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ROAD RESEARCH LABORATORY

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Roadmaking Materials in Northern Borneo

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FOREWORD

MANY RAPIDLY developing countries overseas are now engaged in the overall planning of their road systems, which must expand to meet future traffic needs. It is therefore necessary for each country to know, among other things, what roadmaking materials are available and where they occur, so that patterns of suitable types of construction may be evolved. This Technical Paper describes a survey of gravels, soils and other potential roadmaking materials in northern Borneo, made by the Road Research Laboratory with the co-operation of the Directors of Public Works in Sarawak and Sabah and the State Engineer in Brunei. The Paper is the second of a number of papers, the first of which was Technical Paper No. 57, "Soils and other roadmaking materials in Nigeria"; each paper deals with a different country or geographical region. In this instance it has been felt that it would be helpful to include a preliminary map of the roadmaking materials of northern Borneo, in the preparation of which the Laboratory has been fortunate in having the assistance of the Directorate of Overseas (Geodetic & Topographic) Surveys in the United Kingdom.

It is hoped that each survey in the series will provide a starting-point for more detailed work within the country or region concerned, and some indications are therefore given of the lines which are considered to be worth pursuing in the future. In centres of learning overseas these publications should also facilitate the teaching of civil engineering as applied to local circumstances.

Finally, it is intended that the series will assist those consulting engineers and contractors who, in steadily increasing numbers, are turning their energies to road construction in the developing countries of the world.

W. H. GLANVILLE,
Director of Road Research

ROAD RESEARCH LABORATORY,
November, 1964

CONTENTS

The investigation on which this Technical Paper is based was made between 1960 and 1962, before the establishment of the Federation of Malaysia in 1963. The new name of Sabah is used throughout this Paper for the former colony of North Borneo which, together with Sarawak, is a member of the Federation.

Roadmaking Materials in Northern Borneo

SUMMARY

THIS PAPER describes a survey, made by the Road Research Laboratory, with the co-operation of the Directors of Public Works in Sarawak and Sabah and the State Engineer in Brunei, of the location and engineering characteristics of roadmaking materials in northern Borneo. The purpose of the survey was to assist in the development of patterns of road construction in Borneo.

Brief descriptions of the geology and topography of northern Borneo are given, followed by an account of the resources of roadstone, including coral. The ways in which soils are formed, described and classified are then discussed, and the properties they exhibit both in the laboratory and the field are recorded. Methods of inferring soil type from the characteristics of the vegetation it supports are described, and the usefulness of soil stabilization for road construction is reviewed. Appendices describe studies made at the Road Research Laboratory with typical soils to discover their clay mineralogy and their suitability for stabilization with Portland cement. A preliminary map of the roadmaking materials of northern Borneo is appended.

INTRODUCTION

In planning the development of overseas territories, patterns of road construction are needed which will suit the materials available and the climate. Tropical roadmaking gravels and soils differ from those in temperate climates, and one of the aims of work at the Road Research Laboratory is to help engineers to identify and classify such materials, and to record their location, extent and engineering characteristics. The benefits which it is hoped will result are:

(i) The accumulation of road experience despite changes in staff.

(ii) The application of road experience from other territories in which conditions are similar.

(iii) The application of knowledge gained from local full-scale road experiments over a wider area.

(iv) The application with greater confidence of the results of laboratory tests on individual samples to the larger volumes of material encountered on the road.

(v) The opportunity for students educated overseas to be taught the principles of roadmaking with reference to the materials they will encounter in practice.

The stages in the work are:

(a) The development of simple methods (e.g. visual inspection) of identifying different types of soil, and of describing them.

(b) The grouping of materials by reference to the factors which influence their formation, e.g. geology, drainage and climate.

(c) The demarcation of the extent of each group using existing maps of agricultural soil, geology, climate, landform and vegetation.

(d) The recording of existing engineering information about each group of materials.

Studies of this type have already been made by the Road Research Laboratory in Central Africa[(1)] and in Nigeria.[(2)] The present Paper records the results of a preliminary investigation extending over Sarawak, Sabah and the State of Brunei, located in northern Borneo. Information was collected by the authors during a tour of the three territories made in the autumn of 1960 at the invitation of the Governments concerned; during the tour arrangements were made for the collection and dispatch to the Road Research Laboratory of 160 representative samples of soil and roadmaking materials.

GEOLOGY

Northern Borneo is composed mainly of geologically young sedimentary rocks of Tertiary and Upper Cretaceous age (Table 1 and Fig. 1).

Table 1

Percentage distribution of rock groups in northern Borneo

Rock group	Sarawak	Brunei	Sabah	Total
Quaternary	15	38	14	15
Tertiary and Upper Cretaceous	78	62	74	76
Pre-Cretaceous	3	—	—	2
Igneous	4	—	12	7

The sedimentary rocks have been folded to produce mountains with ridges parallel to the coast; these are bordered by an alluvial coastal plain of Quaternary sediments. The main area of igneous rocks is in eastern Sabah and pre-Cretaceous rocks are found only in Sarawak west of the Lupar river.

The Tertiary and Upper Cretaceous rocks are composed mainly of fine-grained sandstone alternating with clays or shales. The sandstone beds vary in thickness from a few inches to several feet, with occasional massive beds hundreds of feet thick. The relative importance of the two types in an area can vary considerably, but it is possible to delineate areas where sandstone is predominant, e.g. on the west coast of Sabah, or where it is subordinate, e.g. on the lower Rajang river. A typical sandstone contains angular quartz grains, 0.5 mm or less in size, together with feldspar grains (most of which have been converted to kaolin); small amounts of carbonate, chlorite and pyrite may also occur. The rock is blue when fresh and is a major source of roadstone in Sabah. Varieties with a very low clay content can occur, and there are also beds of coarser-textured material. The clays and shales vary in colour; the majority are

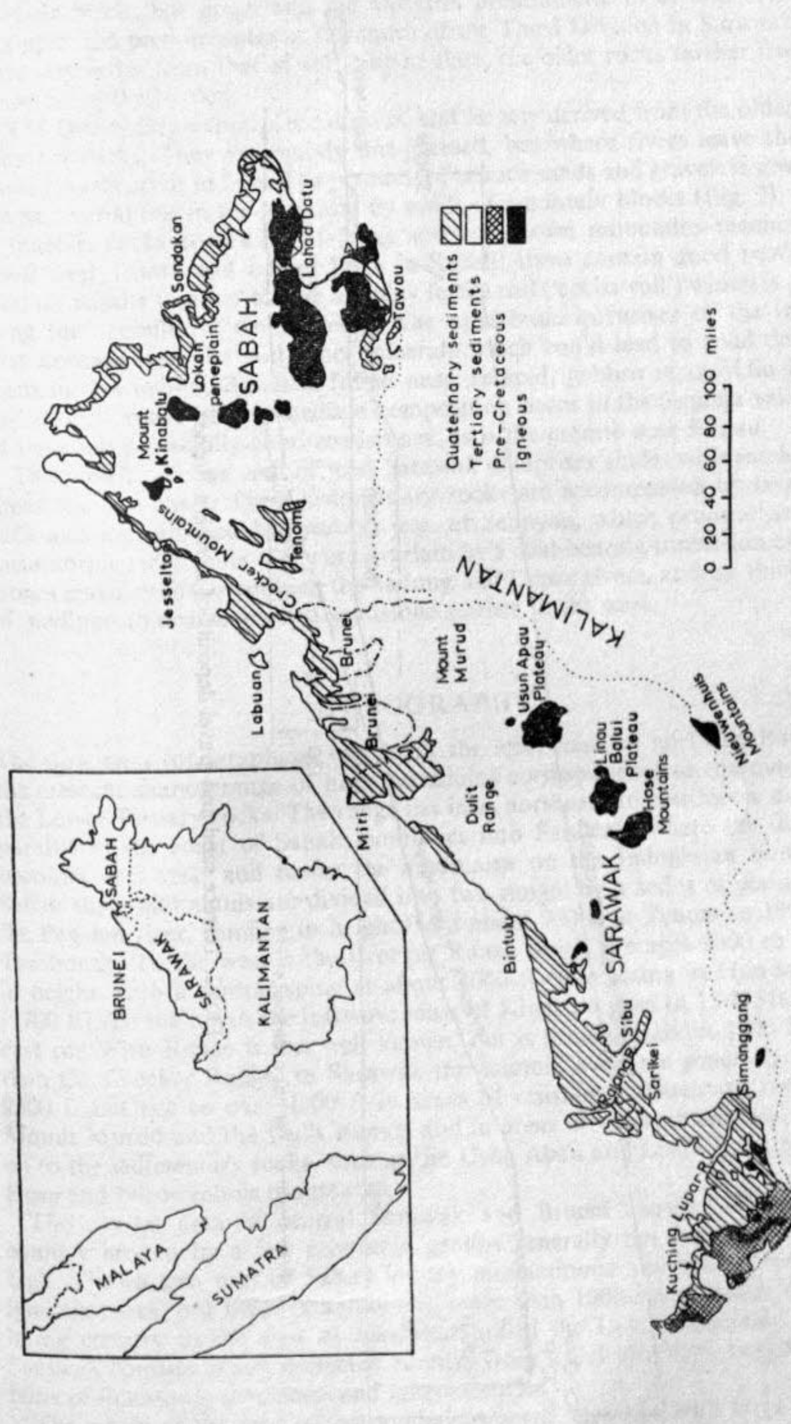

FIG. 1. Sketch map showing geology of northern Borneo (after Geological Survey Department) with inset location map

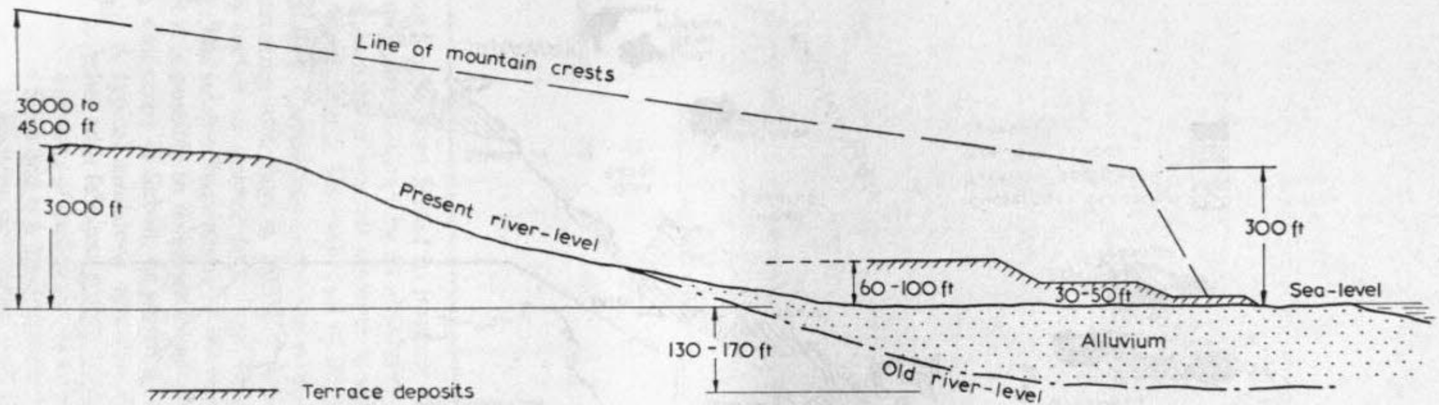

FIG. 2. Terrace sand and gravel deposits of northern Borneo

grey or black, but green and red varieties predominate in certain areas, for example, red predominates in the south of the Third Division in Sarawak. The hardness varies from that of soft clay to slate, the older rocks farther from the coast being the harder.

The Quaternary deposits are alluvial and largely derived from the older sedimentary rocks. They are mainly fine-grained, but where rivers leave the hills some gravels occur in fans. The position of terrace sands and gravels is governed by past variations in sea-level and by uplift of mountain blocks (Fig. 2).

Igneous rocks consisting of lavas and tuffs form mountains reaching the coast near Tawau and Lahad Datu in Sabah; these contain good roadstone. Certain basalts weather to give a highly fertile soil ('cocoa soil') which is promising for agricultural development. The ultra-basic intrusives of the interior may contain chromite and other minerals which could lead to road development in this region. Basalt is found near Telupid, gabbro in the Ulu Merali and dioritic rocks of intermediate composition occur in the Segama valley; all of these are potentially good roadstones, as is the granite near Ranau.

The pre-Cretaceous area of west Sarawak comprises shales with sandstones, limestone and chert. These sedimentary rocks are accompanied by lavas and tuffs and are intruded by granites, e.g. at Sebuyau, which produce areas of metamorphic sediments. They are overlain by a coal-bearing succession of sandstones and clay shales between the Sadong and Lupar rivers, and by thick beds of medium- to coarse-grained sandstone farther to the west.

TOPOGRAPHY

The dominant topographical feature of the west coast of northern Borneo is the crescent-shaped range of high mountains corresponding to the outcrop of the Lower Tertiary rocks. The range lies in a northeast to southwest direction parallel to the coast of Sabah, continues into Sarawak, where the direction becomes east-west, and forms the mountains on the Indonesian border. In Sabah these mountains are divided into two ranges by a series of plains along the Pegalan river, ranging in height from about 750 ft at Tenom to 1900 ft at Tambunan. To the west is the Crocker Range which averages 2000 to 3000 ft in height, with a central spine at about 4000 ft culminating in Gunong Alab (5700 ft). To the north the intrusive mass of Kinabalu rises to 13 455 ft. To the east the Witti Range is less well known, but is generally about 1500 ft lower than the Crocker Range. In Sarawak the summit levels are generally 1000 to 2500 ft but rise to over 4000 ft in areas of resistant sedimentary rocks, e.g. Mount Murud and the Dulit Range, and in areas of volcanic material erupted on to the sedimentary rocks, such as the Usun Apau and Linau Balui plateaux, Hose and Nieuwenhuis mountains.

The coastal area of central Sarawak and Brunei consists of undulating country broken by a few mountain groups generally not more than 2500 ft high. The eastern part of Sabah is very mountainous and mainly formed on igneous rocks, but there is an area of more than 1000 square miles of undulating country to the west of Sandakan called the Lokan peneplain.[3] West Sarawak consists of low dissected country from which rise high, rugged mountains of limestone, sandstone and igneous rocks.

The whole of the area is surrounded by a coastal plain with large areas of peat swamp which varies in width from over 100 miles to less than half a mile.

The predominance of young sedimentary material in northern Borneo means that suitable quarry sites are relatively scarce and in the past stone was imported from Singapore and Hong Kong. It is now known that adequate supplies of local stone for road surfacings are available in Sabah and Sarawak and in 1960 only Brunei was importing stone for use in bituminous surfacings. The inconvenient location of present quarries, however, means that water transport and/or long-distance road haulage have to be faced in several areas.

In Sarawak the main quarries are in the pre-Cretaceous area of the First and Second Divisions; details of rock type and quarry sites are contained in Memoirs 1 and 3 issued by the Geological Survey Department.(4)(5) In 1961 these sources accounted for more than 90 per cent of the total rock production (Table 2).(6)

Table 2

Production of stone in northern Borneo, 1961

Locality and producer	Production (yd^3)	Estimated value ($ Malay)	Estimated price at source ($ Malay/yd^3)
Sarawak			
First Division			
Stapok quarry	88060	509200	5·78
Stabar quarry	36500	162300	4·45
Stebun quarry	3693	16620	4·50
Ensebang quarry	31326	114000	3·64
Abok quarry	15054	67760	4·50
Second Division			
Sebuyau quarry	52005	574400	11·04
Lachau quarry	2838	12770	4·50
Klambi quarry	5095	36280	7·12
Third Division			
Takang quarry	5089	54790	10·77
Fourth Division			
Beraya quarry	1500	45000	30·00
Batu Gading quarry	4468	102705	22·99
Sg. Uban quarry	706	5648	8·00
Total	246334	1701473	6·91
Sabah			
Total stone	235434	1572970	6·68
Total coral	21240	89360	4·21

In Sarawak, production costs appear to be lowest in the First Division. Stone from Sebuyau, which is of very high quality, is dearer. Even allowing for the cheaper transport by water, the 100-mile journey by sea from Sebuyau to Sibu makes crushed-rock base construction more expensive in the Third than in the First and Second Divisions, since few alternative quarries exist, and potential sites are believed to be scarce. This suggests that for large-scale construction in this area, soil stabilization may be worth consideration.

In the Fourth Division limestone is quarried at Beraya, near Miri, and at Batu Gading above Marudi. Beraya quarry is worked by contractors for local building requirements; the outcrop is not very extensive and poor access and working conditions are believed by Wilford[7] to limit development. Batu Gading is a better site and has been exploited for development in the area, but because of difficulty of access the price of the stone is very high. Much of the existing road construction in this area uses bitumen- or cement-stabilized beach sand.

In parts of the First Division in Sarawak there are large heaps of mine tailings, some of which would be useful in road construction, and in the Bau district roads surfaced with this material are successfully carrying light traffic.[8] Quarry waste is available in the First Division, and is being used on the shoulders of the bitumen-surfaced pavement on the Serian-Simanggang road. Some of the material from which gold is extracted consists of a clay derived from limestone. When this material is treated with 1 per cent of hydrated lime it maintains a structure while being leached, and drains well at the end of the process.[9] Such clays might, after investigation, be found to be suitable for use in road base construction, as a form of pre-mixed stabilized soil.

In Sabah, the main road aggregates are a fine-textured blue-grey sandstone on the west coast and a variety of igneous rocks on the southeast coast. The sandstone is used as hand-laid pitching or as crushed rock in road bases, and as coated macadam in surfacings. In the experience of the Public Works Department three varieties can be recognized in the stone quarried in the Jesselton area:

(i) A very hard dark grey stone
(ii) A light grey stone, quite hard and durable
(iii) A brown stone with the same texture as (i), possibly a weathered variety of it, unsuitable for road use.

