ROADS AND RUNWAYS
ROUTES ET AEROPORTS

W. A. Lewis
Road Research Laboratory
Crowthorne Berks
England.

Introductory Notes prepared by Mr. W.A. Lewis, Mr. M. P. O'Reilly and Mr. N.W. Lister of The Road Research Laboratory, United Kingdom.

1. INTRODUCTION

The application of Soil Mechanics to Roads and Runways covers a very wide field and a whole conference could easily be devoted to the subject. To try to avoid a diffuse and disjointed discussion it is proposed to concentrate the Speciality Session on three main topics:-

(1) Soil Compaction (including specifications and control of embankment construction)

(2) Soil Stabilisation (particularly the question of the strength or other design criteria which should be employed)

(3) Interaction of soil and pavement (the effect on pavement design of the properties of the soil)

These three broad topics were selected on the basis of the replies received to the original circular letter about the possibility of running a Speciality Session.

It is the aim that the Session will provide an opportunity for the exchange of new ideas and suggestions for further research rather than a forum for the restatement of existing knowledge. The following notes have been prepared to help to stimulate discussion.

2. SOIL COMPACTION FOR ROADS AND RUNWAYS

2.1 Standards of compaction

A great deal of knowledge has been gained during the last 20 - 30 years on the subject of soil compaction. High standards of compaction are now commonly required for the earthworks for roads and runways. The aim in this is to try to control settlement of fill within reasonable limits and to produce as high a strength in the fill as is possible. Earthwork specifications for roads and runways have been influenced to a considerable extent by specifications for large earth-fill dams where major problems of stability often have to be overcome.

Although the existing standards of compaction for roads and runways can now be confidently expected to produce satisfactory results in general, the question may well be posed as to whether unnecessarily high standards are being required. Fills for roads and runways are often relatively shallow (less than 10 m in height) and it is not very often that serious instability problems are present within the embankment. Some settlement, provided it is reasonably uniform, can usually be tolerated. Where embankments are founded on compressible soil likely to consolidate beneath the weight of the fill and produce 30 cm or more of settlement it seems unrealistic to go to great efforts to try to keep the settlement within the main bulk fill to a few cms (different criteria will, however, apply to the top 0.5 - 1 m of embankment where it is essential to avoid the occurrence of local settlement of the foundation of the pavement due to traffic loading).

In some countries difficulties are often presented by the fact that the natural moisture content of soil from cut areas is either very much drier or very much wetter than the optimum moisture content for compaction by plant. Under these conditions it may be difficult or impossible to achieve a high relative compaction unless the moisture content of the fill is adjusted to bring it close to the optimum. This adjustment of moisture content can be costly and may well be impracticable if the soil is very much wetter than the optimum. Wet material from cut is, therefore, often rejected and replacement material may have to be imported at considerable expense from borrow pits.

High standards of compaction and moisture control coupled with strict enforcement of specifications can, therefore, involve significant expense and clearly the costs must be matched by the benefits likely to be obtained. It seems apparent that there is now a real need for positive information relating to the state of compaction and moisture content of fills to the ultimate performance of embankments.

Laboratory research has been and is being carried out[1][2] to relate the compressibility of compacted soil specimens to the initial state of compaction and moisture content but the results are difficult to apply to field conditions because of the lack of a sound basis for estimating the time required for the equilibrium conditions achieved in the laboratory specimens to be attained in the field. (There is the further difficulty that the density gradients in the laboratory specimens will, inevitably, be different from those produced by compaction plant in the field). Thus the only really satisfactory way the required information can be obtained at present is from care-fully observed field trials. There is a lack of published information on this subject and this is clearly an important topic on which research should be directed in the future.

2.2 Methods of control

Although traditional methods[3] of measuring the moisture content and dry density of compacted fill e.g. sand replacement, water balloon etc., can produce reliable results[3], considerable staff effort is required to carry out the tests and the results may not be available until the following day. Very large outputs are now possible with modern earthwork plant and it is therefore often impracticable to attempt to control the quantity of the compaction work in a rigorous manner using traditional test techniques. In recent years, to try to overcome this problem, considerable effort has been spent in developing alternative methods of measuring the state of compaction and moisture content of earthworks.

A great deal of attention has been paid to the use of nuclear techniques but there is clearly a divergence of views as to the accuracy and reliability of these methods.[4][5][6][7] Although it is claimed that the problem of the effect of soil type on the calibration has been overcome by the use of the 'air gap' method when 'back-scatter' equipment is used,[8][9] the relatively shallow effective depth sampled still presents difficulties.[5][8] If thick layers of fill are being compacted, large and variable density gradient conditions are inevitable and under these circumstances it is difficult to see how meaningful results can be obtained with 'back-scatter' Equipment. It is possible that deeper sampling may be obtained by collimating the radiation[10] and it would be useful to have more information on this aspect. The difficulties of density gradients are eliminated by the use of 'direct-transmission' equipment[5][11][12] but on the other hand errors may be introduced due to the disturbance effect, particularly with stoney materials, caused by the insertion of the probe.

Research on the other techniques for assessing the state of compaction of fill such as scientific forms of 'proof rolling', in which a quantitative measure is made of the deformation under a loaded wheel, is still in progress.[12] However the measurement of some form of strength parameter is not entirely a satisfactory solution to the problem as the strength of fill will be influenced by the moisture content and dry density as well as the type of material and the existence of pore water pressures. This makes it difficult to interpret the results of deformation or strength measurements particularly if they are obtained under dynamic conditions of loading, and with the soil wetter or drier than its final equilibrium moisture content.

The situation at present, therefore, is that no really satisfactory technique is available for the rapid and accurate measurement of the state of compaction of earthworks. Simple and reliable tests are required for assessing the suitability of fill from the viewpoint of moisture content and type of material and for determining whether compacted fill has the necessary properties of strength, resistance to deformation and the ingress of water which are shown to be required to provide a satisfactory performance as an embankment for roads and airfields. Clearly this is a field which would justify a great deal more research effort in the future and is one which could be very usefully discussed.

Because of the problems involved in attempting to employ strict quality control in earthwork compaction, there has been a reversal, in some countries, in the trend which has occurred during the last 20 years towards the employment of end result types of specifications. In Great Britain, for example, the latest Ministry of Transport Specification for roads[14] now employs a method specification for the compaction of earthworks. Superficially this might appear to be a retrograde step but there are, nevertheless, clear advantages in the use of a method specification particularly with small works where the employment of rigorous control by testing can rarely be justified. However this approach is not entirely satisfactory as there are practical difficulties in both the writing and the application of a methods specification. In the long term therefore, a more satisfactory solution would still appear to be in the development of really satisfactory rapid, simple and economical tests for controlling earthwork construction on an end-result basis.

2.3 Points for discussion

(1) To what state should soil be compacted in fill under roads and airfields?

(2) What methods are suitable for specifying and controlling the state of compaction in such fills?

(3) What criteria should be set in specifications and should these vary with different soils in different environments?

