

Discussion.

The President. The PRESIDENT, in proposing a vote of thanks to the Authors for bringing before the Institution so interesting a subject, remarked that it was surprising that concrete arches had not been more widely adopted. No doubt this was due largely to the difficulty arising from expansion, which had been met on the Continent by the adoption of joints in the springings and in the crown of the arch, sometimes of asphalt, sometimes of rolled lead, and sometimes with hinges. In Germany several important bridges had been built in this way, notably two at Dresden, with skew-angles of 18 degrees and 30 degrees respectively, and spans of about 140 feet. No difficulty seemed to have occurred in connection with those bridges. The concrete bridge over the Upper Danube at Rechtenstein Württemberg,¹ had two spans of about 75 feet, and the Vevey Bridge,² with a skew-angle of 71 degrees, had a 63-foot span. In Switzerland a small road-bridge of about 40 feet span had been built in 2 days, the abutments being finished in one day and the arch in the second day. A second bridge at the same place had been built entirely in 1 day by sixty-five men.³ He hoped the discussion would elicit some facts as to the difficulties arising from expansion.

Mr. Wood-Hill. Mr. WOOD-HILL exhibited some lantern slides illustrating the progress of the work.

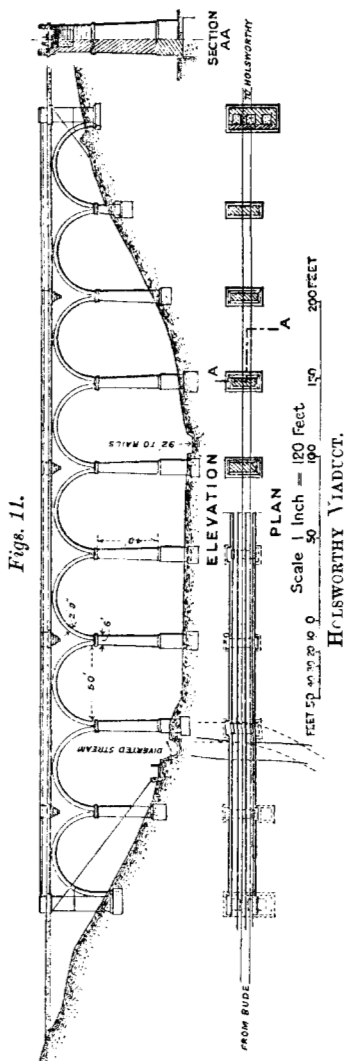
Mr. Galbraith. Mr. WM. R. GALBRAITH, Vice-President, considered the Paper very useful, because, as far as he knew, there were few viaducts in England which were constructed wholly of concrete. On the new line of the London and South Western Railway between Lydford and Plymouth, constructed by Sir James Szlumper and himself, some concrete viaducts had been built, but they were partly of masonry and only partly of concrete. The first concrete viaduct constructed in the South of England with which he was acquainted was that on the Holsworthy and Bude branch of the London and South Western Railway, for which he was the engineer. Before preparing the designs for that viaduct, the contract for which was let in 1896, it had been necessary to consider what materials were available on the ground for construction. The district was one

¹ Minutes of Proceedings Inst. C.E., vol. cxv. p. 413.

² *Ibid.*, vol. lviii. p. 310.

³ *Ibid.*, vol. lxxix. p. 394.

of the worst in England for the construction of bridges and Mr. Galbraith. viaducts, as no brick-earth and no stone of any value was to be found there. A good deal of stone mixed with shale existed, but there was no length in it, and it was full of backs. Therefore, in view of the impossibility of getting any stone suitable for constructing heavy works, it had been decided to try a viaduct wholly in concrete. At Holsworthy there was to be found stone which, when crushed, was available for making concrete. It was not gritty, but rather greasy. Sand, however, had to be brought from Plymouth or Bideford, and the cost of the viaduct had been increased on that account. In many respects the Holsworthy viaduct (*Figs. 11*), did not differ greatly from the Cannington viaduct. There were nine arches, each of 50 feet span, as compared with ten arches in the Cannington viaduct; and the height from the bottom of the valley to the rails was exactly the same, namely, 92 feet. In design, however, they differed considerably, the Cannington viaduct having elliptical arches, and the Holsworthy viaduct semi-circular arches. He considered the design of the Holsworthy viaduct to be in many respects preferable to that of the Cannington viaduct: for one thing, the semi-circular arches were much more easily built. The piers of the Holsworthy viaduct were battered continuously from the plinth to the springing of the arch, 1 in 24 on the ends of each pier and 1 in 48 on the sides. The essential difference in the construction was that at Holsworthy separate concrete blocks had been used as far as possible, instead of mass concrete as in the Cannington viaduct. The piers above the plinth and the arches



Mr. Galbraith, were built wholly in concrete blocks, as were also the spandrels, except the first 15 feet, and the greater portion of the parapet. The piers were 6 feet thick at the springing, against 5 feet in the Cannington viaduct; and he could not help thinking that the Cannington viaduct had been cut rather fine. Perhaps the smaller dimensions were due to the fact that the viaduct was intended for a light railway with lighter engines: the Holsworthy viaduct was built to carry the ordinary traffic of the London and South Western Railway, and heavy engines. He also thought that the continuous batter had a much better appearance than the offset at every 6 feet due to the rectangular construction of the piers. The Holsworthy viaduct had been easily constructed, by means of a staging about 40 feet above the level of the valley, or 50 feet below the level of the rails, on which were two Scotch cranes. There had been no expansion, and therefore allowance for it would have been unnecessary. Not a single crack had occurred in the viaduct from beginning to end, and no settlement whatever in the arches. Instead of being an advantage, the division of each arch of the Cannington viaduct into three portions to provide for expansion was, he thought, a disadvantage; and he could not see the use of it. The settlement of about $2\frac{1}{2}$ inches in the arches appeared to be largely due to their shape; the flat part of the ellipse seemed to have settled down, and probably the haunches had risen to a certain extent. Without wishing to criticize unduly the Cannington viaduct, he considered that concrete blocks were much superior to concrete in mass for such a structure; and that to build high and slender piers in mass concrete was a mistake: some undiscovered flaw in the concrete might endanger the whole structure—a fact of which he could give an instance. On a railway in the south of England, 700 to 800 blocks, intended to be used extensively in construction, had been made and laid aside to set. But it was noticed that the blocks did not set, nor was there any improvement in this respect after 2 months; and it turned out that they had been mixed with water impregnated with mundic. They had all had to be rejected. If, in one of the piers of the Cannington viaduct, concrete mixed with water or sand impregnated with mundic had been used, the work would have soon collapsed. By building the heavier parts of the viaduct, such as the abutments and spandrels, of blocks, it was possible to see what was happening. The use of blocks had another advantage. In the Holsworthy viaduct each block extended right across the arch; and the blocks had been set by foremen, without the aid of masons. If Mr. Inglis would state his experience with masons in the West of England, the advantage