Some loads of sandstone may contain occasional pieces of iron pyrites which break up following expansion on weathering, giving a rusty stain to surfacings and leaving a small hole, usually after one or two months on the road. Oxidation of the pyrite to give soluble sulphate compounds may be involved, since it has been observed that the disruption of a surfacing spreads out in a circle centred on the defective stone. Fortunately, the occurrence of pyrite in roadstone does not so far appear to have been extensive and, provided it is adequately sealed, the sandstone should continue to be suitable for use as a base.[10]

Discoloration of surface-dressing stone has been observed on the runway at Labuan airfield; in Jesselton it was found that ten months after the construction of a retaining wall consisting of sandstone blocks laid in mortar, dressed to show flat faces, the faces of a number of blocks were stained dark brown or black to a depth of 1 - 2 mm and many of the stained layers were flaking off. A similar, lower, wall near the main Administrative Offices was not so badly discoloured. If future experience shows pyrite-bearing stone to be of general occurrence, an investigation will be needed to discover the maximum permissible quantity of pyrite and to develop visual methods for distinguishing good stones from poor ones of similar appearance. Sedimentary rocks would weather by flaking if the bedding plane in the individual blocks was parallel to the exposed face of walls, but with sound rock this would be a long-term effect which could be avoided by laying blocks with the bedding planes horizontal, although in some varieties of the sandstone bedding planes may be difficult to recognize because of its homogeneous appearance.

Stone is not plentiful in the Sandakan area; the local sandstones are soft and the main source of supply of aggregate is a basalt island in Sandakan harbour. The Tawau district is well supplied with good roadstone: two quarries work dolerite and other sites are available on similar rock This stone has weathered to produce boulders about 5 ft in size, which is a disadvantage in large-scale working since each boulder must be reduced independently.

CORAL

Coral is the calcareous skeleton produced by colonies of small organisms growing on the sea floor. It occurs in a massive form in reefs along the shores of Sabah and on islands in Brunei Bay, where coral sand is also found on the beaches. It does not occur along the Sarawak coast, however, where rivers bringing large quantities of sediment and fresh water into the sea create unfavourable conditions for coral growth. On the Semporna peninsula in Sabah old coral reefs are found on the land, as a result of a relative fall in the sea-level since their formation.

Massive coral is the main type used in road work and is won from the reefs with axes and crowbars in the form of bulbous pieces 2 to 6 ft across. In Sabah the Public Works Department specification states that it should be obtained from below water-level, a requirement presumably based on the fact that coral can vary in quality, possibly as a result of biological differences. It is usually delivered to a site in 18-in blocks which are cut while still fresh to the 6- to 8-in size used for hand-pitching. After drying out the coral becomes more brittle and tends to shatter rather than to cleave. Other types of coral also occur on reefs but are generally not sufficiently solid for road construction, although they have been used successfully to produce lime.

Coral has been used on the west coast of Sabah for constructing hand-pitched roads covered with a layer of crushed stone, surface-grouted and sealed by surface-dressing. In Lahad Datu coral is used to construct non-bituminized roads which have a good surface; in reconstruction works in 1962 at Lahad Datu airfield, a 19-in coral base was laid on a sand blanket over clay. Before reconstruction, Labuan airfield consisted of a surface-dressed coral base, and when Jesselton airfield was reconstructed a crushed coral sub-base was used.

At Labuan coral is passed through a small crusher to provide graded aggregate, in which the pieces are well-shaped but much softer than crushed-rock chippings. An experiment has been carried out in the island, on MacArthur Road, using coral aggregate in a concrete road. Four mixtures were used with cement and fine and coarse aggregate in the proportions $1:1\frac{1}{2}:3$, $1:2:4$, $1:3:6$ and $1:6:12$. The first series was laid in 1955 and is unsurfaced. Six years later the two richer mixtures were in good condition, but the other two had been abraded by traffic. In later work with the leanest of the mixtures, a surface-dressing of bitumen emulsion and granite chippings was applied and results have been satisfactory. In 1961, a few small cracks had appeared, and the surface-dressing had become slightly corrugated, but the road was otherwise in good condition. Normally, crushed coral provides an adequate base for lightly-trafficked roads without an admixture of cement, but these trials show that where for any reason a concrete pavement is required, it can be successfully made with coral.

Coral aggregates have been used in bituminous pre-mixes[11] and in surface-dressing outside Borneo, but in general they have proved satisfactory under conditions of light traffic only, because of the softness of the stone. Adhesion of bitumen to coral is excellent, but mixes may need more than the usual proportion of binder because of the high porosity of the material.

SOIL FORMATION

Soils are formed over long periods of time by natural forces acting on rocks, which weather to beds composed of individual mineral crystals or crystal aggregations. In such residual soils the original texture and some structural patterns of stratification of the rock may be evident in the soil. The geological and petrological characteristics of the parent rock are significant in determining the nature of the soil or gravel formed. In wet areas, such as northern Borneo, rainwater percolates through fissures and contributes to the breaking-up of the rock by leaching out the more soluble constituents, which may act as cementing agents when redeposited elsewhere. Soils composed mainly of the material left after leaching are often white and rich in the least soluble of the rock constituents—silica. The term podzolic, derived from a Russian folk-name for an ash-coloured soil, is often used to describe such soils, e.g. 'yellow/red podzolic', 'humus podzol', etc.

The majority of the rocks of northern Borneo are sedimentary sandstones and shales which contain relatively small proportions of soluble material. However, igneous rocks containing rather more soluble constituents occur in some parts of Sarawak and Sabah. Water percolating through these drains down to lower-lying parts of the ground, where dissolved materials such as iron or aluminium could be deposited as oxides, e.g. following evaporation of the water during dry periods, or as a result of change in the chemical environment. The absence of a very marked dry season in northern Borneo, as well as a topography producing limited differences in environment, reduces these effects and may account for the limited occurrence of the iron-rich soils and laterites so characteristic of tropical Africa. (These are restricted to occasional deposits in the First Division of Sarawak, and in the Labuk valley in Sabah.) Water also erodes material from the surface of the ground and deposits it in lower-lying areas, giving rise to transported soils such as alluvial silts and sands; most of northern Borneo has a high rainfall and a significant proportion of these transported materials occurs. The texture of the deposits varies with the distance from the source of supply of the material, the rate of water flow, and lateral deposition from the transporting water-channel; thus topography has an important influence on this type of soil formation.

Calcium in calcareous parent rock is fairly readily leached out by rainwater; when solutions containing it find their way through the rivers to the sea, the calcium is absorbed by marine organisms, the skeletons of which later form coral. Reefs occur off the coasts of Sabah and coralline limestone is also found in one or two places on the coast of Sarawak following a relative change in sea-level.

METHODS OF DESCRIBING SOILS

Soils, and to a lesser extent gravels, are the most important group of road-making materials which concern the engineer in Borneo. As a first step towards rationalizing knowledge about these soils an attempt has been made to evolve an engineering soil classification, but before discussing this it is useful to indicate the different ways in which it is possible to describe soils. Information about roadmaking gravels and soils can be conveyed by descriptions of any or all of the following units:

A hand sample

From a hand sample the texture and colour of the material, and with gravels the appearance of the larger stones, is obtained. The results of chemical and particle-size analysis and plasticity tests are also helpful.

A soil profile

A soil profile describes the variation in appearance in the vertical direction of material exposed in a trial pit, cutting or quarry, usually to a depth of 5 to 10 feet. Reference is made to texture, colour, horizons, structure (i.e. blocky, crumbly, etc.), and modern practice is to record these on colour photographs. A number of profiles were taken during the work, and these are available for inspection at the Road Research Laboratory.

A soil association

A sequence of adjacent soil profiles which is repeated at intervals across a region is referred to as a soil association. A simple example of this in the tropics is the catenary type of association which consists of a series of profiles at points running down the side of a hill.

Records of soil profiles or geological conditions along the lines of roads or traverses yield information of value in building up landscape units. Such studies may embrace a number of soil associations and are valuable in indicating the influence of regional geology and topography on road materials and on the environment of the roads (Fig. 2, p. 4).

The form of the present surface of the ground is a product of its basic geology and subsequent weathering. Each form is known to be associated with its own soil associations and terrain. If, therefore, the ground surface of a region can be divided into areas containing landforms of recognizable type, it should be possible to predict the soil type and drainage condition at any given site, e.g. by the use of aerial photographs. Diagrams are included in this Paper (Figs. 3, 4 and 5) which indicate in general terms the forms the land takes in northern Borneo, to aid the road engineer in his appreciation of the country. It is hoped that this will also facilitate the utilization at a later stage of the 'recurrent landscape pattern' concept of classification suggested by Beckett.[12] For example, in Fig. 5 a volcanic lava pattern can be seen superimposed on a volcanic ash pattern, both similar to patterns already recognized in the Kenya highlands.

The soil classification given below is based on soil profiles, although in many cases it is not yet possible to give detailed descriptions of these, and most information was drawn from hand samples. As the soil survey work of the territorial Departments of Agriculture extends, more detailed descriptions of the different soil profiles will become available.

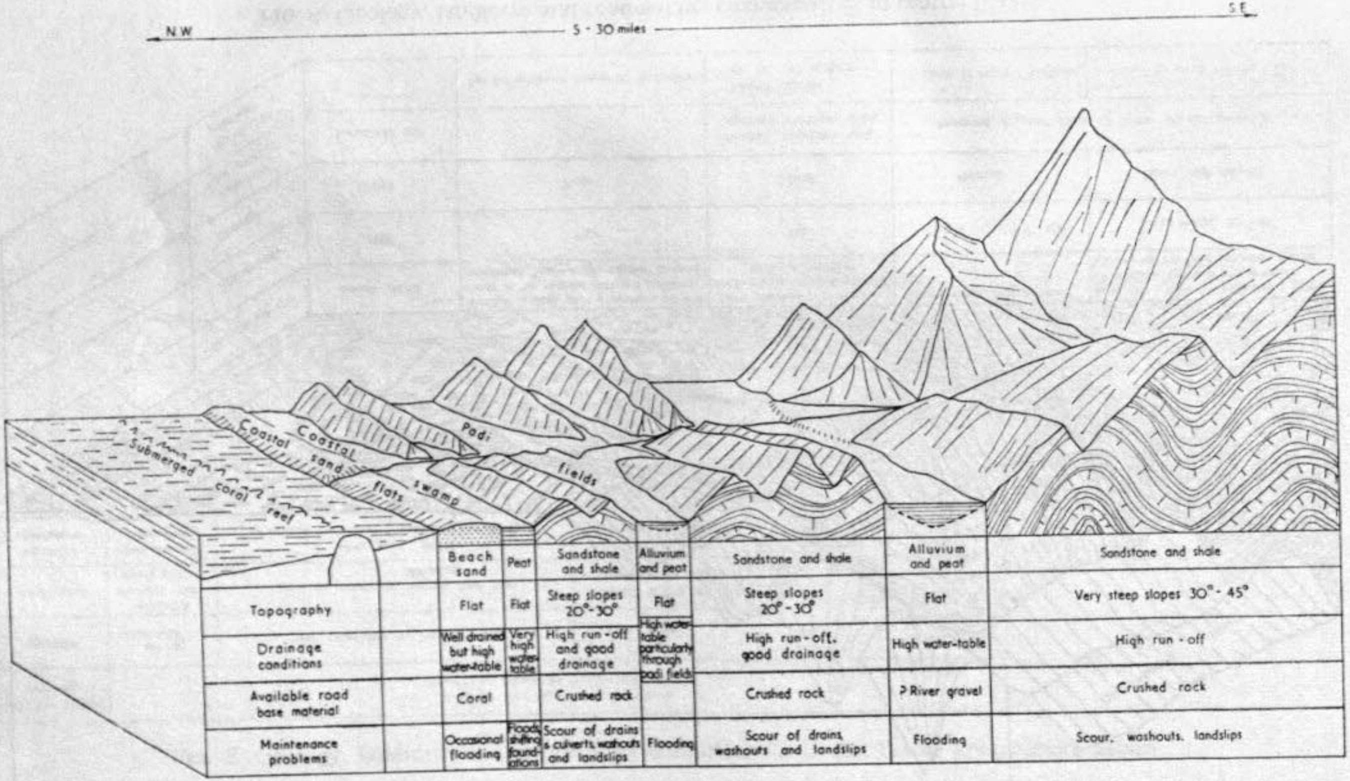

FIG. 3. Geology, landform and roadmaking characteristics on the western coast of Sabah

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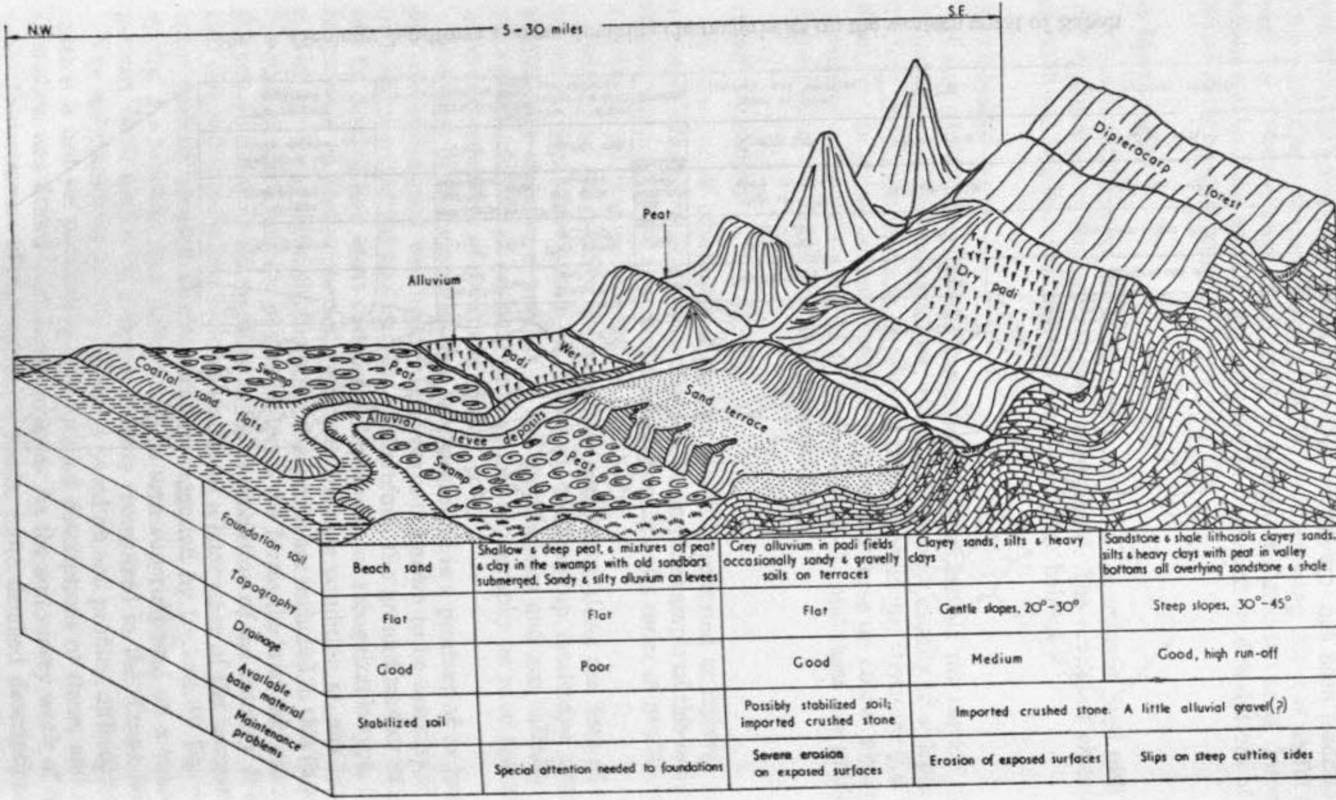
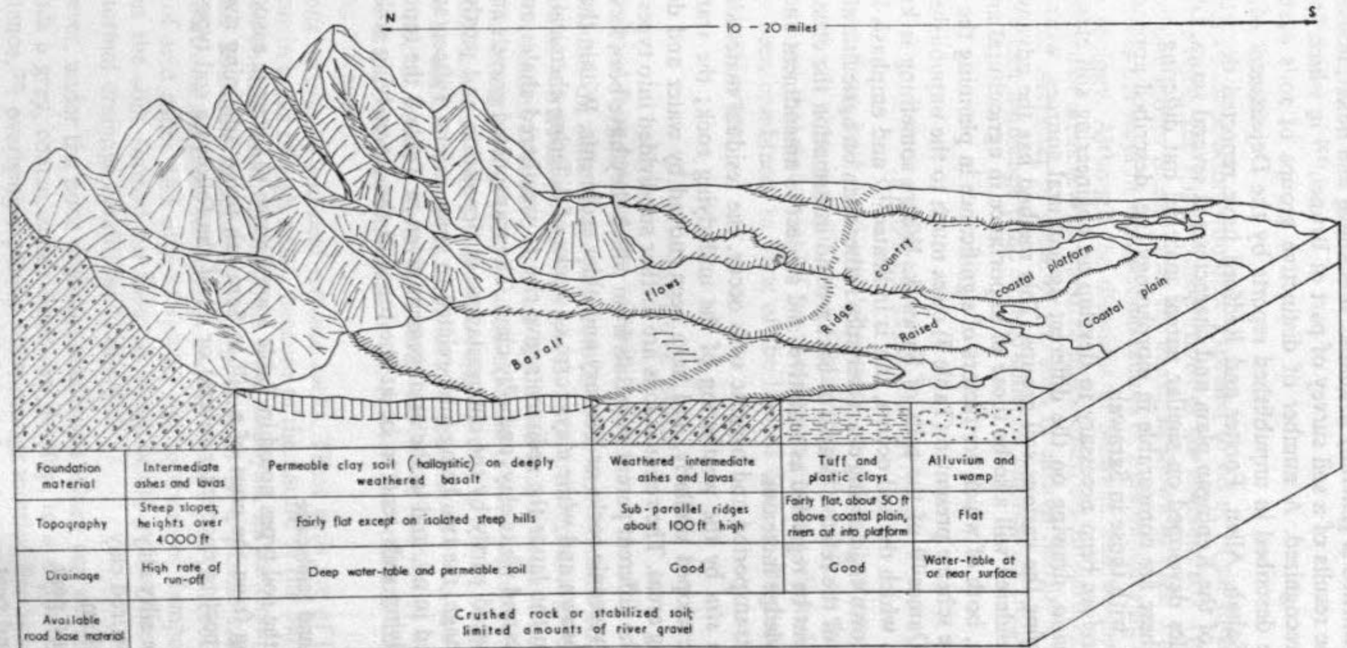


Foundation soil	Beach sand	Shallow & deep peat, & mixtures of peat & clay in the swamps with old sandbars submerged. Sandy & silty alluvium on levees	Grey alluvium in padi fields occasionally sandy & gravelly soils on terraces	Clayey sands, silts & heavy clays	Sandstone & shale lithosols clayey sands, silts & heavy clays with peat in valley bottoms all overlying sandstone & shale
Topography	Flat	Flat	Flat	Gentle slopes, 20°–30°	Steep slopes, 30°–45°
Drainage	Good	Poor	Good	Medium	Good, high run-off
Available base material	Stabilized soil		Possibly stabilized soil; imported crushed stone	Imported crushed stone. A little alluvial gravel(?)	
Maintenance problems		Special attention needed to foundations	Severe erosion on exposed surfaces	Erosion of exposed surfaces	Slips on steep cutting sides

FIG. 4. Geology, landform and roadmaking characteristics in central Sarawak



Foundation material	Intermediate ashes and lavas	Permeable clay soil (halloysitic) on deeply weathered basalt	Weathered intermediate ashes and lavas	Tuff and plastic clays	Alluvium and swamp
Topography	Steep slopes, heights over 4000 ft	Fairly flat except on isolated steep hills	Sub-parallel ridges about 100 ft high	Fairly flat, about 50 ft above coastal plain, rivers cut into platform	Flat
Drainage	High rate of run-off	Deep water-table and permeable soil	Good	Good	Water-table at or near surface
Available road base material	Crushed rock or stabilized soil; limited amounts of river gravel				

FIG. 5. Geology, landform and roadmaking characteristics in the Tawau area, eastern Sabah

As yet no agricultural or pedological classification of soils covering the whole of northern Borneo is generally available. Blackburn and Baker, however, have published the results of a soil survey of part of Brunei,[13] in which five classes of soil are recognized. A number of distinctive groups of soils occurring in Sarawak are described in unpublished reports by the Department of Agriculture.[14] In Sabah, Allen, Forster and Redford have reported departmentally on the soils of the Keningau plain and characterized several series, i.e. groups of soil profiles developed on similar parent material but differing in physical texture;[15] these are comparable in morphology (i.e. described appearance), if not in name, with those in Sarawak.

