Paper No. 6491

Western Avenue, Lagos: the design and construction of a soil-cement pavement†

by

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Discussion

The Chairman (Mr Henry Grace) said that the Paper recorded a large amount of factual data which had been collected during the investigation or during the actual construction of the work, and this type of information was of great value when it related to such forms of construction as soil-cement which were still in the development stage. The data which interested him most related to the base. For many years engineers in Britain had been trying to determine the criteria for the strength of bases for new roads, and the latest specification for motorways called for a strength of 1,200 lb/sq. in. for the cement-bound granular base; this base was normally protected by approximately 4 in. of high-quality hot-rolled asphalt. The strength of the base on Western Avenue, Lagos, was between 250 and 600 lb/sq. in., and it was protected by only 1¼ in. of the premix Macadam, which was a very inferior material compared with hot-rolled asphalt.

109. The author had told him that the traffic on Western Avenue was about 8,000 vehicles a day, which on a two-lane carriageway was quite a heavy density. Approximately 50% of this was heavy goods traffic, and therefore corresponded to the sort of traffic on the main trunk routes in Britain. If it was calculated, lane for lane, it would be found that the intensity was about the same as, or possibly greater than, the intensity on the M1 motorway. The Author had stated that the base had performed extremely well. To what did he attribute his success?

Dr R. S. Millard (Head of Tropical Section, Road Research Laboratory) said that the Paper provided a record of one of the first major road constructions in West Africa using cement-stabilized soil. Soil stabilization with cement and with lime was now a part of standard practice in most other parts of Africa, but in West Africa it was not yet being used extensively. One reason had been the reluctance of local contractors and engineers to take up what was to them an unfamiliar process. The Paper should go a long way to dispel these doubts. With its detailed record of how the difficulties in design and construction had been overcome, it should be of great value to other engineers in all tropical countries.

111. The approximate traffic prediction in Fig. 3 might startle engineers who were struggling with the rapid growth of traffic on the roads of Western Europe. However, the overall rate in Nigeria on the main roads over the past few years was of the order of 17% per annum, considerably more than in the developed parts of the world. There was every reason to believe that on the roads near the towns in Nigeria traffic was increasing even faster. Moreover, Western Avenue was the type of road which would itself encourage development. The predicted rate of growth in the Paper was about 17% per annum but it would not be at all surprising if it were in fact much faster. Had the Author any recent figures of traffic flow on the road to show what was now happening to the traffic there?

† Proc. Instn civ. Engrs, vol. 20 (Sept. 1961), pp. 107–140.

112. Over most of Africa the work with soil stabilization was rather different from that described in the Paper. Most of the stabilization was being done on existing main roads and subsidiary roads which were getting, for the first time, the benefit of a bituminous surface.

TABLE 1. TRAFFIC FLOW ON THE MBARARA–LYANTONDE ROAD, UGANDA

	1951	1952	1953	1954	1955	1956	1957	1958
Average daily traffic flow, from two counts each year.	44	127	150	186	225	295	394	407

113. The growth of traffic on a typical main road in Africa was shown in Table 1. It was a road in Uganda, where, over the past decade, traffic had increased by about ten times. Most such roads were initially surfaced with gravel, and when dry and well-compacted they were remarkably strong. But road bases made from such gravels weakened when they became wet, and the main object of stabilizing was to prevent this weakening. This was, in fact, the main use for cement or lime stabilization on roads in Africa. Many miles of road now in South Africa, Central Africa and East Africa were built with such gravels, stabilized cement and lime, and carried traffic ranging from 200–2,000 vehicles per day, or even more, including quite heavy traffic. These roads normally had a base of about 6-in. thickness with a double bituminous surface dressing as the only surfacing, and there was now considerable experience to support a design criteria for this kind of road, based on the penetration test, calling for a CPR (cylinder penetration ratio) in the region of 100% at the density at which it was practical to compact the material for the field. In effect this meant that cement and lime contents ranged between 2 and 5%.

114. There was as yet not a great deal of experience of more heavily trafficked roads such as Western Avenue. When one started to build such roads there was a natural tendency to call for strong mixtures, with high cement contents, and this brought difficulties in compaction and in greater shrinkage on setting, such as were indicated in the Paper. The record the Author had provided of how these difficulties were at least partially overcome was extremely valuable. Both difficulties were aggravated by high tropical temperatures; both were likely to have been less severe had hydrated lime been used as a stabilizer. Had hydrated lime been considered?

115. Cracking was certainly a fault, and this was illustrated by Figs 33 and 34*. Fig. 33 showed the construction of a road to the airport in Accra in 1956. It had a 6-in. base of gravel stabilized with cement, with a thin bituminous carpet of about 1½ in. laid on top. Fig. 34 showed the same road in 1960, and it could be seen that a regular pattern of longitudinal and transverse cracks had developed over the whole surface. Part of the reason for that undoubtedly was that the asphalt had been laid on the freshly made soil-cement and had cracked sympathetically as the soil-cement shrank on the curing. But even when the surfacing was delayed those cracks must be there in the soil-cement below. On lightly trafficked roads this did not matter a great deal, and in any case the relatively thick film of bitumen used in surface dressing such roads might well accommodate a certain amount of movement. However all engineers knew of examples of heavily trafficked roads in Britain and elsewhere where bituminous surfacing cracked and broke up over joints of concrete 4 in. or even more below. There, the trouble arose not so much from shrinkage of concrete during hardening as from thermal movements of the concrete with temperature changes, and sometimes also from vertical movements at the joints under traffic. This appeared to be a problem in the use of soil-cement in

* Figs 33 and 34 are photographs and are placed between pp. 112–13.

the tropics, too. With high temperatures the soil-cement quickly developed high strengths. The stabilized soil should not be so strong that it broke into large regular slabs to relieve shrinkage and temperature stresses. On the other hand, it must not be so weak that a substantial thickness of bituminous surfacing was needed above it to reduce the stresses to a tolerable level. It was necessary to find how close a course could be steered between these two extremes, and this was one of the values of the experience in Western Avenue. In Lagos the seasonal and daily temperature ranges were not very high and there would not be very big temperature movements, except possibly when rain fell on a sun-drenched surface. Also, the fact that a two-layer construction had been used would probably help to prevent the vertical movement which could cause cracks to appear in the surfacing. This would be one of the most important lessons learned from this particular project.