3. CEMENT AND LIME STABILIZED BASES FOR ROADS AND AIRFIELDS

3.1 Introduction

Cement and lime-stabilized materials are now widely used as bases in road and airfield construction. In the stabilization process cheap locally available natural or waste materials are made capable of sustaining traffic loads by the admixture of low proportions of cement or lime. Even in highly industrialised regions with a dense road network and a well developed quarrying industry there are many situations where stabilization of locally available soils or waste materials is the cheapest and best means of providing a road base. In less developed regions with a low density road network the stabilization of naturally occurring materials is even more attractive to the road builder. For example some 60 per cent of the paved roads constructed by the State of Sao Paulo, Brazil from 1956 to 1962 had soil-cement bases[15] while in Uganda almost all bituminous surfaced main roads built since 1960 have had lime-stabilized bases.

3.2 Design Criteria

Despite the widespread acceptance and use of cement and lime stabilized base materials there are significant differences in the design criteria used to select the proportion of cement or lime required to produce an acceptable base material. The present design criteria are largely empirical and are strictly valid only for the environmental and traffic conditions of the region in which they were developed and proved. Used in other regions they may need to be modified and adapted to the altered conditions.

A striking example of the mis-application of design criteria is the use in tropical regions of design criteria for soil-cement which were developed in the temperate climates of the northern United States of America and in the United Kingdom where resistance to the effects of frost and a high water table are the major factor to be considered.

3.2.1 Soil-cement. At the present time there are three main approaches to the design of soil-cement mixtures.

(i) Durability Tests. The wet-dry and freeze-thaw tests developed by the Portland Cement Association (PCA), Chicago, are the best known tests in this group[16]. In these tests soil-cement specimens are subjected to 12 cycles of either wetting and drying or freezing and thawing and the allowable loss of material during the test is governed by the soil classification of the soil being stabilized.

(ii) Compressive Strengths Tests. This form of test is widely used to assess soil-cement and cement-modified materials for use as road and airfield bases.[14][17] Cylindrical specimens with a height diameter ratio of 2:1 or less and cubical specimens are used. Acceptable materials are commonly required to have minimum unconfined compression strength at an age of 7 days in the range 14-53 Kg/cm^2 (200-750 lb/in^2) for specimens compacted to the dry density expected in the field.

(iii) California Bearing Ratio (C.B.R.) Tests. This test is commonly used in tropical countries particularly in Africa to evaluate stabilized base materials.[18][19][20] Specimens are normally cured for periods of 3 to 7 days and soaked for a further 1 to 4 days before testing. Acceptable C.B.R. values range from 100-240 per cent depending on the dry density to which the specimens have been moulded. These limiting criteria correspond to a laboratory C.B.R. value of 80-100 per cent or greater at the dry density expected in the field.

The above durability and strength criteria determine stabilizer requirements in the majority of instances but a minimum or maximum cement content is occasionally specified. Limits are also imposed on the particle-size distribution and the plasticity of the finer fractions of the materials being considered for cement stabilization.[22] These limitations ensure that the materials selected are capable of being processed in the field by mixing machines or plant currently available; they also eliminate uniformly graded sand soils which have a poor record of performance under traffic.

3.2.2 Lime-stabilized materials. The use of lime-stabilized base materials has been mainly confined to tropical and sub-tropical regions where the high temperatures accelerate the reactions between lime and the clay fraction of the soil. Unconfined compression and C.B.R. tests are normally used to evaluate these materials. The limiting C.B.R. criteria are very similar to those used for soil-cement but occasionally materials may be tested at ages up to 28 days with specimens being soaked for the concluding 1 - 4 days.[18][19][20][23] When an unconfined compression strength is used, a value of 7 kg/cm^2 (100 lb/in^2) is a common requirement.[24]

As with soil-cement, strength normally determines the proportion of lime required but again limitations may be imposed on particle-size distribution, on the plasticity of the finer soil fractions and on the minimum and maximum proportion of lime.

3.3 The application of existing design criteria

At present there is a general tendency among highway engineers to design cement-and lime-stabilized materials using the design criteria with which they are most familiar irrespective of the conditions in which they are working. The effect of this is best illustrated by considering the quantities of cement required by a typical gravel-clay soil from West Africa to meet the various design criteria. This gravel-clay contained 68 per cent gravel and 20 per cent clay and the liquid and plastic limits of the material passing the B.S. No. 36 sieve were 60 and 26 per cent respectively; the maximum dry density in the B.S. Compaction test 2.5 Kg (5.5 lb) rammer method was 2.11 gm/cm^3 (134 lb/ft^3) at an optimum moisture content of 14 per cent.

The quantities needed to satisfy the range of design criteria are shown in Table 1 where the cost implications of the various requirements are also considered. The differences in cement contents are not of great significance where the cost of cement is low and represents at most only some 30 per cent of the total cost of the base layer. Where cement has to be transported over long distances and the on-site cost is high, as is often the case in thinly populated rural areas, the cost of the stabilizer becomes very important. In these situations which are common in much of Africa, Australia and South America, cement costs usually represent at least 40 per cent of the total cost of the base layer and when the highest stabilizer contents are used could occasionally represent more than half the total cost of the complete pavement.[25]

In considering the data in Table 1 the environment concerned is crucial. Thus, the cement content required to satisfy the durability and unconfined compression strength criteria would be appropriate in temperate climates where materials must be frost-resistant. But even in this environment there is a marked disparity in the quantities of cement needed. There is clearly much scope here to ascertain whether these various criteria stem from differences in external factors, such as traffic loading, surfacing thicknesses or subgrade conditions. In areas with tropical or sub-tropical climates where frost is not a factor in disrupting the pavement there is ample evidence that road bases incorporating the lower stabilizer contents given in Table 1 have performed satisfactorily. [18][20][23][26]

A gravel-clay soil was chosen for this comparison since soils of this type represent at least 75 per cent of the materials used in tropical regions for cement and lime-stabilized bases. As the soils become more cohesive the differences illustrated in Table 1 diminish because the relation between unconfined compressive strength and C.B.R. is dependent on soil type.[27] On the other hand with lime-stabilized materials the reverse is true. Here both the unconfined compressive strength and C.B.R. criteria give substantially the same stabilizer content on the more granular soils. On the more plastic soils the differences become quite large, with the unconfined compression strength

TABLE 1

Quantities of cement required and the costs for stabilizing a gravel-clay with cement to meet various design criteria

Design Method	Durability Tests (P.C.A. Method)	Unconfined Compressive Strength (Cylinders 2:1 height: diameter ratio)		California Bearing ratio	
		17.6 Kg/cm² (250 lb/in²)	28.1 Kg/cm² (400 lb/in²)	100 per cent	150 per cent
Cement Requirements:- (per cent by weight)	6 +	6	10*	3	4
Cement cost for 15 cm thick base (shillings/m²)					
(a) Cement 120/- per ton on site	2.3	2.3	3.8	1.1	1.5
(b) Cement 400/- per ton on site	7.6	7.6	12.7	3.8	5.1
Cement cost as a percentage of total cost of 15 cm thick base					
(a) Cement 120/- per ton on site	20 - 40	20 - 40	30 - 55	10 - 25	15 - 30
(b) Cement 400/- per ton on site	45 - 70	45 - 70	60 - 80	30 - 50	35 - 60

+ The cement requirement to meet the durability tests was estimated by the short-cut test method.[2]

* Extrapolated value assuming linear relation between unconfined compression strength and cement content.

criterion leading to substantially lower lime requirements.

