreman of adding a little additional mortar, as and when he deemed it to be necessary, be regularized, and the limit of the permissible extent of such intervention by him be carefully defined ?

Mr Francis Walley (Civil Engineer, Structural Engineering Branch, Ministry of Works) said two separate topics seemed to have been dealt with, and he would have thought that for clarity they should be completely separated. Mr Stewart had referred to single-sized aggregates, whilst Mr Bate had been more concerned with the omission of part of the grading, usually part of the fines.

The first method might lead to supply troubles from the pits, whilst the second had none of those troubles; he doubted whether a contractor using such a designed mix would know it was gap-graded except for the difference in workability.

The expression "gap-graded" should, Mr Walley considered, be reserved for mixes where the size of the coarse aggregate was restricted to one single size or at the most two. The great exponent of that method was Valette, who delivered a Paper on the subject to the International Association for Bridge and Structural Engineering in 1948, and amplified it giving the rules for the design of such mixes in a Paper [3] for the Institut Technique du Batiment et des Travaux Publics.

A further contribution [4] to that subject might also be noted—that of Professor Bolomey of Switzerland, and his conclusions were worth while quoting:

> "The choice between continuous and gap grading will depend upon local conditions. Natural occurring ballast is normally composed of particles of all sizes: in this case continuous grading is the economic

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

[3] M. R. Valette, "*Composition des Bétons*" ("Concrete mixes"). Ann. Inst. Tech. Bat. Trav. Publ., New Ser.—Béton. Béton Armé No. 6 (Mar.–Apr. 1949).

[4] J. Bolomey, "*Granulation continue ou discontinue des bétons*" ("Continuous and gap grading for concrete"). *Tech. Travaux,* vol. 24, p. 254 (Jul.–Aug. 1948).

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method. If, on the other hand, sand and stones are obtained separately, it may be better to adopt a gap grading. In this field, as in others, care must be taken to avoid fixed rules and preconceived ideas ; a decision must be based on the materials available, avoiding an excess of medium-sized particles."

What Mr Walley felt the Paper demonstrated more than anything else, was that by designing a mix, as opposed to merely utilizing a nominal mix, it was possible to " lean " down the mix and obtain a good quality concrete. In the course of demonstrating that it pointed out that an omission of part of the grading resulted in a better all round mix. Above all, it was a plea for designing mixes. The use or otherwise of single-sized aggregates was an off-shoot and not the main issue.

Mr I. M. Wallis (Agent to Messrs G. E. Wallis & Sons Ltd, London) said that site No. 21, for which data were given in Table 3 was a site upon which he had been employed for a year. The materials had been checked daily for water content and the necessary adjustments made to the weigh-batching of aggregates and water. He had been personally responsible for the records and he was quite certain that the water/cement ratio used was 0·39, not 0·45 as shown in Table 3.

Gap-graded rounded aggregate had been used throughout the job, and with a water/cement ratio of 0·39 a very workable mix with a very high compacting factor had been obtained. It had thus been possible to place the concrete at a rate of more than 6 cubic yards per hour ; but taking into account also the time spent in rubbing the green surfaces, after striking, with wood floats, that figure should be taken as the usual working rate.

The gap-grading of the aggregates had cost the supplier considerable time and labour, for he had found it necessary to dispose of almost as much material in the smalls as he was able to deliver to site.

The following information regarding site No. 21 might be a useful addition to the data given in Table 3 for that site :—

Specific gravity of sand	2·63
,, ,, ,, aggregate	2·59
Density of aggregate delivered to site . .	104 lb. per cubic foot

By making use of the formulae given on pp. 595–596 it would be found that the ratio of sand to combined aggregates would be 21 per cent. (In practice, a ratio of 25 per cent had been used and found satisfactory.)

Maximum obtainable fluid density would be	155·23 lb. per cubic foot
Maximum attained on site was	155·00 ,, ,, ,,
Minimum attained on site was	149·00 ,, ,, ,,

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On the basis of those figures, the compacting factors would be :—

Maximum	0·998
Minimum	0·959
Average over 60 cubes tested	0·977

Summing up, it had to be admitted that it was very unusual to be able to use such an aggregate with such a sand ratio ; however, in that case, by careful control of the water/cement ratio, good results and especially good workability had been obtained. The variation percentage had been high but that was probably the result of variations in the supply of gap-graded aggregate. Such aggregate, if used to any great extent, would always be an expensive item to be considered by the contractor at the tendering stage.

Mr J. S. M. Willis (Chief Assistant Engineer, Sheffield Waterworks) observed that the Authors, in their example of mix design, specified "fair" control and related to that a control factor of 1·33, which multiplied the minimum (or structural design) strength to the maximum (or mix design) strength ; i.e., under works conditions, the minimum strength was to be taken as 1/1·33 or 75 per cent of the maximum. In Road Note No. 4 it was stated that that proportion required "very good control with weigh batching, moisture determinations on aggregates, etc., constant supervision." Did the Authors indicate a rise in standards of control since the Road Note was published or did they believe it to be unduly pessimistic ? Incidentally the curves published in the Road Note showed a strength of 4,000 lb. per square inch (28 days) to correspond with a water/cement ratio of more than 0·6, not 0·56–0·58 as given.

The aggregate/cement ratios in Table 1 appeared to hold good for very low workability concrete only. Was it the Authors' belief that adequate and skilled mixing, placing, and vibration made such mixes suitable for all normal works ?

There was no doubt that quality concrete was best specified by its guaranteed strength, but that led to a practical difficulty in site control. Assuming that placing, etc., was satisfactory in each case a concrete specified by its mix could easily be checked at the batcher ; if thereafter the concrete was found to be deficient in strength the fault must be presumed to be with the design of the mix and therefore with the engineer. On the other hand, where a guaranteed strength was specified and the aggregate/cement ratio was set within wide limits, was the contractor to be permitted to vary the water/cement ratio at will or was that also to be set within limits ? If the latter, there was the risk of a contractor claiming that in the particular circumstances obtaining he could not attain the strength within the limits set ; whilst if he was left quite free to choose the water content he was continually tempted to increase it to obtain maximum workability. If he succumbed to that temptation, sailed too close to the wind, and the strength dropped, that would not be known for

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some days. Two alternatives were then open, to remonstrate with the contractor and request him to use less water, or to order the removal and replacement of the offending concrete. Neither of those was satisfactory; if the concrete then supported other and later work, the former and weaker alternative might be unavoidable.

It would appear better then to give the contractor the choice of a mix, to test and approve it, and then to take the agreed mix in its exact proportions as part of the specification and to base the site control of mixing upon those proportions rather than upon strength tests.