116. The Author had given assurance that so far there was little evidence, if any, that the cracks in the base had come through and begun to cause trouble in the surface. Would he amplify that comment, and also say whether in the design any provision had been made for adding a bituminous surfacing as the traffic increased?

Mr D. J. Maclean (Head of Soils Section, Road Research Laboratory) considered that the successful outcome of the project at Western Avenue in Lagos was an indication of the great potentialities of soil stabilization processes in Africa. These potentialities had been evident at the Conference on Soil Stabilization held in 1960 in Nairobi[4] where he had been impressed by the high level of the discussions that had taken place between road engineers from many countries of the African continent.

118. Fig. 3 indicated that an actual vehicle count on Western Avenue in March 1960 gave a figure of 5,000 vehicles per day. Would the Author say approximately what proportion of these were heavy commercial vehicles? If this proportion were sufficient to place the traffic well into Category 2 (1,500–4,500 commercial vehicles per day),[5] the future performance of the road would be of considerable interest in indicating the potentialities of cement-stabilized soil as a base material for heavily-trafficked roads, not only in Africa but in Britain and elsewhere.

119. An interesting feature of the construction work was the use of central-batching plant-mix for both the sub-base and base materials. While the plant was satisfactory for mixing the base material it appeared that incomplete mixing was obtained with the more clayey sub-base material. Determinations of mixing efficiency had been made at the Road Research Laboratory with a similar type of mixer to those used by the Author. The results had shown that there was a significant decrease in efficiency when working with a clayey soil. It would be expected that as a result of the poorer mixing the strength of the sub-base would have been comparatively low, and he would be interested to know whether the Author had any information that bore on this point and whether he felt that it would have been preferable to use mix-in-place plant for constructing the sub-base in order to obtain more efficient processing.

120. The Paper had included some interesting relations showing the influence of factors affecting the strength of the soil-cement mixes, but of greater interest would have been a histogram showing the range of strengths actually obtained in the sub-base and base. Would the Author provide such an estimate from the available data?

121. With regard to the relations between strength and dry density of the stabilized materials shown in Figs 19–22, Mr Maclean pointed out that F. J. Grimer of the Road Research Laboratory had shown that these two quantities were related by a power law which could be represented by a linear plot on a log.log. diagram, shown in Fig. 35. It was generally true that there was a very close relation when the two quantities were plotted in this way.

122. Fig. 25 showed a relation between the unconfined compressive strength of the base material and its CPR. If the results for the well-compacted material were considered, this relation seemed to fit in quite well with the results of tests given in a paper published in 1956[6] and shown in Fig. 36. This was making due allowance for the

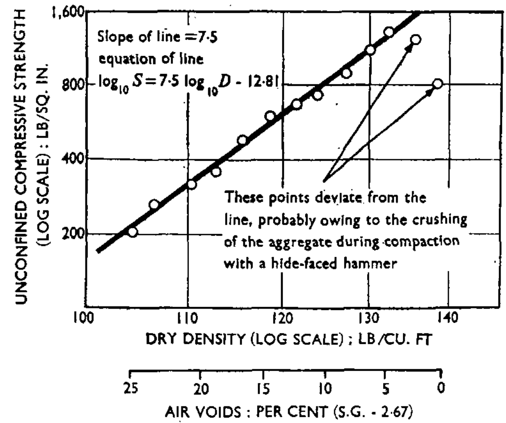

FIG. 35.—RELATION BETWEEN STRENGTH AT 7 DAYS AND DRY DENSITY FOR A SANDY GRAVEL AT A MOISTURE CONTENT OF $8\frac{1}{2}$% STABILIZED WITH 10% OF CEMENT

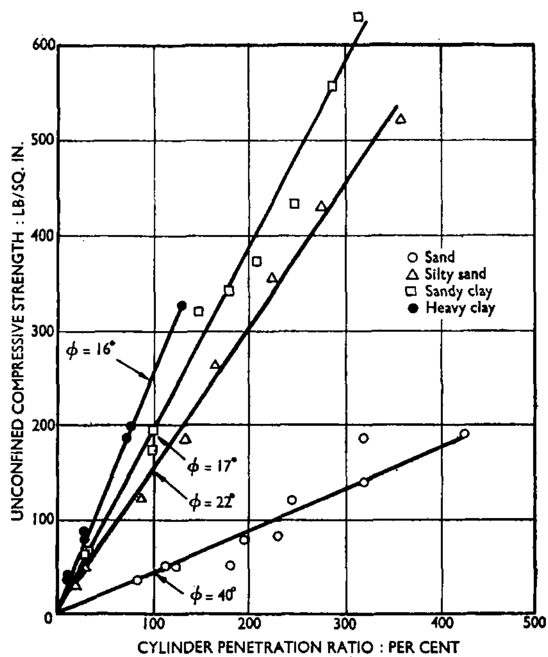

FIG. 36.—RELATION BETWEEN CPR AND UNCONFINED COMPRESSIVE STRENGTH FOR SOIL-CEMENT MIXTURES

fact that the soil was a mixture of a sandy clay and cement. It would be seen that the relation between the two quantities depended on the type of soil being stabilized, and this must be taken into account in designing the composition of soil-cement mixes. The comparison should always be based on the results of tests on well-compacted material with different cement contents.

Mr F. H. P. Williams (Deputy Head, Tropical Section, Road Research Laboratory) confined his remarks to the interpretation of the soil test results with regard to pavement and soil-cement design.

