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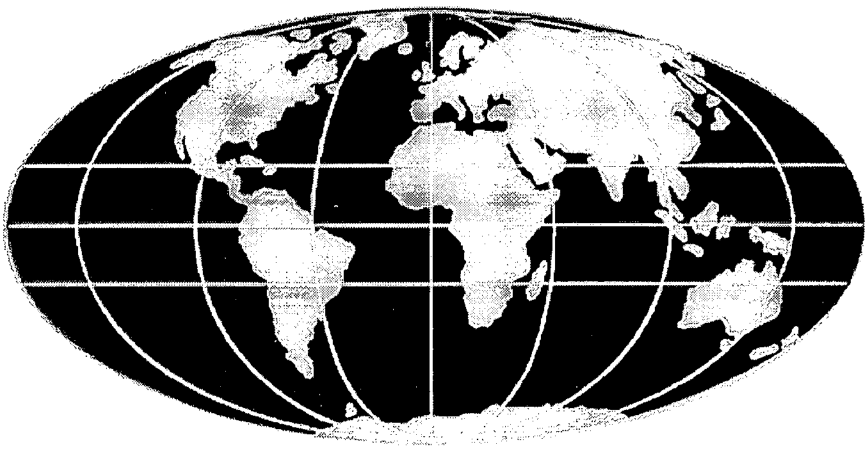

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Aspects of soil mechanics of particular importance to highway engineering in Africa

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1 INTRODUCTION

The continent of Africa, which extends over 8000 km from Tangier to the Cape of Good Hope, contains an immense diversity of geological formations, the oldest of which date from the pre-Cambrian period about 3500 million years ago.

As a consequence of this geological diversity, a wide variety of soil types exists. The highway engineer working in Africa is thus concerned with almost every aspect of soil mechanics that is relevant to highway engineering. He is spared only the problems concerned with glacial materials and frost action, and is not usually concerned with the problems of road construction in mountainous areas since only a very small proportion of the continent is truly mountainous.

The application of the science of soil mechanics is a fundamental aspect of highway engineering. In designing and constructing even quite simple roads the highway engineer has to take into account the strength and moisture characteristics of the subgrade soils along the roadline which are likely to be highly variable over distances of only a few kilometres. The engineer often has to make use of variable soil, gravel, or rock materials to construct the road. The engineer is also often concerned with factors that reflect the relation between the road and the terrain such as slope stability problems, erosion, soil moisture movement, consolidation, and the effects of swelling soils.

Limitations of space do not permit even a superficial examination in this paper of all the aspects of soil mechanics that are significant to highway engineering in Africa. Instead those aspects which are considered to be of particular significance or which are especially characteristic of Africa will be discussed briefly and research needs will be suggested.

2 TERRAIN EVALUATION AND SOIL SURVEY

In planning the location of a road, in selecting the materials required to built it, and in designing the pavement, the drainage, and the side slopes, the highway engineer needs to have a thorough appreciation of the terrain through which the road passes. For major road projects in areas where favourable subgrade conditions are limited in their extent, or roadbuilding materials are scarce, this appreciation of the terrain may need to extend over a distance of tens of kilometres on either side of the preferred route for the road in order to permit the most economical alignment to be selected and the best available materials within economic haul distance to be located.

The terrain evaluation technique enables the highway engineer to acquire the information needed with a minimum of geotechnical survey and materials testing effort. (Dowling and Beaven, 1969). The technique, which utilises geological and geomorphological concepts, has been established for many years, and has been the subject of many papers presented to African regional conferences on soil mechanics. (Atkinson and Haine 1963, Aitchison and Grant 1967, Brink and Partridge 1967). The application of the technique to highway projects and regional engineering materials surveys has been widely reported (Dowling and Williams 1964, Beaven and Lawrance 1973, Lawrance 1972 and 1978), although regrettably too few major road projects benefit from the application of the technique early enough in the design process to derive the maximum benefit.

Essentially, terrain evaluation comprises two processes; in the first,in a process called land system mapping, the terrain is divided into areas which have similar landforms and which contain similar rocks and soils; in the second process this classification is 'primed' by the addition of quantitative data on the soil and rock properties obtained by conventional ground survey methods. In the first process the preparation of a land system map requires the interpretation of some image of the terrain concerned, most commonly an aerial photograph or photographs in which the skilled interpreter can recognise distinctive patterns associated with the various landforms present.