Mr G. B. Gifford Hull observed that the tests described in the Paper and the study generally, appeared to have been made on material supplied by "the aggregate supply industry" (top of p. 591), but in some countries there was no such industry and aggregates for concrete must be obtained without that specialized help.

Under the heading of "Heating, shrinkage, and permeability" some useful and accurate comments were made on concrete for a dam. Did the Authors consider, however, that for a gravity dam sufficient advantage was gained to justify the expense of grading the aggregates. In his experience first-class dams—first class in strength, weight, and watertightness, which were, as the Authors had correctly stated, the main desiderata—could be built with straight crusher-run aggregate less some of the dust. If that view could be substantiated and publicized by those who had the facilities for making comparative tests, it would be of great help to those who had to build dams, especially in countries where there was no aggregate supply industry and where men had to rely upon their own efforts to produce the aggregates necessary.

It would surely be of great help to those concerned with gravity dams in the sparsely populated regions to which the Authors had referred, and to which Mr Hull's remarks were wholly confined, to know that there was no need for:

(1) the purchase of screening plant, and to face the effect on a work schedule which delayed deliveries caused;
(2) outlay on transporting and erecting it;
(3) power and operators to run it;
(4) maintenance and renewal of worn-out screens and other parts;
(5) separate stockpiles of the various sizes requiring separate handling equipment.

First-class work could be produced at a better rate of progress and with less trouble and at less cost without any of the foregoing.

In that connexion the concrete for a dam 200 ft high now being built in the Far East was made from crusher-run aggregate with jaws kept to as nearly $2\frac{1}{2}$ in. as was practicable. For the heart, the mix was one part low-heat cement, 5 parts of fine and 7 parts of coarse aggregate by weight, with a water/cement ratio of about 0·80, and the average 90-day strength

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for the year 1954 was 3,180 lb/sq. in. Concrete for the face was, of course, made for watertightness and was also made with the same crusher-run aggregate—sand and cement being modified to give a 1 : 2·7 : 3·9 mix with a water/cement ratio of 0·52. Tests for the watertightness of that mix, which were made on month-old concrete cylinders with an outside diameter of 18 in. and walls 4 in. thick, with water pressure applied at the outside, showed them to be watertight in the sense that no dampness had appeared within 24 hours at 100 lb/sq. in. In fact many rings had been watertight at more than 150 lb/sq. in.

Under the heading of " Client and contractor " the Authors had referred briefly to the advantages of leaner and drier mixes. So far as mass work was concerned, some of the advantages enumerated had been known since the construction of the Vyrnwy Dam, but they had not been stressed in Papers on concrete presented to the Institution as often as they deserved. Mr Hull was sorry to note from the Paper that the conflicting requirements of client and contractor had now, in the United Kingdom, reached a stage when a serious effort must be made to reconcile them and questioned whether that was really the case. It was one of the engineer's functions to see to it that such a tug of war, which was apparently a common occurrence, did not take place. Mr Hull found it difficult to imagine why a contractor should want to use a rich wet mix when the engineer had specified a lean dry one. If the engineer specified concrete which met the client's view as given in (*a*), (*b*), and (*c*), and the contractor knew it would not be easy to mix and place, he could charge more for it and the client would still get good value for money. Both client and contractor wanted to make a profit and they were therefore equally interested in the durability of the structure, the former for the annual profits or other benefits from it, and the latter for his reputation. If the interests were indeed so conflicting then the serious effort at reconciliation which the Authors advocated should undoubtedly be made. Had they had time to consider how best it could be done ?

Mr M. Spindel (research engineer and consultant) remarked that it was important that the theoretical aspects of the mix design should be based on the absolute volumes of the main components of concrete, i.e., cement, aggregates, water, and air. The percentages and ratios of those four absolute volumes, especially in the freshly placed concrete, were known to have a decisive effect on the compressive strength obtained and on other important properties of the concrete. He had dealt with those important relations in his so-called " Four Matter Parallelogram." It had been used for the design of concrete mixes with regard to the qualities of the fresh placed and hardened concrete since 1928. Then the air voids were caused only by trapped air and not yet deliberately entrained in the concrete.

The results given in Table 3 showed the mix proportions, and the aggregate/cement and water/cement ratios, but neither the void/cement

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ratio on which the compressive strength depended, nor the volume weights of the concrete from which the void/cement ratios could be calculated. Since one of the concretes given in Table 3 had air-entrained, and even well designed and properly vibrated concrete, if it was lean and very dry, might still have a certain percentage of air voids, a supplement to Table 3 showing densities and voids in the concrete would be useful.

The size relation of the small and large particles of which concrete was made was of fundamental importance, especially so for the extremely gap-graded concrete used by the Authors. Such an extreme gap-grading was used at the very beginning of concrete making when the usual fine sand used for masonry was mixed with coarse aggregate of large size only, i.e., of about 1 in. to 2 in. That original gap-grading was soon replaced by continuous grading according to various formulae, such as to the "Fuller," "Bolomey," "EMPA" and other well-known grading curves. Those were not equally satisfactory for every type of structure. Therefore, special types of gap-grading were developed, having several gaps and thus giving the necessary flexibility according to the type of structure, etc.

The Authors used two important methods for obtaining, so far as possible, good results with their extreme gap-graded concrete.

(*a*) By calculating for a rhombohedral packing of the coarse aggregate, considered as spheres, the available space for the fine aggregate, again taken as spheres, to find the necessary space in the coarse aggregate, without increasing its voids.

(*b*) By using the most effective means of compacting concrete, i.e., by vibration.

Yet several important problems were still left open. It was not taken into consideration that the cement, too, consisted of solid particles of different sizes and therefore a similar size relation had to be considered between cement and sand as between sand and coarse aggregate. Mr Spindel had investigated and published the size relation of the former on the same basis of rhombohedral packing in 1913. He had pointed out that for the cement particles the minor occupational sphere was about one-fifth and the admittance sphere about one-seventh of the major sphere of the sand. It was then found that a mortar made of a very fine sand even in the proportion of 1 : 1 had neither sufficient strength nor impermeability. A finer standard sand was therefore necessary for testing cements. The question of sands too fine for concrete was still very important.

Although the modern vibration method was a great help for making the extremely gap-graded concrete further questions remained to be considered, such as segregation, the ratio between the areas of coarse aggregate and mortar on the surface of the structures, internal stresses due to the prevention of shrinkage of the mortar, resistance to weather and frost, etc. Those tests would certainly have been made, but some results would be of interest.