3.4 The Rationalisation and Improvement of Design Methods

Soil stabilization with cement and lime has been an undoubted success in the construction of bases for roads and airfields. But this success is no justification for complacency and an unquestioning acceptance of present design methods and criteria. Over the last decade or so there has been increasing evidence that present design criteria may well be conservative.[20][26][28][29] For example a recent investigation of the performance of nine major roads in the United Kingdom having cement-bound granular bases under a 4 in. dense bituminous surfacing[29] showed that for the range of strengths used no correlation could be found between the compressive strength of the base materials and the performance of the road under traffic.

There appear to be three areas where rationalisation and development of design criteria would be immediately beneficial and would lead to the more widespread and economical use of cement and lime-stabilized base materials. These are as follows:-

(i) the effect on design criteria of climate and other environmental conditions such as subgrade support

(ii) the type and thickness of bituminous surfacings needed over cement- and lime-stabilized base materials in relation to traffic intensity, wheel loading and temperature

(iii) the design criteria for cement-stabilized uniformly-graded sand soils.

3.5 Conclusion

These notes have been prepared to highlight the anomalies in the existing methods used to design cement- and lime-stabilized base materials for roads and airfields. They are intended to stimulate thought and discussion and by so doing lead to concerted research studies resulting in the elimination of these inconsistencies, better understanding of the behaviour of stabilized base materials and improved design methods.

4. INTERACTION OF SOIL AND PAVEMENT

4.1 Introduction

To date, lack of knowledge of the real stress-strain behaviour of road materials and soils under repetitional traffic loading and of the influence of environmental factors, such as temperature and moisture changes, upon this behaviour has necessitated the use of methods of pavement design which are empirical. The C.B.R. test developed when the main problem in pavement design was conceived to be the determination of an adequate thickness of granular material to protect the subgrade from overstressing has formed the basis of the most widely used methods of empirical design.

The widespread introduction of relatively stiff cement and bituminous bound bases has however altered the pattern of stress distribution within the road and consequently its behaviour. Even when used in the reduced thicknesses which their superior performance generally justifies the stress levels in the subgrades of such roads are materially reduced and stresses within the bases increased when compared with granular construction. Again the stress distribution is also radically altered by the re-arrangement of the main load distributing elements of a pavement as in the "sandwich" form of construction.

Developments such as these which focus attention on the performance of pavement materials under repeated flexural stresses, and also the need today to design pavements capable of carrying heavy traffic in almost any part of the world has hastened the obsolescence of empirical methods based solely on the correlation of empirical tests with the superficial behaviour of particular types of pavements in particular environments. There is a need to find means of characterising soils that can be used in the more rational methods of pavement design that are now emerging.

4.2 Present Research

Due to the complex behaviour of road materials and subgrade soils it is unlikely that a usable unified theoretical approach will ever be possible which describes both transient deformation behaviour and failure by cracking or excessive permanent deformation of a multi-layer pavement. Present research divides the problem into two parts:-

(a) Examination of the transient stress-strain behaviour of roads with a view to establishing the validity of characterising it in terms of mathematically treatable systems, such as multi-layer elastic or visco-elastic models. These are, by definition, incapable of describing failure conditions but serve to determine with sufficient accuracy the levels of transient stress and strain under which the behaviour of road materials under repetitional traffic loading may be determined.

(b) The study of the behaviour of these materials both individually and in combination in full scale experimental pavements under controlled conditions of load and environment to establish limiting values of stress and/or strain for design purposes.

4.3 The role of the soil

4.3.1 Transient deformation characteristics. These determine both the stresses applied to the soil and to a lesser extent the stress generated within the pavement itself. For example, in a simple two layer pavement assumed to behave elastically the maximum vertical stress in the subgrade at formation is

proportional to $\left(\frac{E_2}{E_1}\right)^{0.65}$ and the maximum tensile

stress in the bottom element of the pavement proportional to log $\left(\frac{E_1}{E_2}\right)$ (30)

Determination of realistic transient deformation behaviour is therefore very important.

Under the influence of the rolling wheel load the subgrade is subject to three unequal principal stresses which increase in magnitude then decay while the planes of principal stress rotate. This condition is impossible to simulate exactly in any laboratory or field test not involving rolling wheels. Methods which are used include the following test procedures:-

(a) Rapid plate loading tests through rigid or flexible circular plates on the surface of the soil. These can be made to simulate a realistic rate of loading and unloading of a reasonable depth of sub-grade but may generate unrealistically high peripheral shear stresses sufficient to cause localised shear failures. In testing non-cohesive soils the influence of the surcharge effect of the pavement is difficult to simulate. Soil tests have also been carried out with buried stress and strain instrumentation.[31]

(b) Wave propagation techniques[32][33] define an elastic modulus which corresponds to an unrealistically low stress level and high frequency of load application. Results however characterize a realistic depth of subgrade and give relatively rapid coverage.

(c) Dynamic triaxial tests allow the simulation of peak principal stresses at realistic rates of load application but not the realistic build up of stresses. Not all research workers however apply a realistic pulse shape and for experimental convenience a squared form of stress pulse is sometimes used.[34]

Both the form of the stress-strain or load-deflection curve and the magnitude of moduli derived from the results show wide variations. The results of dynamic triaxial tests on cohesive soils all show a characteristic curved stress-strain relation corresponding to a decreasing effective modulus with increasing stress [31][35] and analysis of changes of moduli with depth where buried gauges are used under a rapid plate bearing test indicate increasing modulus with depth, i.e. at the lower levels of stress.[31] However many authors report linear soil behaviour under rebound plate tests even at extremely high values of bearing pressure[36] (160 lb/in^2 on soil of C.B.R. 15%) and, by implication, from stresses measured under road pavements[30] which is difficult to reconcile completely with reported non linear behaviour.

There is also wide variation in the values of effective moduli derived by various authors from their tests for use in multi-layer elastic theory. For example, a widely used correlation is that between dynamic modulus measured from wave propagation tests and the C.B.R. value(37).

E (lb/sq.in.) = 1600 C.B.R.

This equation predicts an E of 24,000 lb/sq.in for the C.B.R. of the silty sub-grade at the W.A.S.H.O. test track which has been evaluated by rebound plate bearing tests(36) at only 3,700 - 5,200 lb/sq.in.

It would therefore be helpful to discuss the merits and limitations of available and proposed test techniques intended to evaluate the transient stress/strain behaviour of soil in pavement design research, since the use of a realistic test is of great importance.

4.4 Permanent deformation behaviour under repeated loading.

Tests of this type on soil are normally carried out in some form of triaxial equipment(34)(38)(39) although a repetitional shear machine has been reported.(40) Such tests represent a simplification of the actual stress conditions and in the case of fine grained soils near saturation, of the drainage conditions also. It is not possible to simulate in the laboratory the drainage conditions of an element of such a sub-grade attempting to establish pore-pressure equilibrium with a water-table while subject to partial shear during repetitional loading. Most authors report tests in an undrained condition only. It would be worthwhile for the participants to consider the adequacy of present test techniques particularly from the point of view of simulating conditions of drainage and loading.