Virtually the sole type of photograph used for this purpose in the past was the black and white panchromatic photograh, but in recent years colour photographs, satellite imagery, infra-red aerial photography, and radar imagery are also utilised. (Beaumont 1977). Using the land system map as a guide, field sampling can be disciplined to achieve maximum economy and effectiveness. For example the conventional approach of digging sampling pits at equally-spaced distances along a projected road alignment can be replaced by spacing the sampling points according to the homogeneity of ground along the road line as indicated by the land system map. The ground data obtained in the survey can then be applied elsewhere in the area of interest by making use of the transferrability of data that the recognition of similar land facets and systems provides.

A typical example of this process was a survey undertaken of the soils, foundation conditions, and materials on two alternative alignments for the 70 km Rumpi-Chiweta road in northern Malawi. (Transport and Road Research Laboratory 1978). Aerial photographs were used to divide up the area into land systems, and throughout the period of field work the air photos were used to identify land facets and to plan the sampling programme. The final alignment chosen for the road traversed three land systems of quite different characteristics. The first comprised recent sedimentary rocks in the form of a broad undulating valley floor with wide fans descending from the surrouding hills. The second was an area of deeply dissected steep hills developed on ancient igneous and metamorphic rocks. The third was a very steep and complex land system of faulted old sediments, descending an escarpment in high irregular steps to Lake Malawi. Each of these land systems required different engineering designs for the road, according to their geology and topography. The alignment of the road on the escarpment was necessarily very tortuous and careful study of air photographs was helpful in selecting an alignment as well as for determining soil and rock conditions.

Among the reasons why terrain evaluation techniques are not applied more often to highway projects in Africa is the fact that the quality and scale of existing aerial photography is not always adequate for satisfactory interpretation, and the fact that the availability of the necessary interpretative skills is very limited. It is not generally realised that low-cost multi-spectral aerial photography can be obtained using light aircraft at the cost of a few day's hire for a typical road project. (Beaumont 1977). Likewise the advent of readily available satellite imagery provides highway engineers with a breadth of terrain information on a regional basis that is only just beginning to be utilised effectively. Recent technical developments also offer some hope of overcoming the severe shortage of photo-interpreters with geological, soils, and engineering expertise. Various automatic image processing techniques are being developed which greatly assist the interpretation process.

The launching of the first US Landsat satellite in 1972 ushered in a new era of exploration of the earth's surface. Although prior to that time a large number of photographic images of the earth had been taken from space, principally during the Gemini and Apollo manned space missions, their sporadic coverage, haziness, and random angle of view, rendered them of very little value to the earth sciences as a whole, and they never came into general use for terrain-related surveys. The Landsat satellite however, by virtue of its vertical orientation, its coverage of most of the world's land surface, and its consistency, provided imagery that represented a new capability for recording the appearance of the earth's surface. The imagery also has the advantages of repetitive cover, high planimetric accuracy, and low cost.

Landsat images have been found to be particularly valuable for terrain surveys in developing countries, because of the large areas of land that are often the subject of these surveys, and the scarcity of existing terrain information. In such circumstances Landsat imagery has already come into common use for land use planning, agricultural development planning, and water and mineral resources mapping.

Recently, satellite images have been used by highway engineers for determining the location of new road alignments and for materials surveys. Whilst satellite images do not have sufficient resolution for the detailed interpretation of specific sites, there are several aspects of the process of planning and designing major road projects that are suitable for investigation at a small scale.