of being able to construct such a viaduct with the aid of handy Mr. Galbraith. men under a good ganger, and perhaps one or two masons only, would be quickly appreciated. The concrete of the two viaducts did not differ much; in the Holsworthy viaduct the arch-blocks were in 5-to-1 concrete, and in the Cannington viaduct 6-to-1. The Holsworthy piers were 6-to-1, and some portions of the foundations were 8-to-1 in the Cannington viaduct. As to the cost, the arch-blocks of the Holsworthy viaduct had cost 35s. per cubic yard, and the blocks in the piers and elsewhere 25s. per cubic yard; that was to say, the Holsworthy viaduct, built mainly of blocks, had cost 27s. 6d. per cubic yard, against 32s. 1d. for the Cannington viaduct in mass concrete. The total cost of the Cannington viaduct was given at £10,820, and the Holsworthy viaduct had cost £10,250: there was an extra span in the Cannington viaduct, but the Holsworthy foundations were deeper. Considering the difficulties met with at Holsworthy, and the long distance which the sand had had to be brought, this showed that concrete blocks could be used quite as cheaply as mass concrete. So strongly was he impressed with the advantage of concrete blocks, both in piers and in arches, that in a viaduct of twelve arches over the River Tamar, now under construction by himself and his partner, on the Callington Light Railway, where the height from the river-bed to the rails was about 130 feet, and the span of the arches was 60 feet, they were pinning their faith to concrete blocks, both in piers and in arches. He had also used concrete for tunnel-linings with success, especially in tunnels where there was no great pressure. The Board of Trade required that all tunnels should be lined, even in rock, where there was not much pressure but nevertheless a risk of stone falling. On the North British Railway he had lined two tunnels wholly with mass concrete, with complete success. On a branch of the London and South Western Railway he had lined some tunnels in the chalk, where there was not much pressure, with similar concrete, and that also had been successful. He thought, therefore, that engineers might use concrete a little more freely than they had done.

Mr. F. E. ROBERTSON asked how the Authors had estimated so Mr. Robertson. precisely the pressure which the several foundations could bear. In the Table given in the Paper they varied by $\frac{1}{4}$ ton per square foot. The concrete was said to be 6-to-1, and it was stated that the addition of sand had been found unnecessary. How had that been ascertained? One volume of cement in powder made 0·8 of one volume of paste, and if that was added to 6 volumes of stone it meant either that the voids in the stone were only 13 per cent., or that the concrete was full of holes. He had never seen samples

Mr. Robertson. of ordinary crushed stone in which the percentage of voids would be anything like so small, and he did not think flint was a stone which sized particularly well in crushing. Again, why had the test-blocks had two parts of sand put into them? They then bore no relation whatever to the concrete used in the viaduct. Putting two parts of sand with that amount of cement and stone meant that the voids in the aggregate were supposed to be 37 per cent., which was probably about the truth. Speaking from a general point of view, the usual practice in England—and nowhere else, as far as he knew—of quoting concrete as 4-to-1, 5-to-1 or 6-to-1, should be amended, and the proportion of sand stated: 6-to-1 concrete might be very good, or it might be very bad. He thought that opinion was not a mere fad. He often had to examine young engineers recommended for service on Indian railways, and he found that, as a rule, they had very vague ideas of the real principles of mixing concrete—a fact which was probably due in a large measure to the loose manner of stating the composition of that material. The dimensions of the Cannington viaduct seemed very slender, and it would probably have afforded a good opportunity for trying ferro-concrete, which had been much used on the Continent and in America, but rarely in England. He quite agreed with Mr. Galbraith's remarks as to the comparative merits of blocks and mass concrete. Blocks could be mixed at leisure, and the mixer knew what he was doing; but in mixing concrete in mass a moment's carelessness on the part of a workman might seriously endanger the whole structure. It was a convenience, also, to be able to vary the strength of the concrete in the blocks of a high pier, making the lower blocks of richer concrete. As Mr. Galbraith had said, if anything did go wrong with the concrete blocks, warning was given before they were built into the structure.

Mr. Trench. Mr. E. F. CROSBIE TRENCH remarked that, while it was probably not contended that concrete was better than good brickwork or masonry built of durable stone, it was certainly an excellent substitute where these were not easily obtainable. In the absence of information as to the cost of bricks, sand, or stone, at the site of the Cannington viaduct, it was not possible to make a comparison of cost between brickwork and concrete; but 32s. per cubic yard did not seem a very low price, even taking into consideration the height of the piers and arches. If the viaduct had to be built again, probably many things would be done differently; but he could not help being impressed by the courage of the designers in putting such a load as 3 tons per square foot on a foundation of greensand and lias clay. Engineers now possessed, in armoured

concrete, a means of making large slabs of comparatively small Mr. Trench. thickness, which, without adding any great weight, would distribute the pressure on the ground; and it might have been wiser to do this at Cannington. It must have been a great disappointment to the designers to have the symmetry of the viaduct spoiled by the measures found necessary to remedy the subsidence at the west end. Heavy rains seem to have been the cause; but viaducts in which somewhat slender piers were partially buried in the slope of a newly-tipped embankment were rather liable to fail in the way described. He himself had had the experience—and he had no reason to think the circumstance was unique—of having to rebuild an old brick viaduct, in which, on opening the ground, he had found that both the piers built in the embankment were absolutely wrecked. One was bowed to the extent of 9 or 10 inches, and the other was bowed and cracked practically from top to bottom, the crack opening about 5 inches. No doubt the usual precautions had been taken to wheel the soil in front and pun it in on the side of the pier farthest from the top of the slope; but even when this was done it was extremely difficult to avoid settlement. Nothing was said in the Paper as to whether any plums had been used in the concrete, or whether crushed flints had been used alone; nor was it stated how the flints had been cleaned. As no sand had been used, the face of the concrete, as left by the boxes, would probably be somewhat rough. The shuttering seemed to have been very successfully dealt with, but needed some further explanation. When it was said that all the piers progressed at the same rate, he supposed it was to be understood that when one pier had been raised to, say, the third lift, the lowest box was moved to begin the next pier, and so on: but even then it was not clear how it was possible to build thirteen rectangular blocks of different sizes with only eleven boxes. Again, the reasons for using moulded blocks on the faces of the arches were somewhat obscure. If mass concrete was good enough for the piers and for the bulk of the arches, why was it not also good enough for the facework? It would have been a simple matter to continue the shuttering right across the centering, and to build the whole arch in mass concrete. He had had some slight experience in building arches of concrete on a smaller scale, and what appeared to be essential in order to avoid cracks was to make the centering sufficiently strong to prevent all deformation while the concrete was being laid. The Authors seemed to hint that the blocks had been used to relieve the centering of some weight while the mass concrete was being filled in.

