Discussion

Mr G. S. Cooper, referring to the use of soil stabilization for permanent airfields, observed that most of the pavements constructed during the 1939–45 war had, for a large number of reasons, been constructed in concrete. There had since been little new construction until comparatively recently, and then construction had consisted in either strengthening existing pavements for aircraft of normal weight or constructing new pavements for heavy aircraft. Most of the sites for heavy aircraft had subgrades with extremely low California Bearing Ratios (of the order of 3 per cent) and on those sites about 4 feet construction thickness would have been required if flexible pavements were to be used. On such sites, rigid pavements were more economical, the thickness of concrete required being of the order of 12 inches. Using the Authors' own basis of comparison, where they had pointed out that the cost of soil-cement stabilization was, inch for inch, about one-third that of concrete construction, it was clear that the latter was cheaper. In any case, the problem of laying and compacting thicknesses of stabilized soil of the order of 3 to 4 feet had still to be solved satisfactorily, and there was not as yet sufficient evidence that it was possible to reduce the thickness of pavement required by the C.B.R. design curves when using soil-cement stabilization.

In recent Air Ministry work, on at least three sites with subgrades of high bearing value, soil-cement bases had been used and had been very satisfactory, and soil-cement was proposed on at least two further sites. On at least a further three sites, mechanically stable gravel, obtainable locally at very low cost, had been used and had also given satisfactory results. The Authors could rest assured, therefore, that the Air Ministry was well aware of the potentialities of soil stabilization for permanent airfield construction and made use of the method whenever a suitable opportunity occurred. It was normal practice to investigate all possible forms of construction and adopt the most economic which could be guaranteed to give satisfactory results.

The Authors had described mechanical stabilization as being quite useless for temporary airfields in wet climates. That was a somewhat sweeping statement which might require qualification. Mechanically stable bases ought to work if they were adequately protected from moisture changes. If that could be done, mechanical stabilization, using locally available material, should obviously be the first method to be considered where rapid construction was required. In the penultimate paragraph of the "Conclusions," the argument was used against mechanical stabilization that the transportation problem would often render it impracticable, but if it were possible to obtain mechanically stable material a mile or two away from the site of the construction work, it would be much easier to use that

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material than to import 2,000 tons or so of cement or other material, perhaps by air, which would be an enormous task. The task might have to be faced, but some alternative, if at all possible, had to be considered in the first place.

The Authors had made a very interesting point about the strength of soil-cement bases. On a subgrade of high bearing strength it might be found that the thickness of flexible pavement required would be less than that required for a properly designed rigid pavement, so that if one were to lay a cement-stabilized base, which was stronger than necessary to perform properly as a flexible base, one would in effect have a weak under-designed rigid pavement, which would commence to crack under loading and show all the troubles and faults common to weak rigid pavements.

Referring to comments on pp. 454 and 455, concerning the strength of the base and the thickness of surfacing, Mr Cooper pointed out that not a great deal of experience had as yet been obtained with tire pressures of 250 lb. per square inch or more, but what experience was available tended to show that a 4-inch thickness of surfacing and C.B.R. values of the order of 100 per cent in the upper layers of the base were sufficient. He knew that there was no disputing the mathematical analysis which the Authors gave, but it might be that a surcharge or a cohesive effect was somehow involved, which prevented shear displacement, so that even though there was local over-stressing it did not result in any failure.

Under the heading "Plant Performance Trials," the Authors had referred to the development of suitable plant. What thickness, in the Authors' view, would that plant be able to stabilize with only a single pass, and how should greater thicknesses be dealt with? Would the Authors also give some guidance on the maximum clay fraction beyond which stabilization with cement was not economically practicable?

Mr W. P. Andrews observed that the Authors had stated on p. 449 that stabilized soil had in post-war road construction been cheaper by 4*d.* per square yard per inch thickness than hardcore. That seemed to require some qualification. Mr Andrews had been told in Lancashire, only two weeks ago, that nothing could compete with hardcore there, because it was obtained from slag-heaps. In the south, however, it was becoming more difficult to obtain and much more expensive, and probably the figure there would be even higher than 4*d.* per square yard.

A comparison was made on p. 451 between rigid and flexible pavements. He did not find that comparison very satisfactory, for the Authors had emphasized too strongly, he thought, the fact that cracks might occur in a rigid pavement and that those cracks might open to such an extent that the aggregate interlock might be spoilt. That took no account of the possibilities of prestressed concrete, in which the cracks remained permanently closed, or the use of ordinary reinforcement in the rigid pavement, which would prevent the cracks from opening.