It has therefore been necessary to develop an engineering soil classification almost *ab initio*, drawing on the different agricultural sources, where appropriate, to define the various soil groups. This method has the advantage that the soils considered will also be those of importance in agricultural and forest development, both of which are factors of significance in planning the location of roads. The scheme presented (Table 3) owes much to the unpublished classification by Dames[16] of the soils of Sarawak. Where something is known of the extent to which the soil occurs, this is indicated[17] and emphasis has been placed on known engineering characteristics rather than on agricultural properties. In view of the relative dearth of background information the classification must at present be regarded as tentative, and subject to amendment and expansion as knowledge increases.

Residual, transported and organic soils occur, the residual materials having developed *in situ* by the weathering of the underlying rock; the transported soils have developed similarly, and have been moved by water and deposited in lower-lying areas. The residual soils are further subdivided into types, corresponding to the different parent materials from which they have been formed, i.e. igneous and volcanic rocks or Tertiary and older sediments. Within the former group, red, brown and white clays form on rocks of differing chemical composition, and in the latter the sediments give rise to weathered shales and sandstones, yellow and white clays and silty clays. The transported gravels and sands are differentiated partly by the circumstances of deposition and partly by the state of drainage, the two being inter-related to some extent. Fifteen soil types are recognized in all, and in the arrangement given in Table 3 the topographically higher-lying soils tend to be at the top and the lower-lying soils at the bottom.

Associations and landscape

Several of the soil types noted in Table 3 are known to occur in associations. Thus, walking from the crest of a hill in Sarawak to an adjoining river bank one might expect to encounter several or all of the following soil types, in the order given:

(i) White silty clay
(ii) Yellow/red clay
(iii) Alluvium
(iv) Silt and peat
(v) Peat
(vi) Silt and peat
(vii) Alluvial sand and silt (levee soil).

In Sabah and Brunei a similar sequence might be:

(i) Weathered sandstone
(ii) Yellow/red sandy clay
(iii) Terrace sand and gravel
(iv) Alluvium
(v) Peat
(vi) Beach sand

Both types of association would be expected to occur in all three territories. On a larger scale, the relative proportions of the different soil types seem to change as one moves inland from the coast, as shown in Figs. 3 and 4, which also illustrate the ways in which some factors of road engineering interest alter with the geology. Although the diagrams of Sarawak and western Sabah are representative of areas several hundred miles apart, the similarities are striking. The volcanic character of some of the soils in eastern Sabah[18] is associated with a different landscape (Fig. 5), and different engineering properties.

PROPERTIES OF SOILS

Information from both field and laboratory on the engineering properties of the different soil types is given below. This information follows the grouping in Table 3, except that discussion of the two humus podzol soils and the two peat soils has been combined, in view of the limited data so far available for the individual soil types.

RESIDUAL SOILS

Soils developed from igneous and volcanic rocks

Information on soils developed from igneous and volcanic rocks is largely contained in individual papers or reports, and further pedological and engineering investigation is needed before a connected and systematic account can be given. The extent of the soils is small and the present inaccessibility of those on the highlands of central Sarawak suggests that it will be some time before they can be utilized. However, soils formed on igneous rocks are often rich in plant nutrients making them potentially useful agriculturally, and they may therefore attract road construction in the future. The soils are divided into the following categories:

(*a*) *Soils on granite and acid volcanic rocks.* These soils are of limited extent and occur in areas of high relief. Because of the nature of the parent rock they will often contain sand; an example from Sebuyau, in Sarawak, examined at the Road Research Laboratory, has proved to be a plastic clayey sand. In central Sarawak the Hose Mountains and the Usun Apau plateau[19] are formed largely of acid ashes and tuffs of similar age to those of Semporna. Kirk[20] describes the soils formed on them as being acidic yellow fine clayey sands under normal drainage conditions (Table 4).

However, under the poor drainage conditions which can occur on these flat tablelands a grey, coarse, sandy loam can develop, to a depth of 30 inches in one instance,[20] overlying a plastic white-orange mottled fine sandy clay loam. The water-table occurs at a depth of 2 ft and the pH is very low (4.0 to 4.2).

Table 3

Classification and characteristics of some of the soils of northern Borneo

Sk, Sh, B — occurrence in Sarawak, Sabah and Brunei, respectively

Soil group	Parent rock group	Parent rock type	Soil type and colour	Soil texture	Slope	Depth	Drainage	Occurrence	Vegetation or crop	General information
Residual soils	Igneous and volcanic	Granite and acid volcanic rocks	Red and yellow clays	Plastic clayey sand	Steep	Variable	Variable to well-drained	Sk Sh	——	——
		Andesitic and dacitic volcanic ash	Red, brown and yellow clay	Fine clayey sands to heavy clays	Undulating	Variable to deep	Good to poor	Sk Sh	——	——
		Basaltic tuffs and lavas	Brown and red clays	Friable	Undulating	Deep	Well-drained	Sh (11%)	Cocoa	Probably halloysitic clay; low *in situ* density
			White clays	Plastic	Level	——	Poor	Sk	'Kerapak' forest	——
			Detrital gravels	Harsh, granular	Steep	——	——	Sk	Wild banana	——
	Tertiary and older sediments	Sandstones and shales	Lithosols (Sk) Skeletal soils (Sh)	Sandy and clayey gravels	30°-45°	Shallow	Well-drained	Sk Sh B	Dipterocarp forest Dry padi	Mountain and hill slopes subject to erosion
		Shales and sandstones	Yellow/red podzolic soils (Sk) Tropical yellow/red earths (Sh)	Clayey silts and clays	3°-30°	Variable to deep	Fairly well-drained	Sk (60%) Sh (75%) B	Dipterocarp forest Dry padi	Hill soils on shale slopes not highly erodible. Yellow/red podzolic soils formerly known as 'yellow/red latosols'
		Sandstones and shales	White silts and clays	Silts and clays	——	Variable to deep	Poorly-drained	Sk	——	Unstable when wet

Table 3—continued

Sk, Sh, B — occurrence in Sarawak, Sabah and Brunei, respectively

Soil group	Parent rock group	Parent rock type	Soil type and colour	Soil texture	Slope	Depth	Drainage	Occurrence	Vegetation or crop	General information
Transported gravels and sands	Quaternary sediments	Coastal sand	White or yellow beach sand	Uniformly-graded sand	Level or slightly sloping	Deep	Well-drained	Sk Sh B	*Casuarinaceae* spp.	Good road foundations and airfield sites
		Raised sand terraces	Humus podzol ('giant') White sand	Sands with a little silt and clay	Level or slightly sloping	Deep	Well-drained	Sk (3%) Sh B	Bindang forest (*Agathis alba*)	Good road foundations
		Colluvial sand deposits	Humus podzol ('shallow') White sand	Sands, occasionally gravels	Level or slightly sloping	Shallow	Fairly well-drained, but with 'perched' water-tables	Sk (3%)	'Kerangas' forest	Good road foundations
		Alluvial deposits	White or grey alluvial soils	Gravels, sands and silts	Level	——	Well-drained, ridges seldom flooded	Sk (4%) Sh B	Empran forest, *Eusideroxylon*, *Shorea*, *Nipa*, wet padi, coconut	Deposits of river gravel, levee soils in narrow strips along river edges
		Alluvium	Grey hydromorphic soils	Sands, silts and clays	Level, sometimes sloping	——	Poorly-drained, fluctuating water-table	Sk Sh B	Wet padi	Often clayey subsoil
Organic soils	Quaternary sediments	Silt and peat	Grey and black half bog soils	Fibrous peat and woody remains	Level	Basins < 10 ft	Poorly-drained, often flooded	Sk (4%) Sh B	Mangrove, rubber, sometimes wet padi	Beyond river levees; clayey or sand subsoils, sometimes sulphate-bearing
		Peat	Black bog soils	Fibrous or amorphous	Level	Basins > 10 ft	Mostly under water	Sk (4%) Sh B	Alan forest (*Shorea albida*)	——

Table 4

Characteristics of soils from high-level volcanic rocks

Locality and parent rock type	Depth of sample (in)	Coarse sand (%)	Fine sand (%)	Silt (%)	Clay (%)	pH value
Usun Apau plateau (dacite tuff)	6–12	10	36	17	37	4·7
Hose Mountains – 4400 ft O.D. (dacite tuff)	3–12	5	62	18	15	4·8

(*b*) *Soils on intermediate rocks*. A soil survey of the Semporna peninsula in Sabah by Paton[18] has shown that large areas are covered by Pliocene/Recent ashes of intermediate (dacitic and andesitic) composition, and that the soil type depends on the nature of the parent material and on the topography. The area of high-level plateau is distinct in that it is formed by basaltic lavas, and it is described separately below. Samples of weathered ash collected from the coastal platform by the authors were found to be heavy clays, generally with liquid limits exceeding 90 per cent (Fig. 6(a)).

(*c*) *Soils on basaltic rocks*. Recent basaltic lavas also occur on the Semporna peninsula, and these weather to give deep, well-drained, brown or red friable clayey soils, potentially the most fertile in Borneo. Trials have already been made on them with cocoa by the Department of Agriculture, and development is now proceeding on a commercial scale. Similar soils occur in the Labuk valley.

A sample from Quoin Hill, near Tawau, tested by Dumbleton and Newill,[21] was found to contain 78 per cent of clay, in which the predominant minerals were hydrated halloysite, disordered kaolinite and goethite (see Appendix 1, p. 65). The soil had maximum dry densities of 63 and 82 lb/ft^3 and optimum moisture contents of 62 and 37 per cent in the British Standard normal and heavy compaction tests respectively.[22] The liquid limits and plasticity indices of these soils tend to plot below the line $PI=0.73$ (LL-20) (the 'A' line of Casagrande) whereas the results for most of the other soils in Borneo plot above it (Fig. 6(a)). The results strongly suggest that these red clays are closely related to the red 'coffee' soils of the East African Highlands,[23] which are also halloysitic clays developed on basalts. The African soils are considerably stronger and easier to handle than their classification as clays suggests. In the field they occur at low densities, and some types can hold unusually large quantities of water while retaining strength and ease of manipulation. *In situ* values of California bearing ratio in road foundations are usually 10 per cent or above, and the soils are also amenable to stabilization with both hydrated lime and Portland cement, the crumbly structure making handling and mixing considerably easier than with many clays.

In west Sarawak the basaltic lavas and tuffs weather to produce well-drained, stable reddish clay soils which are some of the most fertile and extensively cultivated on the Kuching to Simanggang road, supporting pepper, cocoa, coffee and dry padi. They are deep, have a crumb structure, and in places contain boulders of unweathered rock. Samples from the Semuja Pass and from near Bukit Antayan have characteristics similar to those of the sample from Quoin Hill, in that the liquid limits and plasticity indices also plot below Casagrande's 'A' lines (Fig. 6(a)), but they differ in that they contain sand and small amounts of gravel, which would be expected to affect their structure and ease of working. Tests by the Public Works Department have also shown that the maximum dry soil densities obtained in the British Standard normal compaction test are low (78 to 85 lb/ft^3), one sample with about 70 per cent of sand and gravel having a maximum of 85 lb/ft^3 at an optimum moisture content of 32 per cent.

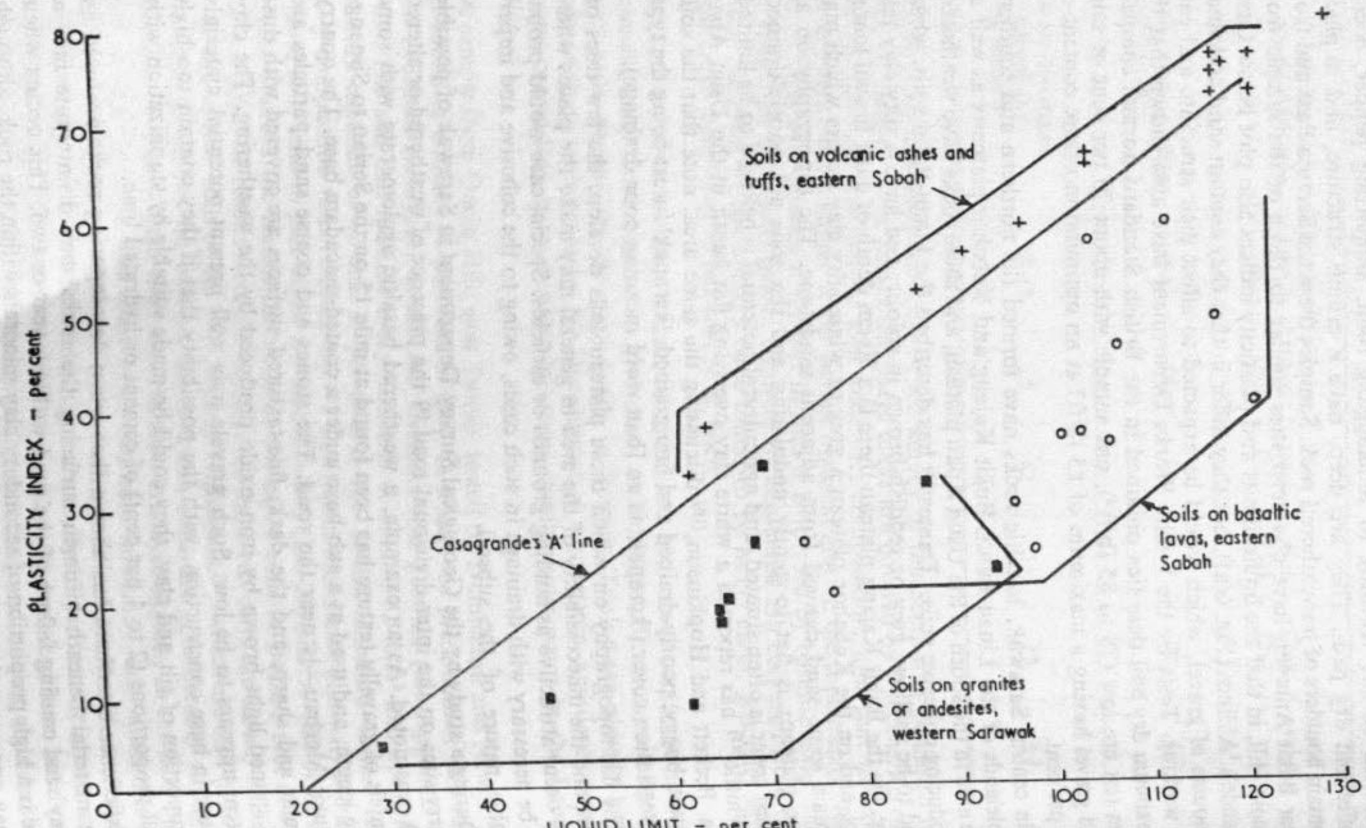
In central Sarawak, basaltic rocks have formed the northern and southern tablelands of the Linau Balui, Bukit Kajang and Kebahor plateaux as well as the area to the south of the Usun Apau plateau, and these rocks have weathered, producing cohesive soils. Dames[24] has described the Linau-Balui soils, which tend to be shallow, grey or reddish-brown in colour, and have a silty clay texture. On the Bukit Kajang plateau there is a 70-cm depth of dark brown loamy clay, and on the Kebahor plateau a grey or white silty clay occurs which may contain some sand derived from adjacent sandstone. The topography on all three plateaux is flat to gently undulating and the soils are poorly-drained. Forest cover is often stunted, and agricultural potential is believed to be limited.

Whittle[25] has reported a white clay overlying flat basalt in the Usun Apau area. Beckett and Hopkinson,[19] discussing the same area, note that the soils are wet, boggy, poorly-drained and fine-grained, 'kerapak' forest being the typical vegetation cover ('kerapak' is an Iban word meaning poor drainage).