Mr. Inglis. Mr. JAMES C. INGLIS mentioned that the incident which had been referred to by Mr. Galbraith occurred on a railway in the south of England. The line traversed limestone country, and all the structures had been designed to be built in ordinary rubble masonry, with nobbled fitted work in the face. The prospect of such a large additional quantity of work having given the local stonemasons hopes of having a good time, they had proceeded to make their terms with the contractor, Sir John Aird; and among these terms was the following stipulation:—The line ran from a large town to a fair-sized village about 8 miles away, where about fifteen or sixteen limestone-masons resided. The masons in the large town were to start from the town at 6 o'clock, and walk out about 5 miles to their work, and the masons in the village were to start at the same time, and walk to the same point; and if the latter party arrived at that point before the others, they were to sit down in the shed, and not to lift a tool until the masons from the city came to work, when the whole of the men were to start! That particular requirement had determined the company to substitute concrete for masonry in all the structures of the line in question. But apart from such considerations he thought every concrete viaduct needed to justify its existence. No doubt the Holsworthy viaduct had good reasons for its existence, and so also perhaps, to some extent, had the Cannington viaduct. All the Cornish viaducts of the Great Western Railway had been built in granite, with the arches in brick, and it had been entirely owing to commercial considerations that those materials had been used. Of course, concrete arches had been built elsewhere. He shared Mr. Galbraith's belief in blocks, and had used them for arches of up to 64 feet span; but he had found that the price demanded by contractors for concrete blocks was the same as for brickwork: in fact, they required more for building the piers in concrete than in blue lias limestone. The cost of the piers and the general work did not come to more than 26s. per cubic yard for granite, and that of the brickwork arching to about 42s.—just the same as concrete. He thought no one would contend that a granite structure, properly built and dressed, was not far superior to a concrete one; and that was why he said that every concrete viaduct required some justification for its existence. Of course, in building a new line the conditions were somewhat different from building viaducts along an existing line, where the materials could be brought alongside the work fairly economically. He had noticed not long ago that all the lining of the Simplon Tunnel was in concrete blocks. These blocks had been compressed in the making, which

he thought was a considerable improvement. The available Mr. Inglis. materials were of very inferior quality, owing to the proportions of the different sizes of material forming the concrete; and the compression certainly gave highly satisfactory results. Ferro-concrete also had its failings and difficulties, and one of these had manifested itself in his experience not long ago, in a structure of fair size, built close to the sea. The scantlings were certainly somewhat small, and having regard to the proportions of the sand and gravel the material was probably not altogether water-tight, though of course the walls were smoothly plastered over with cement. In the course of 18 months the columns began to crack slightly, which he believed was due to salt from the sea having penetrated the cement and attacked the iron, the resulting oxidation causing expansion in the middle of the columns. A defect of that kind was a serious matter, striking, as it did, at the very existence of the structure. But apart from such drawbacks, his experience was that, if effectively protected by a water-tight and air-tight matrix, ferro-concrete seemed to remain as good as when it was put in, in any position.

Mr. JOHN STRAIN had made frequent use of concrete for railway- Mr. Strain. structures during the past 26 years, as shown by the following instances:—In 1878, when building the extension of the Callander Railway from Dalmally to Oban, concrete was used to a large extent, principally for retaining-walls and arches. Except in very small bridges, the concrete was in blocks: the bridges were still in perfect condition, and had given no trouble whatever. In 1882, in building the Lanarkshire lines of the Caledonian Railway, rubble concrete was used throughout the whole of the works, which were of a heavy character. Most of the bridges were faced with stone, backed with rubble concrete, and some of the piers for steel bridges were built entirely of concrete. In 1886, in building the Killin line, a branch of the Callander and Oban Railway, rubble concrete was used for all the works. In particular, one viaduct across the River Dochart, 60 to 70 feet high, with three skew spans of 35 feet each, was built with stone facework packed with rubble concrete, and the arches were formed entirely of concrete deposited in situ. The haunches were brought up to the proper level, with a radial joint, and arrangements were made so that an arch was turned completely in 1 day. In his opinion, that, along with good material, was the secret of success in building any concrete arch in situ. It was the first bridge of the kind he knew of, and though he would not say it was the first ever built, it was

Mr. Strain, certainly the first passed by the Board of Trade for carrying a railway. Naturally, the Inspector, Major Marindin, was rather anxious about it, and in order to test it, he hit upon the plan of comparing the time required by two men for drilling a 1¼-inch hole through hard sandstone, such as would be used for voussoirs, with the time required by the same men for drilling a similar hole through the concrete arches. He was soon satisfied, the time occupied in drilling through the concrete being more than double that needed to drill through the hard stone. He passed the bridge, subject, however, to its inspection by the Board of Trade every 6 months for 2 years, and he came down regularly and examined the structure, without finding any flaw. In 1887 Mr. Strain built the Calañas-Tharsis Railway,¹ in the south of Spain, again using rubble concrete throughout. There was no building-stone in the district, but only a very friable schist, which, with the sand obtained in the streams, made fair concrete. The viaducts had battered piers, like the Holsworthy viaduct, which had been built up in boxes 1½ metre deep, as described in the Paper. The whole of the work was satisfactorily carried out without difficulty by the unskilled labourers of the district, and no failures had occurred. The piers were built by means of a Scotch crane, placed opposite the centre of every third pier, and commanding three piers, which was removed afterwards to another three piers, and so on. The superstructures were of steel. He was rather surprised that—possibly for some local reason—the piers of the Cannington viaduct had been built in pure concrete instead of rubble concrete, which was much cheaper and equally good. In 1888 he carried out the Lanarkshire and Ayrshire Railway, also entirely in rubble concrete. Where local circumstances suited, some of the bridges had concrete faces, and others were faced with stone which was backed with rubble concrete. Throughout the whole of the work 5-to-1 concrete was used, and it had been found very satisfactory. He agreed with Mr. Galbraith that, unless absolute reliance could be placed on the materials and the workmanship, it was much safer to build in blocks; but he thought it was generally possible to be sure of that. Even the most important structures were founded on concrete, and the objection Mr. Galbraith had raised would apply to them. Whether the work should be done in situ or in blocks

¹ See A. M. Anderson, "Concrete-Work on the Calañas-Tharsis Railway, Spain." Minutes of Proceedings Inst. C.E., vol. cxv. p. 321.

depended entirely upon local circumstances; and in case of doubt Mr. Strain. he would certainly favour blocks. In some of the works in Lanarkshire, situated near ironworks, broken blast-furnace slag had been used for making the concrete, and it had been found to be quite satisfactory.

Sir ALEXANDER R. BINNIE, Vice-President, observed that engineers Sir A. Binnie. were of course not limited, in dealing with concrete, to arches of such moderate dimensions as 50 to 60 feet span. Arches of 120 feet to 165 feet had been built on the Continent. One of the most beautiful bridges he had ever seen was the bridge at Geneva, over the River Rhone; and the concrete bridges in Austria and in Germany were models for any bridge-builder of any time. But, directly the building of structures of that kind was contemplated, a difficulty was met with, namely, that the expansion and contraction of the material must be taken into consideration. The question then arose—how did concrete expand and contract? In order to answer this question he had had constructed, a few years ago, a block of 4-to-1 granite concrete 100 feet in length and 1 foot square in cross section, built to rest on rollers, so as to be free to expand in any direction. Proper verniers had been attached to either end, moving against pillars detached from the block itself. For 3 years, summer and winter, that block had expanded and contracted like an iron beam, with changes in the temperature. But the expansion and contraction had been found to be influenced also very considerably by the condition of the atmosphere; and in wet weather the expansion due to absorption of moisture was often as much as that due to summer heat. The action of the sun shining on one side of the block had also had a disturbing influence. Taking the average of all the conditions in various states of the weather, the expansion was 0.005226 inch for a rise in temperature of 1° F., for a block 100 feet in length and 1 foot square in cross section. Assuming a maximum rise of temperature of 60° F., this would give an extension of $\frac{5}{16}$ -inch in 100 feet; but he would not anticipate so considerable an extension in mass concrete of larger cross-sectional area. That observation had led to another experiment, wherein a cube of concrete of 1 foot edge was suspended at the end of a steel-yard projecting through the wall of a small building, and observations were made of the difference in weight of that cube, exposing its 6 square feet of surface to the atmosphere. It had been exceedingly interesting to notice how, within as short a time as 24 hours, that block of concrete would increase in weight by nearly 2 lbs. If concrete was to be used, something