The Paper was devoted to the stabilized-soil base under bituminous

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surfacings. In one or two instances a soil-cement base had been used under concrete roads. It had made an excellent substitute for lean-mix concrete or a granular base. It had the great advantage, in a large job with central mixing, of providing a road over which the concrete could be transported to the site from the central mixing plant without being damaged. Experience in the past few months had shown the necessity for an absolutely impervious surfacing to the stabilized soil, and concrete would supply that.

Fig. 17 showed the special trolley used for simulating airfield traffic. He had seen that at work, and the results of those tests had been remarkable in showing how a 6-inch thickness of stabilized soil stood up to such severe punishment. He hoped that the work which was being done by the Military Engineering Experimental Establishment would show results, especially with regard to the machine shown in *Fig. 20*, which would be very much cheaper than an American single-pass stabilizer such as the P. & H. There was need for British plant for that work ; Great Britain was far too dependent upon the United States. There was need for plant to pulverize the soil and for mixing the soil with the cement, and it was important to produce in Britain a cement spreader to replace spreading by hand, which had been shown to be inefficient. Better plant was needed to distribute moisture uniformly and at a controlled rate.

On the question of the testing of soils, in the United States great importance was attached to a freezing-and-thawing test and to a wetting-and-drying test—especially to the former. The freezing-and-thawing test had never been adopted in Britain, and during the past 3 months there had been several localized failures of soil-cement roads, and in every case the weaknesses had been disclosed by the first winter frost. By the use of a freezing-and-thawing test those small local failures might have been avoided. It would be interesting to have the Authors' views on freezing-and-thawing tests.

Mr G. C. Wilson remarked that he was not entirely satisfied that it was necessary to limit the strength of soil-cement for the purpose of controlling cracking, and that except for obvious reasons of economy, there was no justification for prescribing a maximum 7-day strength of about 500 lb. per square inch. He did not favour the idea of using extra additives to keep down the strength when, for practical reasons, it was necessary to use more cement than was actually required to give a strength value below that maximum.

He also found that the criteria for strength of soil-cement bases, given on pp. 456 and 466, were slightly confusing. On p. 456 the suggestion was made that, with the lower range of tire pressures, the 7-day strength for a permanent airfield should be 250 lb. per square inch, whilst for military airfields a minimum strength of 200 lb. per square inch would be adequate. On p. 466 it was stated that, owing to the possible necessity for putting military airfields into commission with the least possible delay, a higher 7-day strength was required for them than for permanent airfields. In

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view of that apparent contradiction, he would like to ask if the value of 200 lb. per square inch was sufficiently high for military airfields.

With regard to the behaviour of crushed rock in mechanically stable base construction, although he agreed that materials, even quite soft ones, which crushed under the compacting plant could provide excellent bases, he found it difficult to accept the statement that hard rock structures were more susceptible to moisture-content changes than those of softer rock. It had been firmly established by laboratory tests that the angle of internal friction of hard granular material was independent of moisture content, and he would be very surprised if the hard rocks, when adequately restrained by a thick surfacing such as would be used on a permanent airfield, would prove in any way inferior to the softer ones; but perhaps the Authors could refute that suggestion from their own experience.

He had assumed that *Fig. 7* referred to a sandy gravel in which there was a proportion of clay, in which case the results shown could well be understood. Would the Authors confirm whether it was a clay gravel or a clean hard material?

Finally, on the question of mechanically stable bases, he did not think that the condemnation of gravel-sand-clays for use in wet climates was entirely warranted. As stated on p. 462, those materials were virtually impermeable after compaction and did not suffer unduly in the presence of water. Surely, then, it was the condition of the material when placed which was the controlling factor. Admittedly those materials could be difficult to handle in wet weather and were far from easy to dry out subsequent to becoming wet, but once properly compacted and covered with an impervious surfacing they should be capable of good service, even for temporary airfields.