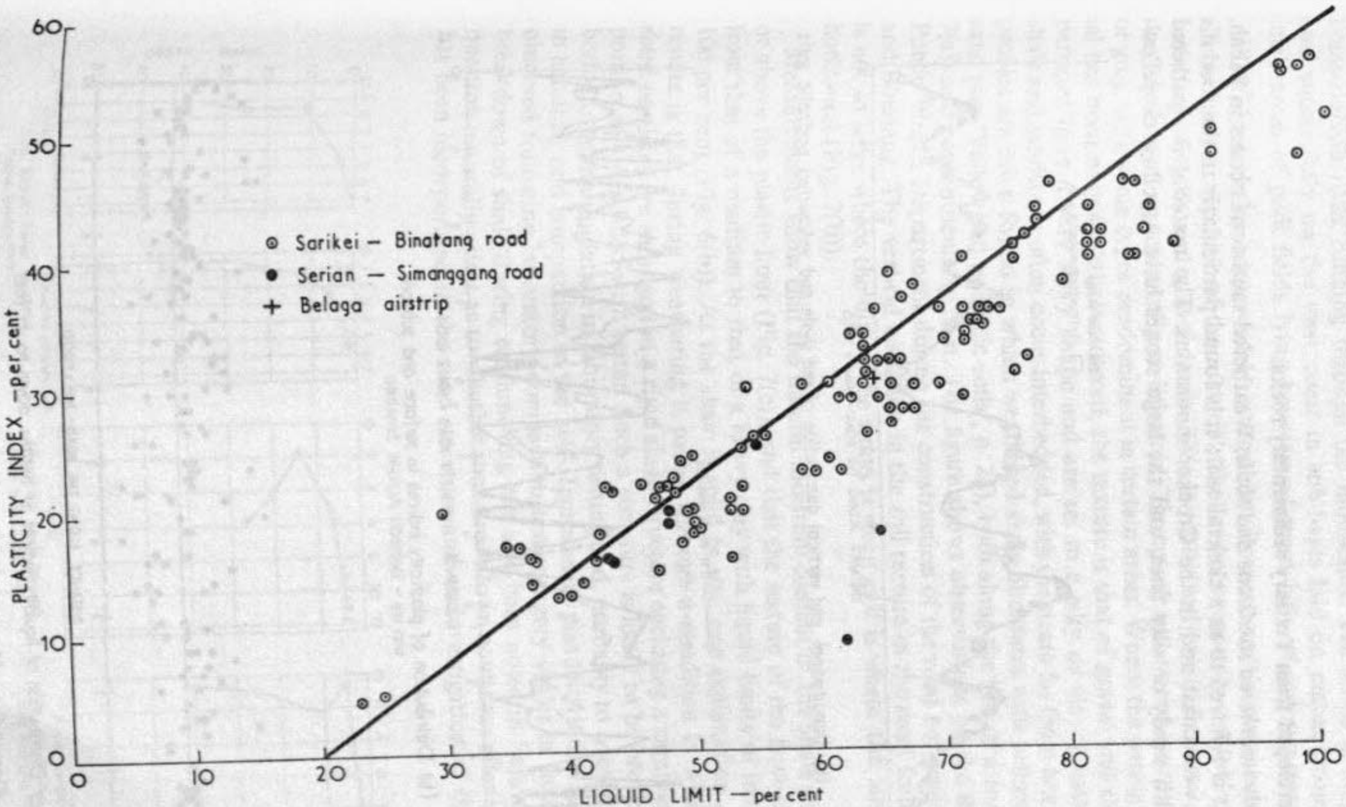
The flat topography on which these plateau soils develop, the few trees on them, and the inaccessibility of the area in general may make the places where they occur attractive as landing grounds or airfields. Special care would probably be necessary with drainage in such cases, owing to the cohesive and impermeable nature of the subsoil.

During a study by the Geological Survey Department in Sarawak of possible quarry sites on the inter-divisional road,[4] the presence of weathered or altered rock was noted. As an example, a weathered basaltic agglomerate with some hornfels of gravelly texture has been found at mile 15 on the Serian to Simanggang length, and used as a sub-base under a coated-macadam base. The quarry —Bukit Merbau—is near the road. The stones and coarse sand particles are angular and sharp, and the dark, fine-textured surfaces are covered with dust and stained light brown by iron oxide produced by the weathering. The clay content appears to be low. Such gravels may well present potential materials for use in base construction, with the possibility that if they contain too high a proportion of silt and clay, they could be made suitable by stabilization with small proportions (2 to 4 per cent) of cement or hydrated lime.

Experience elsewhere has shown that when decomposing rocks are used as base material beneath bitumen surfacing the rocks may disintegrate into a clayey sand causing failure of the road within a year or two. This occurs when there is a high proportion of secondary clay minerals within the rock, although it may appear to be sound. Such material can be identified by petrographic



(a) Residual soils developed on igneous rocks



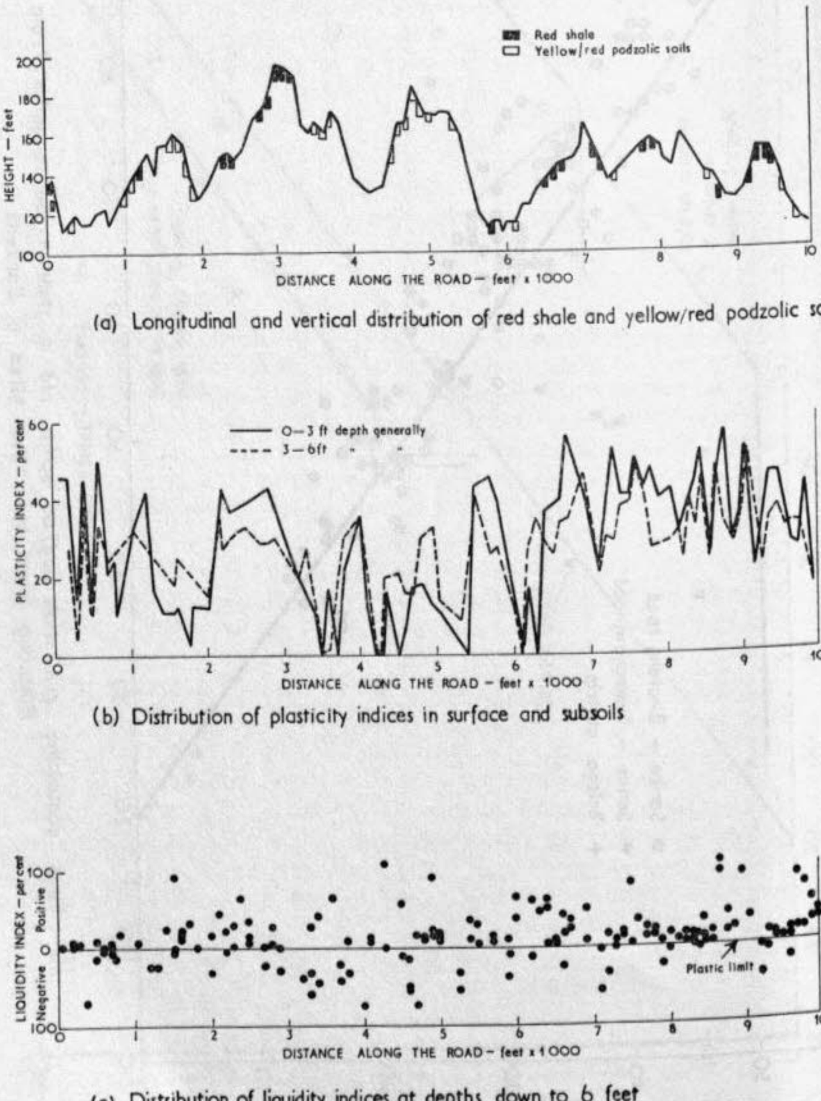
(b) Soils containing red shale and/or some red in their colour: samples from the Sarikei to Binatang road, and other sites in Sarawak

FIG. 6. Plasticity characteristics of soils from northern Borneo

examination, and it is certainly desirable that those decomposing rocks likely to be used in road bases in northern Borneo should be examined, to determine the extent to which they are likely to break down further in the road.

Soils developed from Tertiary sedimentary rocks

Lightly weathered sandstone and shale. Weathered sandstone occurs in Sabah, where it is referred to as a skeletal soil; it is found particularly in the foothills on the west coast and in the Crocker mountains. The material is weathered rock with sandy or silty fines, and the large stones have a yellow or yellow-



(a) Longitudinal and vertical distribution of red shale and yellow/red podzolic soils

(b) Distribution of plasticity indices in surface and subsoils

(c) Distribution of liquidity indices at depths down to 6 feet

FIG. 7. Ground profile and distribution of soil types, plasticity and liquidity indices for a length of the road between Sarikei and Binatang, Sarawak

brown colour. Experience has shown that selected material behaves satisfactorily in road bases, and it is hoped to make use of it on the sections of the Trans-Borneo road running through the mountains. The stone is at present used successfully on the west coast in sub-bases laid on embankments over small areas of padi fields lying between adjacent hills of sedimentary rocks.

Weathered shales occur widely in northern Borneo, and in some areas they are the most acceptable of the materials that are conveniently available for the surfacing of earth and gravel roads. This is particularly so in Sarawak, where they are known agriculturally as lithosols. The colour can be red, purple, black or grey, with some types predominant in certain areas. Where the parent material has been only slightly weathered, the texture is that of gravel and the large particles have a very flaky shape and are set in a silty or clayey matrix. As shale and sandstone often occur interbedded, with the strata far from horizontal, profiles are often found in which weathered shale alternates with yellow clayey sand (see 'Yellow/red podzolic soils', p. 25), both along the line of a road (Fig. 7(a)) and perpendicularly to it. The figure shows observations by the Sarawak Public Works Department during the construction of the road between Sarikei and Binatang. The vertical variation in the soil texture in the road foundation is not so large where the dip of the strata is steep as it is where the strata are horizontal (Fig. 7(b)).

Measurements show that the natural moisture content of the shale can be at or above the plastic limit (Fig. 7(c)), and that the texture of the fines can vary from that of a medium to that of a heavy clay with liquid limits of from 35 to 100 per cent (Fig. 6(b)). As the shale is solid *in situ*, one explanation of these results is that during weathering it passes through a condition in which clay-sized particles are arranged in a rigid shale structure enclosing a significant proportion of voids filled with water. Such a structure is likely to be broken down both during manipulation in laboratory testing and, probably to a lesser degree, in handling and compaction in the field. Increases in plasticity index have been observed following laboratory compaction tests on grey shales in Brunei, and breakdown of shale during earthmoving has also been noted in Sarawak. The question naturally arises as to whether such breakdown continues after the shale has been incorporated in the road structure and an investigation of this point

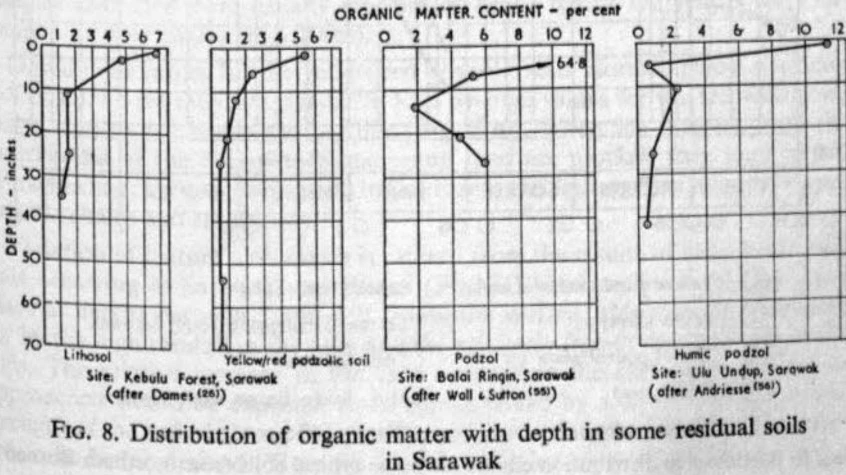


FIG. 8. Distribution of organic matter with depth in some residual soils in Sarawak

is being made. As laboratory tests on disturbed samples may give results at variance with experience in the field, further research is needed.

Dames[26] has found, in at least one instance, that the organic matter of weathered sandstone and shale may be 1 to 2 per cent in the subsoil, which is rather high for engineering gravels (Fig. 8).

Weathered shale is a useful filling material in Sarawak, partly because it is trafficable almost immediately after heavy rain, and partly because it rarely becomes so fluid during handling that it becomes a problem to deal with. The natural moisture content is often so close to the optimum for compaction that the material can be compacted without being wetted or dried to give a good density. Where several soils are available for constructing an embankment, the red shale is frequently reserved for use in the top layer. Here, and on the surface

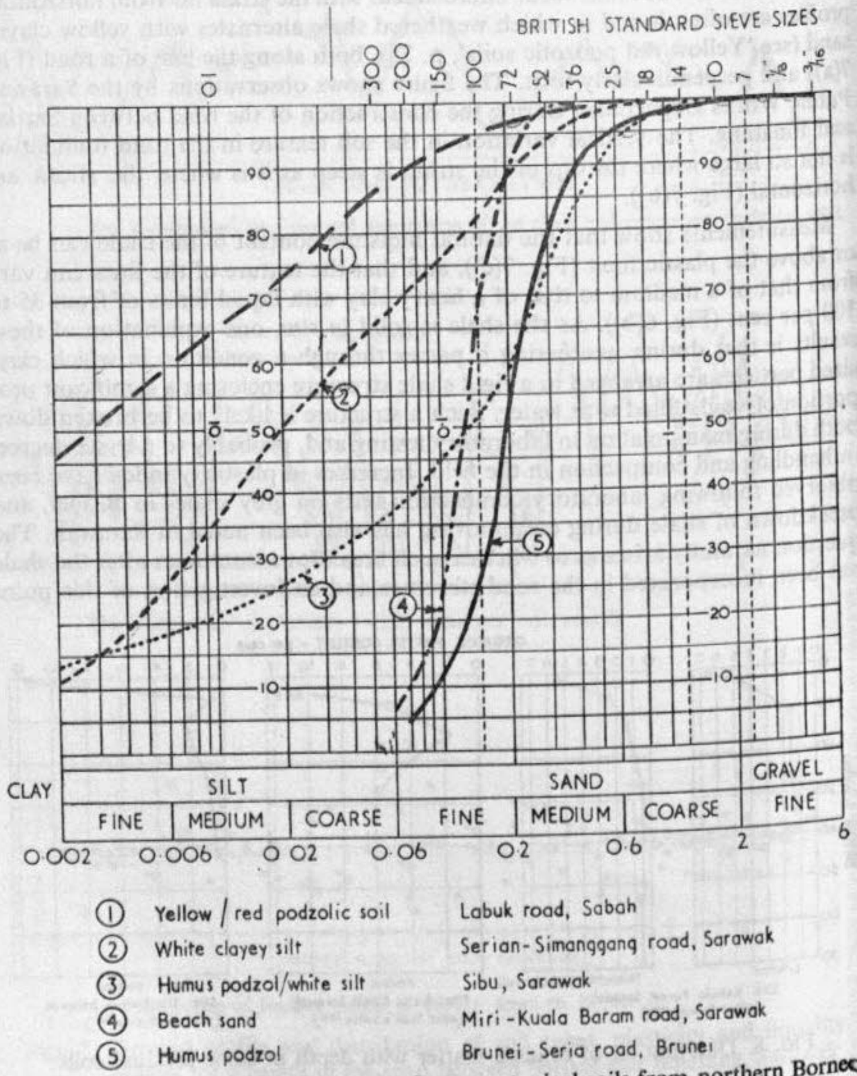


FIG. 9. Particle-size distribution curves for some typical soils from northern Borneo

of cuttings through poor materials, red shales after compaction provide a running surface that is acceptable even in wet weather, during the period between the completion of the embankment and the laying of the base-course gravel or stone. Weathered shales have been used similarly during construction of the Trans-Borneo road in Sabah to blanket earth formations in the early stages of work; such surfaces have been found to improve with age, possibly due to washing-out of clay and fines by rain. Shale and weathered shale surfaces in cuttings resist erosion well, presumably because of the consolidated nature of the material; some shale is so strong that it must be excavated by ripper and in Brunei explosives have had to be used in a hundred-foot cutting.

Shales, with colours including grey, green, chocolate, purple and black, occur in different parts of northern Borneo, and as far as is known their engineering properties are substantially the same as those described above for the red variety.

Yellow/red podzolic soils: composition. Clayey soils containing varying proportions of sand and silt, mainly yellow or red in colour, are a predominant soil type in northern Borneo. The name 'latosol', earlier applied to this soil type in Sarawak, indicates the relation that some soil scientists felt existed between these soils and the red laterites of the tropics, which contain significant proportions of iron and aluminium oxides. Despite their colour, however, these soils do not appear to contain large proportions of oxides and are therefore significantly different from the laterites. In Sarawak, red podzolic soils are believed to derive mainly from shales, while the yellow varieties are thought to be formed mainly from sandstone. Profiles may be 5 to 20 ft deep and usually merge into the parent sandstone or shale at depth. The organic matter content reported for the subsoil[26] is of the order of 0.5 per cent (Fig. 8). The particle-size distribution would be expected to be variable; examination of samples from the Labuk road showed that the sand component was of medium fine rather than coarse texture (Fig. 9). Most samples have a measurable plasticity as exhibited in the standard tests;[22] the texture is mainly that of light or medium clays, although some heavy clays do occur (Fig. 10(a)). Results, chiefly from the west coast of Sabah (Fig. 10(b)), show that the soils here also are mainly light- or medium-textured. The only data available from Brunei[27] were obtained during investigations of a site for the new Brunei Town water supply, when a search was made for impermeable clay needed as fill in an earth dam. The samples examined were usually medium or heavy red or red/yellow clays developed on grey shales (Fig. 10(b)).

Liquid limit values for the yellow/red podzolic soils plotted against plasticity indices fall above the Casagrande 'A' line, whereas values for the red weathered shales tend to fall below the 'A' line (Fig. 6(b)). When the samples from the western end of the Serian to Simanggang road are plotted, they tend to fall below the line; the parent material in this case is the Sadong formation of Upper Triassic shales and sandstone.