Sir A. Binnie. must be done to accommodate such expansion and contraction. In the viaducts under discussion it had been met in two ways. The Authors had effected their object by building into the mass concrete at certain places, soft mortar joints; and in block concrete, such as Mr. Galbraith had used, there were so many joints that the expansion and contraction was of no account. The block concrete might be regarded as stone. Continental engineers had started on what he could not but think were the true lines. They had treated the arch in mass concrete as a steel arched bridge, and, by placing pins at the two haunches and at the centre, they had afforded it freedom of expansion and contraction according to temperature, to the humidity of the air, or to the load upon the bridge. In some cases, when the centres had been removed, the parapets built, and the rolling load established for some little time, the vacuity at the hinged joint had been filled with pitch, or other semi-elastic material, which allowed for the slight movements of the arch due to changes of temperature. He always regretted that the prospect he had once had of building a large concrete arch, or series of arches, over the Thames had unfortunately not been realized. The building of a large span, if properly designed with regard to the rise of the arch, was a matter of easy accomplishment. When dealing with elliptical arches in mass concrete, however, he was always puzzled how to treat them. The best way, he thought, would be to carry up the haunches of the arch to what might be called the angle of repose of the material, and to consider them as cantilevers; and from that point, if he were bound to an elliptical arch—he would not choose one himself for a concrete structure—he would begin the hinges as at the abutments.

Dr. Deacon. Dr. GEORGE F. DEACON congratulated Messrs. Baldry and Yerburch upon adding the name of another firm of contractors to those who were not afraid of using cableways in building structures of the kind described in the Paper. Fifteen years ago he did his best, but without success, to induce certain contractors to use the system, which had been long in vogue in America for such work. Now important examples of the cableway were to be seen, including one in London itself, and three very large ones in the Derwent valley. He also congratulated the Authors upon not shirking an explanation of a partial failure. As had often been said in the Institution, a description of one failure taught more than accounts of many successful works. It had been suggested by several speakers that the work, which was in mass concrete, should be compared

with concrete blocks used as masonry. Concrete blocks were to Dr. Deacon. all intents and purposes artificial masonry, and there was nothing more to be said about them. They might be made stronger or weaker; but they were in effect masonry, and the action of temperature upon them was the same. He had had a good deal to do with concrete in mass, and he would scarcely call the Cannington Viaduct a monolithic structure. The largest mass of concrete appeared to be less than 20 feet in length, and such a mass, if properly made, would no doubt remain intact for an indefinite period. The only question was whether the junction between the blocks was satisfactory. He was inclined to share the view that if those concrete blocks had been hinged at the two lower expansion-joints, the probable life of the viaduct would be longer. Those expansion-joints must cause, where they crossed the soffit of the arch, a pressure which was greater than anywhere else. The structure might be able to bear it, but the pressure could not be well distributed. As other speakers had observed, the principle of hinging an arched rib near its haunches, and sometimes at the crown, in order to maintain the line of pressure within safe limits of the centre-line, had been largely adopted on the Continent; and 33 years ago he had employed it very successfully in an iron bridge, whose arched ribs were of necessity exceptionally shallow. He could not regard with equanimity the almost perpetual movement which must occur at the lower expansion-joints of the elliptical arches in the Cannington Viaduct. If the concrete had been armed at each of those joints with cast-iron abutment-plates, separated in the middle of the depth of the voussoir by a properly-designed hinged joint, the tangential pressure would be duly distributed over that depth, and its centre would necessarily pass through the centre thereof. Such a device would be inexpensive, and would have greatly increased the durability of the structure. The general question of concrete in mass, and the effect of temperature upon it, had not been investigated to the extent that was desirable. It seemed clear that, so long as concrete was buried, very long lengths—2,000 feet at least—would remain intact and unaffected by temperature. Perhaps one of the best examples of that was a concrete culvert under Lake Vyrnwy, which, though obviously affected slightly by changes in the temperature of the water passing through it, in that it wept a little more freely in the winter than in the summer, contained no crack from end to end. The length of that culvert was 2,300 feet, and in it there were joints (surfaces at which new concrete had

Dr. Deacon. been begun upon concrete already set) aggregating more than 1 mile in length; and yet not one of those joints had shown the slightest leakage under 53 feet head of water. The mass was surrounded by gravel, so that the water above had access to it.¹ With regard to large masses of concrete above ground, he had never been able to see how it could be expected that a concrete mass, exceeding, say, 100 feet in maximum dimension, could possibly remain intact, when the hardest natural rock did not do so. He believed that in nature there was no rock to be found which had been exposed to the air for a long period, and which was not full of cracks in every direction; cracks which in Great Britain were generally less than 12 feet apart, and nearly always less than 20 feet apart. Therefore it could scarcely be expected that monolithic concrete could be successfully used as it certainly had been attempted to use it. The results of the tests of the concrete might have been quite sufficient for the Authors' purpose, but they were not high; and he thought the reason was that the Authors had not obtained that density which alone could produce high results in concrete, and which alone produced high results in any stone of a single class. Other things being the same, the compressive strength of stone and of concrete varied according to its density, and the first thing to be secured—not a difficult task—was density; not the high proportion of cement which was sometimes thought to be sufficient, but enough cement to bind the particles together, and after that density, and nothing but density. By increasing the density it was possible to treble the strength of a mass of concrete. He entirely agreed with Mr. Robertson's remark, that such terms as "6-to-1," or "5-to-1," were altogether inconclusive. Without further specification, they formed no prescription of what the concrete should be. High density could not be attained merely by mixing a matrix, the proportions of whose ingredients were unknown, with a given proportion by volume of cement, and by then filling up with water. Such a method led to the paradoxical result that, with different ingredients, the volume of cement bore no known relation to the spaces which it ought to rather more than fill. Gravel and sand in bulk, whether got in their natural condition or produced by crushing rocks, varied very much in density, or, in other words, in the ratio of their weight (when put together as closely as possible) to the weight of a corresponding volume of the solid rock of which they were composed. In order to obtain the

¹ See Minutes of Proceedings Inst. C.E., vol. cxxvi. pp. 42 and 43.