Turning to the construction aspect of stabilization, Mr Wilson gave some details of the work carried out at Wisley, to which reference was made in Table 4 of the Appendix. So far as he was aware, that was the largest single contract for cement stabilization which had been completed in the United Kingdom. It had involved the improvement of an existing runway and taxiway pavement which consisted of a base of hoggin of 8 inches nominal thickness covered with a bitumen-macadam surfacing $2\frac{1}{2}$ inches thick. A few areas had been provided with an asphalt wearing-course. The description in Table 4 of the original base material as "gravel" was rather misleading. The mix-in-place method had been employed and the procedure had been to rip up the surfacing and base, break up the lumps of macadam by pulverizing with rotary machines until the coated stone had been evenly distributed throughout the hoggin, and produce a loose tilth to a depth of 10 inches. Cement had then been spread on the surface and thoroughly mixed in with rotary machines. Water had been added from pressure distributors, and after further mixing the whole base was compacted in a single lift to give a finished thickness of 8 inches. Progressive rolling had been adopted, employing three machines of increasing weights.

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After compaction, the surface had been kept damp by repeated applications of water until the seal coat of 35 per cent bitumen emulsion had been applied a day or so later. The pavement had been completed by a two-course bituminous surfacing consisting of a $2\frac{1}{2}$-inch base-course of asphalt or bitumen-macadam with a $1\frac{1}{4}$-inch hot-rolled-asphalt wearing-course.

Several types of mixers had been employed, ranging from small rotary hoes attached to Fordson tractors, to a purpose-built self-propelled Seaman's Pulvi-Mixer. Other types had included an older version of the latter machine which was towed by a separate tractor and had the rotor driven by an independent power unit. Another machine which had proved very useful was the heaviest model of rotary hoe attached to a TD.18 crawler tractor. As would be appreciated, the material resulting from the combination of the existing pavement components was extremely stoney and it had proved too heavy for the lighter machines. The mixing efficiency for the self-propelled Pulvi-Mixer had been found by the Military Engineering Experimental Establishment to be 78 per cent. The cement had been supplied both in bulk and in bags, the bulk cement being distributed by a mechanical spreader. The rates of output mentioned on p. 449 did not seem to be really significant without the daily working time being specified. At Wisley, during a 6-week period when no factors outside the contractor's control had interrupted the work, the average output had been of the order of 4,200 square yards per day. The maximum output on any one day had been 6,300 square yards. It had been estimated that the cost of the stabilization work together with the provision of the new two-coat bituminous surfacing was approximately 70 per cent of the cost of the equivalent concrete construction, whilst the time taken to complete the work was probably less than 80 per cent of that which would have been required for the replacement of the pavements in concrete on a formation that had already been prepared.

Dr A. R. Lee said that it would probably be correct to say that the use of soil-cement for the construction of roads was one of the most revolutionary advances made in recent years in the science of road-making in Great Britain. Soil-cement was a logical development to be expected in certain districts in North America, where suitable road-stone did not exist and where for many months of the year the soil was naturally in a dry and friable condition, and could easily be mixed with cement by means of suitable machines.

When engineers in Britain had first heard of the American work they had hardly looked upon the process as a serious competitor, in Britain, to broken rock or concrete; broken rock was available almost anywhere in the country within 100 miles of a supply; also much of the soil in Britain contained a high percentage of clay, and it rarely dried out to produce a naturally friable material. The pioneer work of one or two highway engineers, however, particularly that of Mr H. E. Brooke-Bradley, had shown that that unorthodox process could, in certain circumstances, be

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used as an excellent alternative to, and as a cheaper process than, traditional flexible and concrete methods of construction. The Road Research Laboratory had been encouraged to intensify their investigations and with the aid of their engineer friends had now produced a specification for the construction of soil-cement roads for housing estates. The Authors had described how that revolutionary process was carried one stage further. The ideas put forward were the result of active co-operation between the Road Research organization and the Military Engineering Experimental Establishment of the Ministry of Supply. The co-operation had enabled the results of laboratory investigations to be tried out on a full scale at an early and critical stage with the facilities and backing of the Ministry of Supply.

The Authors were to be congratulated on showing how the possibilities of the soil-cement process could be extended to airfield conditions. The advantages put forward in its favour in comparison with orthodox methods were the savings in the amount of material to be transported, the increased speed of construction, and the reduction in costs. Those were very real advantages today and it was gratifying to know that the Air Ministry was giving it serious consideration in relation to the construction of permanent airfields.

The information given in the Paper on the results of the tests with the loading machine raised the general problem of the structural design of runways of the flexible type. Dr Lee understood from the Authors that, in the more recent field tests, a 12-inch thickness of cement-stabilized clay base with a 2-inch bituminous wearing surfacing had been laid on a soil subgrade with a C.B.R. value of 3 per cent, and that it had been quite unaffected by 15,000 passes of a 5-ton loaded axle carrying two pneumatic-tired wheels.