Variation of texture with depth is evident from the results of tests made with soils occurring in Sarawak and Brunei (Fig. 11). Accumulation of clay takes place at depths between 3 and 6 ft below the surface; this may be accounted for by the high rainfall in the area and the relatively free-draining nature of the soils. The relative increase in the sand content as the surface of the soil is approached would be expected to be accompanied by a slight increase in the strength of the soil as a road foundation, and the surface layers would be expected to be better drained. The soils have a fairly low *in situ* dry density and a

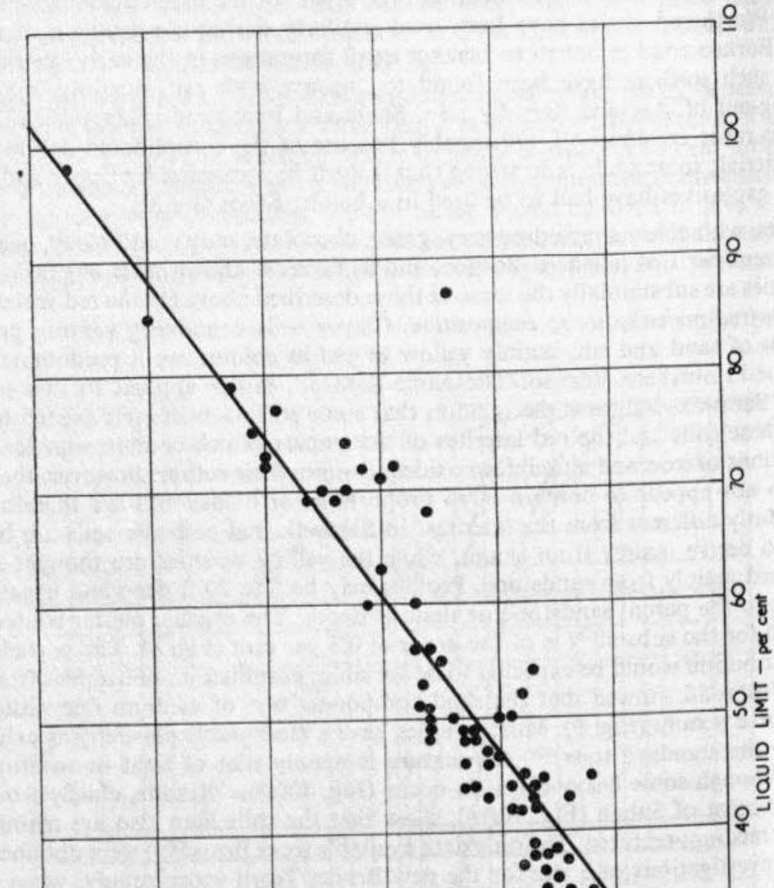


FIG. 10(a). Plasticity characteristics of yellow/red podzolic soils from Sarawak

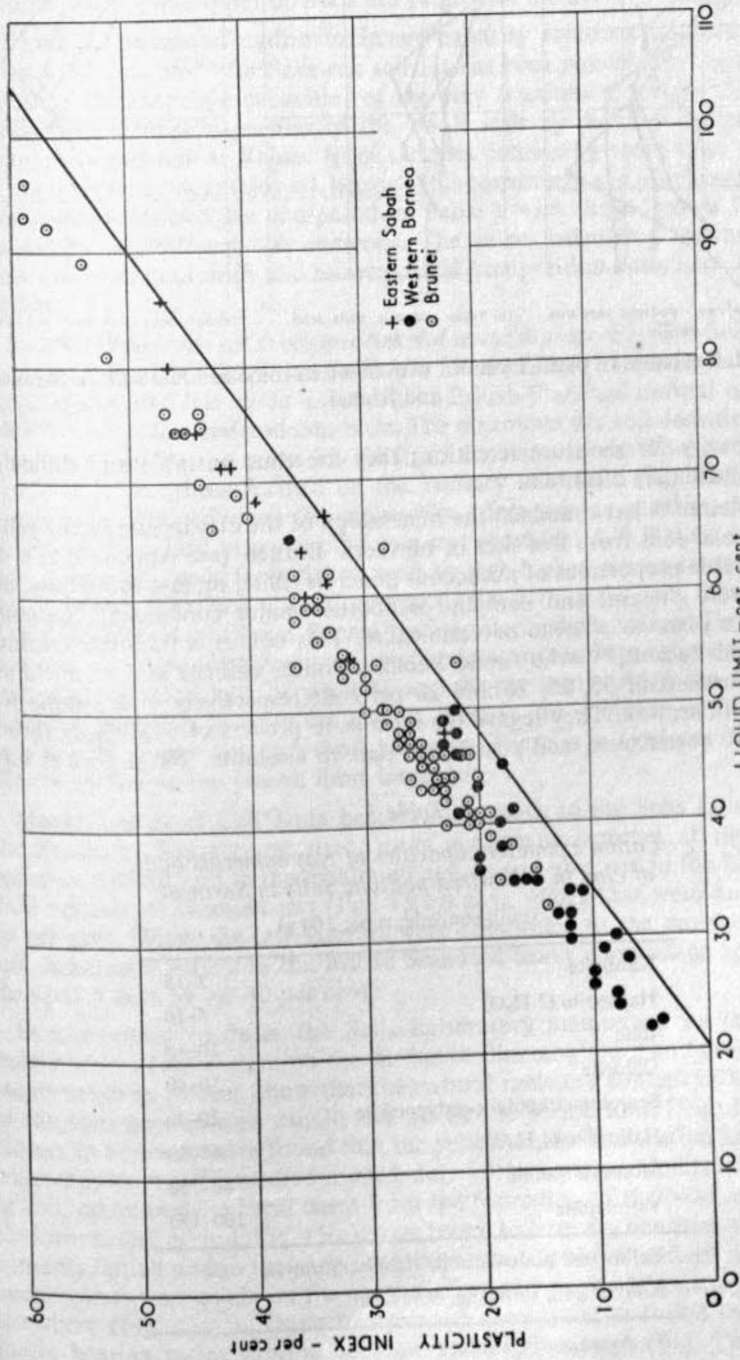


FIG. 10(b). Plasticity characteristics of yellow/red podzolic soils from Sabah and Brunei

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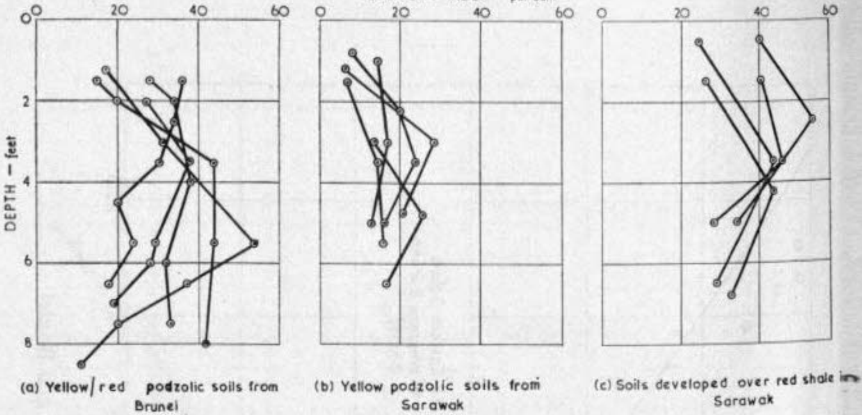


FIG. 11. Variation of plasticity index with depth in some residual soils in Sarawak and Brunei

high capacity for moisture retention; they are thus unstable and difficult to work immediately after rain.

Dumbleton[28] has examined the mineralogy of the clay in samples of yellow/red podzolic soils from five sites in northern Borneo (see Appendix 1, p. 65). Considerable proportions of micaceous minerals (illite, or, less commonly, muscovite) were present, and kaolinite is another major constituent. Sometimes illite gives place to chlorite or vermiculite. This confirms the observations of Wood and Beckett,[29] who found kaolinite, mica, chlorite and vermiculite in the proportions of 35, 25, 20 and 20 per cent respectively in a sample from Bintulu in Sarawak. They regard the mica as in process of weathering through chlorite to vermiculite, and possibly in part to kaolinite. When present in the

Table 5

Cation exchange capacities of clay minerals and of clay in yellow/red podzolic soils in Sarawak

(milli-equivalents per 100 g)

Kaolinite	3–15
Halloysite (2 H_2O)	5–10
Illite	10–40
Chlorite	10–40
Sepiolite-attapulgite-palygorskite	20–30
Halloysite (4 H_2O)	40–50
Montmorillonite	80–150
Vermiculite	100–150
Yellow/red podzolic soil, Kebulu, Sarawak	34*
Alluvial soil, Limbang, Sarawak	25†

* Average of 39 values

† Average of 45 values

clay fraction none of these minerals is known to be associated with difficult engineering characteristics in soils, although problems of compaction are known to arise when some types of mica are present in the silt and sand fractions.

From the values of cation exchange capacity reported by Dames[26] and Dames and Sutton[30] for Sarawak soils, it has been possible for the authors to calculate the exchange capacities of the clay fractions alone, by dividing the measured exchange capacities of the whole soils by the clay contents, which were also determined. Values from samples containing more than 1 per cent of organic matter were rejected, because this constituent can also absorb cations. The results obtained are compared in Table 5 with those known from other sources[31] for different clay minerals. The values calculated for the Sarawak soils are consistent with the mineralogical composition found by Wood and Beckett.[29]

Yellow/red podzolic soils: compaction and strength properties. The Soils Laboratory maintained by the Sarawak Public Works Department on the Serian to Simanggang road has made a number of British Standard normal compaction tests[22] with yellow/red podzolic soils. The maximum dry soil densities obtained (Fig. 12(a)) fell in the range 85-100 lb/ft^3 for soils on the Triassic rocks, and 95-120 lb/ft^3 for those formed on the Tertiary sediments (Fig. 12(b)). Higher values were obtained when the compactive effort was increased to that used in the British Standard heavy compaction test (modified A.A.S.H.O. compaction test). Generally, soils from Sabah tend to give higher maximum dry densities in the British Standard normal compaction test than do soils from Sarawak (Fig. 13(a)), with soils from Brunei having intermediate values. This is consistent with the trend for Sabah soils to contain more sand than those in Sarawak. Soils with plastic limits between 15 and 20 per cent yielded the highest dry densities, probably because the clay in them is just sufficient to fill the voids between the larger silt and sand particles. There is a tendency for the dry density to fall as the plastic limit increases.

Measurements of California bearing ratio made in the Soils Laboratory on the Serian to Simanggang road, using samples compacted at the optimum moisture content and to the maximum dry density obtained in the British Standard normal compaction test (Fig. 13(b)) gave values that were mostly above 10 per cent. When the test samples were compacted at the moisture contents and densities obtained in the British Standard heavy compaction test many of the results were above 40 per cent.

Measurements made in the Soils Laboratory maintained by the Sarawak Public Works Department on the Sarikei to Binatang road, and other measurements made in Brunei, show that the natural moisture content of the majority of the soils encountered usually lies above the plastic limit (Fig. 14), and engineers in Sarawak have found that the yellow/red soils are often highly plastic when they have to be worked immediately following rain. Undisturbed samples of soil, taken in cylindrical cores from the formation of the road at the end of the low-rainfall period (Fig. 15(a)) were found to have dry densities and moisture contents falling within the range obtained when British Standard normal compaction tests were made on the same kind of soil under laboratory conditions elsewhere (Fig. 12(a)). These undisturbed samples were found to have California bearing ratios varying between 5 and 15 per cent (Fig. 15(b)).

Determinations of California bearing ratio made *in situ* on the Serian-

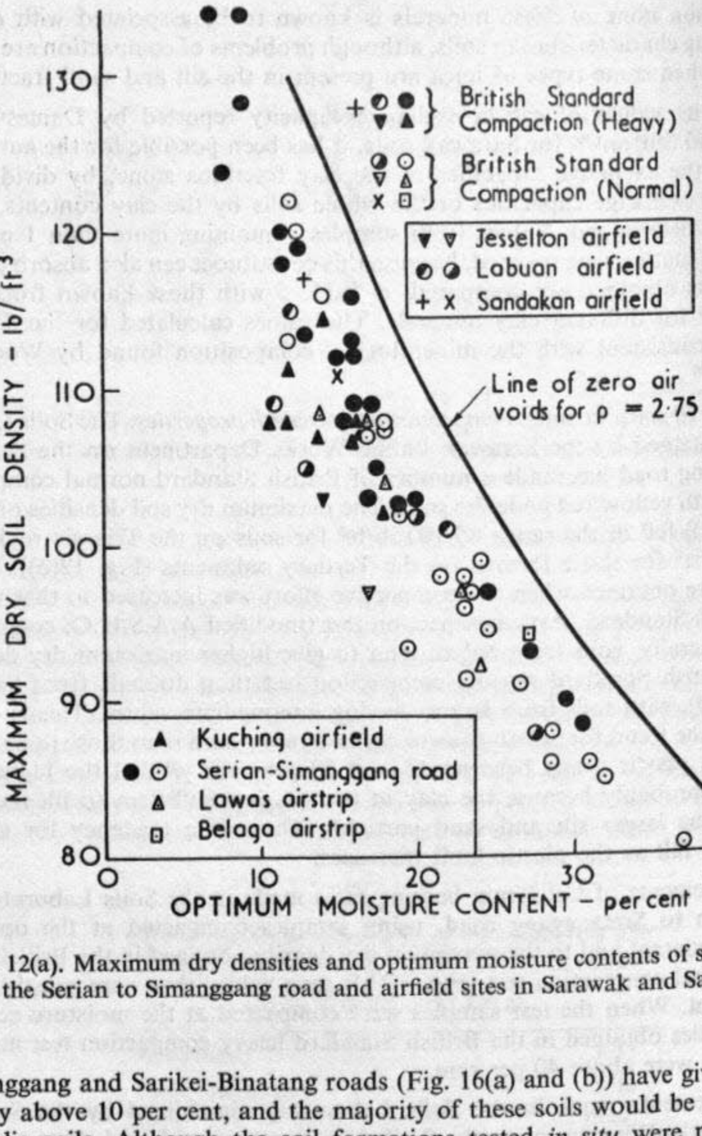


FIG. 12(a). Maximum dry densities and optimum moisture contents of soils from the Serian to Simanggang road and airfield sites in Sarawak and Sabah

Simanggang and Sarikei-Binatang roads (Fig. 16(a) and (b)) have given results mainly above 10 per cent, and the majority of these soils would be yellow/red podzolic soils. Although the soil formations tested *in situ* were not sealed, climatic conditions in Borneo are such that marked drying is unlikely. If it can be assumed that the dry soil densities in these field tests were within the range used in the laboratory work described earlier (Fig. 13(b)), then the results confirm Black's observation[32] that *in situ* California bearing ratio tests on cohesive soil give values similar to those obtained in laboratory tests using remoulded samples.

This evidence suggests that a design California bearing ratio of between 7 and 10 per cent is appropriate for these soils in the local environments, provided they are well-compacted and adequately drained. In Sabah, the Public Works Department is employing the lower figure and in Sarawak the design thicknesses used on pavements on trunk and feeder roads are in good agreement

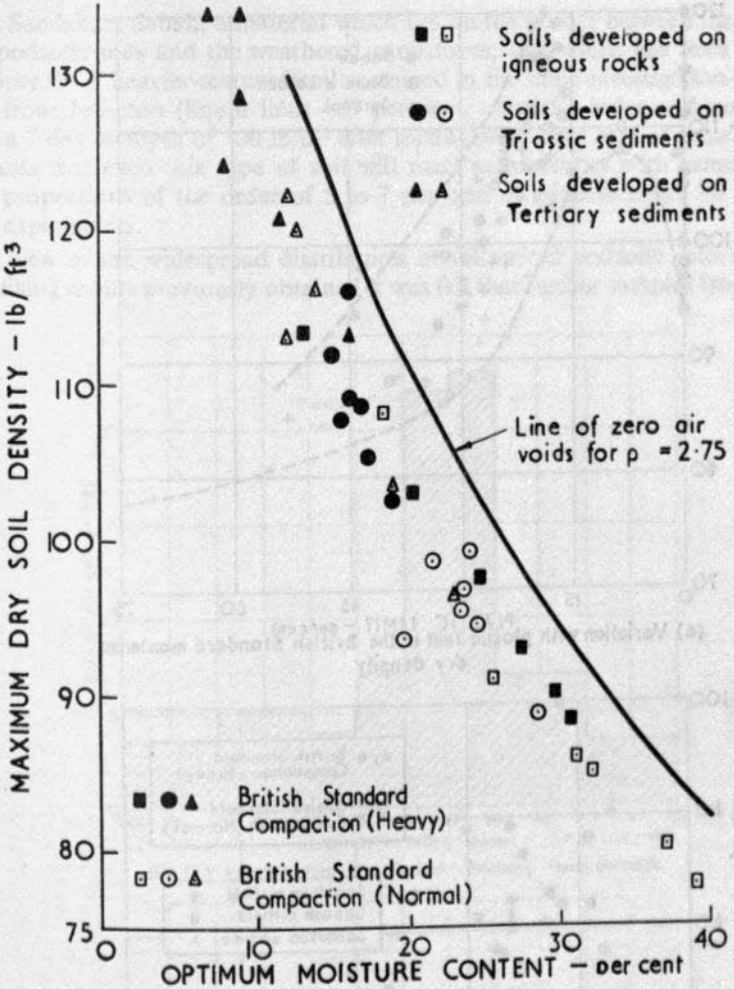


FIG. 12(b). Maximum dry densities and optimum moisture contents in relation to parent material for soils from the Serian to Simanggang road, Sarawak

with those indicated by the curves suggested by the Road Research Laboratory for bituminous-surfaced roads in tropical countries,[33] when a California bearing ratio value of 10 per cent is employed.