4.5 Looking to the future

The development of pavement design methods based on a fundamental understanding of soil and pavement behaviour will still find the engineer faced with the same basic problems, that is,

(a) Obtaining the sufficient data for design purposes to characterize the changes in soil type along the line of the road

(b) Establishing the condition of the soil when it has reached compaction and moisture equilibrium after construction of the pavement.

These problems are in some ways becoming more difficult as the development of motorway systems requires a considerable proportion of the road's length to be built on fill whose strength is not possible to assess in the field at the design stage.

Research techniques developed to examine the fundamental behaviour of soils are, with the possible exception of wave-propagation tests, generally too complicated as design tests. Any such tests must fulfil the requirements of simplicity, speed and cheapness to give adequate coverage. Thus a further stage of correlative research involving several or all of the following parameters will be necessary.

(a) soil classification data,

(b) simple drainage, temperature and frost parameters.

(c) in situ soil strength at depths below the zone affected by superficial climatic changes which would not affect the soil under the completed pavement.

In view of the considerable length of time which must elapse before any such programme is completed and the problems involved in its practical application it seems unlikely that laboratory research will in the forseable future do more than help in refining the empirical techniques currently in use for the design of road and airfield pavements.

5. REFERENCES

1. BARDEN, L. Consolidation of compacted and unsaturated clays, Geotechnique, 1965, 15, 267-286

2. HUANG, Y.H. and F.D. SHEPARD. Laboratory investigation on the use of high moisture content soils in high fills. Highw. Res. Rec., No.223, 1968, 45 - 58.

3. REDUS, J.F. A study of in-place density determinations for base courses and soils. Bull. Highw. Res. Bd. Wash, 1957 (159), 24 - 40.

4. SMITH, P.C., A.I. JOHNSON, C.P. FISHER and L.M. WOMACK. The use of nuclear meters in soil investigations: A summary of worldwide research and practice. A.S.T.M. Special Technical Publication No. 412 Philadelphia 1968 American Society for Testing and Materials.

5. LEWIS, W.A. Nuclear Apparatus for density and moisture measurements. Study of factors affecting accuracy. Rds. and Rd. Constr. 1965, 43, (506) 37 - 43.

6. RALSTON, H.H., and ANDAY, M.C. Nuclear Measurement of soil properties. Highw. Res. Rec., No. 66. Washington, 1965. pp. 15-33.

7. WORONA, V, and GUNDERMAN, W. Field evaluation of nuclear gauges used in compaction control of embankments. Highw. Res. Rec., No. 66 Washington 1965, pp. 34 - 50.

8. KUHN, S.H. Effects of type of material on nuclear density measurements. Highw. Res. Rec., No. 66. Washington 1965, pp. 1 - 12.

9. HUGHES, C.S. and ANDAY, M.C. Correlation and conference of portable nuclear density and moisture systems. Highw. Res. Rec., No. 177, 1967, pp. 239 - 279.

10. CHEVRIER, J.P. Mesure de la densite par diffusion gamma a l'aide d'mn appareil experimental. Bull. Liaison Labo. Routiers. Ponts et Chaussees. No. 34. Oct. - Nov. 1968, pp. 47-64.

11. TODOR, P.C. and GARTNER, W. Evaluation of direct-transmission-type nuclear density gauge for measuring in-place densities of soils. Highw. Res. Rec., No. 107, 1966, pp. 13 - 24.

12. GABILLY, Y. Les gammadensimetres R. Bull. Liaison Labo. Routiers Ponts et Chaussees No.36.

Jan. - Fef. 1969, pp. 53 - 76.

13. DURIEU, J. Pourune nouvelle politique des controles d'execution en technique routiere. Bull. Liaison Labo. Routiers Ponts et Chaussees. No. 24. Mar. - Apr. 1967, pp. 5 - 1 to 28.

14. MINISTRY OF TRANSPORT. Specification for Road and Bridge Work, London 1969 (H.M. Stationery Office).

15. de SOUSA PINTO, C. Soil mechanics for roads and airfields. (Contribution to discussion). Proc. 2nd Panamerican Conf. on Soil Mech. and Fondn Engng, vol.2, Sao Paulo, 1963 (Associacao Brasileira de Mecanica dos Solos), pp. 714 - 8.

16. PORTLAND CEMENT ASSOCIATION. Soil-cement laboratory handbook. Chicago, 1959 (Portland Cement Association).

17. STATE OF CALIFORNIA, DEPARTMENT OF PUBLIC WORKS, DIVISION OF HIGHWAYS. Standard specifications. January, 1960.

18. GREGG, J.S. The performance of several stabilized roads and some concepts on design. Proc. 3rd Regional Conf. for Africa for Soil Mech. and Fndn Engng, Volume 1. Salisbury, Southern Rhodesia, 1963 (Rhodesian Institution of Engineers), pp. 77 - 9

19. MARAIS, G.P. Transvaal Roads Department. Private communication.

20. HAYTER, M.A., and H. CAIRNS. A field and laboratory investigation into the strength of a trial stretch of lime-stabilized soil pavement in Eastern Nigeria. Ministry of Transport, Road Research Overseas Bulletin No. 20. Harmondsworth, 1966 (Road Research Laboratory).

21. U.N.E.S.C.O. Routes dan les pays en voie de developpement. Paris, 1968 (Editions Eyrolles).

22. HIGHWAY RESEARCH BOARD. Soil stabilization with Portland cement. Bulletin 292, Washington, D.C., 1961 (National Research Council).

23. CARTMELL, H.S. and A.O. BERGH. Lime stabilization of soils for use as road foundations in Northern Rhodesia. Department of Scientific and Industrial Research, Road Research Overseas Bulletin No. 9. Harmondsworth, 1958 (Road Research Laboratory).

24. McDOWELL, C. Evaluation of soil-lime stabilization mixtures. Highway Research Record No. 139. Washington, D.C., 1966 (National Research Council), pp. 15 - 24.

25. ANDREWS, J.H. and J.B. METCALF. Development in Western Queensland and road transport with particular reference to beef roads. Conference on Civil Engineering Problems Overseas. London, 1968 (Institution of Civil Engineers), pp. 167-83.

26. HARLEY, B.V. An experimental stabilized-soil road, Mukuyu, Kenya. Department of Scientific and Industrial Research, Road Research Overseas Bulletin, No. 13. Harmondsworth, 1961 (Road Research Laboratory).

27. MACLEAN, D.J. Considerations affecting the design and construction of stabilized-soil road bases. J. Instn. Highw. Engrs. 1956, 3(9), 16-33.

28. REDUS, J.F. Study of soil-cement base courses on military airfields. Highway Research Board Bulletin 198. Washington, D.C. 1958. (National Research Council), pp. 13 - 19.