That was a remarkable result and indicated the seriousness with which the flexible type of soil-cement construction for permanent runways should be regarded, even on weak subgrades. On p. 453, the Authors had stated that "in the present stage of knowledge, stabilized soil bases should be constructed to the same thickness as that required with any other type of base material." Well-compacted soil-cement might perhaps be regarded as a granular base having completely ideal interlocking properties. Dr Lee suggested that the close interlocking and high internal friction that could be obtained with a well-compacted soil-cement base might far exceed anything possible with any other granular material and thus enable it to be used in thinner layers than was necessary with broken stone and other traditional flexible-base materials. Whether or not that was in fact possible could only be decided at the present stage of knowledge by further full-scale experiments. Furthermore, how far that type of flexible construction could compare in performance with concrete for permanent airfield runways could also only be decided by full-scale experiments, coupled with knowledge of the limiting degree of irregularity of the surface which was

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regarded as indicating failure. The amount of permanent deformation of a flexible pavement made by a vehicle appeared to be a function of the logarithm of the number of passes of the vehicles over any particular spot. The application of the results of the field-tests carried out by the Authors to the design of airfield pavements consequently necessitated a knowledge of the distribution of aircraft across the runway. That matter had been mentioned in a Paper by Maclean and Pollitt,[1] in which results were given for the transverse distribution of aircraft landing on a runway. The maximum concentration per foot width of a 150-foot runway was only 1½ per cent of the total traffic, whereas the corresponding figure for traffic on a 30-foot road was more than 40 per cent. That might not be typical for a permanent airfield, but it did indicate that the spread of traffic was considerable, and consequently that the frequency with which traffic ran over any particular spot might be quite low. That spread of traffic might well mean that the number of repetitions of loading for design purposes for flexible airfield construction might be surprisingly low, certainly considerably lower than was required for the design of a concrete airfield pavement. On that assumption, the huge thicknesses that were considered necessary for flexible runways on weak subgrades might not in reality be necessary at all. That point would never be settled, however, until full-scale experiments were carried out with the correct loading and distribution of vehicles.

Perhaps the Authors had considered that matter and would say whether they thought it was one on which further research would be likely to lead to economies in airfield construction.

Mr W. S. Catlow said he felt that more information should have been given in the Paper on the subject of plant. Indeed, the only mention of plant seemed to be on p. 466, where it was stated that plant had been adequately dealt with in a recently published book, "Soil Mechanics for Road Engineers." In referring to that, however, he had found that there was only about half a page on mix-in-place plant. There had been great developments since the early days of soil stabilization, when agricultural harrows had been the only plant available.

Some years before the 1939–45 war, he had been responsible for the construction of a short length of road in which the base had been stabilized with emulsion, and he remembered becoming very weary with the number of passes that the harrows had to make before it was considered that the emulsion had been properly mixed with the soil. Modern plant, of course, reduced the number of passes necessary when using the mix-in-place method; indeed, he understood that single-pass machines of American make were now on the market, and that there were prototypes of similar British machines.

It was obvious that single-pass machines were costly and of great weight

[1] "Fundamental Soil Problems in Military Road and Airfield Construction." *Géotechnique*, vol. III, p. 97 (Sept. 1952).

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and power, and it was a matter for consideration whether smaller and less powerful, but cheaper, machines which did the same job in a number of passes were not a better proposition. The number of passes required was, of course, dependent on the type of machine and the nature of the soil. The great advantage of the single-pass machine appeared to be that the technique was more simple and that it was not working on the fluffed-up surface caused by previous passes, so that a consistent depth of soil was treated. The main disadvantage of the single-pass machine appeared to be its Juggernaut-like bulk and weight. The main advantage of multi-pass machines seemed to be that the cement could first be mixed dry with the soil, and that might give a more even dispersion of the cement throughout the mixture.

Doubtless there were many more factors than those which he had mentioned. It would be instructive and of practical value to have those advantages and disadvantages discussed, bearing in mind the present stage of development of the two classes of machine. It was well known that up to the present only American plant had been available, and with dollars, as always, in short supply he believed that only a limited amount of plant could be imported into Great Britain. The progress of soil stabilization was therefore retarded in Britain, at least with regard to the practical aspect of the subject. It was to be hoped that British manufacturers could be persuaded to produce those machines ; it might well be said that it was almost in the national interest that they should do so, because it was essential that the country should not lag behind in that modern form of construction. The British manufacturers, however, had to be put on the right lines now and told that either single-pass or multi-pass machines were required. Possibly the real answer was that both types were necessary to deal with different conditions and requirements.