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It might also be of interest to have some information on the time of vibration, which in the latest German Standard Specification for concrete vibrating (DIN 4235) were given as about 11, 16, 22, or 29 sec for layers of 30, 50, 75, and 100 cm respectively.

Of similar importance as the proportioning of concrete and size relation of the particles of concrete were the modern surface active agents, the so-called admixtures to cement and concrete, for improving the chemical and physical reactions between cement, water, aggregates, and air—resulting in many improvements in the making and placing of concrete and in its various properties. Their use would certainly help to overcome some of the difficulties shown by the Authors and stressed in the discussion.

Some details were published recently in a Paper by Duriez.[5]

Professor H. N. Walsh (Professor of Civil Engineering, University College, Cork) said the Paper should help to improve specifications and control of concrete making. The part dealing with the theory of mix design was necessarily so short that some points were not made clear. Thus it was not clear whether the bulk density of the coarse aggregate was to be determined in the standard rodded condition or in a vibrated condition. If it was the latter the calculation of the weight of sand would depend on the assumption that the coarse aggregate occupied the same space in the compacted concrete that it did in the bulk density test. It was difficult to accept that. In the concrete each stone was coated with a film of mortar or paste which increased its effective diameter and prevented it coming into as close contact with its neighbours as when vibrated alone in a measure. Furthermore, some particles must be separated by small pebbles jammed between them. There must be some bulking of the coarse aggregate in the concrete as compared with its volume when its bulk density was being measured in the vibrated compacted condition. That view was supported by Lezy.[6] After having dealt with a method of calculating the weight of coarse aggregate to be used in 1 cu. m of concrete, Lezy referred to finding that weight approximately by reducing the vibrated bulk density of the coarse aggregate by 3 to 5% for 25–60 mm coarse aggregate and by 6 to 8% for 10–25 mm concrete. If, on the other hand, the bulk density was determined in the rodded condition less bulking would occur in the concrete and such allowances would be smaller.

Another difficulty occurred in connexion with the calculation of the volume of sand. Apparently like other methods of design based on voids

[5] M. Duriez, "*Les adjuvants du béton: plastifiants, entraîneurs d'air et produits colloidaux. Conditions d'emploi*" ("Admixtures to concrete: plasticizers, air-entraining agents and colloidal products. Conditions of use"). *Suppl. Ann. Inst. Tech. Bat. Trav. Publ.*, vol. 6, June 1953, p. 569.

[6] M. R. Lezy, "*Détermination du Dosage d'un Béton Hydraulique a Compacité Optimum*" (Design of Concrete Mix). *Ann. des Ponts et Chaussées*, Nov.–Dec. 1952, p. 717.

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that method led in some cases to calculated proportions of sand that were too low for practical use. The third condition on p. 594 for applying equations (2) and (4) in practice was that " the volume of sand calculated from equations (2) and (4) should be sufficient to give an approximately uniform distribution when combined with the other materials during mixing. If the value obtained from equation (4) is less than 18 per cent, this uniformity of distribution is difficult to obtain even under laboratory conditions." What was the procedure in such a case ? Was it simply to increase the proportion of sand and correspondingly decrease the coarse aggregate ?

Some amplification of the treatment of those points would be welcome.

Mr J. S. White said he had been a close observer of the Authors' methods where attempts had been made to put them into practice on large sites.

Workability was an essential property of fresh concrete and he would like to ask the Authors for their definition of it, since he believed that the Authors' conception of workability was quite different to that of most present-day concrete engineers. How did the Authors assess and compare workabilities ?

With regard to the coarse/fine ratio and mix stability, the Authors had mentioned the dangers of aggregate segregation and mix segregation but had failed to point out that the latter danger was often increased by using gap-grading, which the Authors recommended. Furthermore, when the mixes were proportioned by the use of the formula (2) the trouble was further aggravated. If the careful theoretical balance between water and sand was upset by the unavoidable fluctuation of the water/cement ratio under practical conditions, there was no reserve of sand to prevent segregation, control was extremely difficult and the appearance and behaviour of those mixes was disturbingly erratic.

Bulk densities to the nearest lb. were used to calculate specific bulk densities to three places of decimals, in order to arrive at a figure for the percentage of sand. The latter figure, therefore, was quite sensitive to changes in the bulk density figure. In the example quoted, if the stone bulk density had been taken as 102 instead of 96 lb/cu. ft the figure for sand was 22% as against 26·8%. Mr Stewart's method of obtaining that figure for bulk density was still apparently to fill a 6-in.-cube mould once with the stone, tap it with a steel float, and weigh the contents. Did not the Authors consider that there was weakness both in the method and in the formula ?

Mr White observed that using a $\frac{3}{4}-\frac{3}{16}$-in. irregular gravel and a water/cement ratio of 0·43, Table 1 gave a suitable aggregate/cement ratio as approximately 6 : 1. Formula (2) gave a sand percentage of 16·7 for a stone bulk density of 102 lb/cu. ft. A column was cast with that mix with the utmost difficulty by a skilled gang at the maximum rate of $\frac{1}{2}$ cu. yd

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per hour. The result was a "poker hole" at the top of the lift which defied all attempts to remove it, and the top layer of the work was completely devoid of all fines for a depth of several inches. The work was repeated using ever increasing amounts of sand until a column was finally cast in which there was no hungry layer. The amount of sand required to produce a satisfactory job was approximately 60% more than the theoretical figure. The formula inferred that if the sand was increased the water must be decreased, but naturally that would only have made placing impossible.

Similar trials to those described above were carried out under similar conditions by a member of the Authors' staff, using various aggregate/cement ratios and gradings of irregular gravel. The gravel was washed and graded by hand sieving, and batching and mixing were under laboratory conditions. Table 7 gave a summary of the results.

TABLE 7

Aggregate/ cement ratio (Table 1)	% sand (formula (2))	Design W/C ratio (Table 1)	Actual W/C ratio (extra water added)	Coarse aggregate : in.	Mean 7-day cube strength : lb/sq. in.
7 : 1	24	0·44	0·60	$1\frac{1}{2}$–$\frac{3}{4}$	4,725
					3,100
8 : 1	24	0·52	0·64	$\frac{3}{4}$–$\frac{3}{8}$	2,125
8 : 1	25	0·52	0·66	$\frac{3}{4}$–$\frac{3}{16}$	2,562
9 : 1	26	0·54	0·73	$1\frac{1}{2}$–$\frac{3}{8}$	2,087

Note.—The design water/cement ratio gave unworkable mixes and water was added until the mix could be placed. During the final mix the vibrator shaft broke due to overloading. The inference to be drawn from columns 3 and 4 was obvious.

