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## " Entrained Air in Concrete " †

by

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### Correspondence

**Mr E. W. W. Richards** was of the opinion that the Author, in suggesting that air-entrainment was unlikely to prove an asset in the construction of concrete roads of high quality in Great Britain, and that it would only find a place in low-grade construction by inexperienced contractors or under inadequate supervision, might have understated the importance of the subject and have missed the essential point lying behind American development of that process. American concrete-road-making plant, developed for high productivity, required a high degree of workability for its most effective operation. It was a common, but mistaken, criticism of American practice to say that that was a defect in American technique, or to allege that American concrete research was directed to finding palliatives for faults arising out of incorrect methods. American engineers were as well aware as British engineers were of the effects of workability and water/cement ratio upon concrete strength. They were of the opinion, however, that productivity came first, and that to sacrifice it for the sake of saving a relatively small quantity of cement or of avoiding occasional trouble from other causes was not good economics.

Mr Richards recalled raising that specific point with a party of American engineers and being told " To understand this you must appreciate our position and what we are trying to do. We know that we could make stronger concrete, and avoid some of our difficulties, if we made a stiffer mix, as you do. But if we did this it would mean slowing down our rate of progress and re-designing our equipment. What we are trying to do is to build roads cheaply and quickly, and to get as many miles as possible into the service of the community as quickly as possible. We reckon to

† Proc. Instn Civ. Engrs, Part I, vol. 2, p. 337 (May 1953).

deal with any difficulties arising out of this as we go along." Judging from their present position it would seem that they were successfully doing so, and thus enjoying the best of both worlds.

As for the extent of the use of air-entrainment, he had been told at the United States Bureau of Reclamation Concrete Laboratory at Denver, Colorado—possibly the finest cement- and concrete-research station in the world—that it was almost universal (the air-entraining agent being generally incorporated in the cement, so that the question of an additional operation or closer control in concrete making did not arise) and that it would now be unusual to find concrete made in the United States in any other way.

Whilst appreciating its academic disadvantages (and the indeterminate nature of concrete-road design), the use of air-entrained concrete had much to offer the constructional engineer in the way of expeditious and satisfactory construction, and notably with centrally-mixed concrete, so commonly used in the United States. It would be unfortunate if its use were relegated in Great Britain to the comparatively minor purposes suggested in the Paper without those aspects being considered.

**Mr R. G. Smith,** of Vancouver, observed that the use of entrained air in concrete had been brought to his attention recently in the construction of a prestressed concrete bridge at Bernera, Scotland. In the initial stages of trial mixes for that job, a concrete mix with a cement to aggregate ratio of 1 : 5 by weight, using $\frac{3}{4}$-inch-diameter irregular gravel aggregate and a water/cement ratio of 0·40 was tried. That gave " low " workability with a compacting factor of 0·78 and was found to be too harsh. The contractor had suggested the use of an air-entraining agent to increase the workability but it was found that that had little effect on the mix. Such a result was confirmed by the curve 1 : 6/0·45, in *Figs 1 (a)*.

It would appear that for mixes richer than 1 : 6, where low workability was necessary, the use of an air-entraining agent, although increasing workability slightly, would reduce the compressive strength by too great a proportion. It would be interesting to know whether the Author had carried out any tests on mixes richer than 1 : 6 with " low " workability.

In the United States it had been suggested that air-entrained concrete should be used for prestressed concrete construction, and at least one prestressed concrete bridge had been constructed in that manner. Since most concrete required for prestressed concrete work was of a relatively rich mix with low to medium workability, Mr Smith was of the opinion that it was difficult to justify the use of air-entrainment in prestressed concrete construction, unless of course the structure was to be subjected to severe frost action. The Author's views on that subject would be appreciated.

With regard to the mix design proposed by the Author (see p. 355), Stage (1) stated that " The mix is designed as for normal concrete, by any reliable method, such as that set out in Road Note No. 4."

It should be remembered, however, as the Author had pointed out.

15

that the use of an air-entraining agent constituted the addition of another variable factor in the control of concrete. That was bound to increase the coefficient of variation of concrete strengths, so that concrete with the addition of an air-entraining agent should be designed for a higher compressive strength than with plain concrete. It would, of course, be necessary to know what degree of variation of percentage air-entrainment could be expected on an actual job but, in Mr Smith's opinion, some allowance for that factor should be made in the design of the mix.