Dr H. Q. Golder observed that the Authors had provided the finest exposition that he had ever seen of the fact that, when referring to pavements, when engineers said " rigid " they meant flexible, and when they said " flexible " they meant either rigid or brittle ! He felt very strongly that they should not just copy the American nomenclature and that it was wrong to do so. He thought that the essential difference between those types of pavement was the tensile strength of one and the lack of it in the other. They should be called " tensile " and " non-tensile," or possibly the Authors after consideration could think of some better terms.

The Authors had said on p. 451 that there would be some permanent deformation of the subgrade from compaction, consolidation, or plastic flow of the soil. Dr Golder thought that the subgrade also should be designed so that those permanent deformations did not occur. If permanent deformations which were cumulative did take place, did not that mean that there would eventually be failure, and did not that mean that the pavement had not been designed adequately ?

The Authors had used considerable space on pp. 452–3 in proving that

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a soil-cement was flexible or non-tensile. Dr Golder would have assumed that.

Like Mr Wilson, Dr Golder found the arguments on pp. 461–3 rather unconvincing. Possibly Mr Cooper's experience also supported that, although he had not said so in so many words. If one got water in a hard rock base, the water did not reduce its angle of internal friction. The interchange of the expressions "lubrication" and "reduction of internal friction," and saying that the latter was due to water, was a little loose. It was known that the angle of friction was not reduced by immersion in water.

Dr Golder agreed with Mr Wilson in not believing *Fig.* 7, if that was a clean sand and gravel. If it was, and the Figure was true, then he thought that the test did not properly indicate the properties of the material which were of importance in the field.

Mr Robinson had said that the military requirement was the same as the civil, but Dr Golder thought that that was perhaps not true, and that the military problem was to have a general answer which was applicable in every set of circumstances, like the Bailey bridge. In the case of stabilized soil, there was no such solution, and he thought that the Authors had done very well in developing methods which could be applied by an engineer with some specialized training.

Mr G. H. Hodgson said that, first, he wished to ask the Authors where the dividing line came between stabilized soil and lean-mix concrete, because what he wished to describe was some experimental work which had just been completed using a 24 : 1-mix concrete.

Twelve months ago, through the kindness of the County Surveyor concerned, the Ministry of Transport, and the Road Research Laboratory, he had been given one small section in which the 24 : 1 concrete had been laid and rolled during the morning; in the afternoon a 2-inch-thick bituminous base-coat had been laid and rolled, and the road had been opened to full traffic the following morning.

Three weeks ago, he had had the opportunity of laying about 2,000 square yards, the 24 : 1 concrete being used as a substitute for pitching.

A 200-yard length had been completed in a day, and during the late afternoon a $2\frac{1}{2}$-inch-thick bituminous base-coat had been laid on the lean concrete, and the strip had been opened to full traffic the following morning. Because at the time all the main passes in North Wales had been blocked with snow, that 1-day-old strip had had to carry extraordinary traffic, that coast road through Caernarvon and on to Chester being the only road clear of snow.

Mr Hodgson then displayed a series of slides, the first of which showed the 24 : 1 concrete being mechanically laid; he believed that it was the first time a Barber-Greene machine had been used for that purpose. Further slides showed the $2\frac{1}{2}$-inch-thick bituminous base-coat being rolled on the newly consolidated concrete, and the Barber-Greene machine at

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work, placing the lean-mix concrete and being closely followed by the 10-ton roller.

Since, in places, the depth of the consolidated concrete was 14½ inches, the lean concrete had had to be laid in two layers, and in one place, three layers, one above the other. Where more than one course was necessary, it was important to consolidate only partly the lower course before placing the upper course. That ensured a good bond between the layers.

One pass of the 10-ton roller was sufficient to consolidate the lean concrete so that the Barber-Greene machine and the lorries feeding it could pass back over the partly consolidated concrete to lay the upper course.

The lean-mix concrete, when fully consolidated, had a compaction of about 1½ inch on 6-inch layers.

A 10-ton roller had been used to consolidate the concrete and, in Mr Hodgson's view, when the bituminous material was put down the same day, one should use a slightly lighter roller, say 8 tons, for rolling the bituminous material.

It was interesting to note that the 1-day-old strip of concrete with its covering of bituminous material, 14½ inches thick at its deepest part, had successfully carried the extraordinary traffic, 22-ton cement lorries running within 6 inches of the unsupported edge of the strip.