The above examples gave some idea of the speed and difficulty of placing the Authors' mixes. How many contractors were willing to use the method of "pattern vibration" suggested by the Paper. Mr White agreed that it was necessary but was it practical ?

How many engineers were willing to risk leaving a vibrator tunnel in a structure, resulting from a few square inches missed by the vibrator ?

Had the Authors verified with the trade unions that men could be persuaded to handle two or more vibrators as suggested ?

Had the Authors heard the comments of typical Merseyside gangers when asked to place those mixes even with one vibrator ?

Was not the phrase "effective range" of the vibrator meaningless when at the same time it was stated that on withdrawal the poker should leave a hole ?

The Authors had failed to consider whether the saving in cement claimed more than outweighed the extra costs for mixing, handling, and placing, and for added wear and tear on plant when using ultra-low workability

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concrete. During a period of 20 weeks of placing such a mix fifty-two vibrator breakdowns occurred involving repairs of one day's duration. Did the Authors consider that figure excessive ?

The Authors had used the nominal mixes of the Code of Practice as their basis for assessing cement saved. Would it not have been more realistic to have used a more up-to-date method of proportioning such as that of Road Note No. 4 as a basis of comparison ?

Reference had been made to only one unsatisfactory case. Did that mean one out of those mixes which the contractors had agreed to adopt ? Would the Authors please give an amended figure for the number of unsatisfactory cases, to include those mixes which the contractors could not be persuaded to adopt ?

Mr White disagreed not only with the number of unsatisfactory cases quoted but also with the reasons given for its failure. He wished to correct the Authors on the following points :—

(1) The 9 : 1 mix referred to was never used in the slab. It was unplaceable by the most powerful vibrators available.
(2) The first mix to be adopted was 8 : 1 gap-graded using $1\frac{1}{2}$–$\frac{5}{8}$-in. stone. It did not contain any material less than $\frac{5}{8}$ in.
(3) The above mix was taken from the mixer in single loads, by Muirhill dumper.
(4) The mix finally adopted after 9 months of trial mixes was 7 : 1 continuous graded. That was satisfactory.

Mr White suggested that the Authors should produce data from large sites, not only statistical data but some details of method and rate of placing, men and plant employed, and so forth. Furthermore, the methods of proportioning outlined would require some modification before they could win general confidence and support.

Mr D. C. McKay (Civil Engineer, Ministry of Works), referring to the list (pp. 595–596) of information required before a mix could be designed, suggested that the most complete answer to the question of the type of aggregate and the gradings available would be an actual visit to the quarries concerned. The expense of those visits would be well repayed.

On p. 596 under water/cement ratio it was stated that from Road Note No. 4 a strength of 4,000 lb/sq. in. could be attained at 28 days for a value of 0·56 to 0·58. Referring to Road Note No. 4 for 4,000 lb/sq. in. concrete at 28 days, the value given for the water/cement ratio was 0·62. Would the Authors please signify where they had obtained those values ?

Under mix design data on p. 597 a list was given of typical coarse/fine aggregate ratios. It would be seen from Table 8 that the percentage of sand had been increased in each case. Those figures had been obtained after a considerable number of trial mixes carried out on sites in various parts of Britain. The formula suggested by Mr Stewart had, as Mr Bate

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TABLE 8

	Coarse/fine aggregate ratios	
	Authors' figures	Suggested by Mr McKay
Crushed rock	70 : 30	67 : 33
Irregular gravel	75 : 25	72 : 28
Rounded gravel	78 : 22	75 : 25

had stated later, been the basis of mix design but it had been found that its application was limited. So often the materials available at an economic price were just not suitable but with a slight increase in the calculated value for the sand content, the mix had been satisfactory. The low sand contents were definitely obtainable but not very often at an economical price. One other thing discovered had been concerned with the grading of the coarse aggregate. There was no doubt that the greatest cause for inconsistent concrete so far as grading was concerned was the excess percentage of material between $\frac{3}{8}$-in. and $\frac{3}{16}$-in. sieve sizes. Mr Stewart in his example had a gap in the grading from $\frac{3}{4}$ in. to $\frac{3}{16}$ in. That, of course, would work with a fairly rounded gravel but it had been found that for anything other than a rounded gravel a small proportion of material between the $\frac{3}{4}$-in. and $\frac{3}{8}$-in. sieve was very helpful.

It was stated on p. 591 that one of the technical advantages of leaner and drier mixes was that better weathering was produced. Would it be correct to assume that better durability was then obtained in both walls and slabs and if that was so, had the Authors carried out experiments to substantiate it? Using a leaner and drier mix, the tendency would be to use less fine and more coarse aggregate so that there would only be a very thin layer of mortar on the surface of the slab or wall. If either the wall or the slab were exposed to excessive wear then when that layer was removed there might be a tendency for disintegration. Had he found that?

On p. 593 after outlining the formula to be used in mix design the Authors stated certain conditions necessary so that equations (2) and (4) might be applied in practice. That surely answered much of the criticism on gap-graded concrete. It should be made quite clear that the methods suggested by the Authors were not the be all and end all of mix design. Often the conditions necessary to apply the Authors' method were not available, then it would be necessary to resort to the common practice of using continuous grading, etc. It was quite ridiculous to keep trying to make the mix work when it began to get uneconomical. That had happened to a number of engineers in the past few years, who had not fully appreciated the conditions necessary for applying the Authors' methods, hence the method had gained a certain amount of criticism.

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Mr L. B. Aylen observed that the design (p. 593) was based on the assumption that good graded aggregates were available. Unfortunately, quarries in remote districts of the country were seldom equipped to supply graded aggregate—especially in the limestone districts. The inclusion of a large percentage of limestone dust was inevitable—a variable quantity and quite unpredictable. Few quarry owners showed any enthusiasm to supply well graded stone in the specified proportions to a contract running for a few years, being satisfied with their local markets.

It would seem, therefore, that until greater pressure was brought to bear on those suppliers by more rigid demands on the part of local authorities, and inspection or some system of licensing quarries prepared to expend capital and improve their antiquated machinery and methods, that "design mix" would be confined to areas where the conditions specified on p. 593 of the Paper obtained.

Professor J. W. H. King observed that Mr Bate, when introducing the Paper, had indicated his hopes for a reliable non-destructive test of concrete and had shown a slide of an ultrasonic velocity test in progress.

During the past 5 years more than 3,000 such tests had been carried out at Queen Mary College, and there appeared to be little evidence that such a test would ever be of value as a site control. The following experimental results, which were typical, would perhaps throw much needed light on the snags present in the method.