**Mr M. F. Kennard,** referring to the survey of the use of air-entraining agents in concrete, remarked that no mention was made of its use in connexion with concrete placed by means of a concrete-pump. The water/cement ratio of pumpable concrete was often about 0·70 or higher, and consequently the compressive strengths obtained were comparatively low, and so an increased cement content was often resorted to.

On one particular contract it had been found that the addition of an air-entraining agent had enabled a drier and leaner mix to be used with the same or higher compressive strengths as previously. Because of the increased volume of the mix, and the saving in cement, there was also a slight saving in the cost of materials per mix. Since the mixer driver added the agent into the rotating mix, there was no additional labour or plant cost involved. It was expected that the amount of entrained air might decrease during a long length of pumping, but tests taken, although not sufficient in number to be conclusive, did not show any such loss. The lower amount of air entrained at higher temperatures, mentioned on p. 351, had been noticed, and it could be sufficient to offset in part the saving mentioned above.

With normal concrete without an air-entraining agent, tests taken with an air-in-concrete meter of the type illustrated on p. 354, had shown an air content of about 1·5 per cent. Although it could be said that that concrete was incompletely compacted, Mr Kennard considered that most samples would show an air content when tested in a similar way. In comparing the two mixes on p. 349 did the Author mean that the 5 per cent of air is the total air or the entrained air. If it was the former, the increase in volume would be less than 5 per cent.

**Mr P. L. Melville,** of Virginia, observed that on two points, the Author's opinions were somewhat in conflict with current views of the Virginia Council of Highway Investigation and Research.* The Virginia Department of Highways was now using air-entrained concrete on all construction work because it was believed that with *ad hoc* controls there was hardly anything to lose (negligible loss in strength, low cost of air-entraining agent) and much to gain (increased workability, cohesion, and homogeneity, reduced bleeding, savings due to higher yield) through air-entrainment. It should be noted that increase in durability was not a

* A co-operative organization sponsored jointly by the Virginia Department of Highways and the University of Virginia, U.S.A.

paramount factor since, owing to economic reasons, most of the Departments' concrete (that was, all paving) was used near the eastern seaboard where climatic conditions were not usually very severe.

The Author had mentioned the possibility of " wet batching " by transporting air-entrained concrete in dump trucks, but did not appear to encourage such practice. In 1952, the Council had undertaken an investigation into the transit of air-entrained concrete in non-agitating trucks. From a small mixer, centrally located, concrete having a slump of 2 to 4½ inches and 4 to 6 per cent of entrained air was transported to a series of small bridges. The times of haul ranged between 6 and 26 minutes and the distance between 2·3 and 15·5 miles. As a result of that study the following was reported :

(1) The trucking of air-entrained concrete was accompanied by a reduction of the slump and air content, caused possibly by compaction in transit.
(2) The loss of air and slump was not a function of time of transit or the distance above certain minima (probably about 5 minutes and 2 miles).
(3) As a direct result of (1) and (2) above the compressive strengths increased with the trucking.
(4) The durability through cycles of freezing and thawing as evaluated by the sonic modulus of elasticity was not appreciably affected and was satisfactory in all cases.
(5) There was no evidence of segregation.

From those results it was concluded that :

(*a*) It was safe and reliable to use non-agitating trucks.
(*b*) The procedure might be used for transit times up to about 30 minutes regardless of mileage.
(*c*) The percentage of air should be maintained at or near the upper limit allowed by specifications.
(*d*) Opportunity for moisture losses in transit should be minimized (for example, by the use of tarpaulin cover, good condition of dump-truck).

As a result, the procedure was now commonly used for maintenance or incidental construction at savings to the Department of Highways.

With reference to the control of the admixture, current specifications required that the agent be added at the mixer either to the mixing water or to the sand. Most contractors had installed an approved automatic dispenser. Its use was desirable, but certainly not essential. It was found that manual dispensing could be reliable : an inspector would place the admixture from a calibrated measure, usually a properly trimmed tin cup, although in at least one case an empty mineral-water bottle had been found to be the right-size container to obtain 4 to 6 per cent of air. No difficulties had thus been encountered in dispensing the admixture.

**Mr D. D. Fraser**, drawing attention to the fact that the North of Scotland Hydro-Electric Board was carrying out a full-scale test of air-entrained concrete on the Gaur hydro-electric project, Perthshire, explained that it had been felt that on the high exposed locations of the Board's many projects in the Scottish Highlands, concretes possessing increased resistance to frost attack were not undesirable. Lower permeability and greater resistance to chemical attack were also attractions in structures which would be in permanent contact with corrosive moorland waters.