124. The Author was to be complimented on the programme of tests which he had carried out on the subgrade soils. In particular it was interesting to look at the relation between moisture content, density, and CBR as given in Figs 4–6. In almost every case the CBR at the optimum moisture content for the B.S. compaction test was 10 or rather more, and this value was not changed even when the samples were soaked. Owing to the fact that the CBR fell very rapidly with increased moisture content in the neighbourhood of the optimum, some of the variation obtained might in fact be due to differences in drawing the curves.

125. The general trend of results was, however, in very close agreement with those obtained for a number of Kenya soils in a recent investigation carried out by the Road Research Laboratory. In this investigation, instead of using one compactive effort they had used three, and having obtained the CBR moisture content relation for each

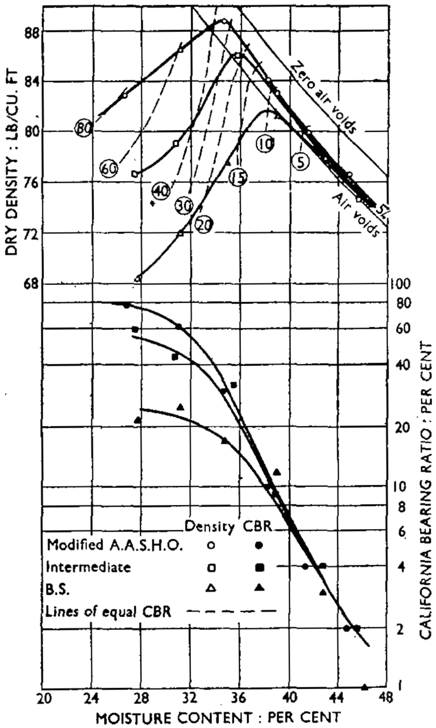

FIG. 37.—COMPACTION AND CBR DATA FOR RED CLAY FROM THIKA SAGANA ROAD SUBSITE (b), KENYA. SOIL NO. 831

of the compactive efforts, the lines of equal CBR were sketched in on the moisture density curves. Fig. 37 showed the result for a Red Clay, and Fig. 38 showed the result for a pumice soil. It would be noticed particularly that the CBR 10 line passed approximately through the optimum moisture content for B.S. compaction. Also, although the compaction curves had a very different shape, the relation of the iso-CBR lines was almost the same, the 10 line going through the optimum for B.S. compaction and the 60–80 line running down the dry side of the modified A.A.S.H.O. compaction curve. That same relation had actually been obtained with four other soils, ranging from gravel to red clay. It was interesting to see that the Author in his tests had obtained a similar result. Mr Williams suggested that if it was assumed that the water table was 3 ft or more below the road surface, the B.S. optimum moisture content was probably the worst moisture condition which would have to be encountered in the subgrade. If this was so, and it could be assumed that they could achieve B.S. maximum dry density, then the design value of 10 would result, and the closeness of the results obtained almost suggested that this design value would be obtained almost irrespective of soil type. He would be glad to hear the Author's comment on this method of testing, since it suggested that if one comprehensive series of tests was carried out on a typical soil from site, then the CBR values could be inferred on the different soils encountered by just carrying out compaction tests, which were much easier to do in the field.

126. In §11 it was stated that the stabilized subgrade material had not developed sufficient strength for use as base material at an economical cement content. Comparable strengths for cement contents were not given, but assuming that the difference in weights of the material were taken into account, the corresponding cement content for the subgrade material to the $7\frac{1}{2}\%$ actually used in the base would have been about $8\frac{1}{4}\%$. With this cement content would the Author have obtained a similar strength

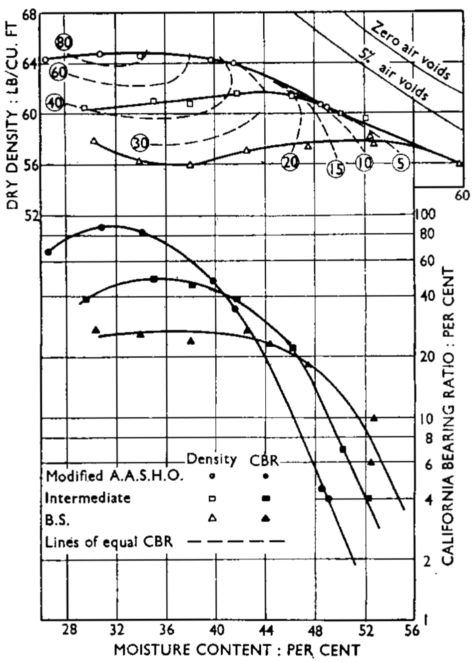

FIG. 38.—COMPACTION AND CBR DATA FOR PUMICE SOIL FROM NAKURU SUBSITE (a), KENYA. SOIL NO. 836

to that obtained with the sandy clay, or had the sand/soil mixture been chosen because it was easier to mix? It was not the percentage by weight of cement that decided whether the material was economical, but the lb/sq. yd, or tons/mile, of cement used. With a clay soil, such as the red coffee soils in Kenya, which had a density of about 70 lb/cu. ft, then 8% by weight of cement on that soil was equivalent to 4% by weight of a gravel running at about 140 lb/cu. ft.

127. The actual strengths which had been achieved in the laboratory tests appeared to be rather higher than necessary as measured by the CPR values. At a depth of 7½ in. below the road surface a CBR value of about 25 was called for from curve F, which the Author had used for his design, and this compared with a figure of 150% which the Author had obtained in his laboratory tests in 14 days. With regard to the base course material, there were considerable differences of opinion as to what strengths were required with stabilized soils when used under thin surfacings in the tropics. The figure of 500% CPR at 14 days obtained in the laboratory tests appeared to be rather high, especially when it was noted that this was only 70% of the value which could be expected at two months. Even at lower densities which had actually been obtained in the field the CPR values were of the order of 400%. It was worth while considering that the more cement used in the field mix the greater had been the expected reduction in density, with a delay between mixing time and compaction. Thus, had the base been designed for a lower laboratory strength, i.e. using about 5% cement, it was possible that higher relative compaction might have been obtained in the field, and the ratio of field strengths to laboratory strengths would have been higher.