The Landsat satellite circles the earth at an altitude of about 900 km, in a progressive orbit such that during the course of 18 days it passes over the entire globe and arrives back at its original orbit path, when the cycle begins again. The satellite carries a scanning device which scans successive strips of land transverse to the orbit path, to build up a continuous picture of the land beneath the satellite as it proceeds. The scanning device, called a multi-spectral scanner, senses the intensity of light reflected upwards from the earth's surface. The intensity response is converted into an electrical signal, and is transmitted by radio back to earth in digital form, where it is stored on a magnetic computer tape. A computer reconstructs the digital information into images, delivering them as a series of 'scenes' of the earth, each representing an area of land 185 x 178 km in size. These images cover virtually all of the earth's land surface, except for areas that are persistently obscured by cloud. The images are made available in photographic form at low cost, and may also be obtained in the form of computer compatible tapes (CCT's). The Landsat imagery has good planimetric accuracy and has the valuable attribute that images of the same scene taken at different times are available. Although the resolution of the imagery is rather poor, being only about 80 m on the ground, the sensors are able to discriminate between subtle differences in the colour or other reflected electromagnetic energy of the terrain. Landsat scenes are available in the four wavebands recorded by the satellite's sensors, the green, red, and two infrared wavebands. 'Colour-composite' images can be created by super-imposing the images recorded in three of the wavebands, using blue, green, and red light to illuminate the selected images. Landsat images are used extensively in the earth sciences and in surveys for land use development. In highway engineering Landsat images are most useful at the early stages of planning and survey. They have found application as a substitute for maps in areas where the available maps of any kind are poor and they are used as aids in the production of topographic, geological, and vegetation maps, and for studies of soil moisture, stream patterns, flooding, the location of road-building materials, and the identification of areas of unstable ground. Increasing use is being made of images produced directly from the digital information recorded on the Landsat computer tapes (CCT's). Computer-generated images, which are displayed on a colour television screen, give the interpreter great flexibility in selecting the optimum image for revealing the characteristics of the terrain of specific interest. Enlargements of any scale can also be displayed on the screen as required, and the contrast and colour balance of the image can be adjusted at will to enhance features of the terrain that the interpreter wishes to study. The further development of these image processing techniques is the most significant area for research in this field.

Remote sensing centres for receiving and interpreting satellite images already exist in various parts of the world; in Africa there are centres in Upper Volta and Kenya. The technology of digital processing is also undergoing continuous improvement, in speeding up and simplifying the interactive exchange that takes place between the interpreter and the machine, without losing the flexibility and high quality that are the great advantages of digital processing. These developments will lead to a much wider acceptance of satellite imagery as a reconnaissance mapping tool, in highway engineering as well as in many other fields of study, for the appraisal of natural resources and their utilisation.

3 SUBGRADE SOILS

A great variety of soil types exists in Africa, but there are certain groups of soils that occur very widely in the continent and which are particularly characteristic of africa. Amongst the most significant of these are the tropical black clay soils and the red tropical soils, descriptions that embrace a wide variety of soil types.

In the last twenty years numerous papers have been written about these soils, and for most part their properties are well understood. For example previous African regional conferences on soil mechanics are an excellent source of reference on these soils. (de Graft Johnson 1975, Gidigasu and Bhatia 1971, Morin 1971, Morin and Ayetey 1971). From the highway engineering point of view the red tropical soils present few problems as subgrade soils. Indeed compared with road subgrades in temperate climates such soils generally provide strong subgrades provided reasonably favourable drainage conditions apply. (O'Reilly, Russam and Williams 1968).

Many of the black clay soils however do present severe problems as subgrades under paved roads bacause of their swelling characteristics. Either seasonal or long term moisture changes in such soils subsequent to construction of the road produce large volumetric changes which induce cracks and loss of shape of the pavement. The black clay soils also generally have a very low bearing strength when saturated. These characteristics are shared to a lesser extent by some of the more plastic red soils. (Dagg and Russam 1966). It has been shown that these adverse effects can be mitigated by incorporating features in the road design that minimise seasonal subgrade moisture changes. Blanketing the shoulders with impermeable material which is not prone to shrinkage is the principal technique, usually combined with the use of broad shallow side ditches. (Strongman 1963, Mitchell 1963, Williams and Simons 1963). Alternatively lime stabilisation of the side slopes or subgrade may be employed. Whilst these techniques can be effective, further research is desirable to define the relationships between climate and the soil moisture variations for particular types of subgrade soils and shoulder treatments.