Yellow/red podzolic soils: stabilization properties. The yellow/red podzolic soils appear to be particularly suitable for stabilization with cement. Myles[34] has described the satisfactory results obtained when a soil of this type was stabilized with 8 to 10 per cent of cement and used as a base, on the road between Brunei and Tutong. The same type of soil is being used successfully on residential roads in Miri in Sarawak, stabilized with only 5 per cent of cement (see section on soil stabilization, p. 60). Unconfined compressive strengths obtained are shown in Table 6, which also includes data for a yellow silty sand

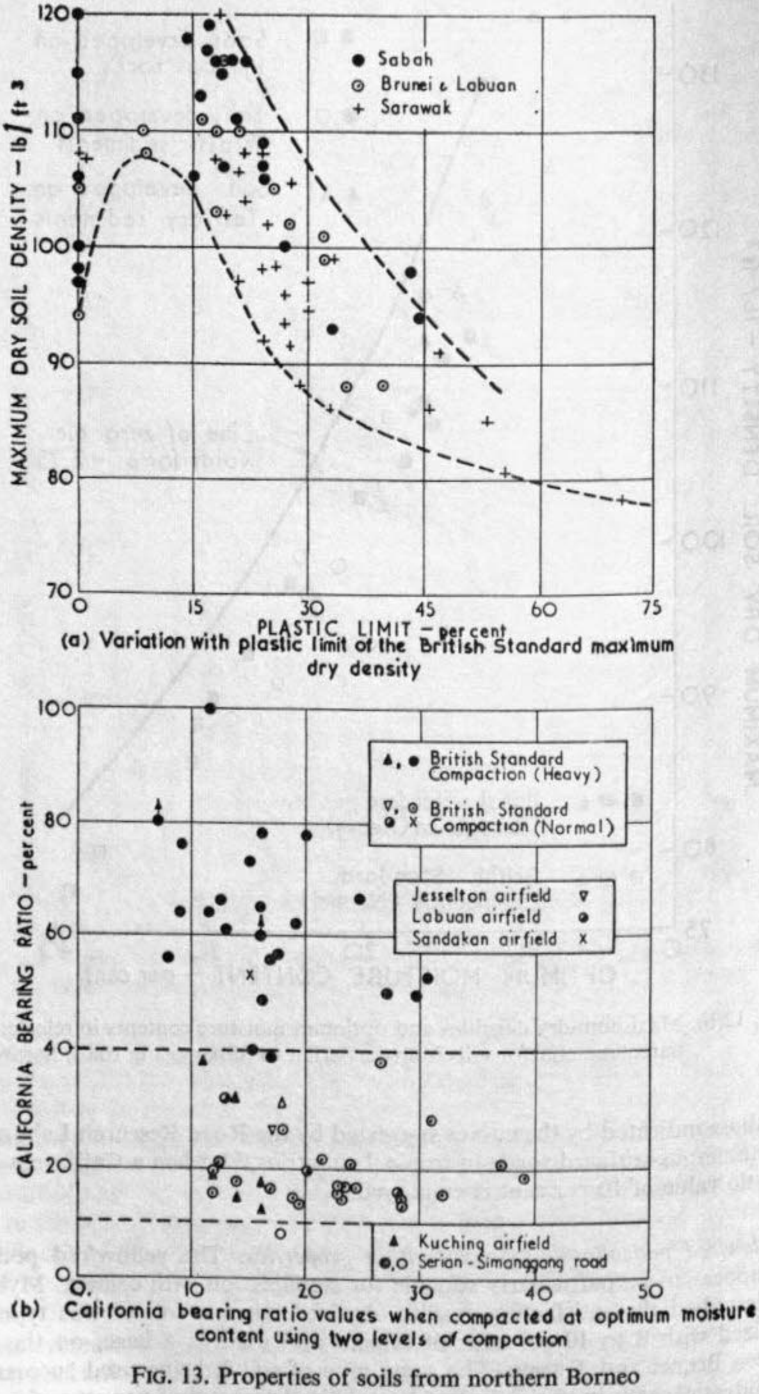


FIG. 13. Properties of soils from northern Borneo

from Sandakan, Sabah, a material which lies on the border between the yellow/red podzolic soils and the weathered sandstones, and which has been studied by Gray.[35] A heavier-textured soil examined in the same investigation—a silty clay from Jesselton (liquid limit=55 per cent, plasticity index=26 per cent), gave a 7-day strength of 100 lb/in^2 after mixing with 3 per cent of cement. This suggests that even this type of soil will react satisfactorily with cement, and that proportions of the order of 5 to 7 per cent of additive could be tried in field experiments.

In view of the widespread distribution of yellow/red podzolic soils and the promising results previously obtained it was felt that further samples from other

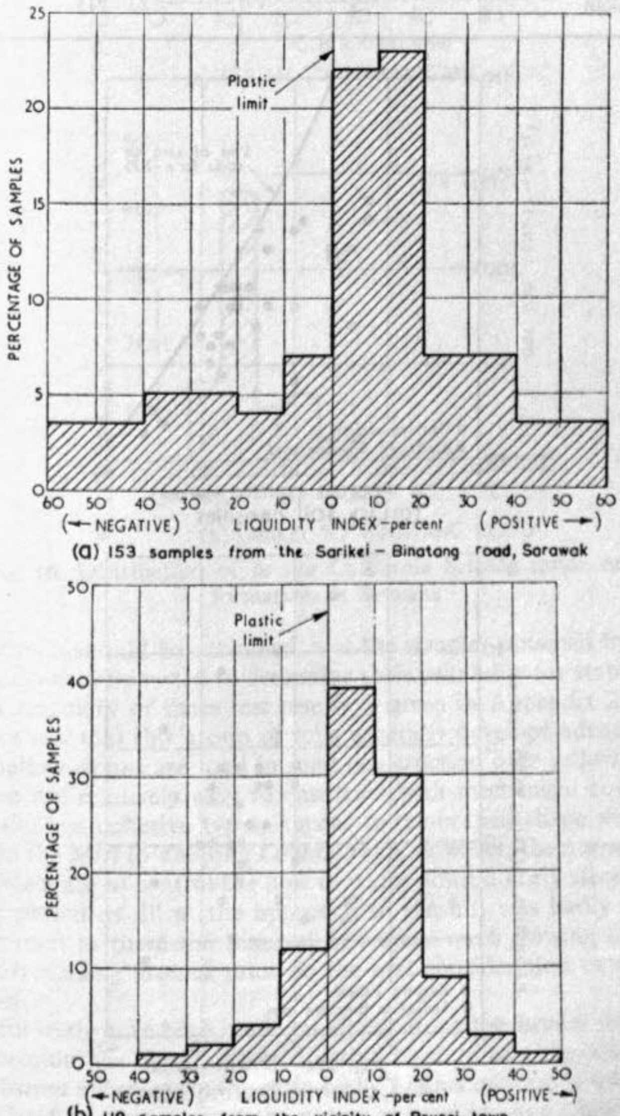


FIG. 14. Distribution of liquidity index in cohesive soils

Table 6

Seven-day unconfined compressive strengths of yellow/red podzolic soils stabilized with cement

Origin of sample	Cement content (%)	Unconfined compressive strength (lb/in²)
Brunei	10	> 250
Miri	4	210
Sandakan	3	215

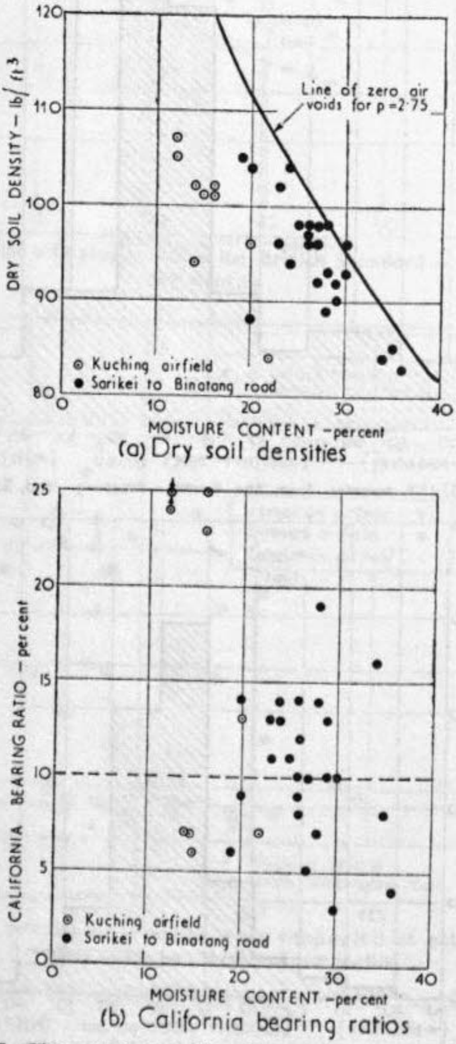


Fig. 15. Characteristics of undisturbed samples of soil taken at two sites in Sarawak

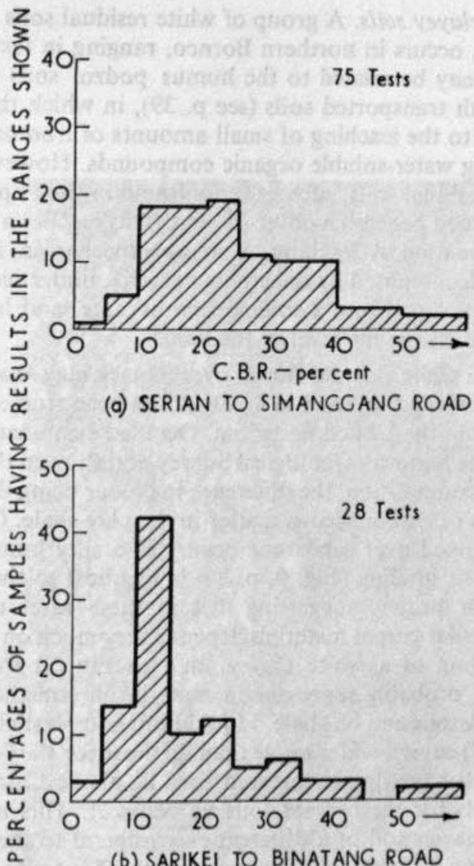


FIG. 16. Distribution of *in situ* California bearing ratios on soil formations in Sarawak

parts of Borneo should be examined, and the samples obtained by the authors during their tour were tested to determine their suitability for stabilization with cement. A summary of these test results is given in Appendix 2 (p. 69), and the results show that this group of soils generally develops adequate strength.

Wide shallow drains are used in road construction over yellow/red podzolic soils. These are relatively easy to construct with mechanical equipment and, except in the less cohesive types, appear to retain their shape without serious erosion. On the Miri to Tanjong Lobang road, however, the normal side drains proved inadequate to control the flow of water down a fairly steep hillside, and sandy soil placed as fill at the approach to the hill was badly scoured. For conditions such as these the removal of surface-water flowing from the road and the surrounding ground must be the first consideration in design and in construction.

Successful trials have been made on slopes along the Brunei to Tutong road in which erosion has been countered with a mixture of *Calogonium muconides* and *Centrosema pubescens* in the ratio of 3 : 1. This mixture is tolerant of most soils, will hold its own against the common roadside grass lallang (*Imperata cylindrica*) and may gradually drive it out in favourable conditions.

White silty and clayey soils. A group of white residual soils formed on shales and on sandstones occurs in northern Borneo, ranging in texture from clay to silty sand. These may be related to the humus podzol soils described in the section dealing with transported soils (see p. 39), in which the white colour is thought to be due to the leaching of small amounts of iron oxide in the parent rock by percolating water-soluble organic compounds. However, Allen[36] considers that white residual soils, such as those found in the Papar area of Sabah, were probably formed beneath a cover of peat. This implies a high water-table, and eliminates formation by leaching. A possible mechanism in this case is that organic matter is decomposed by anaerobic bacteria, under reducing conditions in which iron is converted into a soluble ferrous state, and later leached away following a general rise in the level of the land.

An example of a white clay developed over a black clay shale at Balai Ringin on the Serian to Simanggang road in Sarawak has been studied by the Overseas Geological Survey in the United Kingdom. Detailed examination confirmed the field evidence of the Sarawak Geological Survey and showed that the two materials had the same composition, the difference in colour being due to the presence of a small amount of carbonaceous matter in the clay shale. On the other hand a white soil developed over sandstone occurs as a silty humus podzol on the airfield at Sibu. The grading (Fig. 9, p. 24) is identical to that of a yellow/red podzolic soil from Brunei, suggesting that in these cases the colour of soil developed over similar parent materials depends very much on local soil-forming factors. The grading of a white clayey silt (see Fig. 9) from the Serian to Simanggang road probably represents a material intermediate between those developed on sandstone and on shale. Liquid limit and plasticity index values for these soils (Fig. 17) cover a wider range than do those for the yellow/red podzolic soils. The results for the lighter-textured soils lie above Casagrande's 'A' line, whereas the results for the heavier soils lie below it. This may be due to the presence in the heavier soil of a different clay mineral to that occurring in the lighter members, or it may be due to aggregation of the clay particles by polyvalent ions such as iron or aluminium. Work in the Agricultural Soils Laboratory in Kuching has shown that soluble aluminium is present in many Sarawak soils, in concentrations which can be toxic to pepper, one of the chief crops of the territory. Free aluminium would be expected to impart no colour to the soil, and to result from marked acidity, following intense leaching which would cause break-up of the alumino-silicates of the clay fraction. In this connexion it is interesting to note that Sutton[37] has found that the more leached lighter-coloured soils have much lower pH values than the yellow/red soils (Table 7), and are very acidic.

The values given in Table 7 might suggest exceptional corrosion of buried metal objects such as culverts and drainage pipes. However, pH is a measure of the intensity of the hydrogen ion concentration, and not of the total quantity of ionizable hydrogen in the soil, which is referred to as the soil acidity. The latter is probably more significant in corrosion and is influenced by the types and amounts of clay and organic matter present in the soil. The alluvial and swamp soils of Borneo would be expected to contain more of these constituents than do many of the podzolized soils, and thus may offer a greater corrosion hazard.

Little is known about the engineering properties of pale yellow and white cohesive soils, but when they are wet they are regarded as the most difficult

A transported sandstone gravel used in the base of the runway on the airport at Brunei Town

PLATE 1

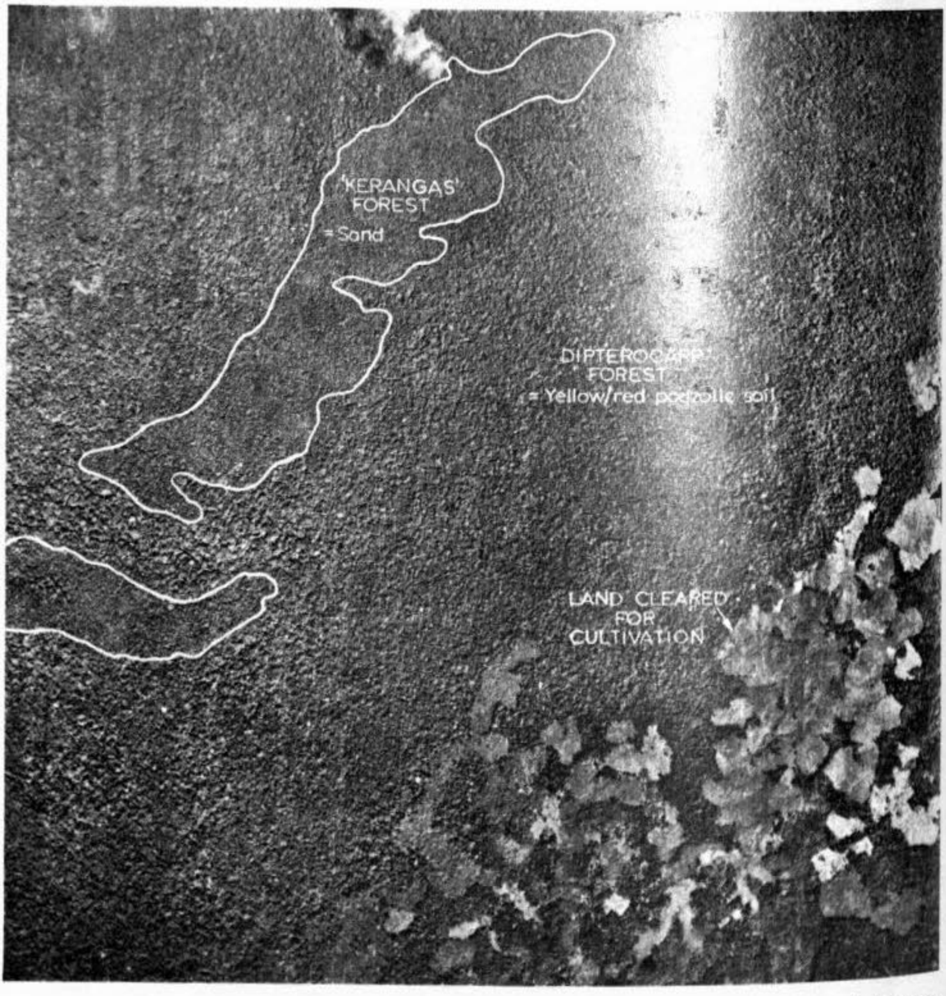
(a) Equatorial rain forest (*Dipterocarpus* spp.) on hill in the background—yellow/red podzolic soils

(b) Mangrove (*Rhizophora apiculata*)—half bog soils, swamps

(c) Nipah palm (*Nipa fruticans*)—brackish alluvial soils

Some types of Sabah forest, and the soils with which they may be associated (after Brown)

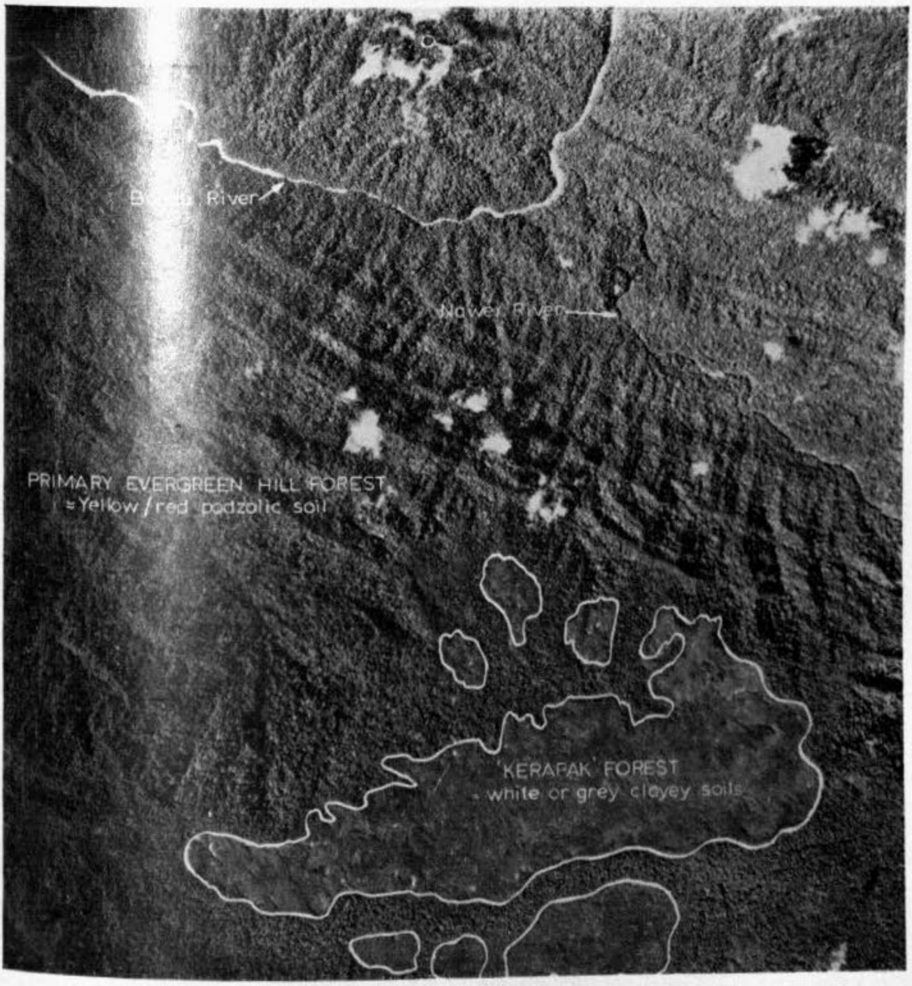
PLATE 2



Photograph by Royal Air Force

Well-drained sandy soil indicated by forest texture in an aerial photograph from Sarawak (after Brunig)