128. In §93 it was stated that the CBR should not be the sole basis of design, but, while agreeing with this comment, Mr Williams wondered whether there was any more reason for using the unconfined compression test. In the road the base material was always confined, and with these cement-stabilized soils they were in fact dealing with largely non-plastic material, and he was not sure that an unconfined compressive strength test was particularly suitable in that case. As Mr Maclean had already said, with the more non-plastic soils the lower unconfined compressive strength would be specified.

129. In §64 it was pointed out that the higher densities were generally obtained at the higher moisture content. There was always a tendency for compaction in the tropics to be carried out on material which was really too dry, and this comment, in connexion with a job carried out in the humid tropics, was particularly noteworthy, since it would help engineers to dispel their fears over having the material slightly too wet.

Mr J. D. Humphreys (formerly Assistant Engineer, Binnie, Deacon, and Gourley) recalled that in delivering the First Rankine Lecture of the British National Society of Soil Mechanics and Foundation Engineering, Professor Casagrande had quoted Rankine as saying, "In theoretical science, the question is—what are we to think? . . . But in practical science the question is—what are we to do?". He had gone on to point out the difference in approach between the theorist whose struggle must always be to explain natural phenomena in terms of more and more general laws, and the practical man whose struggle was to build something by a certain time. The engineer was therefore entitled to use—and to a considerable degree to rely on, with due reservations—empirical laws and to deal primarily in terms relevant to them.

131. Those who concerned themselves with the design of roads and airfield runways appeared to find less and less in common with those interested in other structures. This was not a protest against specialization itself and it was not a criticism of those engineers who operated, or described in contributions to the Institution, calculations and studies of specialized methods of construction. The engineer, however great his own contribution to the advancement of new techniques, and occasionally to the development of the theories themselves, was often forced by the nature of his employment to rely for the pace-making in research (and the technological nomenclature which went with it) upon the specialists. It was thus perhaps the specialists on whom the

onus lay to find the common links between their own studies and those of others. Indeed, one would have thought that to do so would provide both useful checks on their own conclusions and valuable sources of field and other data obtained with some different object in mind.

132. His main interest in soil-cement appeared at first sight a far cry from the design of roads. He had for some years been associated with the design and construction of earth dams. For the past 5 or 6 years he had had a growing conviction that cement-stabilization, carried out in certain ways and applied in certain, perhaps unusual, earth dam problems, stood a good chance of providing a sound and economically attractive solution—not necessarily for merely part of an earth dam but possibly for the complete structure. A paper on this subject had been presented at the 5th International Conference on Soil Mechanics in Paris, 1961.[7] As to its use in practice, he was aware of only two examples of soil-cement being put into use in earth dam building.

133. The U.S. Bureau of Reclamation had used soil-cement, a few feet thick, as the experimental facing to a trial embankment at Bonny Reservoir, U.S.A. The object had been to investigate its suitability as an upstream protection against wave action, and it had been satisfactory. Thus encouraged, they had provided for its use as the upstream facing to Merritt Dam, Nebraska.

134. Several papers on the use of soil-cement, including the present one, had been presented to the Institution, and these had perforce been restricted to the subject of soil-cement roads and airport runways. He had obtained useful information, for example, on the various methods of construction from several of them, and in particular he was glad that the Author of this Paper was able to publish contractor's unit rates for finished material. Belonging to the three-dimensional school he was glad they had been quoted per cubic yard.

135. The technical soil data given in the Paper contained however, little that could be applied to other fields of soil mechanics. It might be argued that the author of a paper on a dam would not be describing methods of building bridges. This was true, but it was normally found that if, for example, it was a concrete dam, the concrete proportions and the properties, both assumed and achieved, would be described in a way that could be understood with no great effort by a bridge designer. The information on soil types given in this Paper, and others, would have had much wider appeal if presented in the form of grading curves, which he had always regarded as being universally accepted by, at any rate, soil mechanics engineers. The given information terminated at the 200 sieve, just where other people's interest quickened. An analysis of the sand added to the soil for stabilization would also enable the student to draw his own composite curve for the as-placed material.

136. It seemed unfair to complain at the preponderance of CBR and CPR test results indicated, since these tests appeared to have become the basis for most design work on road pavements. Nor was it for him to say that this wholly empirical approach was unsatisfactory in practice. (He would have more right, as a motorist, to observe that it did not, at any rate, seem to be entirely foolproof.) It was also conceded that the engineer must look for comparatively simple, reproducible tests which could be used as control criteria in the field laboratory, and obviously the CPR test came under this general category. There was perhaps in general too loose a connexion between properties specified as acceptance criteria and those actually assumed in design.

137. As an engineer, however, he got almost nothing out of CBR and CPR values, and was always vaguely uneasy about a design unless someone could demonstrate how stresses were distributed and how strains were equated—granted that various simplifying assumptions had to be made. Was the Author satisfied with the design equipment with which the research world had provided him? Did he think a more rational, fundamental, approach to road design was feasible? If, for example, a programme, however small, of triaxial tests, coupled with a study of pore-pressure response to different influences, were incorporated in the study of similar schemes and published along with the other data, might it be possible in time to establish a link between

analytical fact and rule-of-thumb fiction? If such an object held the slightest promise of improvement for the road engineer himself, the work involved could not be dismissed as a purely altruistic waste of a client's money, nor would the three-dimensional engineer be the sole beneficiary. In the field of earth dam design alone, considerable technical advances had been made, in a theoretical rather than an empirical direction, in which the road engineer might also be allowed to share.

138. Soil mechanics seemed to be branching off in all sorts of directions, some rational and some entirely empirical, but possibly this was inevitable in certain complicated aspects of road design. However, when using these empirical terms it was too easy to get fixed ideas about their meaning. A typical example was the term "strength", and this could be demonstrated by reference to Fig. 39.