29. LEWIS, W.A. and BROAD, B.A. An investigation of the performance of nine major roads having cement-bound granular bases. Ministry of Transport RRL Report LR 196. Crowthorne, 1968 (Road Research Laboratory).

30. LISTER, N.W. and R. JONES. The behaviour of flexible pavements under moving wheel loads. Proc. 2nd Int. Conf. Struct. Des. Aspht. Pav., Univ. Michigan, 1967, 1021 - 35.

31. BROWN, S.F. and P.S. PELL. Sub-grade stresses and deformation under dynamic load. Proc. Am. Soc. Civ. Engrs., Journals of Soil Mechs. and Foundation Div. 1967 93., No. SM 1, 17 - 46.

32. JONES, R., E.N. THROWER and E.N. GATFIELD. The surface wave method. Proc. 2nd Int. Conf. Struct. Des. Aspht. Pav., Univ. Michigan. 1967 505 - 12.

33. HEUKELOM, W. and A.J.G. KLOMP. Dynamic testing as a means of controlling pavements during and after construction. Proc. 1st Int. Conf. Struct. Des. Aspt. Pav., Univ. Michigan, 1967, (667-679).

34. SEED, H.B. and J.W.N. FEAD. Apparatus for repeated load tests on soils. A.S.T.M. Spec. Publ. No. 254. 1959.

35. SEED, H.B., C.K. CHAN and C.E. LEE. Resilience characteristics of sub-grade soils and their relation to fatigue failures in asphalt pavements. Proc. 1st Int. Conf. Struct. Des. Aspht. Pav., Univ. Michigan 1962, 611 - 36.

36. SKOK, E.L. and F.N. FINN. Theoretical concepts applied to asphalt concrete pavement design. Proc. 1st Int. Conf. Struct. Des. Aspht. Pav., Univ. Michigan, 1962, 413 - 440.

37. HEUKELOM, W. and C.R. FOSTER. Dynamic testing of pavements. Proc. Am. Soc. Civ. Engrs. Journal of Soil Mechs. and Foundation Div. 1960. 86, S.M.1, 1 - 28.

38. GRAINGER, G.D. and N.W. LISTER. A laboratory apparatus for studying the behaviour of soils under repeated loading. Geotechnique, (London) 1962. 12, 3 - 14.

39. LAREW, H.C. and G.A. LEONARDS. A repeated load strength criterion. Proc. Highway Res. Bd. 1962. 41, 529 - 56.

40. SPARROW, R.W. A direct shear apparatus for repeated leading tests of cohesive soils. Civ. Eng. and Pub. Wks. Rev. (London) 1965. 60, (705), 531 - 3.

SPECIALTY SESSION 18

Introductory remarks by the President, Mr. Gerardo Cruickshank

It has been a great honour for me to be invited to be President of this Speciality Session No. 18 on Roads and Runways.

In the first place, I wish to give you the most cordial welcome from the Ministry of Public Works, which is in charge of the design, construction and maintenance of roads and airfields in Mexico, and extend to you the best wishes for the success of this meeting.

Since 1925, when the construction of modern roads started in Mexico the Ministry has been responsible for the construction of nearly 70000 Km. of roads of all kinds, including 1200 Km. of special highways (turn pikes), and during this period, specially in the last ten or twenty years, the improvements in the design and construction techniques have enabled us to produce more and more efficient projects, from the point of view of the geometrical capacity, the stability of earthworks and the quality of pavements.

In addition the Ministry has given special attention to the investigation of those factors which influence the general criteria of design to insure the quality of construction, such factors as the standards of compaction in embankments, and the stability of bituminous mixes used in pavements.

We are preparing a report on an investigation that has been carried out over several years in coordination with the ASSHO tests to investigate in different parts of this country the behaviour of materials to be used in earthworks and also the interaction between those earthworks and the different types of pavements under different loading conditions.

Seeking for non-destructive quality control methods, we have been using nuclear apparatus to determine the water content and density of a compacted material, although up till the present, we have not been able to obtain reliable results. As for the stabilization of materials for embankments and bases, we in Mexico, do not utilize cement or lime very much because of their great cost. However, bituminous stabilisation is more economical and this has been used to some extent.

One of the most important problems in road design is the pavement design aspect. As we all know,essentially it consists of providing a layer or a system of layers made of rocky material, cemented or not, with the quality and adequate resistance to take the loads imposed by the vehicles and transmit them at an adequate stress level to the layers beneath. In consequence all pavements must accomplish the following requirements:

1. Resistance to loads
2. Stability in the environmental conditions
3. Durability
4. Economy

At first sight, this might seem to be easy, but on closer examination it will be found that several uncertainties arise, uncertainties that techniques have not been able to clarify in a satisfactory manner.

In connection with the performance of pavements, two kinds of failure can be distinguished.

a) Due to lack of structural strength

b) Due to the excessive deformation.

This last one is perhaps the most frequent and possibly arises from the first.

In both types of failure, the pavement might fail to fulfil its task. In the first case, in theoretical designs some uncertainties exist due to the variability and anisotropy of the structure of a pavement and subgrade which depends on the critical water content that can be reached during the life of the pavement and on the type, rate and repetition of loads.

In addition, unknowns exist in the evaluation of the resistance both of the materials of which the pavements consist and the materials that support such pavements.

As for the failure due to the excessive deformation, the principal uncertainties arise in the criteria as to the amount of deformation which can be tolerated and the influence that each layer has on such deformations as well as the interaction between different layers.

To conclude, I would like to remind you that the spirit of this Speciality Session is to provide the opportunity to all those present here for an interchange of ideas and to listen to suggestions that might open new ways for investigation in each of the topics pointed out by Mr. Lewis.

Summary of the main points made by the speakers

Topic 1. Soil Compaction

Dig-Ing R. Floss (Germany) described the specifications for compaction which were in use in Germany. These involved measurements of dry density, air content and the deformation characteristics of the fill (e.g. plate bearing tests, C.B.R. tests and deflection measurements using the Benkelman beam). The basis for the specification was the Proctor test and various values for relative compaction were specified depending on the zone in the embankment, whether the soil was cohesive or non-cohesive, the height of embankment and the type of road construction.

One of the major problems was the control of earthwork construction and this was made more difficult by having various specifications. Control posed not only a testing problem but also an organisational one. Close co-operation between the contractor and the engineer was essential. Current testing procedures were still merely expedients and were not appropriate for the statistical evaluation of control results.

Mr. J. Biarez (France) said that the road must keep its external profile with a given accuracy. As a first approximation the deformations must be reversible; that is, the state of stress in-situ must be within the elastic state. To simplify, the stress in-situ must be less than the over-consolidation stress which will be similar to the effective stress produced by the compaction equipment. More precisely, the design and the compaction must give, at each point in the embankment, a limit of the fatigue envelope for n-cycles. This must be greater than the state of stress in-situ as calculated by the finate element method.

Mr. G. Y. Sebastyan (Canada) expressed the view that specifications for compaction could not be separated from the complete design for the road. Road design methods are empirical and rely on experience. In Canada the resident engineer on each road project is responsible for preparing a job history in which the quantity and quality achieved in the materials is recorded. The results achieved depend on many factors including the financial resources of the contractor.