Black clay soils also present difficulties during the construction stage of a road in that they are difficult to handle if they become either too wet or too dry. In arid climates it is very difficult to raise the moisture content of such soils to the optimum moisture content for compaction with the consequence that low densities often result in compacted fills under road pavements built on black clay soils. Recent research (Ellis 1980) has shown that the compaction of black clay soils at low moisture contents is feasible, and that adequate densities can be obtained by such means. Further research in this field is desirable.

Other soil types characteristic of Africa that present special problems for the highway engineer are the micaceous soils and the 'collapsing' soils. Fortunately these do not occur as widely as the black tropical soils, but they can present a severe local problem. (Knight and Dehlen 1963, Knight 1963, da Silva 1971). The adverse effects of building roads over collapsing soils can largely be avoided by applying modern methods of providing compaction at depth such as the use of heavy vibrating rollers, heavy deadweight rollers, or impact rollers. (Wolmarans and Clifford 1975). Micaceous soil subgrades are not susceptible to such treatment and the most satisfactory solution is to remove them to a safe depth if the value of the overlying pavement warrants the expense of such an approach. Alternatively most micaceous soils may be stabilised with cement or lime. For low cost roads the loss of shape associated with micaceous subgrades has to be accepted. It seems unlikely that futher general research on these soils is of high priority from the highway engineering point of view, but studies of particular local aspects of the problems may be required.

4. NATURAL PAVEMENT MATERIALS

In addition to 'conventional' materials such as crushed rock, the highway engineer in Africa has a wealth of natural materials to select from for roadbuilding purposes. Indeed the use of locally occurring natural roadbuilding materials is often the only economically feasible choice. Pedogenic materials such as lateritic gravels and calcretes are widely used for the construction of paved and unpaved roads (Gidigasu 1976, Netterberg 1975, 1971) and in certain regions volcanic gravels, quartzitic gravels, and weathered rocks such as basalt and dolerite play an important role in road construction. (Newill and Aklilu, 1980).

Of course the distribution of these materials varies greatly throughout the continent and in some regions suitable materials are very scarce and may have to be hauled over long distances. Alternatively soil stabilisation may be employed to enhance inferior or marginal materials.

The main problems facing the engineer in using naturally occurring materials are how to control and design for the inherent variability in the quality of such materials. The plasticity of the fines content of pedogenic materials and some weathered rocks is a common problem which can be overcome by stabilisation with a small proportion (3%) of cement or lime, but for low cost roads this will generally not be economically feasible. Mechanical stabilisation, in which two or more materials are blended together, does sometimes offer a possible alternative which is all too often ignored.

In most cases however it is necessary to utilise the locally available materials as they are won, and it is necessary to develop appropriate specifications for their selection and use related to specific materials, the traffic-carrying service required of them, and the climatic environment in which they will be used. The application of specifications derived in temperate climates for different road-making materials and different traffic loadings is invariable inappropriate in Africa, and can lead to unnecessarily expensive construction or to premature failures. The development of appropriate local specifications requires laboratory studies, road performance studies, and sometimes full-scale road experiments. There has been a steady advance in this field over the years, and some African countries have developed excellent national specifications for their road-building materials. However much more research needs to be done in this field, along the lines of that described in papers submitted to this conference. (Newill and Aklilu 1980, Roberts 1980).

5. UNPAVED ROADS

The majority of roads in Africa are unpaved roads, and in rural areas the low traffic volumes on such roads are unlikely to justify paving in the forseeable future. Many aspects of the design, construction and maintenance of unpaved roads lie in the field of soil mechanics.

Not surprisingly the engineering of earth and gravel roads has received much less attention from highway engineers and research workers than the engineering of surfaced roads. Most of the technical literature on unsurfaced roads is concerned with the techniques and the organisation of maintenance, and the selection and specification of natural materials for constructing gravel roads. Several methods have been published for designing the thickness of unsurfaced roads on a structural design basis. However the relevance of the concept of structural design to unsurfaced roads is not widely accepted.

In recent years there has been a growing awareness of the need to improve knowledge of the relationships between the construction and maintenance standards, the climate, the traffic, and vehicle operating costs on unsurfaced roads. The need arises because of the desire of transport planners to improve the quality of investment decisions in the rural road sector in developing countries. A considerable amount of unrecorded knowledge about the interaction between many of these factors exists in developing countries, but quantified data is very scarce.