Air-entrained concrete had been in use at Gaur for the past year. During that time, about 5,000 cubic yards of mass concrete and 5,000 cubic yards of reinforced concrete had been poured in different types of structures, using a normal range of mixes. Naturally, insufficient time had elapsed, as yet, to judge whether air-entrained concrete was likely to prove more durable than ordinary concrete under the conditions prevailing. As regards permeability, however, laboratory percolation tests had indicated that for pressures of up to 100 lb. per square inch, air-entrained concrete was 50 to 100 per cent better than ordinary concrete, although for pressures in excess of 100 lb. per square inch there appeared to be no appreciable improvement.

On the site, air contents of 3·5 to 4·5 per cent were entrained, the agent used being the triethanolamine salt of a sulphonated hydrocarbon referred to by the Author. For most mixes, to offset any possible reduction in strength, the sand content was cut by 100–125 lb., and the water content by 30–40 lb. (both per cubic yard of mixed concrete). The improvement in plasticity and workability was quite noticeable and was a constant attraction to the placing squads. Even for concretes of identical slump, it had been found that the air-entrained variety was more workable than the ordinary. There was also a lessening in the tendency of some mixes to segregate during transportation, and that was particularly noticeable at the main dam to which the 8·5 : 1 hearting concrete—having 2½-inch aggregate—had had to be hauled in lorries over a distance of ½ mile.

Regarding the combined effect on strength and workability, Table 3 gave the average results of field test cubes made from air-entrained concrete during the past year and from ordinary concrete during an immediately preceding four-months period. Because more cubes had been made during the air-entrained period than during the ordinary period, some of the results were not strictly comparable, but nevertheless they did give some indication of the practical effects of an air-entraining agent.

It would be seen that the air-entrained concrete had been more workable than the ordinary concrete, as evidenced by the slight general increase in slumps. On strength and density, the agent seemed to have had no decisive effect one way or the other; in some cases there had been gains, in others losses, but on the whole the variations had been small. The effect of the agent on the lean 8·5 : 1 mix was worth attention, however, since in that particular mix, improvements in strength, density, and

TABLE 3.—ANALYSIS OF FIELD TEST CUBES TAKEN FROM ORDINARY CONCRETE AND AIR-ENTRAINED CONCRETE USED ON THE GAUR HYDRO-ELECTRIC PROJECT

(Ordinary Portland cement used throughout; figures in brackets refer to number of cubes tested.)

| Aggregate/cement ratio and type of concrete | Max. size of aggregate: inches | Average slump: inches | Required compressive strength at 7 days: lb. per sq. in. | Actual average compressive strength at 7 days lb. per sq. in. | Average density of 7-day cubes: lb. per cu. ft. | Required compressive strength at 28 days: lb. per sq. in. | Actual average compressive strength at 28 days: lb. per sq. in. | Average density of 28-day cubes: lb. per cu. ft. |
|---|---|---|---|---|---|---|---|---|
| 4 : 1 normal . . | $\frac{3}{4}$ | 1·8 (13) | 2,700 | 4,430 (16) | 151·0 (20) | 4,000 | 6,460 (7) | 151·5 (2) |
| 4 : 1 air-entrained | $\frac{3}{4}$ | 2·7 (9) | 2,700 | 4,550 (18) | 150·0 (18) | 4,000 | 6,220 (5) | 150·5 (5) |
| 5 : 1 normal . . | $\frac{3}{4}$ | 1·4 (20) | 2,350 | 3,920 (14) | 150·4 (20) | 3,500 | 5,290 (7) | 149·0 (8) |
| 5 : 1 air-entrained | $\frac{3}{4}$ | 2·2 (61) | 2,350 | 3,540 (84) | 150·5 (20) | 3,500 | 5,640 (44) | 150·5 (40) |
| 5 : 1 normal . . | $1\frac{1}{2}$ | 1·3 (16) | 2,350 | 3,880 (32) | 150·8 (32) | 3,500 | 5,190 (16) | 151·0 (7) |
| 5 : 1 air-entrained | $1\frac{1}{2}$ | 1·0 (16) | 2,350 | 4,010 (32) | 151·3 (32) | 3,500 | 5,720 (16) | 151·9 (16) |
| 6 : 1 normal . . | $1\frac{1}{2}$ | 1·3 (15) | 2,000 | 3,510 (25) | 150·5 (20) | 3,000 | 4,420 (10) | 151·5 (4) |
| 6 : 1 air-entrained | $1\frac{1}{2}$ | 1·4 (6) | 2,000 | 3,050 (14) | 150·0 (13) | 3,000 | 4,370 (6) | 150·5 (4) |
| 8·5 : 1 normal . . | $2\frac{1}{2}$ | 0·4 (15) | 1,300 | 2,050 (28) | 150·0 (16) | 1,950 | 2,720 (11) | 150·5 (8) |
| 8·5 : 1 air-entrained | $2\frac{1}{2}$ | 0·5 (16) | 1,300 | 2,160 (28) | 150·4 (20) | 1,950 | 3,000 (10) | 152·0 (9) |