highest density it was often worth while to proportion the ingredients to each other, before adding cement, in such a manner as to produce the greatest possible weight per unit of volume. The necessary proportion of cement would then be comparatively small. Wherever the proportions of ingredients of the aggregate were liable to variation, he prescribed a standard below which the density of those materials—their weight per unit volume—should not fall. Again, the highest degree of density could not be obtained by filling up with water. It could be obtained only by using just sufficient, or a little more than sufficient, water to produce the chemical changes, and by then using labour—the commonest possible labour would suffice—to ram the concrete until it attained the proper density; and when that stage was reached the concrete, before setting, acquired the condition of a jelly. It was then incompressible, but no water was visible—merely a dampness at the surface. Consolidation of concrete by hydraulic or other steady pressure produced high results, but only when superfluous water was excluded. More than 20 years ago he had shown by extensive experiments that, as would naturally be expected, compression by impact—ramming, in fact—was more effective than steady pressure in producing density, strength and water-tightness; provided, of course, that consolidation was not prevented by the presence of incompressible water. When rammed, the cement and sand-particles and pieces of stone intermingled more readily. In concrete rendered dense by steady compression there was often a bridge-like action, which prevented the density from being attained without crushing the stones, which, of course, was objectionable. It might perhaps be thought that he had gone a little too far in saying that it was possible to treble the strength of concrete by merely increasing its density, but that opinion was based on many reliable experiments made on a large scale. Any one who tried it could be convinced that it was much cheaper to obtain the requisite strength by increasing the density than by adding Portland cement. Of ferro-concrete, properly so called, he had had no experience, but he had had perhaps rather unusual experience of iron embedded in concrete and in rubble masonry and brickwork 80 to 100 years old and less. He had pulled such concrete and ironwork to pieces, and had found, as he had expected, wide differences in the results. Clearly oxidation of ironwork and steelwork could not occur in a mass of concrete unless there was access of moisture carrying oxygen; and if the ironwork could be protected effectively that oxidation was prevented. In such cases a slight coating of oxide appeared to form,

Dr. Deacon.

Dr. Deacon. and then oxidation stopped. On the other hand, there had occurred many cases in which the concrete had been broken out by the oxidation of the iron. That had occurred very noticeably from the use of iron clamps in certain steeples. The initial cause was no doubt some defect which permitted the access of moisture carrying free oxygen. He had never used ferro-concrete, largely because he thought it would be out of place in most of the works he had to do with; but he could conceive situations in which it might properly be used. They were not, however, places in which its failure would mean failure of the structure as a whole. At any rate, he would hesitate to use it in such cases until many more years' experience had been obtained with it: for an engineer should not make experiments of that kind where the safety of large works was risked.

Mr. Ross. Mr. ALEXANDER ROSS had been much struck, on visiting the Cannington Viaduct in course of construction, with the facilities given by the overhead cableway, the absence of all scaffolding, the fewness of the men employed, and the facility with which the material was handled. He had also observed the excessive care taken in what might be called small details, and the full consideration given to every point. Of course, situation and circumstances had always to be taken into consideration by an engineer in determining what material he would use; not only in regard to the strength, but also in regard to the reasonable cost of the structure. The Cannington Viaduct was not quite the first instance of the use of concrete in arches, or even in viaducts, although perhaps it was on the largest scale. On the Mallaig branch of the West Highland Railway most of the abutments, the arches, and even the wing-walls, were constructed in mass concrete, notwithstanding that the district produced only rock, of such good quality that it could be used for building. Even where it was so good that the abutments were left in the natural rock, a skewback was made, and the arch was built in concrete. In that instance the explanation he had received of the use of concrete was that masons had been difficult to get, and the time had been limited. The structures of that line were by no means beautiful, and might even be characterized as the reverse; but they met the case, and in railway work, as in other things, necessity had no law. Engineers had used concrete for many years for various purposes, particularly foundations, and he thought the time was coming when it would be used in superstructures on a much larger scale than hitherto. In a case which had come within his own operations many years ago in the North Riding of Yorkshire, where there was abun-

dance of stone, the walls and abutments were all built of hard Mr. Ross. blue limestone, and the arches were specified to be of brick; but the contractor could not get bricks of good quality at a reasonable rate, and it was finally decided to build the arches—at any rate of some of the bridges—of flat stones laid on edge on the centres, grouted up with cement, and completed by concrete. Those arches were not only substantial but also rather good-looking, quite in keeping with the block masonry. He had not turned many concrete bridge-arches, but he had built many large and heavy walls in concrete on the Great Northern Railway for retaining the London clay. Most of these were faced with varying thicknesses of brindle brick, built up about 3 feet at a time, layers of concrete being thoroughly rammed in behind, so as to ensure contact between concrete and brickwork. Those walls had never shown any signs of failure. The brick facing prevented the discoloration and damage caused by water and frost. “Granolithic” facing might be used for the same purpose, but probably it would not be cheaper than brindle brickwork. Like previous speakers, he was not very desirous of seeing concrete and ferro-concrete used in large structures like bridges; but for such buildings as heavy warehouses—as a means of obtaining the necessary strength, and also as fire-resisting materials—they were very desirable. In a large warehouse which he was now building, he had covered the steel girders and stanchions with concrete as a protection against fire, and also, as Mr. Deacon had suggested, as being a good method of preserving the iron and avoiding the heavy expense of frequently scraping and painting the steelwork. He was glad the engineers of the Cannington Viaduct had had the confidence to bring the matter forward for discussion. No doubt this viaduct, like all engineering structures, carried its own lesson; and probably, if the engineer had another such structure to erect, he would introduce some improvements. Among such improvements was, Mr. Ross thought, the substitution of segmental for elliptical arches. The expansion-joints might have been filled with some plastic material such as a composition of bitumen, so that they might be affected by heat and afford the necessary yielding.

Mr. A. C. PAIN explained why he had constructed the viaduct of Mr. Pain. concrete rather than of any other material. The structure was in a valley, with a road approach from the railway, rising to 600 feet above ordnance datum. The cost of cartage from the railway-station was about 6s. per ton. About 2 miles from the viaduct there was a small port, cartage from which cost 5s. per ton. Practically, therefore, it would have been too expensive to construct the viaduct

Mr. Pain. of any material which had to be brought by rail or by sea. In the cuttings on either side of the viaduct there was material which was suitable for concrete, namely, chert and flints, the chert from the greensand formation, and the flint, locally called "sheep's heads," from the debris of stone and clay lying on the top of the greensand. The presence of those two materials, unsuitable as they were for building in ordinary masonry or in rubble, had led him to think that it would be best to crush them and make them into concrete. The viaduct was not the first structure he had built in Portland-cement concrete, as he had had many years' experience in the construction of railway-bridges, of long retaining-walls, and of reservoirs, in that material. That experience had convinced him that if a structure such as the Cannington Viaduct was to be built in mass concrete, it was desirable to make some provision for the contraction and expansion of the material, and also for taking up the movement which occurred in structures of the kind, whose foundations were not quite as satisfactory as was desirable. Having ascertained as far as possible, by borings and otherwise, the nature of the ground on which the viaduct had to be founded, he had seen that it was desirable to make the structure as reasonably light as possible, because the centre portion had to be founded practically on quicksand. He did not mean to say that quicksand was not a good foundation sometimes; but he would prefer something rather more solid. In this particular case the foundation of the largest pier was so soft that it sprang beneath a man's feet almost like india-rubber: yet this was one of the piers in which there had been the least settlement. Then had arisen the question whether concrete in mass or concrete in block should be used, and again he had thought that, other things being equal, concrete in mass was better than concrete in block. He ventured to think that anybody who visited Lyme Regis and walked over to the viaduct would see that it was an exceedingly creditable piece of work to the contractors; because it was absolutely free from top to bottom of any touching up, plastering, or painting. It remained exactly as it had left the shutters, any touching up being absolutely barred; and therefore the work had had to be done with the utmost care. As to the reason why a batter had not been given to the piers instead of offsets, the whole principle of the shuttering, cleverly devised by Mr. Wood-Hill, was, that it rested on those offsets, without any scaffolding whatever. He might be prejudiced as to the appearance of the work, but he did not think any one would say that it was other than satisfactory. Although