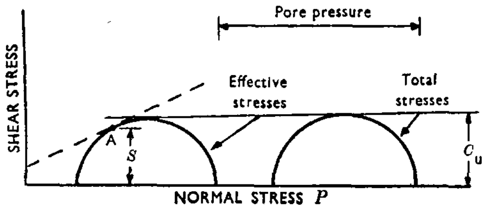

FIG. 39.—MOHR STRESS DIAGRAM

139. Those who followed the triaxial school (as Mr Humphreys did) would express the stresses in any material, soil or otherwise, in the form of the Mohr circle, and would say that the material would always fail in shear, having in mind a failure plane represented by a point such as A in Fig. 39. Some engineers using the term "strength" would mean the quantity shown as C_u. Apart from the small difference between C_u and S on a given diagram, the C_u concept often led to the use of an altogether different circle anyway. The road engineer, on the other hand, referring to unconfined strengths, would automatically imply a different diagram again, such as Fig. 40, and might be referring either to the quantity C_1 or the maximum p stress $2C_1$.

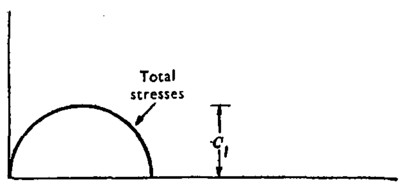

FIG. 40.—UNCONFINED COMPRESSION TEST

140. Mr Humphreys had the general impression that some eminent engineers using the word "strength" did not know which of these quantities they meant. He would discourage the unqualified use of the term—and several others, such as "factor of safety"—and he suggested that the research schools should do likewise.

Mr Stanley Serota (Managing Director, Foundation Engineering Ltd) drew attention to two principles which he believed, had actuated the Author. First, consideration of level, pavement design, and materials had not each been treated as separate and consecutive factors. On the other hand each, to a greater or lesser degree, had influenced the others. Secondly, once the Author had decided on the raw materials he was going to use, the sources were proven in quantity before the bill was prepared.

142. This constituted real design. The engineer had seen his path clear to the end of the project before the construction had actually started. Not only had this resulted in a well balanced design but, also, the competing contractors had been left in no doubt as to the source and quantity of materials available. This was reflected not only in the tender price, which was only £4,000 above the estimated £200,000, but particularly in the final costs, which had shown no change on the tender. This type of thinking at the design stage must have saved the client considerable sums of money, and was well worth the initial cost of investigation which had preceded the design.

143. Such detailed studies were even more applicable to the design of long trunk roads, where much larger quantities were involved. On such projects geologists should be employed in the design team to help locate the route, the most economic line to be chosen being a function of the foundation material traversed and of the location of raw materials as well as just the topography. This really was an extension of the principles on which the Author had worked, but they were applicable to longer roads, perhaps running hundreds of miles, rather than only about 2 or 3 miles long.

144. It seemed probable that the earth mix would have responded rather better to vibratory compaction, using either vibrating rollers or vibrating plates. Would the Author consider vibration as a method of compaction?

145. The Author had suggested in § 76 that the design of the earth mix should take into account delays between mixing and spreading. What were the Author's views on specifying a maximum time limit between mixing and spreading?

Mr G. F. Farquhar (formerly of Monier Construction Co. (Nigeria) Ltd), who had been engaged on a similar construction in the Eastern Region of Nigeria, in Port Harcourt, made several comments from a contractor's point of view. Relatively speaking, the most important point regarding soil-cement construction was the time lag between mixing and compacting. The Author had stressed this, and had shown that the maximum dry density, for the same compactive effort, was reduced after one hour from 100% to 96%, and so on down to about 92% after 3 hours.

147. The final setting time of an ordinary Portland cement in the tropics was about 3 hours. However, cement was now being manufactured locally in very large quantities in the most modern plant; it tended, therefore, to be finer ground than normal ordinary Portland cement, and, consequently, had rapid hardening properties. The final setting time being, therefore, about 1½ hours, it was even more evident how critical the time delay between mixing and compacting could become. Since strength of pavement was not even approximately a function of density unless the time factor was included, would it not be more realistic to plot CPR or UCS values against elapsed time? Tests carried out by Mr Farquhar had shown that, while the density dropped by approximately 8% with a 3-hour delay, the drop in CPR value was of the order of 12%. The soil-cement contractors must therefore look at their programmes from this point of view. Soil-cement construction lent itself to the principles of time and motion study which, to a contractor, was always important, and where a higher strength was obtained in the road, it was probably important to some other people also!

148. From the figures given in the Paper it seemed that by using four Millars mixers a total of approximately 1 cu. yd of "equivalent compacted material" had been obtained from the plant about every 5 min. Even at that 5 min was very optimistic, knowing conditions in Nigeria, and it seemed that at this output the plant that had been used was rather uneconomic. There would be long delays in carrying out the contract, uneconomical use of the compacting plant, and a particularly low output of the order of 100 linear yards of 22-ft wide carriageway per day (assuming there was a 10-hour working day) with such mixing plant.

149. On the contract on which he had been working in Port Harcourt they had used a Seaman Pulvi Mixer, and a grader for spreading, and it seemed that in constructing long stretches of road an output of ¼–½ mile/day would be possible. Would the Author comment on the output from the plant? It was not made clear in the Paper why the

spreading had not been done by grader. In Port Harcourt they had spread by grader, and the only difficulty experienced had been that the very high local compaction under the tyres left ruts about ¼–½ in. deep, even after the finished compaction. Had the grader been dispensed with for this reason? In their contract this was quite serious, but where there was a 1¼-in. bitumen carpet on top apparently it was not particularly important. The tolerances of ¼ in. in 10 ft seemed very severe, considering the carpet that had been laid, and he wished to know whether, using the plant described, this tolerance had been maintained. How many labourers had been used in the spreading operations?

150. He noted that the contract had been commenced in February 1958. There seemed to be a great number of road contracts in Nigeria which started in February, and considering the fact that the rainy season starts about two months later it was rather surprising, and annoying to the "money conscious" Contractor.