workability had all been obtained. That bore out the Author's remarks and was in agreement with site opinion that the agent had a more beneficial effect on the leaner harsher mixes using 1½-inch and 2½-inch aggregates than on the richer mixes using ¾-inch aggregate. In the 8·5 : 1 mix, the aggregate was held in position much better, the workability improved to a greater extent than the tiny increase in slump might suggest, and placing and consolidation were made easier. Perhaps that was the explanation of the increased strength and density.

The Author had rightly pointed out that air-entrainment was not likely to be adopted generally in Great Britain. However, for large mass structures using lean mixes, such as dams, it appeared that it might prove advantageous. Nor were possible improvements in the durability of thin-walled structures, such as aqueducts, to be rejected lightly, especially when all those advantages were to be had at little or no extra cost.

**Dr M. M. Kansoh**, of Alexandria, referring to the statement on p. 340: "The improvement in workability has not been satisfactorily explained," observed that a successful foaming or air-entraining agent should contain a wetting or so-called surface-acting agent in addition to agents which improved the stability of the foam produced. A satisfactory explanation of the improvement in workability arose from the knowledge of the ability of surface-acting agents to keep fine particles in suspension, which facilitated the motion of individual sand and cement particles past one another.

It was stated on p. 346 that "an increase in air content results in a loss of strength, but the entrainment of air enables the water/cement ratio and the sand content to be reduced substantially, thereby regaining most if not all of the lost strength." Responsibility for regain of strength was also a known attribute of the wetting agents which assisted in the wetting-out of the dry cement particles, with the result that the amount of dry or imperfectly hydrated cement in the mixers greatly reduced or, in other words, the cement was fully or more efficiently utilized. Ordinary concrete containing no such agent could sometimes be re-set after being crushed and mostened. That was an indication of the existence of dry or imperfectly hydrated cement.

Reduction of water content resulted in a reduction in cracks during drying out. That was another advantage to be added to the credit of air-entrained concrete, especially in "precast concrete" industry where too-wet mixes were used (p. 338), and in the construction of liquid containers.

Regarding the measurement of air content, the gravimetric method was the most accurate one. The standardization of vibration methods did not seem to be impossible. At least, a vibrating table of chosen stroke and frequency could be used for a standardized length of time. Such a method could be used in the laboratory and, wherever possible, in the field to eliminate the human element. In other cases, results obtained from one such apparatus could be used, as a measure, to standardize manual methods of vibration.

The volumetric method was doubtful because the air could not be completely removed by agitation since the air bubbles " are very stable " (p. 342). In any case, the volume of displacing water represented not only the volume of entrained air, but also the volume of the voids which existed unintentionally in the concrete.

The pressure method could give only relative, not absolute, results. The apparatus should perhaps be calibrated before use.

Could the Author give some account of the effect of air-entrainment on heat and sound conductivity and on the tensile and bond strength of concrete, all of which one would expect to be improved, the first two as a consequence of the existence of billions of air bubbles, and the last two on account of minimizing the number and depth of cracks ?

**Mr G. S. Eldridge,** of Canada, remarked that air-entraining admixtures in concrete had been in use in Vancouver, B.C. since 1929. At that time, central mixing plants had just become general, and the matter of transportation of concrete without segregation had been a problem. Adding fines did not solve it. Certain waterproofers had shown a marked improvement in transportation in fixed-body bathtub trucks, even over plain concrete mixes in revolving-drum trucks, and it had appeared that in that existed a principle of fundamental importance. It was soon found that the amount of air added to a mix was the criterion of non-segregation and of workability of the concrete. Too much air gave great stability to the mortar, but reduced the strength. The greater the percentage of air ; the greater the reduction in percentage of water, but there was a definite point (between 3 and 4 per cent of air) where the loss of strength due to increase in air more than offset the benefit of the reduction in water.