The distinction between earth and gravel roads is rarely well-defined, but a commonly accepted distinction is that earth roads are constructed only of the natural materials that are encountered on the road line or immediately adjacent to it. Gravel roads on the other hand may incorporate imported material, normally a selected natural gravelly material, but sometimes processed gravels may be used.

The best service will be obtained from earth roads if they are located on the better drained parts of the terrain, and on the more granular soils if any choice of soil type is available. In most situations skill in locating earth roads in the landscape is thus fundamental to their subsequent performance. Often the location of earth roads is undertaken on the basis of a brief reconnaissance of the ground by an engineer, but in complex terrain much better results will be obtained by using terrain evaluation techniques assisted by aerial photography and other remotely sensed ground data as described earlier.

Clearly the traffic-bearing ability of earth roads depends heavily on the type of soil forming the running surface, and on the prevailing moisture conditions. The ability of earth roads to carry traffic can be substantially enhanced if they are 'engineered' by such measures as raising the formation in low-lying areas, by clearing trees and shrubs well back from the road so that the sun and wind can more readily dry out the road surface when it is wet, by cambering the surface, and by cutting suitable side-drains. In favourable circumstances earth roads can carry substantial volumes of traffic, as is evidenced for example by the behaviour of sand and clay roads in Kenya (Hodges et al 1975).

There are two basic attitudes to the design of the thickness of gravel roads. One of these is the quantitative structural design approach, which presents the designer with the difficult problem of deciding what moisture content should be assumed for the subgrade and the gravel layer. Clearly in seasonal climates the change in moisture content and hence the change in strength of these materials will be large between the wet and dry seasons.

The other approach to the design of gravel roads starts with the assumption that thickness design of gravel roads is unnecessary, and the important issue is the selection of gravel material with specified grading and plasticity characteristics which is placed in a layer of standard thickness (15cm to 20cm). This approach is the one usually adopted in Africa in which subgrades under adequately maintained gravel roads are commonly strong enough for the greater part of the year to support the imposed wheel loads with no more than 15cm of gravel cover.

In areas with strongly seasonal climates it may not be economically feasible to build gravel roads on plastic subgrades that are capable of sustaining traffic throughout the wet season without excessive deformation. In these circumstances the level provided can usually be maintained at an acceptable level by increasing the frequency of grading, or in some areas where this is not possible roads are closed for short periods after heavy and prolonged rain to prevent traffic causing excessive deformation when the subgrade is saturated.

Whichever approach is adopted provision must be made within the maintenance budget for the replacement of gravel that is lost over a period of time due to the action of traffic and weather. Clearly the influence of maintenance of the performance of gravel roads is very strong. At traffic flows of more than 30 or so vehicles per day most gravel roads require grading at regular intervals of time to remove corrugations, to restore the transverse profile, and to bring back into the centre of the road gravel that has been thrown to the sides by the action of traffic In addition, the clearing of side ditches and the restoration of material removed by erosion are required at regular intervals. All these operations are necessary if the level of service provided by a gravel road is to be maintained, but perhaps the crucial operation is the maintenance of an adequate camber. Camber must be sufficient to prevent rainwater being retained on the surface of the road. If it is not the road will deteriorate very rapidly in wet weather.

Whilst there is a great deal of useful local knowledge about the performance of unpaved roads in Africa, there is a need for more quantitative information on the relationships between road deterioration, material type, climate, traffic and maintenance techniques and policies. Research in this field is required to improve decisions made about maintenance policy and expenditure at both the national level and at local level.

6. SOIL STABILISATION

When the natural roadbuilding materials that are available locally are not suitable for use as bases or sub-bases in paved roads, stabilisation may offer a means of providing satisfactory roadmaking materials at a cost comparable with the cost of crushing rock or hauling other materials over long distances. This is a situation that is quite common in Africa, and in several African countries virtually all the early bitumen surfaced roads built outside of towns had stabilised soil bases.