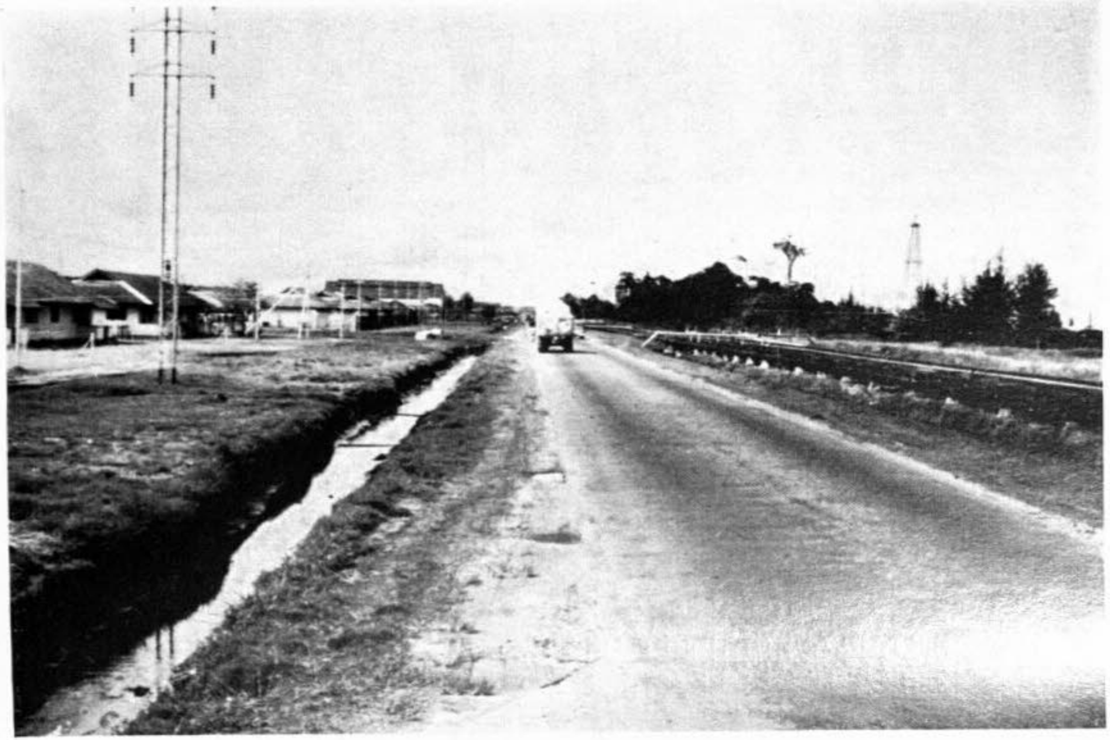
PLATE 3



Photograph by Royal Air Force

Poorly-drained clayey soil indicated by forest and ground texture in an aerial photograph from Sarawak (after Whittle)

PLATE 4



A typical wet sand-mix road in the oilfield at Seria, Brunei

PLATE 5

Mixing soil and cement in a stationary mixer, Krokop, Sarawak
(P. W. D. photograph)

PLATE 6

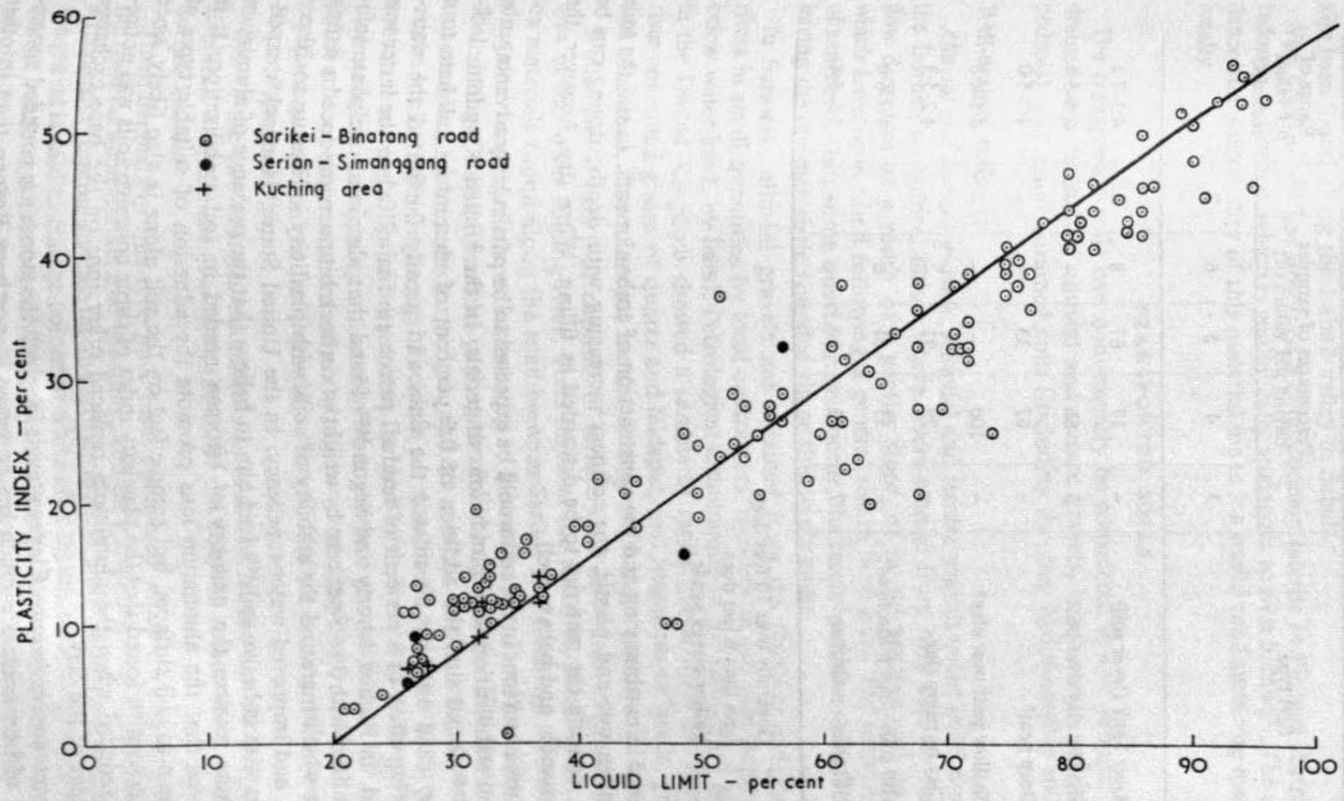


FIG. 17. Plasticity characteristics of yellow/white and white clays from the Sarikei—Binatang road and other sites in Sarawak

Table 7

pH values of 41 soils from Serian, Sarawak

Soil type	Percentages of samples having pH values of:					Range of pH values recorded
	3	4	5	6	7	
River bank (levee soil)	–	17	67	8	8	4·3–7·1
Shallow clay over peat	3	86	7	–	–	2·6–5·1
Deep peat*	–	67	33	–	–	4·7–5·0
Shallow peat over clay†	–	100	–	–	–	4·1–4·8
Clay or peaty clay	–	79	21	–	–	4·2–5·3
Hill soils—not podzolized‡	–	33	61	6	–	4·0–6·0
Hill soils—podzolized	7	73	20	–	–	3·6–5·4

* Generally over 10 feet deep
† Less than 6 feet deep
‡ Yellow clayey sands

material in earthmoving and the construction of embankments. *In situ* the soils are often wet and plastic, the softness increasing with depth; drying can be slow, causing the material to be discarded as filling. When dry, however, the soils handle and behave well.

Aluminium ions in the soil would be expected to be particularly advantageous in soil stabilization with bituminous materials. In the United Kingdom, Jackson,[38] found that the addition of 0.5 per cent of aluminium sulphate to a loamy sand strongly flocculated the fines and greatly facilitated the waterproofing effect of 3 per cent of residual petroleum fuel-oil when the latter was added. In France, Lhorty and Segond[39] found that aluminium sulphate solution added with 3 to 5 per cent by weight of cutback bitumen produced a setting effect which increased the stability of soils with plasticity indices up to 20 per cent, and improved water-repellency. In the United States, Hancock's experiments with cohesive soils[40] lead him to believe that the presence of aluminium sulphate reduces the quantity of bitumen needed in soil stabilization. It is believed that the aluminium ions promote the adhesion of suitable types of bitumen to soil surfaces, but some effect on the soil alone is also likely, since Winterkorn[41] found that the plasticity index of three cohesive soils was noticeably reduced when the aluminium replaced other ions on the base exchange complex of the clay.

Concretionary laterite. Clayey gravels in which the stones are rounded concretions of iron oxide are much less common in northern Borneo than in other parts of the tropics, possibly due to the scarcity of iron-rich parent rocks and to the continuing erosion. Wilford has surveyed the most likely area in Sarawak west of the Lupar river,[5] but the material that occurs is inadequate both in quality and quantity for roadmaking on a large scale. Laterite deposits have also been found along the Labuk valley in Sabah.

Von Gaertner[42] has observed a concretionary laterite in Pleihari district of Indonesian Borneo, which is geologically analagous to west Sarawak. The abundance and accessibility of this material make it a useful road surfacing material locally.

TRANSPORTED SOILS

The transported soils can conveniently be considered in two groups: well-drained soils (including alluvial and terrace gravels, beach sands and humus podzols), and poorly-drained soils (including the grey hydromorphic soils).

Well-drained soils

Alluvial and terrace gravels. Alluvial and terrace gravels occur in all three of the Borneo territories, either where rivers emerge from hills and the rate of flow decreases as a result of a gentler slope, or in old beaches and terraces which have been lifted following a general rise in land level. The majority are of sandstone, but some quartz gravels occur, the larger particles in both types having the characteristic rounded shape due to abrasion.

In Sarawak, alluvial gravels are obtained from the Kuching and Rajang rivers in small quantities by local contractors, recovery in one case being from below water-level, by hand. Petrological examination at the Geological Survey in the United Kingdom showed a sample of sandy gravel from the Kuching river contained grains of quartz and feldspar, and fragments of basalt, granite and sandstone. The principal use for such gravels is as aggregate in concrete.

Wolfenden[43] lists four deposits of terrace sand and seven of gravel in the area of the lower Rajang river. Tests made at the Road Research Laboratory on materials found along the road between Sarikei and Binatang showed that they were sandy gravels with stones up to $\frac{3}{4}$-in and above in size and between 10 and 20 per cent of particles passing the B.S. No. 200 sieve. The stones tend to be cubical, with some sharp edges, and are so weak mechanically that many can be broken with the fingers. The fines are non-plastic and the organic matter content is between 0·5 and 0·8 per cent. In the British Standard compaction test the maximum dry density obtainable under normal compaction is 123 to 127 lb/ft^3 at a moisture content of about 10 per cent. Specimens at this state of compaction and soaked for three days have California bearing ratio values of 50 to 57 per cent.[44]

One of the two samples examined was found to harden satisfactorily when stabilized with cement (Table 8), the other did not; the reason for the latter is not yet known.

Three deposits of this type have been discovered which traverse the line of the road between Sarikei and Binatang, and the gravel has been used to provide a successful running surface on an earth formation. Buff-coloured on extraction, the gravel is said to change colour to white after laying, compaction and drying on the road, and this colour change is said to be accompanied by a hardening.[45] Too much rolling is said to be undesirable, as this breaks the larger stones.

Table 8

Seven-day unconfined compressive strength of a cement-stabilized terrace gravel from Sarawak

Cement content (%)	Unconfined compressive strength (lb/in²)	
	Sample 1	Sample 2
2	20	88
5	63	213
7½	80	264
10	80	260

In Brunei, large quantities of terrace gravel are being extracted by the Public Works Department from deposits on the coast at Berakas. Wilford has surveyed the gravel deposits near Brunei Town and in the adjoining Limbang district of the Fifth Division in Sarawak[46] and estimates the possible reserves in the area as nearly 7 000 000 yd³. Similar surveys elsewhere in northern Borneo, in areas of similar landform, might well reveal further deposits.

In the Berakas gravel beds quartzitic sandstone cobbles and stones in a sandy matrix occur as lenses up to 20 ft in thickness, interleaved with sand and clay. The beds dip seawards at an angle of about 15°, and as much as 40 ft of over-burden may have to be removed as the working approaches the shore.[47] It has been found that particular care is needed in working the pit face to avoid the inclusion of excessive clay, and the larger stones can also vary in strength, some breaking down into sand under compaction on the road.

The base of the runway on the airfield at Brunei Town has been constructed with a 3-ft layer of Berakas gravel containing stones up to 12 in in size (Plate 1), with a regulating layer of crushed gravel on the surface. In 1958, the traffic rose to over 3000 movements, mostly of Viscounts and D.C.3's. Soft spots were subsequently detected which are believed to have been due to the sporadic presence of excessive clay, which was removed and replaced by less clayey material. Alternatively the addition of a small proportion (2 to 3 per cent) of cement or hydrated lime would have neutralized the effect of the clay.

In Brunei, the mornings are usually fine and warm, and it frequently rains in the late afternoon and at night. When the runway was inspected during a morning the greater part of the asphalt surfacing was dry, but water was seen bubbling through it in places. It has been suggested that changes in temperature or atmospheric pressure could cause air trapped in the bottom of the surfacing to expand and push out an overlying layer of rainwater, the mechanism being similar to that considered by Peck.[48] Over several patches there was a grey-brown-red deposit, apparently of iron compounds which could have been formed by evaporation of successive accretions of water enriched in iron by passage

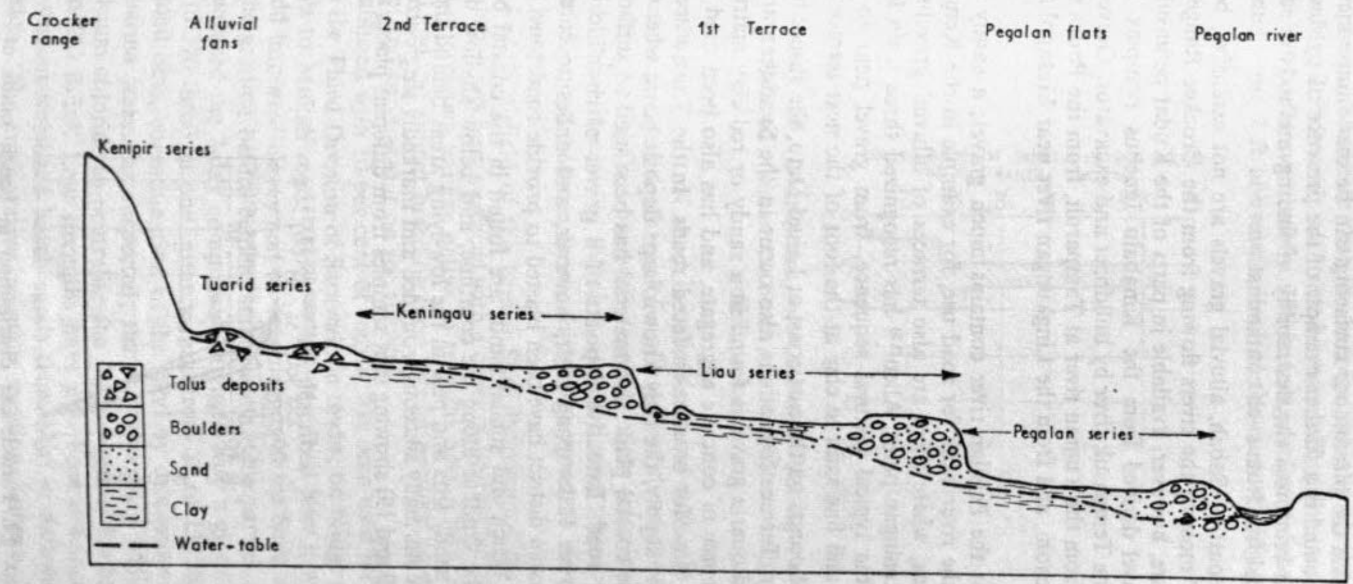


FIG. 18. Diagrammatic section of gravel terraces on the Keningau plain, Sabah (after Allen [15])

through pyrites in the gravel. In one such area coated aggregate had become detached from the main body of the surfacing to a depth of $\frac{3}{8}$-in, leaving a small incipient pothole. This effect would probably be reduced in proportion to the extent to which the bituminous surfacing can be made impermeable, and as the instance quoted is a further example of the presence of pyrites in sandstone material, it reinforces the desirability of finding methods of identifying and using material free from such contamination.

On the west coast of Sabah, alluvial gravels are not extensive, because of the shortness of most of the rivers flowing from the Crocker Range. Sources of chert gravel are, however, available in parts of the Kudat peninsula, and at Kota Belud gravel derived from the Kinabalu igneous complex has been obtained from the Tempasuk river by bulldozer and excavator. Gravel has also been extracted from the Tuaran river at Tamparuli, from the Padas river near Beaufort and Tenom, and from the Lingkungan river near Mesapol and Lingkungan.

In the interior the Pegalan river contains much gravel; a sandy variety is obtained from the river bank for road use, for example in the Keningau and Tambunan plains, where there are also terraces of alluvial gravel-sand-clay. Thus, on the Keningau plain, Allen[15] has recognized three main levels; the deposits show the typical textural sequence, from gravel near to the river through coarse and fine sand to clay at the foot of the next terrace (Fig. 18).