In mixing that lean-mix concrete it was very important to see that the coarse aggregate had been well wetted. That ensured the even coating of all particles and helped to prevent segregation of the materials in the finished mix. The mix used was 1 cwt cement, 10 cwt quarry sand (3/16 inch and down), and 14 cwt graded crushed rock (1½ inch to ¾ inch). The water/cement ratio had been 1.

Another slide illustrated Mr Hodgson's theory of how the material was consolidated. When the surface was rolled, the angular particles were squashed together and became interlocked. That showed the importance of using angular material. The last slide showed how the angular particles interlocked, giving mechanical stability.

The Borough Engineer of Conway had been so pleased with the system that he was constructing 500 square yards of new road on virgin soil. The lean-mix concrete was being placed to a consolidated thickness of 4 inches, on which a 2-inch-thick layer of bituminous base-coat was laid, the final surface being fine cold asphalt.

There was an entrance to a garage which had had to be kept open, and traffic, including a 10-ton tanker, had run over the freshly placed concrete, without its bituminous base-coat, but no damage had been done to the concrete. That method of using a lean-mix-concrete base and at once putting on a bituminous top and opening the road to traffic the following day had very interesting and distinct possibilities for rapid work, whilst for airfield work, where traffic was not such a nuisance, it would be even simpler to carry out.

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*** **Mr H. E. Brooke-Bradley** commended the Authors for including in the Paper one of the main groups of soil stabilization processes, namely, mechanical stabilization. That method was too often ignored when considering the possibilities of stabilizing soils, although deposits or supplies of suitable material were available at economical cost and cheap haulage. It was often cheaper to effect stabilization of an inferior base by mechanical means than by the use of additives, and for that reason the comments made by the Authors on that process deserved careful consideration.

Mention was made of the proportions of cement added to the soil, ranging from 5 to 15 per cent by weight. If an excess of 10 per cent of cement was used, the process became costly and sometimes did not compare favourably with other forms of construction. During the 30-odd years in which Mr Brooke-Bradley had employed soil stabilization in road construction, on no job (other than preliminary experimental work in 1917) had it been necessary to use more than 10 per cent of cement to obtain a satisfactory result.

In dealing with the stabilization of clay soils, he had found that hydrated lime usually gave better results than cement, and on a trunk road carrying 20,000 tons per day, a heavy sodium clay had been successfully stabilized by the addition of 20 per cent waste chippings, 8 per cent hydrated lime, and 2 per cent cement.

Many clays suffered from acidity, which was undesirable since that increased plasticity, swelling, and shrinking more than a neutral or slightly alkaline clay soil. In Worcestershire, where much of the clay was found in the central and northern areas, high acidity was encountered in the flat plains. For that reason, hydrated lime gave better results than cement, but the acidity could be overcome by spreading about 1 lb. of limestone or slag dust per square yard over the site to be stabilized, prior to processing. The use of waste granular particles incorporated in heavy clay soils was extremely beneficial, particularly if the moisture content was high and had to be reduced by aeration.

Mr Brooke-Bradley agreed with the Authors that bitumen could not be satisfactorily utilized with clay soil, and its use with granular material required very careful control and reasonably good weather conditions.

There was considerable scope for special plant for processing soils, and a comprehensive machine, which combined in one operation, cutting, pulverizing, blending, and mixing, would seem to be the only satisfactory type to deal with the new technique.

Mr D. J. Maclean, in reply, referred to Mr Cooper's comment that, if flexible construction was used on soft soils with a C.B.R. of 3 per cent, 4 feet of construction was required. Mr Maclean was very doubtful indeed whether anything like so much thickness was necessary, and he thought that Dr Lee had adequately answered the point later in

*** This contribution was submitted in writing upon the closure of the oral discussion.—SEC. I.C.E.

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the discussion in referring to the very much lower intensity of traffic which airfields received compared with roads. As Mr Cooper was aware, Mr Maclean had been very anxious for a long time to see the validity of those full-scale trials, where a small area was intensely trafficked, checked with actual airfields; he felt that there was need for a great deal of work in that direction.

Mr Cooper had also referred to the fact that the presence of a bituminous surfacing on a granular base might increase the resistance to shear by a surcharge effect. That seemed very likely to be the case, in which event it would be expected that a bituminous surfacing would have the same effect on top of stabilized soil.

Turning to the possible stability of mechanically stable soils on forward airfields, Mr Maclean's experience was that such airfields were usually provided with a pervious surfacing, and he believed that mechanically stable soils under those conditions were likely to be very unstable. If an impervious surfacing could be provided, mechanically stable soils might well provide the stability required.