Mr T. N. W. Akroyd (Chief Engineer, Constructional Services Ltd) said that Mr Humphreys had wondered why the unconfined compression strength of stabilized soil and the CBR value should be used by soil mechanics experts when these tests were of no value to engineers who built earth dams. It was true that the CBR value was of no use in the fundamental stress analysis of soils and that the unconfined compression strength would not necessarily give a true measure of the shear strength, but this did not mean that these tests were of no value. Methods of tests designed for specific purposes were brought forward from time to time; if they were of general value then they were rapidly adopted, but if they did not prove popular they were soon abandoned. For example, in the United States, a method of tests for soils known as the North Dacota Cone had been invented, and R. R. Proctor, who had invented what was now called the standard compression test, had also invented a probe. These tests had been tried out in Britain over 10 years ago but they had not proved popular, and in Mr Akroyd's view this was because they were not of much value for work in Britain. But where a test was of value then it was readily adopted, even where the necessary comparative tests to establish its validity had not been completed. For example, it was a fair criticism of the CBR test to say it was empirical, and in its application to road works we had not in this country carried out the comparative tests which in California had led to its formulation and so really we had never established its background; but still it was of great use.

152. The use of such a test, which was entirely empirical and had little application to fundamental soil analysis problems, did not prove that in applied soil mechanics, engineers were diverging and traversing different paths; they were simply making use of a test which was of particular value in solving a particular problem.

153. As regards the unconfined compression test on stabilized soil values obtained from testing soil cylinders were used in the design of stabilized soil pavements. The optimum values for successful stabilized soil had never been established although it had been suggested that an unconfined compression strength of 250 lb/sq. in. at 7 days was a suitable strength for soil cement in the South of England. The basis for this figure was not known and the same criterion was used both in laboratory work and in site construction which was contrary to usual practice when dealing, for example, with concrete. In soil stabilization one often got in the field strengths equal to or greater than the strength obtained in the laboratory. This again was contrary to results expected from concrete.

154. Mr Humphreys had raised the question of the use of the unconfined compression strength instead of the value of C_u and had pointed out that the confusion which existed cast serious doubt on the use of unconfined compression tests for soil stabilization. But the same doubt could easily be raised in other fields; for example, no one considered it strange to use the strength of a concrete cube as the design strength of concrete, and yet the cube strength of concrete bore no relation to concrete's fundamental shear strength. It might be said that in the United States where they crushed

12-in. × 6-in.-dia. cylinders they were using the unconfined strength of concrete, but if one investigated the strength of concrete fundamentally by carrying out triaxial compression tests under conditions of no drainage then on saturated concrete one would find, as Mr Akroyd had found from his tests, that a $\phi = 0$ result could be obtained for concrete. In other words under certain conditions of test, concrete behaved as a frictionless material although it was, of course, a frictional material, and it failed as a frictional material. These triaxial tests on concrete did not condemn the use of the unconfined compression strength; they merely illustrated that the unconfined compression strength was only one aspect of the true strength.

155. Since, therefore, one could use the unconfined compression strength for concrete and yet not know much about the true shear strength, so, Mr Akroyd contended, one could use the unconfined compression strength for stabilized soil. In addition, since, for stabilized soil the unconfined compression results depended so much upon the amount of compaction put into the sample tested, the difference between the value of C_u and the unconfined compression strength was negligible by comparison. When one remembered also that the optimum compression strength required for stabilized soil had never been established then Mr Humphreys' criticism, while valid, was not of importance.

Mr I Wyn Pugh (Richard Costain Ltd) drew attention to another Paper presented by the Author to the West African Joint Group of Engineers in Nigeria on the subject of Road Surveys in Tropical Countries.[8]

157. The Author's traffic predictions for the Western Avenue were being fulfilled, and the traffic was heavy. It served the main port for Nigeria at Apapa, and the traffic wheel loads were similar to the wheel loads of heavy traffic in Britain. He had not seen the road for some months but his colleagues had confirmed what the Author had said—that it was standing up to the traffic. Due to the increased volume of traffic he understood that the Government intended to put in the second carriageway to provide a dual carriageway road for the whole length of the scheme described by the Author and also to extend it to Apapa.

158. Had the Author's investigations on this particular project produced any information of value to another major sand-stabilized road project with which his firm was associated near Maiduguri in the hot northern part of Nigeria? On this latter project the Author was responsible for directing the construction of a road on which the sand was being stabilized with bitumen; had he any comments or comparisons to make?

The following contributions were received in writing.

Mr S. A. W. Bowman (Executive Engineer, Ministry of Communications, Power, and Works, Tanganyika), referring to the difficulty experienced in obtaining the desired densities, asked if the Author would state what length of time was regarded as the maximum permissible period between mixing and final compaction, and whether this length of time was effectively enforced, since it was thought that this might have affected the effectiveness of compaction if unduly long. In this connexion, was the lighter pneumatic-tired roller mentioned in the Paper of the ordinary 12-ton wobbly wheel type? In Tanganyika more than 100% B.S. compaction was regularly achieved with this type of equipment without undue effort.

160. It appeared from the Paper that the possibility of constructing the sub-base by mix in place methods was not considered. It would be interesting to know if this was, in fact, so, since it seemed possible that mixing in place would have been cheaper than the plant mixing actually used and no more difficult, judging by the troubles described in the Paper with the sub-base materials. Also, although no indication of speed of construction was given, it was implied that mixing in place might well have been considerably quicker than plant mixing. The extra speed would have been especially attractive in view of the necessity of laying the sub-base before kerbing could be carried out, and the Author's reasons for deciding on plant mixing throughout would be welcomed.

161. In Tanganyika the application of an M.C.1 prime coat too soon after construction of the base course had apparently caused rotting of the surface and it was suspected that the cutting back agent in an M.C. grade might have had a deleterious effect upon the cement in a soil-cement pavement when insufficiently cured. Had anything of this nature been found on the one or two occasions mentioned in the Paper when the prime coat was applied immediately after grading?