What really had delayed the general acceptance of air-entrained concrete was the fact that 24 years previously, concrete mixes were designed on a maximum-density basis, and attempts were made even to remove (by vacuum) the 1 per cent of air usually contained in plain mixes. Those mixes were harsh, and were very difficult to place without gravel pockets, so that there was very little maximum density, or even waterproofness, in the emplaced concrete.

Generally speaking, plain concrete required about 10 per cent more water than did air-entrained mixes with about 4 per cent air and properly controlled sand and slump. MacMillan, of the Portland Cement Association, had stated in 1930 that the main problem remaining unsolved after 30 years of research was the elimination of the 10 per cent of *excess* water needed in plain mixes in order to get reasonable placement. It was that 10 per cent of excess water that caused most of the troubles with concrete through bleeding, forming water channels, and floating cement to the surface, resulting in laitance, and giving poor bond between pours in walls and dusting on slabs.

At the outset of his investigations, Mr Eldridge had felt that air-entrained concrete would not be accepted unless it produced equal strength for equal cement, and it was not long before he was able to achieve that. Since then, numerous tests had been made in many independent laboratories which proved that equal strength could be obtained from air-entrained concrete using equal cement. It was true that that was contrary to many theories published at the present time, but a recent pamphlet by the Portland Cement Association showed a *gain* in strength of air-entrained concrete over plain concrete when the amount of air was kept down to a certain level, depending on the size of the gravel used. For example, greater strength was obtained on $1\frac{1}{2}$-inch gravel with less than 3 per cent of air, on $\frac{3}{4}$-inch gravel with less than $5\frac{1}{2}$ per cent of air, and on $\frac{3}{8}$-inch gravel with less than $6\frac{1}{2}$ per cent of air.

On two large projects, in Canada, keeping the air down to 3 or 3·5 per cent, and seeing that the slump was not greater than in plain concrete, had resulted in a gain in strength of 7·9 per cent on an average of 56 cylinders of air-entrained concrete compared with 56 of plain concrete. (See Table 4.)

TABLE 4

| Cylinders 6″×12″ | Cement: sacks/cu. yd of concrete | Average slump: inches | Compressive strength: lb./sq. in. | | Average of air in total mix: per cent |
|---|---|---|---|---|---|
| | | | 7 days | 28 days | |
| Job "A"—a dam: | | | | | |
| Average of 28 cyls | 4·28 plain concrete | 3 | 2,187 | 3,599 | — |
| Ditto | 4·28 with admix. | 3 | 2,444 | 3,879 | 3·0 |
| Average of 53 cyls | 3·5 with admix. | 3 | 1,957 | 2,966 | 3·8 |
| Average of 75 cyls | 4·0 with admix. | 3 | 2,164 | 3,321 | 3·8 |
| Job "B"—a bridge: | | | | | |
| Average of 35 cyls | 6·0 plain concrete | 3·35 | 2,140 | 3,196 | — |
| Ditto | 6·0 with admix. | 1·75 | 2,865 | 3,984 | 3·1 |

NOTES.—In job A, 6-inch crushed gravel had been used in the mix, and all rock larger than $1\frac{1}{2}$ inch screened out to make the cylinders. That was why strength had appeared so high on the cement content of that concrete.

The difference in slump in job B of 1·6 inch in favour of air-entrained concrete should not increase the strength more than 400 lb. per square inch, whereas the increase for air-entrained concrete was nearly 800 lb., a gain of 400 lb. per square inch using the same cement content per cubic yard.

Mr Eldridge thought *Fig. 5* was very misleading, and should not have been published for the very reasons mentioned in the paragraph below it.

Air-entrained concrete could not be compared with plain concrete with the same water/cement ratio, since the main object of air-entraining was to cut out the 10 per cent of excess water and still get better placement. Further, a 6-sack mix with 8 per cent of air would have a yield of 8 per cent more than a plain mix, and the Author was comparing a plain 6-sack mix with a 5·5-sack air-entraining mix with 8 per cent of air and about 20 per cent more water than required to give equal placement.

The Paper indicated a loss of strength by the use of air-entrained concrete. Such loss of strength was not necessary if proper control was exercised by (1) cutting the water down by 10 per cent, (2) using not more than 4 per cent of air, and (3) reducing the amount of sand by 3 per cent.

In the past, mixes were often designed for maximum density, on the theory of an ideal grading that would give minimum voids and maximum density. Such mixes were much too harsh to place, and in practice on structural work the concrete would be badly honeycombed, and would have far from uniform strength or uniform maximum density in place.