The question of what strengths should be avoided in soil-cement was a subject on which more research was required before an adequate answer could be given, but when a soil-cement of higher strength was used it seemed that its flexural strength was being increased to a point where it might behave as a weak concrete, and it would therefore be unsatisfactory for that reason.

Mr Andrews had commented on the statement in the Paper that soil-cement had been found to be 4*d.* per square yard cheaper than hardcore, and said that he had recently been in Lancashire, where that situation did not arise. The Authors had said "on an average," and if, of course, one had granular material on one's door-step one might be able to construct a granular base for a similar price, as with soil-cement. However, transport costs were continually increasing, and granular material had not to be transported for many miles before its cost began to rise steeply.

Mr Andrews had also commented on the reference to the possible flexural failure of concrete. The Authors did not suggest that concrete would always fail in flexure, but merely used that to illustrate their argument, in order to give their views on the actual structural behaviour of soil-cement in an airfield pavement structure. Mr Maclean felt that weathering tests, which were mentioned in the Paper, were best used in conjunction with actual measurements of strength, by measuring the strength of the material after it had been subjected to a weathering test which simulated the practical conditions thought likely to occur at the site. There was a very big difference between American climatic conditions and those of the United Kingdom.

Mr G. S. Wilson had given a very interesting account of the work which his firm had carried out at Wisley. He mentioned, as one or two other speakers had done, that in his view hard rocks would, if used as a

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compacted granular base, give quite a good stability, particularly under a bituminous surfacing. In the Paper, the Authors had simply suggested that the stability would be lower with hard rock, particularly when rounded, than with soft rock, and, whilst it might be true that granular bases made of hard rocks were satisfactory in roads, it should be borne in mind that airfields were subjected to much higher traffic stresses, and it was not possible to be certain that hard rock would be as satisfactory in that case. He could recall one instance of a road where hard rock had not been particularly stable. *Fig.* 7 referred to a clean sandy gravel.

Dr Lee had brought out the important point that airfields were much less intensely trafficked than roads. Research on that point would be very valuable in connexion with obtaining an economical design of airfield runways.

Mr Catlow had referred to plant problems. It should be pointed out that British machines were now becoming available. Mr Maclean would leave Mr Robinson to deal with the more detailed points about single-pass and multi-pass machines.

Dr Golder had referred to the question of nomenclature, and preferred "tensile" and "non-tensile" to "flexible" and "rigid." Dr Golder might be right, but in civil engineering there were many such terms which had come into common use and, since most people understood what was meant by those terms, the Authors had felt that it was better to use them rather than to adopt a new terminology. He did not think that those who were concerned with concrete would be pleased if the term "brittle" were adopted for that material.

Dr Golder had made a very interesting point on the question of cumulative deformation and whether one should design so that there was no deformation at all. Mr Maclean's own view was that in flexible-pavement design it was desirable to design for cumulative deformation, so that the actual deformation in so many years would not exceed a certain critical value. That was a means of securing economy. If engineers were to design, as Dr Golder had suggested, to prevent any deformation occurring at all, the designs would be likely to be very expensive. Precisely the same problem arose in regard to roads.

Dr Golder had suggested that the Authors had laboured the discussion of mechanically stable soils. The reason they did so was that they had found that so many failures arose from a lack of understanding of the principles involved. Those materials were frequently unstable in practice.

Mr Hodgson had made some very interesting comments on lean-mix concrete and had given a most interesting description of experiments in North Wales. The Authors would look forward to seeing the results of that work in due course. On the practical side, the only difference between lean-mix concrete and stabilized soil with granular aggregate was that, in the case of lean-mix concrete, the aggregate was actually prepared before mixing in a concrete-mixer whereas that was unnecessary with stabilized

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soil and use was made of other types of mixer which would mix efficiently, even if there was some clay present in the soil. In other respects the materials were very similar.

Mr Brooke-Bradley had contributed from his extensive experience in using soil stabilization for constructing roads in Worcestershire. The successful stabilization of the heavy sodium clay with hydrated lime and cement was a brilliant achievement and an excellent illustration of the considerable potentialities of stabilization processes.