Dr. W. J. Turnbull (U.S.A.) said that there were two factors to be considered in specifications for earthworks. These were:-

(1) strength of the fill

(2) compressibility or consolidation of the fill.

With regard to the question of specifications, the Corps of Engineers has tried all types but were now tending towards methods specifications. A background of experience of the performance of compaction was, however, necessary. If the water content of the fill was adjusted correctly and the right type of compaction equipment was used no control testing was necessary. Testing was only required to produce information as a record of the job.

Mr. B.A. Vallerga (U.S.A.) agreed with Dr. Turnbull that on good jobs the minimum of control is required and also with the views expressed by Mr. Sebastyan. Mr. Biarez was also correct in specifying limiting stress. However he felt that there was a lot to be learnt regarding the stresses in pavements and research was necessary in the field of material characterisation. The stresses can be calculated but the accuracy will depend on the stress system chosen (elastic or elasto-plastic).

Mr. A. Kézdi (Hungary) said that where large amounts of fill and large sums of money were involved in Hungary, the relevant soil properties needed, e.g. strength or permeability were related to the phase composition of the soil. Where only small quantities were involved statistical relations between the soil properties and the geological classification of the soil were employed. On the question of specifications and control, method specifications were favoured in Hungary.

Mr. R.I. Kingham (U.S.A.) pointed out that one of the disadvantages of the methods specification was that the highway department had to evaluate the performance of every piece of new or modified compaction equipment and this involved a good deal of effort. He felt that the trend towards method specifications was retrograde and that effort should be directed towards overcoming the problem of end result type specifications.

With regard to compaction standards (top ½ - ¾ m of the subgrade), different compaction specifications could be employed depending on the anticipated vertical stress in the soil. Pavements such as full depth asphalt concrete and portland cement concrete that have sufficient thickness, reduce the traffic stresses to less than 5 lb/sq.in. For these types of pavement uniformity of subgrade support is far more important than a high degree of compaction and he felt that compaction specifications might be relaxed without adversely affecting performance.

Prof. G. Moraldi (Italy) agreed with Dr. Turnbull that the specification was not everything. Density control alone was also not sufficient. In Italy density control was used plus the determination of the modulus of deformation by the Swiss method. The plate bearing test was carried out immediately after the completion of the compaction work; the results were influenced by rapid changes in moisture content. Tests on only fully saturated materials are, therefore, sometimes specified. There must also be control of compaction equipment to ensure its suitability. In Italy proof-rolling is used to locate soft spots which can then be dug out and replaced.

Mr. E. Readshaw (Canada) said that in British Columbia they used rather similar methods to those used by Prof. Moraldi but the Benkelman beam was employed instead of proof rolling. They distinguished between bulk fill and the subgrade. The former was not really controlled very strictly because of the difficulty of testing on congested sites and the problem of the variability of fill. For example, materials ranging from silts to broken rock might be encountered on jobs involving the placement of material at the rate of 1 million cu.yds per month.

In the upper layers the deflection beam was used and this ensured uniformity. They recognised that the moisture content at the time of the test could differ from the final equilibrium moisture content but they had developed relations between the deflection and the most adverse conditions expected. Although there were limitations they found this the most practical method at present.

General Conclusions on Topic 1

The specifications for the state of compaction of fill should be related to the requirements for the embankment and the superimposed pavement as well as the soil conditions and the height of the embankment.

There was considerable support for the use of methods specifications and general agreement that the use of in-situ measurements of dry density with strict quality control procedures were not practicable with mass earthworks.

There was some agreement that the use of in-situ strength measurements (plate bearing tests, proof-rolling or Benkelman beam) were very useful for controlling compaction and particularly for the location of soft areas.

Topic 2. Soil Stabilisation

Mr. R.I. Kingham (U.S.A.) reviewed four projects involving asphalt stabilisation that the Asphalt Institute has under study with co-operating agencies. Three projects are full-scale road experiments and the fourth, an outdoor circular test track. All the experiments have bases, both treated with asphalt and without, laid directly on clay or silty clay subgrades. The thicknesses of each type of base had been varied to determine equivalent structural sections based on performance. The test roads are located in Ontario, Colorado and San Diego, California. The test track is at Washington State University. These locations cover both warm and cold environments. The aggregates stabilised with asphalt range from well-graded materials for the asphalt concrete bases to uniformly graded sands. In all cases the percentage passing the 200 sieve is less than 10 per cent. Asphalt cement, emulsion asphalts and cut-back asphalts were employed and the Marshall and Hveem mix design procedures were used. Mr. Kingham, summarising said that uniformly graded sands, which present a mix design problem for portland cement, are not a problem when asphalt is used.

Prof. A.E.Z. Wissa, (U.S.A.) observed that when one spoke about strength one was not talking about a unique property. What is really required is resistance to deformation. He showed the results of undrained triaxial tests on cement stabilised soil. As the stress was increased friction was mobilised. As peak strength was passed the friction increased but the cohesion decreased. Summarising his results he said that frictional properties are independent of environment. Cohesive properties are a function of many factors (cement type and content, state of compaction, loading conditions, etc.). To give a stabilised sand a sufficient strength to raise it above the level of stress which would cause disintegration, a very high cement content was required. For clays or silty soils, however, the material can be upgraded to a sand or sandy gravel with low cement contents and the cohesion factor could be neglected. Prof. Wissa questioned whether high strength was really necessary or whether the aim of stabilisation was just to improve soil properties. If cracks occur no reliance can be placed on the tensile strength and he did not believe that stabilised bases would have an uncracked performance over a long term.

Prof. W.R. Hudson (U.S.A.) thought that often one of the primary reasons for stabilisation was to provide a material capable of resisting the tensile stresses developed in the base. The difficulty of determining the tensile strength parameters had now been overcome by the use of the indirect tensile test. It was possible to describe the transient stress-strain behaviour of pavements under load and this provides information on the tensile strength properties required. However tensile strength was not the complete answer as undoubtedly a complex state of stress exists in the base. Nevertheless he strongly advocated the use of the indirect tensile test to evaluate both modulus of elasticity and Poissons ratio.

Dr. L.M. Zalazar (Argentine) said that the selection of the type of stabilising agent to be used should depend on the situation. Lime stabilisation should be employed for the foundation of the pavement, cement stabilisation for the sub-base and bituminous stabilisation for the base. The amount of bituminous stabiliser could be determined using the gyratory compaction apparatus.

Mr. J. Biarez (France) described tensile tests carried out in the triaxial apparatus using a special shaped test specimen. This equipment enabled any required stress to be applied to the specimen.

Dr. W.J. Turnbull (U.S.A.) agreed with Dr. Zalazar's views. He thought it important to be sure that the base would perform the function required of it. He was impartial with regard to the type of stabilisation which should be employed. However, care was needed to ensure that material which would perform satisfactorily in the unstabilised state was not stabilised although, of course, marginal materials should be stabilised.

Mr. A. Kezdi (Hungary) pointed out that not only tensile stresses had to be considered; there was a combined stress state. This could be simulated using the indirect tensile test and this test, when combined with the unconfined compression test enabled the relevant portion of the Mohr's envelope to be determined. The results so obtained could be used with multi-layer elastic theory to determine whether stabilised material has sufficient strength. He also expressed the view that high cement contents are likely to cause cracking.