(1) A concrete of composition $1:1\frac{1}{2}:3:0{\cdot}675$ and a mortar of composition $1:2:0:0{\cdot}5$ had the same velocities as one another at 3 days, and at 28 days. The concrete had crushing strengths at those ages of about 600 and 2,000 lb/sq. in. respectively, and the mortar of about 2,500 and 5,000 lb/sq. in. Thus neither the strength nor the rate of gain of strength was indicated by the velocity.

(2) The concrete mixes shown in Table 9 all had the same transmission velocity.

TABLE 9

Mix	Age	Crushing strength : lb/sq. in.
$1:2:0:0{\cdot}5$	17 months	7,860
$1:1\frac{1}{2}:3:0{\cdot}6$ $\frac{3}{8}$-in. aggregate	14 days	2,340
$1:1\frac{1}{2}:3:0{\cdot}5$ $\frac{3}{8}$-in. aggregate	3 days	2,165
$1:2:3:0{\cdot}5$ $\frac{3}{8}$-in. aggregate	3 days	2,215
$1:2:3:0{\cdot}5$ $\frac{3}{4}$-in. aggregate	3 days	1,437

(3) In an attempt to use ultrasonic methods as an early control 24-hour velocities were taken on cubes subsequently tested at 28 days, with the results shown in Table 10.

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TABLE 10

Mix * (cement : aggregate : water)	1 : 3½ : 0·5	1 : 4½ : 0·56	1 : 5½ : 0·6	1 : 6½ : 0·65
28-day crushing strength (lb/sq. in.)	5,170	4,500	3,500	3,220

* Graded aggregate used up to ¾ in.

Apart from the particular figures quoted above, the general facts were :—

(*a*) Extra water and extra aggregate had opposing effects on the velocity so that a lean over-wateıed mix would give the same test as a richer drier mix. (Results (3) were a case in point.)

(*b*) After 3 days or so, the rate of change of velocity was very slow, whilst concrete strength gained was still fairly rapid. Thus a false picture resulted. For instance, the mortar quoted in results (1) and (2) above had a very small velocity change from 28 days to 17 months. Thus even with one specified mix, accurately made, the error in predicted strength resulting from a small error in velocity measurement could easily amount to 1,000 lb/sq. in. as the concrete age increased.

(*c*) At early ages in the laboratory where only one variable was known to be present at one time the method had some measure of value, since any single change would usually effect the velocity. Since the effects on velocity were not necessarily in phase with the effects on strength (e.g., velocity increased with leaner mixes, as well as drier mixes) nor in proportion, there seemed to be no future for the method as soon as a second variable appeared, whether by accident or design. It was therefore of negligible value as site control method.

The Authors, in reply, stated that their intention having been to stimulate interest in an admittedly difficult problem, they were very pleased at the amount of controversy aroused. Since workability had been referred to by several speakers in the discussion, it seemed preferable to deal with it in a general manner.

First, the Authors had used that word in a practical sense. A workable concrete was one readily compacted by the methods actually in use on site and, since the Paper referred almost entirely to vibrated concrete, workability must be understood to mean a concrete which would quickly reach its maximum density when vibrated. When designing a mix for normal work it was the practice to aim at a degree of workability which permitted the compaction of not less than 5 cu. yd/hour of concrete per vibrator, the vibrators being of the poker type requiring an input of

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about $1\frac{1}{2}$ h.p. For high-quality concrete required for prestressed concrete a lower workability would be used. It was unfortunate that there was no simple test for workability giving quantitative results. The practice on Ministry of Works sites was to fill an 8-cu.-ft wooden box with concrete, insert the vibrator, and observe the time taken to level out the surface and show a line of mortar all round the sides of the box including the corners. If the sample failed to reach that condition in about $\frac{1}{2}$ min the workability was considered unsatisfactory.

In considering the results in Table 3 it should be remembered that nearly all the contracts referred to were relatively small (500 to 3,000 cu. yd of concrete) and that it was not practicable to institute all the controls which were possible on large works. It was for that reason that the control was described as "fair." That had a bearing on some of the points raised by Dr Murdock and others, which would be dealt with in detail later.

It had been found that the coefficient of variations of the flexure tests was always less than that for the crushing tests on corresponding cubes or beam ends, and the Authors were interested in Mr Creasy's suggestion of an Izod type of test for control purposes. It was proposed to try the suggested method on early contract.

The Authors agreed with Mr Manning that defective concrete was far too common and it was that very fact which had caused them to experiment with methods for improving the quality of concrete generally. The most important development in concrete-placing technique of recent years had been the introduction of vibration, but it had not been sufficiently appreciated that concrete mixes suitable for placement by hand were not suited for vibration.

In the opinion of the Authors the use of properly designed mixes with vibration was the answer to Mr Manning's troubles. The Authors agreed entirely with his proposal that every design engineer should have served for a period on the works side, preferably with contractors.

Mr Sparkes raised a number of points regarding the theoretical and practical aspect of mix design.

Basically the Authors believed that a mathematical approach to the design of concrete mixes was not only logical but desirable. They also accepted that, in common with much engineering design, there should be a considerable element of art involved if the design was to prove successful.

The use of spheres allowed complete mix designs to be made on paper of an idealized form in which all aspects such as voids, specific surface, and bulk densities could be calculated and later examined and checked experimentally because of the possibility of being able to purchase suitable manufactured aggregates of spherical form. The reason for taking rhombohedral packing was because it represented the densest possible packing of single-sized spheres and was the type of packing which tended to arise when an irregular assembly of single-sized spheres was subject to

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appreciable vibration in a relatively large container. The same tendency to increase density of packing took place with single-sized aggregates irrespective of their origin or shape. That surely was a logical connexion which provided the licence for considering the subject mathematically. The divergence of practice from theory occurred from three causes :—

(1) Variations in grading.
(2) Variation in particle shape.
(3) Difference in the degree of compaction attained by the vibration applied in the field compared with that applied in the laboratory per unit volume.

The variation in particle shape was often brought about by the introduction of crushed material into an aggregate supply normally rounded or irregular.

Referring to the sphere sizes mentioned on p. 594, the major occupational sphere was of a diameter to nest exactly in the central void formed by the five spheres in Fig. 1. If another major sphere, diameter D, was nested in the hollow formed by the top sphere (No. 5) and any two adjacent spheres of the base grouped, say Nos 3 and 4, a void would be formed at the point indicated in Fig. 1, into which a minor occupational sphere could be fitted prior to locating the other major sphere. It was obvious that the only way of getting those occupational spheres into position was to build them into position manually ; it could not be done by the normal methods of placing concrete. It was further obvious that a concrete made from spheres of the sizes D, $0{\cdot}41D$, $0{\cdot}225D$, and $0{\cdot}155D$ would be bound to show serious segregation of the two intermediate sizes.