Mr P. J. M. Robinson, who also replied, said that Mr Cooper had referred to mechanical stabilization being an advantage in places where it might be necessary to bring in, say, 2,000 tons of cement by air. It was, of course, difficult to compare hypothetical cases but, in the first place, if 2,000 tons of cement were necessary for construction, probably more than 20,000 tons of mechanically stable soil would have to be imported. Secondly, if it was necessary to import the cement by air, it would also, presumably, be necessary to import any plant by air. Consideration would, therefore, have to be given to the difference in tonnage of the cement and the plant necessary to import the large quantities of mechanically stable material.

The advantages in working and construction given by the use of cement stabilization would also have to be closely considered.

It had not perhaps been made sufficiently clear in the Paper that heavy rainfall during construction would defeat mechanical stabilization completely. The disadvantages of that from a military point of view were obvious.

Mr Cooper had asked about the thicknesses to which a single-pass stabilizer could work. It was safe to say that existing single-pass stabilizers could work up to thicknesses of 10 inches. The requirement for any greater thickness would be based only on the existing illusions concerning thicknesses of pavement. Probably no greater thickness than 18 inches would ever be necessary for an airfield. except in exceptional cases such as on peat, and that thickness would be achieved by bituminous surfacing on the cement-stabilized soil.

It was not possible to define the clay fraction which a single-pass stabilizer would mix, since the effect of the clay fraction was different on different soils, but a single-pass stabilizer had been used to stabilize soils well within the cohesive range. Probably the limit of single-pass machines at present was to stabilize soils with a Casagrande classification of CL.

Mr Wilson had referred to the mention in the Paper of 200 lb. per square inch as the general military requirement and to the suggestion that, owing to the necessity for putting military airfields into commission as soon as possible, a higher 7-day strength was required for them than for permanent airfields. The figure of 200 lb. was the estimated strength required, not at 7 days, but at the time of trafficking. Only very limited experiments had been done on the subject, and the figures quoted were intended to be

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a guide more than anything else; they were not definite, because the materials themselves would vary. If a set of experiments were duplicated there would still be a variation. However, a soil-cement road had been trafficked 24 hours after construction with $2\frac{1}{2}$-ton traffic and it was found that it required a 7-day strength of 400 lb. per square inch.

Mr Catlow had referred to single-pass and multi-pass machines. The problem was a very involved one, and Mr Catlow was quite right in what he had said about the bulkiness of single-pass machines. They were bulky at present, but the aim was, with the machine shown in the illustration, to reduce that bulk considerably and to make the single-pass machine no more, if not considerably less, bulky than some of the multi-pass machines. Mr Robinson could think of no advantages of having more passes than one; he did not think that it had ever been demonstrated that it was advantageous to mix cement dry. In the very limited work which had been done in trying to compare mixing-in the cement with the soil dry and the soil wet it had been found that there was no difference, and from the point of view of the technique required it was much simpler, for military work, to use a single pass.

Dr Golder had referred to nomenclature. It had been difficult enough to introduce a new process without introducing a new nomenclature as well. Dr Golder appeared to have been misled by the statement that the military requirement was the same as the civil. Mr Robinson had meant that to apply simply to the slides which he had showed when introducing the Paper, as meaning that economy in cement was equally advantageous in military and civil work. Otherwise there were many differences, though they were not major ones.

Mr Hodgson's remarks had been very interesting, because the work which he had done had largely parallelled the work with which the Military Engineering Experimental Establishment and the Road Research Laboratory had been concerned. Mr Robinson thought that the division between lean-mix concrete and soil-cement depended on whether one called the main bulk of the material "aggregate" or "soil." He thought that that would be decided by saying that when one paid for it, it was aggregate, and when one got it free, it was soil. Probably Mr Hodgson would find that he could make his lean-mix concrete with soil and get just as good results.

The Authors had used the spreader which Mr Hodgson had mentioned for various types of soil, and in many ways it was successful, but it was not adapted to spread a great thickness. Mr Hodgson seemed to have got over the difficulty by spreading a thinner layer. In the Military Engineering Experimental Establishment trials, they normally spread 10 inches, and the rate of feed into the machine in their case had not been enough to cope with the rate at which it came out of it, so that it was necessary to stop from time to time to fill it up. That led to some differential compaction and lumpiness. As for opening the road to traffic after 24 hours,

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unsurfaced, they themselves had had the same experience with a very great concentration of traffic. It bore witness to the good quality of the mixed material. In the Military Engineering Experimental Establishment trials a rapid-hardening cement was used, and with ordinary Portland cement no mixes would stand up to traffic after 24 hours. With such a selected aggregate as Mr Hodgson had used, therefore, it might be questioned whether any additives were required for its stabilization.

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