It was well known that about 25 per cent excess mortar over that required to fill the voids was necessary to obtain reasonable placement. Even then, without air-entrainment the extra work involved in placing, and the difficulty of ensuring a good stripping job, did not justify the use of plain concrete, especially on structural or architectural work. In fact, so much advantage had been found in using air-entrainment, in the prevention of segregation, obtaining greater uniform strength and density in place, greater workability and ease of placement, reduction in bleeding of slabs and absence of laitance, that no contractor on structural work in Canada would consider using plain concrete.

In short, air-entrained concrete produced at least equal strength with much greater workability, but a rigid method of *quick control* was imperative. Such control had been found in the weight per cubic foot of an average sample of the mix compared with the weight of a cubic foot calculated from absolute volume of each ingredient.

Mr. Eldridge gathered that the Author considered air-meters a more accurate way of measuring the air content. The Paper emphasized that to obtain an accurate figure of the air content with the weight-per-cubic-foot-method it was necessary to take an average sample of the concrete. That was quite true, and until an inspector was reasonably good at taking average samples he should prove his figures by taking three samples from the same mix. If an average was difficult to obtain on a cubic-foot sample, or half a cubic foot, it was still more difficult with 0·25 or 0·2 of a cubic foot, which was the amount used when testing by air-meter.

The percentage of air recorded by an air-meter is three or more times less often accurate than when obtained by the weight-per-cubic-foot method, even if one could rely on the assumption that the air-gauge zero had been checked and the gauge was reading correctly. The air was in the cement paste, and if too much gravel was included in the sample the percentage of air obtained would be too low, whilst if too much mortar was taken in the sample the air content would be too high. Whenever possible, when using an air-meter, Mr Eldridge weighed the sample in the bowl and checked the gauge reading against the weight per cubic foot.

The Author, on p. 351, mentioned the fact that Walker and Bloem had found that sand between No. 30 and No. 50 A.S.T.M. sieve had a marked effect on the amount of air that could be entrained. Mr Eldridge's experience had been that while the No. 30 to 50 portion was beneficial to air content, the portion between No. 50 and 100 had much greater effect on air entrainment, as also on the workability of plain concrete.

It had been found that a glass gauge with a 3-way valve was the best admix dispenser. The inspector could see the actual amount going into the mixing water. Automatic dispensers were not visual, and should be frequently checked as to actual delivery to the mixer.

A proper test for bleeding was probably the best indicator of non-segregation and workability. A slump cone was often used to determine workability, but it was not all that one could wish for. A simple comparison might be made in the field by driving a bucket of each kind of concrete of exactly the same slump over a rough road and measuring the amount of water coming to the surface.

A simple explanation of the greater flowability of air-entrained concrete might be arrived at by considering the fact that in a heavy-duty engine it was cup grease, not thin oil, that was used to keep the shaft from contact with the bearing metal, to reduce friction. Similarly, the fat plastic mortar in air-entrained concrete kept the gravel pieces apart, and the friction of rock on rock was greatly reduced. A well designed concrete (air-entrained) might be made to flow horizontally at least 25 feet when necessary without segregation of the gravel.

On p. 339 it was stated that air-entrainment had been discovered in the north-eastern States, where certain pavements in which there had been air-entraining cement gave a more durable concrete and greater freedom from surface scaling due to freezing and thawing and also to the addition of calcium chloride. That discovery was, to the best of Mr Eldridge's knowledge, about 1936, 7 years after air-entrained concrete had been used for structural purposes in British Columbia. It's use in mass concrete had not been considered at that time, owing to the comparative ease of placing pavements and other large masses. The climate in Vancouver, where it was first developed, was somewhat similar to the South of England, where freezing and thawing were not a problem as in the eastern and middle-western parts of America.

Mr Eldridge was convinced that the main advantages of air-entrainment were the prevention of segregation, the much greater ease of placement, and the greater uniformity of strength and waterproofness in place. Those were advantages that were world-wide in application—in hot, cold, or moderate climates.

It might be of interest to mention that there were six central mixing plants in the Vancouver area, and that practically all the concrete produced by them was "air-entrained."