A concrete made with the aggregate sizes D and $0{\cdot}115D$ would, however, give quite satisfactory results, because the smaller sphere could infiltrate between the larger. It was instructive to note that the four sizes of sphere mentioned showed a close relation with the B.S. sieve ratios.

The subject of point contact in its importance in respect of strength was extremely academic since in general the coarse aggregates were only displacers of mortar and the number of possible points of contact in the mortar and cement paste itself were very much greater ; so far as the Author knew no one had worried about those to date. There was a very real difficulty about the lodging of large sand particles between pieces of coarse aggregate and thus increasing the void space above that anticipated when making the design. That condition arose, to an appreciable degree, when the coarse aggregate was flaky or when the fine aggregate contained a considerable percentage of coarse flat particles and was deficient in material below the No. 25 sieve. Materials of that sort required that the voids in the coarse aggregates should be artificially increased, that was, the weight of coarse aggregate per cubic foot reduced and additional mortar be provided to fill the space. Usually the mix had to be increased in richness to give the required finish, and to permit more water being added to provide adequate workability for a particular strength.

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The reduction of the true bulk density of the coarse aggregates per unit volume allowing the introduction of a larger volume of sand was the continuous grader's haphazard method of obtaining a result which could be more easily reached by adopting gap-grading design.

Mr Sparkes asked for a clarification of the difference of method in determining a mix by the Authors' system and that given in Road Note No. 4. To examine the matter fully would occupy too much space but the main features could be described reasonably briefly.

Road Note No. 4 divided aggregates into three categories, rounded, irregular, and angular. It also supplied four type-gradings and a set of curve families showing the relation between workability, aggregate/cement, and water/cement ratios for each of two aggregate-size ranges, three shape categories, and four gradings. With the assistance of a set of strength water/cement ratio curves and the other curves provided in the Note, concretes of any required strength and workability were said to be obtainable. However, shape characteristics of the coarse material seldom lay within those sharply defined categories nor could available grading often be made to comply with any of the type gradings especially in regard to the sand which was assumed to be constant in its effect except insofar as the quantity used affected the workability of the concretes. The Note gave therefore what amounted to a set of fixed Tables derived from a prolonged and meticulous research on materials and their performance confined within a relatively narrow range of variability compared with what the engineer met in practice ; from those Tables it was hoped to design a complex particle assembly having certain fixed characteristics in the fresh and set state. In all that mass of information there was no attempt to examine the packing characteristics of the main materials forming the concrete except in regard to the grading which in itself provided very little vital data.

It was obvious that a compacted concrete should be an organized system of particles of sizes and quantities best suited to form a homogeneous mass. If that was agreed, then the way in which the particles packed together and the number, shape, and size of the voids formed in the system were of vital interest. Therefore in the method of mix design advocated by the Authors the bulk density, apparent specific gravity, and the ability of the fine material to infiltrate into the coarse compacted aggregate was examined and noted. The data thus obtained was used in the design of the mix taking into account the mode of placing.

The Authors agreed that in most concretes designed in that way up to 4% of sand was added to that shown by the calculations.

There were perfectly good reasons for doing so, which were the following :—

(1) As a result of grading and shape variation in the aggregates the bulk density of the coarse aggregate was likely to vary and

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where it decreased harshness and honeycombing would result.

(2) The calculations were made on a basis of dry sand and since sand at sites contained from 2 to 12% of water a shortage of sand could easily arise despite sporadic moisture checks by the Clerk of Works.

(3) With semi-dry mixes used in vibration it was common to find sand sticking in the mixer from time to time thus giving rise to a shortage of sand in the concrete. Furthermore, many mixers gave a very uneven distribution of the mix materials so that unless an excess of sand was present the segregation produced by the " mixer " became both obvious and serious.

(4) Although shuttering was improving in design and construction, leakage frequently occurred at joints and at those points of leakage grout was lost, producing local honeycombing.

Finally the Authors considered that an addition of 16 lb. of sand in 100 lb. was a relatively small factor of safety for an in-situ-made material formed largely from untreated material ingredients compared with the 200–300% required by structural engineers in their design.

The Authors summarized their answer to Mr Sparkes's last question by saying that Road Note No. 4 offered a method of mix design based on arguing from the particular to the general whereas the Authors' method treated each case on its own merits, which they considered the more scientific.

In the Paper they pointed out that there was no means of calculating workability from a knowledge of the physical properties of the aggregates, the cement content, and the water present in a mix. They knew that there was some connexion between the specific surface of the combined aggregates and the workability but that connexion appeared to be rather erratic. That might be seen by an examination of the compacting-factor curves for Road Note No. 4. The figures in Table 11 had been extracted as an illustration :—

TABLE 11

Aggregate		Grading No.	Sand : %	W/C ratio	A/C ratio	Compacting factor
Type	Size					
Angular	¾ in.	1	30	0·6	7·3	0·85
,,	,,	2	35	,,	,,	0·835
,,	,,	3	42	,,	,,	0·81
,,	,,	4	48	,,	,,	0·76

In that research the sand type and particle shape of the sand was constant for all mixes and since in general the bulk of the surface area of

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the aggregates was supplied by the sand the total surface of the mix would increase as the sand content increased. It would be noted that the variation in the value of the compacting factor was erratic when compared with the sand contents, because a change from 30% to 35% of sand reduced the C.F. value by 0·015, whilst an increase from 42% to 48% of sand reduced the C.F. by 0·05.

Experience had shown that with the Authors' method of design by increasing the sand content above the calculated minimum for the packing characteristic of the coarse aggregate, the workability usually improved until an optimum quantity of sand was present in the mix. After that, any addition of sand reduced the workability, the water content and the W/C ratio having been kept constant throughout.

With reference to the difficulty of obtaining both cement economy and increased strength the Authors would call the attention of Mr Sparkes to sites 2 (a) and 27 in Table 3 where the leaner mix had a compressive strength approximately 1,000 lb/sq. in. greater on average.

The curves in Fig. 15, which related to a particular investigation on the relation between strength and A/C ratio, showed that in all cases the compressive strength of the concrete increased as the aggregate content of the mix increased.[7]

It was noted that the Road Research Laboratory were able to obtain satisfactory results with the use of $\frac{3}{4}$-in. aggregate in 4-in. cubes. That was no doubt because the weight of $\frac{3}{4}$-in. aggregate present in such a cube would be less than in a similar cube made in conformity with the Authors' system of design. It was obvious that provided that sufficient mortar was present in the mix one piece of 2-in. aggregate could be incorporated in a 4-in. cube.