162. It was noted that the original specification called for double surface dressing as the surfacing to the soil-cement base. This was regarded with interest, because with a specification in Tanganyika calling for a double surface dressing using ¾-in. and ¼-in. chippings for the first and second coats respectively, the use of a 6-ton smooth roller on the ¾-in. chippings had caused crushing of the surface of the soil-cement base and it had been necessary to lay an initial sand-blinded seal coat before proceeding with the ¾-in. chippings. Had the Author had any experience of similar difficulties? What size of chippings was it proposed to lay with the double surface dressing originally specified?

Mr R. L. Mitchell (Materials Engineer, Division of Roads and Road Traffic, Southern Rhodesia Government) said that the problems described by the Author were similar in many ways to those encountered in Southern Rhodesia, where, fortunately, haulage costs were not so high. In Rhodesia soil stabilization did, however, in general terms, become economic when haulage to conventional materials exceeded 20 miles.

164. The climate of Rhodesia was subtropical, and uncovered soils ranged from dryness to saturation. Since a seasonal pattern of moisture movement in subgrades had not yet been established it was not possible to carry out CBR tests on samples at the in-situ moisture, as the Author had done.

165. Referring to Figs 7 and 8, a CBR of 150–250, and an unconfined compressive strength of 250 lb/sq. in. was normally considered satisfactory for a base (Mr Mitchell used a value of 150 in each case, but he used a delay of 4 hours, corresponding to mix-in-place field conditions, between mixing and compaction). Presumably this standard would have been reached by the local sandy clay without admixing soils with 7½% of cement, or by the mixture with possibly half of this cement. Why, therefore, had the Author worked to the higher figures? While agreeing that a factor of safety against unknown mixing conditions was desirable, did such a factor necessarily follow in practice with the use of richer mixes with the accompanying higher shrinkages? This argument could, of course, be extended to the sub-base layer.

166. The Author had mentioned the success which had been achieved by delaying priming for a week to allow most of the shrinkage to occur while the base was cured under damp sand. In the low humidities of Rhodesia, and with the output achieved, it had not been possible to maintain wetness in this manner, and it was felt that if the base was allowed to dry even momentarily the process of curing had been defeated. Polythene sheeting had also been tried, but this was unsuccessful due to thermal activity, and as a result it was necessary to prime immediately. This process had been taken further, and emulsified prime was applied as a routine procedure immediately after rolling and even before acceptance testing. The cracks encountered by the Author still occurred, but they were sealed by the subsequent addition of the surfacing, and did not constitute a sealing problem as had been feared. The real problem might be the development of shrinkage cracks for a year or two after construction, particularly where cement contents in excess of 3% had been used, although Mr Mitchell doubted whether they were, in fact, a source of potential failure when widely spaced. Were such cracks developing in Western Avenue, and, if so, did they come through the premix surfacing, or was this a self-sealing surface?

167. The Author's statement in § 74 could not be over-emphasized. It seemed that if plant or, for that matter, single pass, mix was used, then only single pass compaction equipment should be used, so that not only the shortest time interval should elapse between mixing and compaction but, more important still, the interval should be constant. Without this, a variable material would be compacted.

168. This was borne out in Fig. 17 and the density histograms. Mr Mitchell had encountered similar graphs even with lime, although many authorities specified mixing with lime several days before compaction.

169. It was assumed that, in measuring the B.S. standard density, the Author had allowed for no delay in the laboratory between mixing and compaction. Had this been done, in view of the 2- to 3-hour field delay, the standard density would have dropped by about 7%—in which case the average density of both base and sub-base would have been found to pass the specification. Mr Mitchell felt that a revision was called for in B.S. 1924:1957, to bring the test procedure in line with practice even though a higher standard of acceptance might be necessary, as it certainly would be in areas where frost penetration occurred, to offset for the reduced densities resulting in the laboratory.

170. The Author had observed in § 65, that densities increased by about 2%, with delay in test. Mr Mitchell had observed this phenomenon even in unstabilized materials in Africa, and asked whether the Author considered that the timing of the tests should be allowed for in contract documents. In this connexion, the Author had condemned stretches of pavement as being too low in density. Did the contractor have to re-process the same material? If so, how much more cement was called for, and how were the densities in the re-processed material assessed?

171. Referring to the effect of temperature upon setting time (§ 78) would it be possible to devise a satisfactory retarder? Would it be too much to hope for a chemical additive that could be admixed to delay this for as much as two days? This would ease the problems of the contractors, and prices for cement stabilization would fall.

172. Mr Mitchell was interested in the shrinkage studies mentioned in §§ 94–106, and understood that research on this problem was being undertaken at the National Institute for Road Research in South Africa. Where seasonal variations in moisture content in highway bases was expected, such studies were more fundamental to the design of bases than mere strength tests, either soaked or at compaction moisture content.

173. Professor E. J. Yoder had strongly recommended him to design on the A.S.T.M. wetting and drying test, but to substitute compression testing for the measurement of the loss of weight. He agreed with this procedure, although the effect of the heat of drying on strength was a factor that had to be taken into account.

174. In Mr Mitchell's experience he had not encountered a soil-cement base that had failed through lack of structural strength, but he had some experimental sand-cement bases which might be considered to have failed after 4 years through shrinkage and possibly rigidity cracking. This experiment, incidentally, had not shown the 8% and 6% sections to be an improvement on that with 4%—if anything the reverse was true. He was therefore coming to the conclusion that shrinkage was a more important factor than strength, and that low cement contents were more promising than high ones—certainly the addition of extra cement to allow for poor mixing was no panacea.

175. While accepting the principle mentioned in § 106 that wet curing was desirable in that it replaced hydration water and water lost due to plasticity, he doubted whether curing water would penetrate more than the skin of a properly compacted base, and thus still preferred to cure by priming.