Mr. B.A. Vallerga (U.S.A.) mentioned one test, which he thought might have some value, which had been used in another connection. This used a triaxial technique which allowed independent control of the applied vertical and lateral stresses. A tension failure could be induced by decreasing the vertical stress.

Mr. J.J. Girard (France) said that tensile properties have been found to be of major importance in the study of durability of stabilised materials. To investigate the tensile behaviour of such materials it was first necessary to consider whether the usual Mohr-Coulomb criteria was valid. Since stabilised materials may be considered as brittle materials he felt that the modified Griffith criterion was more applicable. The ratio of the unconfined compressive strength to the tensile strength had been shown to be dependent on the angle of internal friction. Good agreement had been found between the results obtained experimentally and those derived from theory. The indirect tensile test was used to determine the tensile strength.

General Conclusions on Topic 2

The need to consider environmental conditions, traffic intensity and the purpose for adding stabiliser was generally recognised. If it is assumed that the base is a continuous elastic layer, the strength requirements for cement stabilised bases can be assessed theoretically from the tensile stresses likely to be developed as calculated by multi-layer elastic theory. The tensile strength of the material can be determined very easily using the indirect tensile test.

However, the use of the tensile strength approach can lead to very high cement contents which is undesirable and in any case this approach is not really valid because cracking of cement stabilised bases is inevitable due to shrinkage of the material.

There was some support for the view that the aid of adding cement or hydrated lime should simply be to improve the soil properties and upgrade them to correspond to those of a granular base material.

Topic 3. Interaction of soil and pavement (discussed on Wednesday 27th August)

Introductory remarks by the President, Mr. Gerardo Cruickshank

First I would like to tell you about the Mexican experience in the design and construction of roads and airfields pavements, and at the same time make a proposal for the final recommendation of this session.

In the design of the thickness of pavements for the Mexican roads, generally we have been using the CBR method, adapted to the characteristics of our own materials and climatic conditions. However, we believe that the CBR method has some lack of accuracy because the test results are not always representative of the actual conditions of the subgrade over which the pavement lies.

To provide more reliable information on pavement design, several years ago we commenced a programme of investigation using some existing roads as test roads to enable experiments with bases, sub-bases and surfacings of different kinds to be carried out. The report of this investigation is being prepared by Mr. Santiago Corro Caballero from the Engineering Institute of the National University of Mexico and Mr. Corro will present some of the information obtained in the discussion.

One of the most important contributions that Mexican experience might provide to those countries in the development stage, relates to the construction of asphaltic pavements consisting of one or two surface treatments, that have been able to support as much as 1000 vehicles per day with an average load of three tons. The main characteristic of this kind of pavement is its low cost. With regard to runways, several airfields are now under construction and by the end of this year, Mexico will have 30 modern large airports designed for modern jet aeroplanes. In the design of the pavements for these new runways, we are following the Portland Cement Association Method using the Westergaard curves, determining beforehand the reaction modulus of the subgrade and the deflexion modulus of the concrete to be used in the pavement.

I feel that the discussion should be concentrated on the question of the provision of the necessary subgrade support in relation to the traffic loads and climatic conditions. Information on pavement failures would also be very useful. For this reason I suggest that we might recommend that members interested in the question of roads and runways should provide information on the performance of pavements in relation to the subgrade conditions, the types and thicknesses of material used in the pavement layers and the traffic and climatic conditions. This information might possibly be collected by a special group of the International Society for Soil Mechanics and distributed by all National Societies to those concerned with the planning, design and construction of roads and runways.

Prof. I. Holubec (Canada) described a stress path method for studying the behaviour of granular materials by triaxial techniques and discussed the selection of stress regimes to be applied. For the initial state of stress representing zero load on the pavement, zero vertical and horizontal stresses are chosen. The final vertical stress is estimated from Boussinesq's theory and the final confining pressure is taken to be the mean of two limiting conditions. These are the lowest confining pressures needed to prevent failure under a given vertical stress and that required to prevent all lateral expansion of the specimen. The specimen can be tested using an isotropic consolidation stress path and then a constant all pressure stress path to the final stress state. Good agreement has been found between elastic and permanent deformations predicted by this method and those measured in the field. The method has been applied to granular s[illegible]-grades, sub-bases, bases and to bituminous stabili[illegible] materials.

Prof. H.E. Harr (U.S.A.) was concerned about the serious situation caused by the rapidly changing, and generally more onerous, conditions for which the road and airport engineer has to design, using as a basis, empirical experience which is increasingly inadequate for the purpose. Fuller understanding of pavement behaviour is essential.

A series of questions were posed designed to provoke consideration as to whether stress-strain models for pavements which ignored dynamic or inertial effects were adequate to describe pavement behaviour. His answers indicated that they were not.

The difficulty of applying the results of laboratory tests to complex field conditions was due to the irrelevance of many of the tests to field conditions and which anyway, generally gave different answers when measuring the same parameter. Establishment of truly realistic laboratory tests is crucial to progress.

Dr. N. Chryssofopoulos (U.S.A.) pointed out the advantages of being able to draw upon published agricultural soil maps in road design. He described an investigation into the correlation between pedological soil type and the performance of 28 miles of concrete pavements in Illinois. The existing data was supplemented from lengths of road in poor condition.

His main conclusions were:

(1) The drainage conditions are important in controlling pavement performance

(2) Transverse cracking correlates well with soil type when the pavement is constructed on the A horizon but not with the lower horizons.

(3) Degree of damage increases as the pavement is placed lower in the natural profile, especially in deep cuts and also at transitions from cut to fill.

(4) Pavements on embankments show less distress due to better drainage conditions.

Prof. G. Moraldi (Italy) said that fundamental methods cannot wholly replace empirical ones but are a powerful tool in examining the validity of empirical methods enabling, for example, a correct choice to be made between empirical methods which give conflicting results. Much research is required before fundamental methods are proven and Prof. Moraldi considered that the controlling parameters should be strains rather than stresses as fatigue resistance of materials is strain dependent. Plate bearing tests, eventually in combination with wave propagation techniques are the best means of assessing these parameters. The use of trial sections in every major road project was recommended.

He also supported the concept of proof rolling as a means of detecting weak areas in a newly constructed fill or when resurfacing an old pavement. He suggested the use of heavy pneumatic rollers of 60 to 100 tons on airports.

Prof. Moraldi felt very strongly that there was a real need to co-ordinate research on pavement design and that an international committee should be set up to carry out this task.

Mr. A. Readshaw (Canada) said that pavement design in British Columbia is based on investigations of the behaviour of existing roads throughout Canada by the Canadian Good Roads Association.

Pavement performance is measured subjectively by a small panel of Highway Engineers who drive over a section of road at the speed limit and rate it on a scale from 0 to 10. It has been argued that the rating method is not sufficiently reliable but comparison of successive annual ratings by different teams shows good statistical consistency as do changes in the ratings of pavements constructed in different years.