Part of Mr Sparkes's queries on the strength variation in concrete having the same W/C ratio were answered by Mr Haswell's comment and Figures on cement variations. The fact that cements varied from works to works as well as from batch to batch was well known ; it was one of the reasons why the Authors had indicated the desirability of making tests on the cement that it was proposed to employ on the contract when designing the mix for the job. It should be noted that the workability of the concrete was affected by the physical characteristics of the cement, a point not taken into account in Road Note No. 4.

Mr Hamilton had pointed out the difficulties which might and occasionally did arise in using gap-graded concrete. The Authors agreed with him that an appreciable change in either or both the grading and bulk density of the coarse aggregate could have an unfortunate effect on the behaviour of the concrete. That was also true of continuous grading but was ordinarily attributed solely to the grading variation. However, the

[7] D. A. Stewart, " Economic factors in the choice of aggregate grading in relation to quality control." Symposium on Mix Design and Quality Control. Paper No. 16, p. 317, C. & C.A., London, 1955.

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presence of 4% $\frac{3}{8}$-in. stone was not serious if it was known to exist, provided that (*a*) the sand was suitable in regard to maximum particle size and (*b*) the bulk density of the coarse aggregate was measured and samples had the correct percentage of $\frac{3}{8}$-in.-down material present. Where the sand was coarse in relation to the void sizes then the total sand content would have to be increased so that sufficient of the " effective " filler was present.

The Authors agreed that a properly designed and made gap-graded concrete was more sensitive to variation in water content and in aggregate. That was an advantage in their opinion since it imposed a more realistic control on the contractor than could be accomplished by volumes of specification and expensive supervision. Mr Hall's remarks seemed to indicate that one contractor had found that to be the case. It was regretted that Mr Hamilton's first experience with the use of a so-called gap-graded concrete had proved abortive. It was thought that undoubtedly his difficulty had been due to the use of what was termed a good class A sharp concreting sand and that the substitution of a clean coarse plastering sand would have simplified the whole problem of making and placing.

Dr Murdock seemed to take a rather limited view of concretes. The Authors would like to see the aggregate maximum size logically related to the size of section, the density, and the distribution of the reinforcement. There was a very large demand for $\frac{3}{8}$ in. to $\frac{3}{16}$ in. stone for small precast and prestressed sections as well as for decorative purposes and road surfacing. In much reinforced concrete work and even in sparsely reinforced mass machine foundations the maximum size of aggregate was frequently specified as $\frac{3}{4}$ in., yet no one seemed to have become disturbed about the increase of price of aggregates because of the necessity of crushing or alternatively stockpiling material in excess of that size. Frequently it would be found that $1\frac{1}{2}$-in. single-sized material was quoted at a lower price than the smaller sizes.

The Authors were not bigoted on the subject of grading but asked only that suppliers should conform to the limits given in Table 2 of B.S. 882 for single-sized aggregates. They agreed with Dr Murdock that the sand grading had a very important bearing on the behaviour of the concrete at all stages.

Creep was of significance at present only in prestressed and post-stressed structures ; in those the reduction of creep represented a reduction of steel. It was suggested that in a gap-graded concrete the concrete in a member was more closely related to the creep behaviour of the coarse aggregate than was the case when a continuously graded concrete was used since the latter concrete consisted of a coarse aggregate suspended in a mortar matrix which would therefore tend to dominate the behaviour of the concrete.

Despite statistical prophecies the number of cube failures in all the jobs quoted in Table 3 did not amount to more than sixty, equivalent to 2·7%.

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In Table 6 Dr Murdock quoted various compacting factors and mix proportions and it was noted that the proportion of sand was reduced as the compacting factor rose. The Authors would have thought that a more economical way of decreasing the workability, where ½ in. and 1½ in. slumps were required, would have been to increase the A/C ratio. All the mixes quoted seemed rather richer than was necessary or desirable for ordinary structural work.

Mr Greeves referred to concrete being good but at the same time giving a poor bond with the reinforcing steel. The Authors would be interested to have particulars of such a state of affairs since their experience, which was rather larger than Mr Greeves seemed to think, had shown that the bond improved with the quality of the concrete in the job. On the subject of labour and the suggestion that it would be desirable to institute a trade of Concretor, the Authors felt that no greater difficulty would be experienced with concretors on site than at present arose in the case of carpenters, steel fixers, and any other of the recognized skilled occupations.

The Authors would not agree with Mr Cameron entirely since the formula did not take any cognizance of the grading of the aggregate. However, in practice it was usually difficult to obtain a sand fine enough to infiltrate the voids of a continuously graded coarse aggregate. It should be observed in that connexion that since the bulk density of a continuously graded coarse aggregate was high compared with that of a single-size material, the sand content required by calculation was often below the value which could be used with imperfect mixing.

In regard to the use of the average strength as the controlling factor, the Authors would point out that such a requirement would not necessarily ensure the desired result since the variation on either side of the average might be wide. It would seem that the present Ministry of Works General Specification, which called for preliminary tests results one-third above the minimum requirement, did in fact meet Mr Cameron's point with the additional advantage of imposing a limit in the downward direction.

The account given by Mr Hall of his firm's experience in the use of design mixes was of great interest, and the Authors would like to congratulate the firm upon the success of their endeavours.

The Authors were not clear as to how the results quoted by Mr Mackintosh were obtained since their experience had shown that in general the workability of the gap-graded concrete when properly designed for the given strength was greater than that when a continuous grading was employed.

With reference to Professor Baker's comment, in designing the mixes for any job regard had to be paid to the average sizes of section. If the job happened to fall into well-defined classes of work, mixes had to be designed accordingly. The variation of the mortar content during placing was not advocated and in practice the necessity had not so far arisen.

The Authors welcomed Mr Walley's contribution and agreed that the

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quotation from Professor Bolomey covered the essential point. It should be stressed nevertheless that mixes should be designed on the characteristics and properties of the available aggregates and not predetermined on a basis of arbitrary proportion.

Mr Walley referred to different approaches to the subject of gap-grading by the Authors. The difference was largely due to practical difficulties caused by the wording of specifications and reluctance to abandon traditional ideas. In the field it had been necessary to move step by step, the first step being to introduce a measure of gap-grading by omitting the $\frac{3}{8}$ in. to $\frac{3}{16}$ in. fraction.

Mr Wallis's comments on the concrete at site 21 might be justified but the Ministry records supplied from the site were as given in Table 3 and average cube strengths obtained were more compatible with a W/C ratio of 0·45 than with one of 0·39.