176. It was to be hoped that the valuable practical data recorded by the Author would encourage a programme of laboratory research so that the lessons learned could be applied and anticipated by pavement designers in the future, by the employment of improved standard test procedures with complete confidence—which was far from the case at present.

The Author in reply to Mr Grace (the Chairman), wrote that the success of Western Avenue was due to good standards of workmanship and control which ensured that adequate standards of strength were achieved and maintained.

178. Dr Millard had requested recent figures of traffic flow on Western Avenue.

The Author believed that daily figures were now of the order of 8,000 to 10,000 vehicles and he was endeavouring to obtain confirmation of these figures. The use of lime was not considered as it was more expensive than cement and it was thought that sufficient strengths might not be realized commensurate with the traffic intensity growth. There was no evidence of reflected cracking in the road surface. The original design allowed for a 2- to 3-in. bituminous carpet to be applied as the traffic increased.

179. Mr Maclean had requested information on the proportion of heavy commercial vehicles on Western Avenue: this would be a minimum of 40%. The Author thought that it would have been neither cheaper nor more satisfactory to use mix-in-place plant for the sub-base. Control would have been difficult in respect of moisture.

180. Mr Williams's remarks on subgrade testing were very interesting and the Author thought that there was merit in doing a series of tests on one soil, presumably the worst, and inferring CBR values from density tests on other similar soils. He felt that the soil/sand mixture with 7½% of cement was preferable to the soil alone with a higher cement content but he was unable to confirm that a reduction in cement content would have improved the pavement and he, himself, would have been loath to reduce on anything in view of the potential traffic volume. In respect of testing procedures, he thought that there might be more accurate establishment of moisture content/strength relationship in the unconfined compression test and would again like to draw attention to the merits of a wetting and drying test in certain cases.

181. In reply to Mr Humphreys, the Author agreed that the triaxial test was perhaps a more satisfactory one. However, it was not always possible to carry all the equipment one would like, nor to do all the tests one would wish to do, but he had found that the testing methods and equipment he actually used afforded satisfactory guides to suitable designs based on considerable past experience and information available.

182. The Author was pleased that Mr Serota had drawn attention to the estimated, tender, and final costs, as these did reflect the degree of preparation and supervision that went into the job. Small vibratory equipment had been tried on the soil cement but without success and the Author felt that heavier vibratory equipment might have favourable applications. The specifying of a maximum time lapse of, say, 2 hours between mixing and compaction was probably desirable under circumstances similar to those on Western Avenue.

183. Replying to Mr Farquhar, the Author felt that, apart from the fault in delays between mixing and compaction, enforced by the plant used, the latter lent itself to close control of the many factors involved in ensuring a sound pavement. Output was important but so were the control and the strengths achieved on a pavement which would be carrying 10,000 vehicles a day in a matter of a few years. The grader was found to display the same phenomenon on Western Avenue as found by Mr Farquhar in Port Harcourt and the premix surfacing had not been envisaged during the earlier course of the work. In reply to Mr Farquhar's last two points he added that the specified tolerance was not achieved everywhere using this plant and that some half dozen labourers were used in the spreading operation.

184. The Author was indebted to Mr Akroyd for providing a reply to the points raised by Mr Humphreys which included a very able defence of the laboratory testing methods used.

185. Mr Wyn Pugh had referred to the Maiduguri–Bama Road where the Author had investigated the stabilization of the local sands with both cement and bitumen. Both stabilizers gave favourable results and, in the course of tendering by Contractors on the alternatives, the bituminous stabilization proved more favourable, and the road has been satisfactorily completed accordingly. It was noticed in the course of testing the sand cement mixes that the unconfined compressive strengths were relatively lower than the strengths of comparable mixes on Western Avenue.

186. Mr Bowman had raised again the question of delay between mixing and compaction. This was controlled largely by the area of spread material required for satisfactory operation of the pneumatic compactor. This time-lag undoubtedly affected the

standard of compaction and determined the density achieved. The lighter pneumatic-tired roller referred to was of not more than 5 to 6 tons. There was no apparent reason for assuming that mix-in-place construction would have been any cheaper or more satisfactory than the central plant mix, but it was felt that better control could be exercised in the case of the latter. Many awkward areas were involved and it was thought that these did not readily lend themselves to mix-in-place construction. It was anticipated that there might be problems in respect of moisture control which could be best met by central plant mixing. It would undoubtedly have been considered less economical to introduce two methods of construction for the soil cement pavement, hence the decision to use a central plant mix for both base and sub-base. No trouble had been experienced in the areas where the M.C.1 prime was applied immediately on completion of the base course. The Author had experience of the crushing of the surface of a stabilized base course during rolling of chippings by a steel-tired roller and had found that a light pneumatic-tired roller overcame this problem. The original surfacing specified for Western Avenue included the use of ½- and ¼-inch chippings for the first and second dressings respectively.

187. Replying to Mr Mitchell, the Author had felt it desirable to consider the normally accepted design standards as minimum figures in the case of Western Avenue. The shrinkage problem had been met by the addition of 50% of sand into the base course; no cracks had developed on Western Avenue since its completion. The Author concurred with Mr Mitchell's comments in § 169 but would like to see the delay factor given more attention in the field, with a view to its reduction to a minimum. This would require the co-operation of the contractors and the use of the right plant. A possible solution to the problem of density reduction with delay in compaction might be the use of super-compacting plant. The Author felt that the timing of density tests in the field might be more suitably left to the site engineer; normally such tests were carried out with a minimum of delay. Where stretches of pavement on Western Avenue were condemned, the contractor had to replace these entirely. Mr Mitchell's comments in § 171 were noteworthy but might not the result be an increase in price rather than a fall? He found Mr Mitchell's further comments to be of considerable interest.

188. The Author expressed his appreciation of the interest shown in his paper and the encouraging remarks made by the contributors to the discussion. Further, he wished to refer particularly to the assistance provided by Mr Holt, of his staff, and by his fellow Partner, Mr Henry Grace, during both the constructional work and the compilation of the Paper.

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