Pavement design studies have shown:-

(1) The rating method described is a valid way of judging the present condition of a road and it reflects the degree of public acceptance.

(2) Pavements deteriorate in a predictable manner.

(3) Environmental factors such as variation of cut and fill height, frost and moisture conditions and non-uniformity of soils are more important than traffic in determining road deterioration. Laboratory tests have not proved satisfactory in evaluating these environmental effects for design purposes.

(4) Preliminary design is carried out on a basis of general experience of the soil types and climate and the final design is based upon the relationship between the deflection and the performance of roads in the neighbourhood. The Benkelman Deflection Beam is also used as a control tool at all stages in the construction of pavements.

(5) Lack of uniformity of construction is probably the most important factor causing failure.

(6) The highway should be designed as a complete system. Design should be such as to give an acceptable life without overdesigning against any particular factor contributing to development of failure.

Mr. B.A. Vallerga (U.S.A.) spoke of a design approach being used to assess the load carrying capacity of runways and to indicate what strengthening is required for future increased loads. Details will be published in the November A.S.C.E. journal. Both conventional multi-layer elastic and finite element systems are used. The parameters of the pavement materials, Young's Modulus, Poisson's Ratio and Modulus of Resilience are obtained from laboratory testing. The basis of design was to analyse the stress-strain behaviour of existing airports and to correlate the results with observed performance. Several speakers questioned the basis used for establishing the design criteria used and Mr. Vallerga indicated that the maximum stresses in the soil depended on the number of load applications expected and the strain in pavement materials on the extent of observed cracking in existing runways.

Dr. W.J. Turnbull (U.S.A.) felt that the approach being advocated by Mr. Vallerga was still basically empirical, like the U.S. Army Corps of Engineers C.B.R. method, with respect to the selection of the limiting values of the various parameters used. He thought empiricism would continue in this field for some time to come and suggested that more attention should be paid to the variability of the factors involved in design.

Mr. R.I. Kingham (U.S.A.) discussed the problem of estimating the moisture equilibrium of subgrades.

This was a controversial subject as some engineers soak the soil to determine the design value (after Hveem) whereas others design on a lesser degree of saturation (e.g. Great Britain). Recent studies in the Asphalt Institute's co-operative field experiment in Colorado suggested that the soaked soil design value would produce too thick a design when asphalt bases are laid directly on the subgrade. Moisture studies in almost adjacent test sections both 3 and 4 years after construction showed significantly lower values for the asphalt base sections as compared with untreated aggregate base sections (3 per cent below optimum moisture content compared with 4 per cent above).

With regard to the question of estimating the equilibrium stiffness modulus of the subgrade, he suggested that the value might be estimated from a knowledge of the soil type and its equilibrium soil suction condition. The latter is easily measured in the laboratory whereas the determination of stiffness modulus requires rather sophisticated dynamic triaxial testing.

Prof. R. Hudson (U.S.A.) stressed the need to extend the range of the present, largely empirical design methods to include new materials and changing load conditions.

A mathematical systems approach is proposed to provide a co-ordinated framework for the solution of pavement problems which is described in the Transportation Journal, A.S.C.E. in June 1969. Its advantages include the fact that problems must be adequately defined, it provides a background and structure for co-ordinating research, it helps to define the areas requiring research, it allows the use of optimization techniques and permits the proper consideration of economics. It also takes into account inter-action and feed back effects which is not a feature of present design methods. A pavement design method for immediate application using present information has been developed by the Texas Highway Department.

Prof. F. Balduzzi (Switzerland) agreed that major problems are a) obtaining sufficient data to characterize changes in soil type along a road and he recommended the use of some form of proof rolling with subsequent rapid strength measurements to divide the road into lengths of equal strength for design.
b) establishing criteria for compaction and moisture equilibrium.

These must be determined by field tests and the preliminary laboratory testing must, therefore, be designed to cover the range of likely values.

A design method must be used which can take into account the difference between the values of soil strength originally assessed and those existing during construction.

A rapid method of examining the frost susceptibility of soils by testing simultaneously five samples compacted to different moisture contents was described. C.B.R. tests are also used to determine the loss of bearing capacity after being subjected to one cycle of freezing and thawing under drained conditions.

Sandwich construction had been used when soil drainage or freezing conditions made conventional design uneconomic.

Dr. H.L. Jessberger (Germany) spoke on the important influence of frost action in reducing the bearing capacity of subgrades and the need to predict this reduction. He proposed a test involving several freezing cycles using either the C.B.R. test or a specially developed one to establish the residual bearing capacity. Results of tests of this type are to be presented at a meeting of the Highway Research Board.

Mr. R. Sosa (Mexico) briefly described the problems encountered and the solutions adopted during the construction of the runways at three Mexican airports. One was to be constructed on a clay where swelling tests had indicated that it would be unsuitable as a foundation. Mixing locally available silt with the clay had reduced the swelling to about 10 per cent of the original value and a satisfactory pavement had been constructed.

At Mexicali airport inability to compact the natural sand subgrade to a satisfactory C.B.R. value had been overcome by stabilising the sand with bitumen.

At Mexico City airport differential settlement of the soft clay subgrade had been controlled by a special pavement 49 inches thick in which the subbase was formed with pre-cast lean concrete blocks as a construction expedient. This work was reported in the 1967 Ann Arbor Conference.

Mr. S. Corro (Mèxico) described aspects of a co-operative research programme on lightly trafficked highways between the Ministry of Public Works and the Institute of Engineering. Three road experiments comprising a total of 80 sections have been built with construction thicknesses ranging from 4 to 12 inches, base and subbase thickness being the main variables examined. Replication and randomization of sections was used.

After 5 years life only failures in 4 and 8 inch thick sections at one site with an A-6 subgrade had occurred. All other sections had a serviceability index greater than 2.5.

A circular test track (14 m. diameter) in which accelerated traffic loading is to be applied by a three-armed loading frame to experimental pavements was described. The profile of the deflection bowl was considered to be a better indicator of the strength of pavements than the rebound deflection.

General Conclusions on Topic 3

The diverse positions taken by many contributors reflects the design problems they have to face. Where an engineer is responsible for design in a limited area he is likely to have a good working knowledge of his soils and road materials and is likely to be content with a proven empirical method. On the other hand a consultant with world wide design commitments involving the use of many different materials in widely differing environments is much less likely to be adequately served by such methods and the university research worker must also be looking to the future.

Progress in the field of pavement design in the next few years will most likely be made by the rigorous comparison of the results of theoretical approaches with the real behaviour of roads under traffic. Where good agreement is reached the first result will probably be to modify existing empirical methods as the development of a truly fundamental method, which by definition must be cabable of world wide application, will be a lengthy process.

There was considerable support to the suggestion that there is a need for an international committee to co-ordinate research on pavement design.

Concluding remarks by the President, Mr. Gerardo Cruickshank

I would like to remind you that the spirit of this Conference as well as the spirit of our profession is that we must all collaborate to solve the engineering problems that face us so as to bring some help to the inhabitants of this world. Mexico is very proud to have had you all here and we hope that your stay has been a very pleasant one.