in the drawing the piers rather recalled the puttee leggings of Mr. Pain. soldiers, the structure itself did not do so, the lines in the drawing not being seen. With regard to concrete blocks versus mass concrete, blocks had to be made and kept for a considerable time, and there was always the risk of their being affected by frost: there was less liability to that when the work was done in mass. During the whole progress of the work he had had an inspector on the spot, and he was quite satisfied, for reasons which he would give, that, owing to the care exercised by his son, and the strictness of the inspection, the work was excellent throughout. The elliptical arches he had selected because they were rather lighter than semi-circular arches. The expansion-joints he had put in because he found, about 25 years ago, when building railway-bridges in mass concrete, that they almost invariably cracked; he had therefore imitated nature, and the joints were as nearly as possible in the positions in which the cracks took place in nature. With regard to the subsidence at the western end, the embankment was 55 feet high, and the contractors' trains with the excavation had been running across the viaduct for 6 months, when, in May, 1903, heavy rains saturated the bank, and probably the base of the bank as well, and caused the abutment and embankment to sink 18 inches, cracking arch No. 1, slightly affecting pier No. 1, and also moving arch No. 2. It did not affect piers Nos. 2 and 3. In a measure the expansion-joints of arches Nos. 2 and 3 took up the movement, which gradually died out; but so great was the strain upon the centre portion of arch No. 1 that his son had told him that when it was moving he could hear the masonry crushing. In consultation with the Resident Engineer of the London and South Western Railway, it was decided that the best remedy was to put in diaphragm-walls, as illustrated in arch No. 3, and that was done immediately. The most suitable white bricks that could be obtained were brought 70 miles by rail, and red bricks were brought over 30 miles by rail. The diaphragm-walls were built first, then the centre portion of arch No. 1 between the expansion-joints was cut out. That operation had shown what monolithic concrete could be like. Notwithstanding the strain to which the structure had been subjected by the subsidence, it had been a difficult task for men with steel wedges and hammers to cut it to pieces, owing to its hardness. In that particular case the blocks had certainly shown signs of more damage than had the monolithic concrete. For the sake of rapidity in getting the line open, the diaphragm-walls had been built in brickwork. He ventured to think that if the viaduct had been built in brick or stone

Mr. Pain. there would have been more damage after the subsidence of the embankment. Apparently the movement was not an absolute subsidence of the ground; there was no trace outside the bank of any swelling up of the ground. If he were about to build another viaduct he would not hesitate to build it in mass concrete, not in block-concrete, and with expansion-joints.

Mr. Griffith. Mr. C. L. T. GRIFFITH observed that so far the discussion had dealt with the design of the bridge as a whole; and it would be a pity for it to end without some reference to the cement used. In all structures of concrete, whether with iron embedded in it or not, the cement was of great importance. The cement used for the Cannington Viaduct had the high tensile strength of 563 lbs. per square inch, and, what perhaps was more important, the blocks showed a good increase in strength with age, the compressive strength more than doubling itself in 1 year. It was rather a pity that, when such good cement as that could be obtained, the specification for it should be what might be termed a little old-fashioned. The specified tensile strength was only 350 lbs. per square inch, and it was to leave not more than 4 per cent. residue on a 50-mesh sieve. He had had some experience of cement in America, having been for 2 years in some American works where what was considered very good cement was made, and he had never heard there of a 50-mesh sieve, except for testing the standard sand used in making the cement briquettes. So far as he could gather, some of the best English manufacturers were prepared to supply cement quite in accordance with the most rigid American specification ever issued. Some of them, far from using a 50-mesh sieve, used a sieve with 180 meshes, and even 234 meshes per lineal inch. The point was an important one. Sieves as coarse as 50, 76, and 100 meshes per lineal inch furnished no indication of the quality of the cement. As was well known, it had been found by experiment that the material retained on a sieve of 100 meshes, or even 120 meshes, per lineal inch, had no value as cement. He had collected on a 200-mesh sieve the residue which had passed through a 100-mesh sieve, and with that material he had been unable to make briquettes which would hold together. The cement thus examined was of very good quality, showing 700 lbs. per square inch at 7 days, 900 lbs. at 6 months, and yielding about 98 or 99 per cent. through a 100-mesh sieve. A very finely ground cement, among its other advantages, was all cement. With 4 per cent. on a 50-mesh sieve, he would expect at least 25 per cent. on a 108-mesh sieve; and that 25 per cent. was simply weak sand, and

not cement at all. With 25 per cent. of weak sand in so-called Mr. Griffith. Portland cement, instead of 6-to-1 concrete, it was $6\frac{1}{4}$ -to- $\frac{3}{4}$, which was about 8 to 1. As the bridge was evidently properly designed for the cement which had been used, 8-to-1 cement concrete might just as well have been specified with finer cement. Nothing was said in the Paper as to the setting-time of the cement. It was, of course, very important for mass concrete not to use a quick-setting cement. The future of engineering work in cement concrete depended upon the material which was obtainable, and if English cement-manufacturers were prepared to supply cement of the highest class, engineers should take care to obtain such cement.

Mr. R. J. G. READ considered the viaduct an elegant piece of Mr. Read. work; it had a singularly light appearance, and the stepping of the piers did not offend when the structure itself was viewed. He could bear testimony to the treacherous nature of the ground in the district, having had to do with the building of a retaining-wall at Lyme Regis. Although the wall stood, it had not prevented the slipping of the ground, which had filled up the back of the wall and rolled over it; and all hope of stopping the slip had been given up. The whole of the formation underlying that district was blue lias, and along the coast at Lyme Regis could be seen layers of blue lias limestone apparently horizontal. Above the limestone lay beds of sand and then rubbly oolitic rock. The water percolated through the upper beds to the blue lias, and when the latter became wet it was very greasy and caused the overlying ground to slip, at even the flattest slope. In many places it could be seen breaking away for hundreds of yards back from the shore. Work founded on the blue lias itself, like the wall of which he had spoken, was safe enough; it was the ground above which moved on the slippery clay. Probably the ground beneath the Cannington Viaduct was of a similar character, and the subsidence of the west abutment might have been due to this cause. As to the use of the dust from the crushings, instead of sand, for making the concrete, in a discussion on the subject of ferro-concrete and concrete at the recent Engineering Congress at St. Louis, it had been stated that such dust was of high value for making mortar and concrete. Results had been given of tests made on Portland cement mixed with sand, with quartz-stone crushings somewhat resembling flint, and with ordinary dust from stone-crushing; and also results of tests of briquettes made by the engineer of the Chicago, Milwaukee and St. Paul Railway, from limestone crushings and Portland cement. Those tests had shown that briquettes made with crusher-dust were much stronger than briquettes made with sand—in one