The most commonly used stabilising agent in the great majority of African countries is cement. Lime and bitumen are also used but to a much lesser extent. Bitumen is usually only employed for stabilising non-plastic sandy soils and thus finds its main application in desert areas, especially in the countries surrounding the Sahara. It is perhaps surprising that lime stabilisation has not been more extensively used than it has been, since many natural gravels occurring in Africa lend themselves to stabilisation with lime and the construction process is in several ways easier to carry out than when cement is used. Also for black cotton soils lime is really the only feasable stabiliser. Zambia and Zimbabwe have opted for lime-stabilisation on a large scale but most other countries have tended to use cement in preference to lime. This is probably partly due to the difficulty of obtaining lime commercially in many countries and its relative high price because of the lack of local production facilities. It is not always appreciated that a fairly low quality of lime is satiafactory for soil stabilisation and that it can be produced on a rural industry basis in simple lime kilns. Similarly the construction process of lime stabilised road bases lends itself particularly well to the use of very simple agricultural equipment and labour intensive methods.

For satisfactory stabilisation with lime it is necessary for a soil to possess a clay fraction since the strength of the stabilised material is derived from the reaction that takes place between the lime and the clay particles. The most successful lime stabilisation is achieved with clayey gravels and gravel-sand-clays which have about 15 per cent of material finer than 425µm (no 36 BS sieve) and a plasticity index of between 10 and 25. Non-plastic soils will not stabilise with lime.

Cement can stabilise most soils that it is practicable to process, provided they are free from gross contamination with organic matter. Soils that cannot be stabilised for this reason can easily be detected by means of the pH test developed by Sherwood. (Sherwood 1962). The ability of the available machinery to pulverise soil sufficiently for stabilisation puts a limit on the plasticity of soils that can be processed, and the practical upper limit with powerful machinery is when the plasticity index of the soil multiplied by the percentage of it that is finer than 425m (no 36 BS sieve) is greater than approximately 3500. More plastic soils than this can be stabilised in special circumstances by employing pre-treatment with lime for instance, but the feasibility of doing so depends on factors like the field moisture content of the soil and the incidence of rain, and usually only when there is absolutely no other choice is it economic to do so.

Non-plastic soils can be readily stabilised with cement and they also lend themselves to stabilisation with cut-back bitumens. The 'single size' sands (those with a uniformity coefficient less than about three) present a special problem because of their inherent lack of internal friction of cohesion and generally a more satisfactory solution will be found by stabilising them with bitumen than with cement.

The great majority of stabilised soil roads in Africa have bases which are 10cm to 15cm (4 to 6 ins) thick with thin bituminous surfacings of the 'spray and chip' type. Sub-bases of untreated gravel with an effective California Bearing Ratio (CBR) of 25 or more are commonly used and only very rarely is it necessary to stabilise material for the sub-base. The overall thickness of construction is usually determined by the application of a simple design method based on the early CBR method devised by Porter. (Porter 1938). Many of these roads have given excellent service, although there have been some spectacular failures.

However the dangers of laying stabilised soil bases too thin are real. A 10cm (4 in) thick base of stabilised soil on a sub-base of CBR 25 material can be badly damaged by the passage of a single heavy wheel load and the evidence is that stabilised soil bases need to be a minimum of 15cm (6 in) thick if they are to provide satisfactory service. The rapid growth of the magnitude of the axle loads of commercial vehicles in recent years has accelerated the deterioration of many roads in Africa and the maintenance effort available has not been capable of arresting the accelerated deterioration. As a consequence stabilised soil roads have acquired an undeservedly bead reputation in some countries; the road deterioration that gives rise to this would have occurred with any other comparable form of construction. The failures that have occurred are frequently a consequence of gross overloading in terms of the traffic loading envisaged in the design.

Even so some stabilised roads have given remarkable service in Africa over the last ten years to fifteen years. For example long lengths of the Nairobi to Mombasa road in Kenya are still giving good service with no more than normal maintenance inputs after having carried more than 10 million equivalent standard axles as compared with the 2.5 million envisaged when the road was designed. (Smith et al 1980).

Nevertheless the strength criteria used in Africa for the design of stabilised materials for road pavements are inadequate. They are usually based on the empirical criteria that have been developed in the temperate climates of North America and Europe. This prompts the suspicion that they may not be valid for African conditions: in particular the need to resist frost penetration is absent in most