In conclusion, there was no doubt that air-entraining in concrete had made a very definite advance in eliminating the serious fluctuations in strength, density, and waterproofness in the average structural concrete job. It was essential, however, that a specification be laid down for admixtures, as to their uniformity, and that a proper measuring device be used, too much variation in measuring admixtures having been responsible in the past for an unnecessarily wide variation in air content. The grading of the sand should also be kept fairly uniform, especially the portion between 48 and 100-mesh, in order to keep the percentage of air constant for the same amount of admix. With plain concrete, sands with less than 12 per cent of 48-mesh gave harsh mixes, but sands with as low as 5 per cent of 48-mesh had been used when no fines were available, by adding double the amount of admixture ordinarily used. That gave about the same amount of air as a well graded sand with half that much admixture.

**The Author,** in reply to Mr Richards, observed that whilst the explanation was commonly accepted, it was not necessarily true that the reason for the use in America of more workable concrete for road construction than was used in Great Britain was largely to expedite the construction. For example, on an airfield contract at present in progress in England, concrete of low workability was being produced for runway construction at the rate of 15,000 cubic yards per week, which corresponded to 3 miles per week of a roadway 24 feet wide and 8 inches thick. The conditions in airfield work lent themselves more readily to rapid construction than did those of road work, but that rate was believed to be as high as that reached in the United States. Further, more workable concrete was found to make the construction of high-quality concrete roads more difficult, for it tended to flow under the action of surface vibrators in the direction of even a slight crossfall or gradient; that led to poorer riding quality. It was for those reasons that the use of air-entrained concrete was not considered to be highly advantageous for high-quality road construction in Great Britain. The building of high-quality concrete roads, however, represents in Britain one of the very minor uses of cement. The largest uses were in the building and precast-products industries, and it was suggested in the Paper that the manufacturers of certain precast products could benefit by the use of air entrainment as was the case in America.

In contrast to Mr Richards' suggestion that in the United States the air-entraining agent was generally incorporated in the cement, Mr Melville had written as though the usual practice were to add the agent at the mixer. The Author had had no first-hand experience of American methods, but from conversation with a number of American engineers and from numerous Papers on the subject it appeared that both methods were widely used, and that whilst each had its own merits and demerits neither was gaining universal approval.

Mr Smith's doubts about the use of air-entrained concrete for prestressed work, where high strengths were necessary, were supported by the results shown in *Fig. 7.* Such doubts, however, were based on the results of laboratory tests and it was possible that, because of reduced segregation and greater ease of compaction around congested reinforcement, the use of entrained air might be advantageous in prestressed concrete. There seemed to be insufficient evidence so far to enable a valid judgement to be given. No tests had been made at the Road Research Laboratory on air-entrained mixes richer than 1 : 6, since the work had been confined to mixes in the range suitable for use in roads.

The Author had no comparative figures for the variability of ordinary and air-entrained concrete and such figures would be difficult to obtain. If results from different jobs were compared it would be almost certain that differences would exist which would not depend upon whether or not air-entrained concrete had been used, whilst if experimental work was undertaken to obtain the particular information it was likely that rather more careful control than normal might be exercised and the comparison would not then be a guide to what might be found in practice. Only by continued experience with air-entrained concrete could it be determined whether the ratios of minimum to average strength used in designing ordinary concrete mixes could be used satisfactorily with air-entrained concrete.

Mr Kennard had made the important point that, for estimating the increase in yield, the effective air content was that in excess of what would remain in ordinary concrete after compaction. Inevitably some air voids were present in all concrete and if, in practice, the air content of ordinary concrete was less than one per cent, the compaction might be considered as satisfactory. In laboratory work it was generally possible to obtain a greater degree of compaction than in practice and the left-hand points of the four lines in *Figs 1* (*a*) and (*b*) showed that air contents below one per cent were consistently obtained. The comparison made on p. 349 did not refer to particular results but to the principle. The figures could be taken as referring to ordinary and air-entrained concrete containing 1 per cent and 6 per cent of air respectively.

The Author was grateful to Mr Melville for his contribution concerning the transport of air-entrained concrete. His conclusions would be of wide interest, for little experience in transporting air-entrained concrete had yet been obtained in the United Kingdom.

Mr Fraser had also recorded some very interesting experiences, which were especially useful because they related to practice in Great Britain. In particular, air-entrainment produced a greater increase in workability than would generally be associated with the observed increase in slump.

That was a feature which could only be fully appreciated by working with air-entrained concrete.

The possibility mentioned by Dr Kansoh of the more efficient hydration of cement in the presence of a wetting agent had been suggested by several other authorities. So far as the Author was aware, however, the reality of that effect had still to be proved and he would be interested to hear of any confirmatory data.