Mr. Read, case 2½ times as strong; and 5-to-1 briquettes made with crusher-dust were stronger than 3-to-1 briquettes made with cement and sand. After hearing the views thus put forward, he had had some 3-to-1 briquettes made with sand and Portland cement, and some with crusher-dust and cement. Those had been broken recently after 7½ days, and one made with crusher-dust had shown a tensile strength of 190 lbs. per square inch, as against 154 lbs. for a briquette made with sand. In another pair of examples the results were 216 lbs. and 156 lbs. per square inch respectively. With regard to ferro-concrete, he had adopted it for some foundations to carry heavy floor-loads of 10 cwt. per square foot, and for the purpose of testing the work he had had made four beams of the concrete that was being used; one without any iron in it; another—a portion of which was on the table—with two bars of iron on the tension side; a third with four bars, and a fourth with a flange of concrete on the top. As the work was being carried out in a tin-plate works, he had been able to get boxes of tin-plate, weighing 1 cwt. each, which conveniently stood on the top of the beam, which was 6 inches wide, 10 inches deep, and 10 feet in span. The first beam broke off short, as he had expected, at 3 tons. None of the other three, made of exactly the same size and the same concrete, could be broken, owing to the impossibility of piling a load of more than 30 tons on them. The beams bent and cracked in many places, and deflected 2 to 2½ inches, and when the load was taken off they recovered about 1 inch. Otherwise they seemed able to carry that load for years. With what Dr. Deacon had said as to the importance of density in concrete he quite agreed. It recalled some experiments made by Mr. A. Considère, in France, which had led that gentleman to invent a system called “hooped” concrete. By crushing cylinders of concrete in water under high pressure, in a hydraulic press, and in the ordinary way, Mr. Considère had found that when a concrete cylinder was compressed sideways it withstood about nine times the pressure which it would sustain without such lateral pressure. Working on this result, Mr. Considère had made columns of concrete, around which was wound a spiral of iron; and when tested in the ordinary way by compression those columns had withstood quite twice as much as columns reinforced only with longitudinal rods and binders. Some had required a pressure of more than 2 tons per square inch of section inside the spiral winding, to crush them. The cement Mr. Read used for ferro-concrete was much more finely ground than that used by the Authors, and it quite bore out all that had been said as to the advantages of fine grinding.

Mr. D. B. BUTLER agreed with Mr. Griffith that the specification Mr. Butler. for the cement was old-fashioned, and, in fact, in a work where everything depended on the quality of the cement, altogether inadequate. Where the ratio of the cement to the aggregate was 8 to 1, the work surely called for the best cement that could be made; and he thought the quality specified—assuming that the requirements mentioned were all that were included in the specification—could scarcely be so designated. It was extremely coarse, and no examination had been made as to constancy of volume, or as to soundness, which was one of the most important things to be determined in cement. However, he differed considerably from Mr. Griffith with reference to the coarser particles of cement being practically sand. As he had shown¹ about 6 years ago, although the coarser particles had not the same value as the flour, they had a slight value, roughly inversely proportional to their diameter; for instance, particles which were retained on a 50-mesh sieve had a much lower value than particles retained on a 100-mesh sieve. Therefore Mr. Griffith was in error in stating that the coarser particles were so much sand.

Mr. H. H. STATHAM wished to say a few words from the archi- Mr. Statham. tectural point of view. He confessed that his own inclination would be in favour of block concrete on the score of appearance, but from what he had heard that evening he thought it must be admitted that the Cannington concrete viaduct had justified its existence. Material on the spot had been used; and the difficulties or failures were simply due to the foundations, and were such as might have occurred in a bridge built of any other material. Speaking as an architect, he was afraid it was not possible to make any abstract statement about the comparative beauty of elliptical and circular arches; much depended on the situation. On the whole, the Cannington arches were more pleasant to himself than those of the Holsworthy Viaduct. As to the piers, their appearance expressed exactly and naturally the way in which they had been built, namely, by superposing stages of concrete: and he considered that a treatment of piers and arches which had that effect could not be said to be in bad taste. In very unpromising material the engineers had produced a structure which was not only adequate for its purpose, but which was actually, in his opinion, an addition to the landscape, rather than an eyesore.

¹ D. B. Butler, "The Finer Grinding of Portland Cement, and the Comparative Value of the Coarser Particles." Minutes of Proceedings Inst. C.E., vol. cxxxii. p. 343.

Mr. Thomas. Mr. P. THOMAS asked for further information on one or two points. The Authors seemed to suggest that the cause of the failure at the west end of the viaduct was the undermining of the foundations by excessive rains. If that was so, it was another illustration of the danger of placing foundations on a slope liable to the action of water, without carrying the foundations down or nearly down to the level of the bottom of the valley; another 7 to 10 feet of depth in the case of the abutment would have made all the difference. It was a significant fact that the Table of pressures given on p. 2 showed plainly that the highest pressures were allowed at that end of the viaduct: which would seem to indicate that the highest pressure which could safely be allowed on the material did not exceed about $2\frac{1}{2}$ tons per square foot. The Table of pressures showed considerable variations, and later on the Authors stated that small variations were observed in the settlement of the piers. It would be interesting to know whether any relation had been observed between the amount of the pressure and of the settlement. With regard to the concrete boxes, two longitudinal L- or T-bars outside each side of the box were often used effectively for the same purpose as the iron rods passed through from side to side. They were fixed securely at the ends of the box, and adjustable wedges were placed between the angle-bars and the intermediate upright stiffeners: by the use of those wedges the sides of the boxes could be kept in the true line. He took it that the eleven boxes used formed a complete set of boxes for 6-foot lifts. As had already been remarked, there were thirteen lifts on No. 3 pier, but two of them were of smaller depth, and naturally shuttering or special boxes would be used in those cases. Seeing that the maximum amount of concrete work carried out in any one day was 30 cubic yards, which the Authors attributed partly to the limited space in which the concrete had to be deposited, it might have been advantageous to have another set of boxes, though of course they would be of no use if the capacity of the cableway were not sufficient to enable material to be brought to them. He could not help thinking that the experience in this case did not encourage engineers or contractors to use cableways. The construction of 30 cubic yards per day, and the building of a viaduct of that size in a little more than 2 years, was rather a moderate rate of progress. He desired specially to ask the Authors whether they considered that the provision of more boxes would have increased the rate of progress, or if the rate attained was the maximum of which the cableway was capable; because it was desirable to know what was the actual capacity of such a cableway in practice.

Mr. WOOD-HILL, replying on behalf of himself and Mr. Pain, Mr. Wood-Hill. thanked the members for the kind way in which the Paper had been received. He felt much gratified that it had drawn remarks from several members of the Council. The President had touched upon the difficulties of constructing concrete works on account of the expansion, and Sir Alexander Binnie had outlined the principle of the three-hinged arch. In addition to having advantages as regarded expansion, the three-hinged arch had the additional merit that it confined the curve of pressure to certain points in the arch. As the curve must pass through the centre of each hinge, its position was known at both springings and at the centre of the arch, and there was less likelihood of the curve getting outside the middle third of the arch between those points. As an alternative to the hinge which Sir Alexander Binnie had described, a strip of cast lead a few inches wide had been adopted in some cases. That had the merit of simplicity; and it was also claimed that if undue pressure was put upon the top or the bottom of the strip the lead expanded in area, and consequently the pressure per square inch was reduced, so that the arrangement was to some extent automatic. It should have been explained in the Paper that the lime-mortar expansion-joints were not really joints in the ordinary sense of the word; they were merely formed with a wash of weak lime mortar, as thin as possible, so that there was no likelihood of the joint crushing or falling out. The skin of lime mortar was merely put in to prevent the adhesion of the cement on those joints. With regard to the question of expansion, on a viaduct on the West Highland Railway flat iron plates were built in, close together, at the crown of the arch, and there was no arrangement of a hinge. It seemed to him that that would be a good way of preventing any crushing at the top or the bottom edge of the arch. He believed the Holsworthy Viaduct was the only other concrete viaduct in England of the same size as the Cannington, and he considered it a fine piece of work. He could not quite agree with Mr. Galbraith on the question of concrete blocks. Before it could be said that the figures of cost for the two viaducts were fairly comparable, it was necessary to know whether Mr. Galbraith's figures represented the scheduled cost of the viaduct or the actual cost to the contractor, and also how far the Holsworthy work had been affected by local conditions. At Cannington, as Mr. Pain had mentioned, cartage was costly; and the whole of the plant used on the viaduct had had to be carted 6 miles from Axminster