The opening remarks by Mr Willis had been answered in the Authors' introduction and in reference to the comments on Table 1 the Authors had found that although the concrete produced had little or no slump it placed easily with correctly applied vibration.

In the design of a concrete mix the W/C ratio was one of the factors. If therefore a guaranteed strength specification was used the W/C ratio must be left to the contractor. The type of specification used by the M.O.W. insisted that the contractor should state what mix he proposed to use, including the W/C ratio and that mix might not thereafter be altered in any respect without the agreement of the supervising officer. In setting the limits of A/C ratios permitted the possible W/C ratios also had to be considered. For example if it was necessary to keep down the amount of shrinkage the limiting A/C ratio had to be set so that it was not possible for the contractor to get the required strength with a rich wet mix. In the past the Authors had known many cases in which a specification had enabled the contractor to obtain his required strengths by using rich wet mixes with dire results owing to excessive shrinkage.

Mr Gifford Hull raised the special case of the construction of mass concrete dams in undeveloped countries. A full consideration of all the possibilities in such cases would demand more space than was available for a reply. As an example it might be advantageous and economical to use two types of concrete in the works. The fraction abstracted from the coarse aggregate used for one type forming the coarse fraction of the second type.

Whilst the Authors would agree that it was possible that the use of a continuous grading would be the most economical in a particular case they would not adopt it without a full consideration of other possibilities.

The Authors agreed with Mr Spindel that the absolute volumes of the materials in a mix were important but suggested that was so mainly because of the necessity of determining their specific gravities; in their opinion the way in which the aggregates packed was even more important since the

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voids remaining after full compaction had been reached determined the volume of cement paste required or alternatively the voids had to be adjusted so as to accept a particular volume of cement paste. The formula given for determining the specific bulk density of the combined aggregates assumed fully compacted concrete so that the air, which was one of Mr Spindel's factors, was eliminated in the design stage. The Authors considered that the amount of entrained air in a concrete when placed was chiefly related to the skill of those placing the concrete and of it being of the correct consistency.

In regard to the fit of the cement particles in relation to the sand, except for cement testing, the Authors considered that of academic interest only since the behaviour of particles as fine as those of cement were subject to a rather more complex set of laws than were sand particles of a size likely to be used in concreting.

The Authors had stressed the importance of using as coarse a sand as possible which, while passing into and through the voids in the coarse aggregate, would at the same time avoid the use of a large quantity of mixing water. Gap-grading had two objects; one was to limit the range of aggregate sizes in use and so improve control, the other was to adjust the void opening to suit an available sand having a particular grading upper limit.

In most gap-graded concrete the shrinkage was reduced compared with that of continuously graded mixes because the cement and the water contents were usually smaller. So far as was known gap-graded concretes in the form of brickwork stood up to weather conditions very well.

The German specification was quite useless as a guide to anyone since no concrete weights, volumes, or workabilities, were mentioned. The time of vibrations must depend upon the vibrator, the workability of the concrete, its ultimate performance requirements, and the section in which it was placed. Usually a 2½-in.-dia. high-frequency internal vibrator would compact 5 cu. yd per hour of mass concrete to a minimum strength specification of 3,000 lb/sq. in.; but that quantity might be as little as 1½ cu. yd for in-situ poststressed work. The Authors agreed that some additives were of assistance in certain conditions.

Professor Walsh's remarks on the bulking of the coarse aggregates were of interest and he was undoubtedly right in thinking that particle interference could invalidate the design where the bulk density of the coarse material was usually measured on vibrated bases. However, except in the case of flaky aggregates, provided that the maximum particle size of the sand was correct, bulking was negligible. In laboratory tests the exact calculated quantities to produce a 6-in. cube had been mixed and the whole mix placed in the mould, even to scraping the bench and trowel to obtain the last particle of mortar to complete the filling. Where a very low sand content of 18% or less was required by calculation for the mix it was usually found necessary, for practical purposes, to increase the sand content and reduce the weight of coarse aggregate proportionately.

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The Authors were not surprised that Mr White's attempts to make concrete by their methods resulted in failures. The figures quoted in Table 1 were for single-sized $1\frac{1}{2}$–$\frac{3}{4}$ in. aggregates but those could be adjusted for $\frac{3}{4}$–$\frac{3}{8}$ in. material by adding 0·005 to the factor. Thus 0·43/0·068 = 5·89 was the A/C ratio and not 6. Furthermore, the aggregates used were graded $\frac{3}{4}$ in. to $\frac{3}{16}$ in. and no doubt a good sharp concreting sand $\frac{3}{16}$ in. down was used as a "filler." The sand which should have been used was one having a maximum size of 0·019 or just passing a No. 30 sieve.

In regard to the breakdown of the vibrator that obviously resulted from lack of maintenance as it was impossible for any concrete to absorb more than a small percentage of that available at the vibrator head. The Authors were very doubtful of the validity of Mr White's test.

The Authors agreed with Mr McKay that visits to pits and quarries were almost essential but that nevertheless the data called for on pp. 595–596 were still desirable. The figure of 4,000 lb/sq. in. should read 4,500 lb/sq. in. in which case the value for the W/C ratio given would seem about right. The figures in Table 8 for coarse/fine aggregate ratios were provisional only and whilst the values quoted by Mr McKay might well apply to mixes leaner than 7 : 1, where richer mixes were in use sand had to be cut out to make room for cement paste.

In a slab the durability or resistance to wear would depend largely upon the hardness and exposed wearing area of the coarse aggregate. When that was harder than the mortar as was common, the closer the coarse aggregate could be packed the better. That was very apparent on sea-defence work where the concrete usually failed by mortar erosion.

Professor King's comments were of great interest although they seemed to condemn to extinction a method of testing upon which many had pinned great hopes.

In his remarks Mr Bate intended to stress his distrust of the results of cube tests and referred to the ultrasonic test only as a possible alternative. Some alternative test which could carry conviction was badly needed.

It was agreed that one concrete of a specific mix could not be compared with another concrete having different proportions even though the strengths of the two concretes were identical at a particular time. That, however, was not the way non-destructive testing was done. In all cases cubes of the works mix were tested ultrasonically and then for density and compressive strength. It was agreed that normal site variation in the mix might throw out of alignment the true interpretation of the velocity reading. It was not clear what Professor King meant by a lean overwatered mix compared with a drier richer mix for in fact there was more water per unit volume of concrete in the rich mix than there was in the 6·5 : 1 mix, quoted in Table 10.

Correspondence on the foregoing Paper is now closed. No contribution has been received.—SEC.

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