The Author could not agree with Dr Kansoh's unqualified statement that the gravimetric method of measuring air content was the most accurate one. It was accurate only if the proportions of the various constituents in the sample being tested, as well as their specific gravities, were accurately known. In the field that information was practically impossible to obtain. Even if weigh-batching equipment was correctly calibrated and carefully used, and the moisture contents of the materials were accurately known, the proportions of the materials in the sample might differ widely from those of the materials entering the mixer. Adhesion of mortar around the blades of the mixer, or the breaking away of adhered material might result in a leaner or a richer batch of concrete; if the concrete was sampled at the discharge chute, the proportions would, in general, depend on whether the sample was taken at the beginning, middle, or end of the discharge of the batch; and if the concrete was sampled after it had been placed in the formwork it was extremely difficult to obtain a sample of representative proportions. Sampling errors, of course, applied to all methods of test, but in using the gravimetric method the effect was two-fold. Not only might the air content of the sample not be representative of the mass but, if the mix proportions were not truly representative, a very considerable error could result when calculating the air content of the sample. Those were some of the very real difficulties associated with the gravimetric method and which, together with the weighing and calculation involved, made it much less suitable than the pressure method for use in the field.

The pressure-type apparatus did, of course, require calibration before use but that had been only briefly referred to in the Paper because it had been dealt with by the various Authors referred to in connexion with the measurement of entrained air. In the usual procedure for calibration, a known volume of air was introduced by placing a cylindrical vessel, with its open end downward, in the container and filling up with water. Pressure was then applied until the indicated air content equalled the volume of air introduced, expressed as a percentage of the volume of the container. The pressure was noted and that pressure was then used for measuring the air content of concrete.

The Author had no evidence that the insulating properties of concrete for heat or sound were affected by entrained air, but it was well known that aerated (lightweight) concrete containing a very much larger proportion of air exhibited much lower thermal conductivity than ordinary concrete. It was reasonable to assume therefore that entrained air would result in some reduction in thermal conductivity, although the effect would probably be very small.

Little was known of the true tensile strength of concrete, but the flexural strength was reduced for a given water/cement ratio in the same way as the compressive strength was reduced. The reduction was smaller, however—about two-thirds as much by proportion—and it was easier to obtain an increase in flexural strength for a given workability than it was to obtain an increase in compressive strength by entraining air.

Few data were available regarding the effect of entrained air on the bond strength of concrete with ordinary steel reinforcement, but some work had been done in America [21, 22] using deformed bars. In general, that work showed a decrease in bond strength with increasing air content, although in some cases a small amount of air had been beneficial. The effect was less, however, than the effect of entrained air on compressive strength.

It was interesting to note that Mr Eldridge considered the gravimetric method of measuring air content to be more accurate than the pressure method. That matter had already been discussed in connexion with Dr Kansoh's comments. The data in Table 4, contributed by Mr Eldridge, were interesting and helped to show that in practice the strength of concrete did not have to be reduced when an air-entraining agent was used. That point was made in the Paper and the Author did not therefore consider that the figures given were misleading.

The Author could not agree with Mr Eldridge's suggestion that a test for bleeding might be the best indicator of non-segregation and workability, for the three properties concerned were not correlated. Most of the work at the Road Research Laboratory concerned mixes of low workability, in which bleeding did not occur. The problems associated with segregation and with workability, however, were as great with those dry mixes as with much wetter mixes. The evidence available indicated that each of the properties of fresh concrete had to be considered separately.

Nor could the Author agree with Mr Eldridge's statement that 25 per cent excess mortar was necessary to obtain reasonable emplacement. Indeed, some excellent concrete structures had recently been built in which gap-graded aggregate of $1\frac{1}{2}$-inch maximum size and little or no excess mortar had been used. In one particular case, a 1 : 8 mix had been used in the vibrated walls of a reinforced-concrete wind tunnel and that had produced the perfectly smooth finish required for the rather special conditions. That type of mix had the added advantage that the shuttering could be removed after 3 to 16 hours, so that the surface could be examined for flaws at an early age.

[21] H. W. Russell and E. Hognestad, " Effect of entrained air on the bond strength of concrete." *Proc. Highway Res. Bd*, vol. 28 (1948), p. 195.

[22] E. Hognestad and C. P. Siess, " Effect of entrained air on bond between concrete and reinforcing steel." *J. Amer. Concr. Inst.*, vol. 21 (1950), p. 649.