Mr. Wood-Hill, station, at a cost of 6s. per ton. Apart from these two viaducts, he found it difficult to see how blocks could be constructed at the same cost as mass concrete, if the same facilities existed for the materials used. Block concrete required a larger surface of shuttering per cubic yard of concrete; there was a larger amount of faced work to execute; and holes had to be left for lifting-irons. When made, the blocks had to be transported from place to place; and they must be stacked and allowed to harden before being set. The labour entailed was considerably greater with blocks than with mass concrete. The whole of the works on the Malling extension of the West Highland Railway had been constructed in mass concrete, and they included four viaducts, the largest of which was the Glenfinnan Viaduct. The three smaller viaducts included a single arch of 127 feet span, the largest concrete arch in Great Britain. As to easier detection of defective concrete in block-work, Mr. Pain had already answered Mr. Galbraith's point by stating that in the whole of the viaduct no concrete had had to be cut out on account of defects of that kind. But even if a flaw did occur, the concrete was not likely to be so bad that it would all fail at once, and there would probably be a chance of cutting out and renewing it in steps without any fear of disaster. He agreed that "6-to-1" concrete should be more clearly defined. The expression was generally understood to represent the ratio of the quantity of ballast or coarse gravel used to the quantity of cement, the quantity of sand being reckoned independently, and varied according to what was found by experiment to be necessary to fill the interstices. Some specifications specified 4 parts of ballast, 2 of sand, and 1 of cement, and yet on turning to the schedule it would be found that "6-to-1" concrete was mentioned. But that was not 6-to-1 concrete. If the sand filled the interstices of 4 parts of the ballast, that was 4-to-1 concrete. It should be generally understood, if that way of describing concrete were allowed, that the ratio should be reckoned between the volume of the aggregates when mixed together and the volume of cement. With regard to the omission of sand, the practice in that matter was ruled to some extent by what the concrete was wanted for. If water-tight concrete was desired, it was well to have rather an excess of sand. If the strongest possible concrete was desired, the sand should be exactly the quantity necessary to fill the voids. In the present instance what had been wanted was a thoroughly strong and reliable, but not necessarily water-tight, concrete; and he did not think the pressure anywhere exceeded 6 tons per square foot. The concrete made would amply stand that, as shown by the tests, although the samples tested

had contained sand. Some blocks of the concrete had been broken Mr. Wood-Hill up on the site, and it had required a great deal of hitting with large steel wedges to effect any sort of cleavage. The pressures on the foundations had not been worked out exactly to $\frac{1}{4}$ ton beforehand, and those given in the Table on p. 2 were calculated from the actual structure. The foundations were drawn to an even size, and if it was found in any of them that the pressure came within the limits to which it was desirable to go, the drawing was not altered. It had been asked how it was possible to construct thirteen different sizes of lifts with eleven boxes. It should have been explained that the ends of the box were reduced after having been used, and the sides were bolted to them again, so that the same sides of the box were used throughout. They were shortened when they got near the top merely for convenience. Mr. Trench's suggestion that by the use of ferro-concrete the weight on the foundations might be spread, without adding to the weight of the piers, was a good one, and had been adopted, Mr. Wood-Hill thought, in some works. On the principle of ferro-concrete construction—that tension should be resisted by the iron and compression by the concrete—the rods or girders should be placed as low as possible in the slab. As to the cost of brickwork on the site, bricks cost 32s. 6d. per thousand, the cartage per thousand would have been 18s., and the sand—which would have been the chief item, as it had to come from a long distance—would have cost 12s. per cubic yard; moreover, with brickwork there would have been the expense of scaffolding. The total cost of brickwork would have been not less than 45s. per cubic yard, which was extremely high, and entirely justified the adoption of concrete for the work. With regard to the cement, a more stringent specification might have been adopted, but it should be remembered that the line was a light railway, and that the cost of materials was an important consideration. No complaint could be made in respect to the hoisting and travelling speed of the cableway, and he was confident that it was the cheapest device for constructing a viaduct of this height. In addition to transporting the concrete, it had been used for lowering the flints from the embankment-head to the stage of the stone-crusher, and for all work in connection with the shuttering and centering, the adjustment of which of course took time. The cableway in this instance had undoubtedly done the work of several cranes. There was no relation between the settlement of the piers and the pressure allowed on the foundations, the settlement being slightly different in cases where the pressure was the same. He thought that, having regard to the length of the boxes

Mr. Wood-Hill. outside T-bars in place of tie-bolts would be too heavy for convenient handling, if made stiff enough to prevent bulging under the pressure of the liquid concrete. The movement at the west end of the viaduct appeared to extend some distance into the green-sand, whose limit was not reached by a boring, more than 20 feet deep, taken before the building of the diaphragms; and he therefore considered that, had the trouble been foreseen, it would have been better, instead of carrying the foundation deeper as had been suggested, to put another span to the viaduct, thus shortening the embankment and reducing the weight upon the hill. He did not consider that the time taken in construction was at all excessive, especially in view of the isolated position of the works and the difficulty of obtaining labour.

The President. The PRESIDENT communicated the following observations on the Paper. He considered it impossible to lay down any hard-and-fast rule for the use of concrete in arches. Each case must be determined by its local conditions. If good bricks or easily-worked stone were available near the site of the bridge, and if the cost of cement was high, the use of concrete might be undesirable. If, on the other hand, there were clean sand and shingle in the bed of the river, if the stone were of a refractory character, or if skilled workmen could not be readily obtained, then concrete might be used with advantage. The objections which had been raised to the use of concrete in mass, as compared with its use in blocks, did not appear to apply with equal force to arches and to piers. There were many advantages in mass building in arches, especially in skew arches; and if proper care were taken and tests were made, during construction, of every part of the arch, there could be no danger from improper setting. Moreover, the mass in arches was comparatively thin, especially if it was formed in successive layers or rings: it could be examined from time to time, and any defect in setting could be detected and remedied before the centering was removed. Railway-arches were generally protected from changes of temperature by the ballasting, and from hygrometric changes by an asphalt coating. Segmental and semicircular arches were preferable to elliptical arches. His early experience had led him to avoid elliptical arches in more mature practice. He thought that a more correct mode of specifying the proportions in concrete would be in pounds of cement per cubic foot; ranging, say, from 10 lbs. or 12 lbs. per cubic foot in abutments to 16 lbs. or 18 lbs. in arches, but varying to some extent with the size and description of the materials used, the proper proportion being found by experiment.