A chert gravel occurs on the east coast at Lahad Datu, the stones being hard though splintery. Terrace formations also occur in the Sandakan area, where a white rounded quartz gravel is found in a sandy or red clay matrix. This is an important source of concrete aggregate, and has also been used on gravel roads and as a base for bitumen-surfaced roads. In the Tawau area alluvial gravel is in short supply, the only known large deposit being where the Apas river reaches the coastal plain; this material has been used to surface parts of the Quoin Hill road. Extensive deposits of a gravel of rhyolitic derivation occur in the lower Kalumpang river, however, and andesitic core boulders found in the Tawau district have been blasted to provide roadstone.

Beach sands. Beach and similar sands are found in the coastal belt, where they occur in the sandbar along the coastline, and below shallow deposits of unconsolidated sandy silts and peat in the low-lying areas behind the sandbar. The particles are normally siliceous, rounded and markedly single-sized, typical gradings (Figs. 9 and 19) showing that samples from different places are noticeably similar.

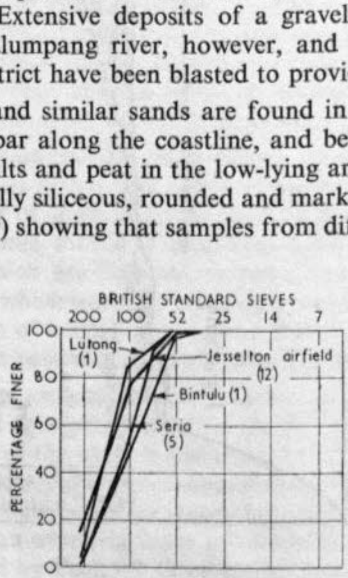


FIG. 19. Particle-size distribution in beach sands at different places in northern Borneo

In situ values of California bearing ratio measured on the sand subgrade of Jesselton airfield at Tanjong Aru show that the values of 83 per cent of samples were above 10 per cent (Fig. 20). More recent measurements by the Public Works Department indicate that the average value is between 16 and 17 per cent. Near Miri and Brunei, unsurfaced sand roads maintained by blade-grader carry moderate traffic successfully. The running surface can be up to 24 ft wide and elevated some 2 ft above the level of the surrounding ground. On such

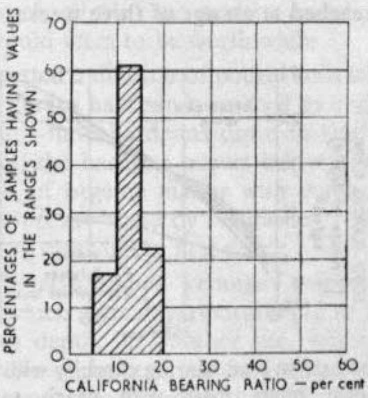


FIG. 20. Distribution of California bearing ratios measured *in situ* on the beach sand subgrade at Jesselton airfield, Sabah

embankments a rampart of sand is maintained on each side of the running surface to prevent rapid discharge of surface-water down the sides of the embankment during rain, thus preventing erosion of the side slopes; this rampart is also said to retain water in the sand so that during periods of dry weather the surface does not become loose, dusty and prone to rut under traffic as rapidly as it would otherwise.

At the Anduki airfield of the Brunei Shell Petroleum Company the beach sand foundation has been surfaced with a cover of Batiki blue grass (*Ischaemum aristatum*), a creeping variety native to tropical Asia. Cuttings were supplied from the Jerudong animal breeding farm,[49] and produce an excellent type of dense, level and springy mat on the runway.

Sand stabilized with 10 per cent of cement has been used for about 2½ miles of road in the Third Division of Sarawak, in towns, on bridge approaches and on the Oya to Mukah road. Myles[34] has described how it was found beneficial to add imported clayey soil to beach sands in the Seria area in order to improve the grading before cement stabilization. One part of soil added to 4 of sand increased the 7-day compressive strength with a given cement content from 160 to 320 lb/in² in one instance, and from 80 to 230 lb/in² in another. In the second case, contamination of the sand by deleterious organic matter from Casuarina trees was suspected; the supplementary addition of 0.2 per cent of calcium chloride to neutralize the organic matter further increased the strength to 630 lb/in². Low strengths have also been obtained in laboratory tests with cement-stabilized beach sands from Miri in Sarawak, possibly for similar reasons. The ameliorative measures mentioned above, however, would probably enable these soils to be used.

Laboratory tests to determine the suitability of beach sand for stabilization have shown that when 2 per cent of hydrated lime and 10 per cent of moisture are present, 3 per cent of bitumen needs to be added to produce cohesion but up to 8 per cent can be added before an impermeable mix is produced.(50) The addition of 4 per cent of bitumen and 2 per cent of lime has been found to produce the usual early development of strength with age (Fig. 21) associated with chemical reaction between the lime and the bitumen.(51) A load bearing capacity of 20 kg/cm² which has been suggested as indicating a satisfactory material(38) is usually reached at an age of three weeks.

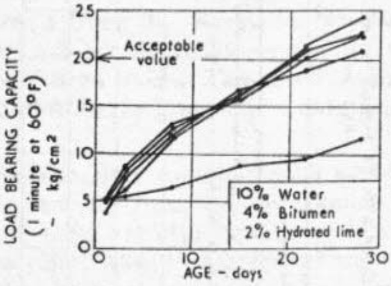


FIG. 21. Increase in load bearing capacity with age of wet sand-bitumen mixes made with beach sands from Borneo (Hodgson(50))

Field experience in Borneo has shown that with bitumen and lime contents of 5 and 4 per cent respectively a more practical rate of hardening is achieved, enabling a 6-ton roller to be carried 24 hours after laying.(52) A moisture content of about 8 per cent in the mixed material has been found to give the best stability,(53) and these proportions have been used in the 42 miles of 15- to 18-ft wide roads in Seria and 20 miles of roads in Lutong laid to the end of 1959. For residential roads the sand-mix is surface-dressed with sand, but for the more heavily-trafficked roads, such as those carrying oilfield equipment, dense asphalt surfacings between ¾ in and 2 in thick have been used, made with ¾-in maximum size crushed stone and 80/100-penetration bitumen.

Humus podzols. Humus podzols are medium or fine sands (Fig. 9), strongly leached, acidic and infertile, usually found in flat topography and with a humus hardpan at depth which may cause impeded drainage. They are often derived from the remnants of raised coastal plain and beach deposits and now exist as flat or gently sloping terraces between 5 and 150 ft above sea-level. In Sarawak, they occur widely in the First Division and are also found in an area stretching from Bintulu to Brunei between the coast and some of the inland peat swamps.(29) They are estimated to occupy one-sixteenth or more of the total land area, and carry a stunted type of forest known as 'kerangas', a local term indicating an infertile soil on which padi will not grow. The deeper formations, however, the 'giant' podzols, support the valuable 'bindang' timber (*Agathis alba*).

A typical sequence of strata in a profile is (i) topsoil, (ii) a layer of sand bleached grey or white, and (iii) a brown layer of sand containing humus, sometimes very compact and known as 'coffee rock'. A little clay may also be present. Water-soluble organic acids are believed to be formed in the topsoil from decaying vegetation, and these are thought to dissolve soluble iron oxides and silicate compounds during their passage through the layer below, leaving behind white insoluble silica, i.e. quartz. Wood[54] believes that deposition of humus in the brown layer is due to the mutual coagulation of dissolved organic matter and soluble silica when the leaching water reaches an acid zone in the profile. Some transformation in the condition of the silica might well account for the hardening of the sand in this stratum, which may also have a connexion with the hardening of the buff-coloured gravel reported on the Sarikei to Binatang road (see section on alluvial and terrace gravels, p. 39). Further investigation of this effect would seem to be worth while.

Wood has also suggested a division of podzol soils into two types, depending on whether or not the humus hardpan is reached by a 4½-ft hand auger. Shallow soils ('kerangas lingkat') have hardpans down to this depth, whereas in deep soils ('kerangas dalam') the hardpan occurs below it. Quantitative determinations of the variations of organic matter with depth at two sites have been reported by Wall and Sutton[55] and by Andriesse[56] (Fig. 8, p. 23), deposition at a shallow depth being clear in the first case.

Wood and Beckett[29] have studied 'kerangas' soil profiles in the Bintulu area of Sarawak in one of which a small proportion (13 to 16 per cent) of clay was present uniformly with depth. At another site, where the soil was closer in appearance to the yellow podzolic type, the texture was that of a non-plastic clayey sand, and X-ray examination of the limited clay fraction showed it to be a 60:20:20 mixture of kaolin, mica and chlorite, minerals that are associated with low rather than high plasticity and with only small volume changes with changes in moisture content.

The brown layer of humus-enriched sand is said to have self-hardening characteristics as a running surface when laid and compacted at its natural moisture content. This strength is lost if the soil is allowed to dry out before compaction. Such hardening might be caused by irreversible dehydration of the soluble silica, postulated by Wood.[54] Whether or not it is worth while making special effort to seek out 'coffee rock' soils for building earth roads remains to be established.

Sand from the leached layer can be used for sand-bitumen stabilization, in much the same way as the beach sands which have already been successfully employed in this way. In the United Kingdom, sand from podzolic formations has been successfully used in wet sand-bitumen mixtures for airfield runways, care being taken to avoid contamination of the sand with organic matter from the zone of deposition or with clay that may have been washed down into the lower layers of the soil. In similar work reported from the U.S.A.,[57] sand from the leached stratum with 95 and 10 per cent passing the British Standard No. 36 and 200 sieves respectively, was stabilized successfully with 4.5 per cent of hot penetration bitumen; the main requirement in this case was that the sand should be non-plastic.

Non-plastic sands are usually good foundations for roads, and this seems to be true in Borneo. Wilford[46] has studied sand deposits near Tutong in Brunei, which are probably of the humus podzol type, and leached to a purity good enough for glass-making, the humus layer lying from 2 to 15 feet below the surface. The fact that it provides a better foundation than surrounding soils can be inferred from the location of the Tutong to Telamba road, which passes over the deposit (Fig.22).

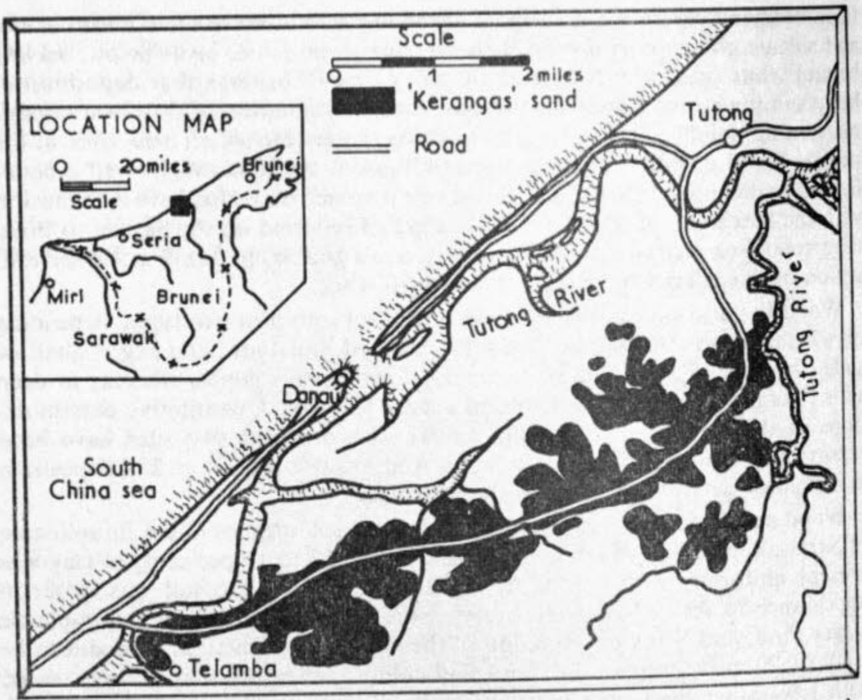


FIG. 22. Location of the Tutong-Telamba road, Brunei, following a 'kerangas' sand formation (map by Wilford [46])

In Sabah, a complex of podzolized soils occurs in the Keningau plain, and has been mapped by Allen as the Baiayo complex.[15] The degree of podzolization varies, and up to 2 ft of white sand has been recorded. The strongly podzolized soils support a characteristic low tree (*Baekia*), the moderately podzolized soils carry bracken (*Pteris*) and occasional *Baekia*, and the weakly podzolized soils carry *Pteris* and *Imperata*. The podzolization is ascribed by Allen to the leaching of the strongly acid-forming litter produced by the vegetation. This unusual vegetation is thought to have established itself on soil already strongly leached as a result of development beneath peat, which at one time covered much of the northern part of the plain and which has now been eroded. Similar podzolic soils are found in the Tambunan and Sook plains.

Poorly-drained soils

Grey hydromorphic soils. These are an important group of soils since they often carry one of the main food crops of northern Borneo—wet padi. In texture they are usually silty or sandy, and drainage is often such that the soil is wet for the greater part of the year. The parent material is usually sandy, and when it is of a heavier texture a related type of soil—the low humic gley—develops. The process of gleization in this heavier material is manifested by a mottled appearance in which red and grey colours are intermingled due to both reduction and oxidation of iron compounds locally in the soil, which occurs as a result of a fluctuating water-table level.

The organic matter contents of the lower strata of these soils are of the order of 1 per cent (Fig. 23). The amount of organic matter in a soil normally represents a balance between accretion from decaying vegetation and destruction by aerobic organisms. Increasing saturation of the soil shifts the balance in favour of accretion, and Fig. 23 shows that as the depth of the water-table below the surface decreases, the organic matter content in the subsoil tends to increase.

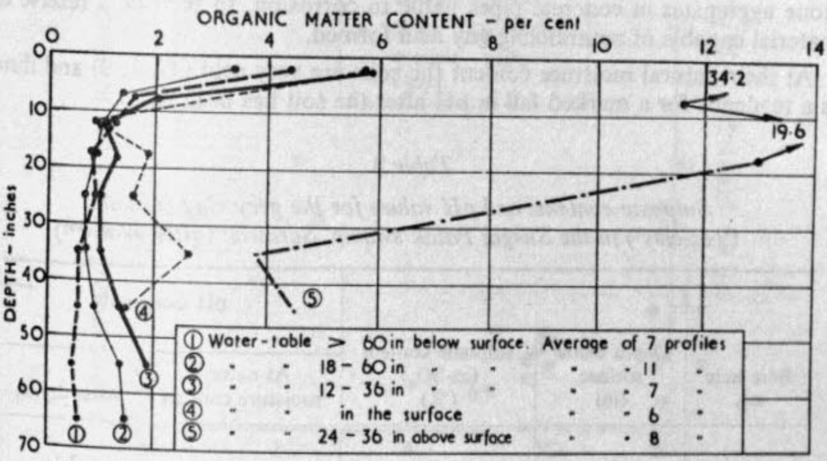


FIG. 23. Influence of the water-table level on the organic matter content of some alluvial and hydromorphic soils in the Limbang valley, Sarawak (after Dames and Sutton[30])

Examination of data reported by Dames and Sutton[30] shows that the cation exchange capacity of 45 samples of alluvial silty clay in the Limbang district of Sarawak was 25 milli-equivalents/100g, suggesting that the clay mineral could be either illite or chlorite. Dumbleton (Appendix 1, p. 65) found that the clay mineral in a grey hydromorphic soil from Marudi, Sarawak, was principally illite, with considerable kaolinite and with a trace of vermiculite also present.

A poorly-drained type of inorganic subsoil that is of interest to engineers is the 'cat-clay' described by Wall,[58] which occurs in the Sungai Patak swamp in Sarawak. This clay is thought to be a Quaternary marine clay containing sulphate derived from a special climax vegetation growing on the clay shortly after, or during, its deposition. Grey at the top, the colour of the clay becomes almost black with depth, because of the abundant undecomposed organic matter, which is generally soft and amorphous. The texture varies from that of clay to silty clay. The soil was exposed wherever ditches had been dug in the swamp, and as it dried out a yellow colour appeared which gradually spread to cover all the exposed surfaces of the soil lumps; this effect was caused by the oxidation of sulphur compounds. The clay occurred over the whole swamp, usually covered by about 24 in of organic topsoil. These sulphate-bearing soils may well be typical of the whole island, since van Wijk[59] and van Dijk[60] have reported them from two places in southern Borneo, while Blackburn and Baker[13] have noted their probable occurrence in Brunei.

In many of the samples examined by Wall (Table 9), the sulphate content is sufficient to involve a moderate, or even high, risk of attack of concrete,[61] e.g. in piling, and special precautions may therefore be found necessary in concrete structures in contact with such soils. These include measures to produce very dense and impervious concrete, and the use of sulphate-resisting or high-alumina cement. Thus, Hogg and Dyer report that, in Malaya, spun concrete pipes up to 6 ft in diameter are available with a spun lining of aluminous cement concrete as protection against sulphur compounds.[62] In South Africa, the National Building Research Institute has suggested the use of limestone aggregates in concrete pipes liable to corrosion, to provide a reserve of material capable of neutralizing any acid formed.

At their natural moisture content the soils are very acid (Table 9) and there is a tendency for a marked fall in pH after the soil has been dried.

Table 9

Sulphate contents and pH values for the grey clay subsoil ('cat-clay') in the Sungai Patak swamp, Sarawak (after Wall[58])

Bore hole no.	Depth below surface (in)	Sulphate content (as-SO_4) (%)	pH measured	
			At natural moisture content	After drying
1	31+	0·38	4·1	3·1
2	35	0·20	5·5	3·2
3	31	0·26	4·8	3·1
4	35+	1·00	3·7	2·7
5	39	<0·05	4·1	3·1
6	31	0·23	4·0	3·1
7	35	0·30	4·9	3·0
8	35	0·20	4·5	3·4
9	40	0·57	3·9	2·9
10	30+	0·32	4·8	3·3
11	20	<0·05	4·1	4·0
12	15	<0·05	4·7	4·7
Classification of sulphate contents of subsoils in relation to the possibility of attack on buried concrete (sulphate contents as–SO_3)		<0·20	Sites with low sulphate content	
		0·2–0·5	Sites with moderate risk of sulphate attack	
		>0·50	Sites with high risk of sulphate attack	

The presence of organic matter has the effect of reducing the dry soil density and strength of the undisturbed soil. Measurements made by the Sarawak Public Works Department (Fig. 24) show that the shear strength of undisturbed samples lies between 0 and 3 lb/in². Following the reasoning of Terzaghi and Peck[63] and Wilson and Williams,[64] it can be inferred that the natural California bearing ratio values of these soils may be as low as 1 to 2 per cent, although higher values could undoubtedly be obtained where it is possible to

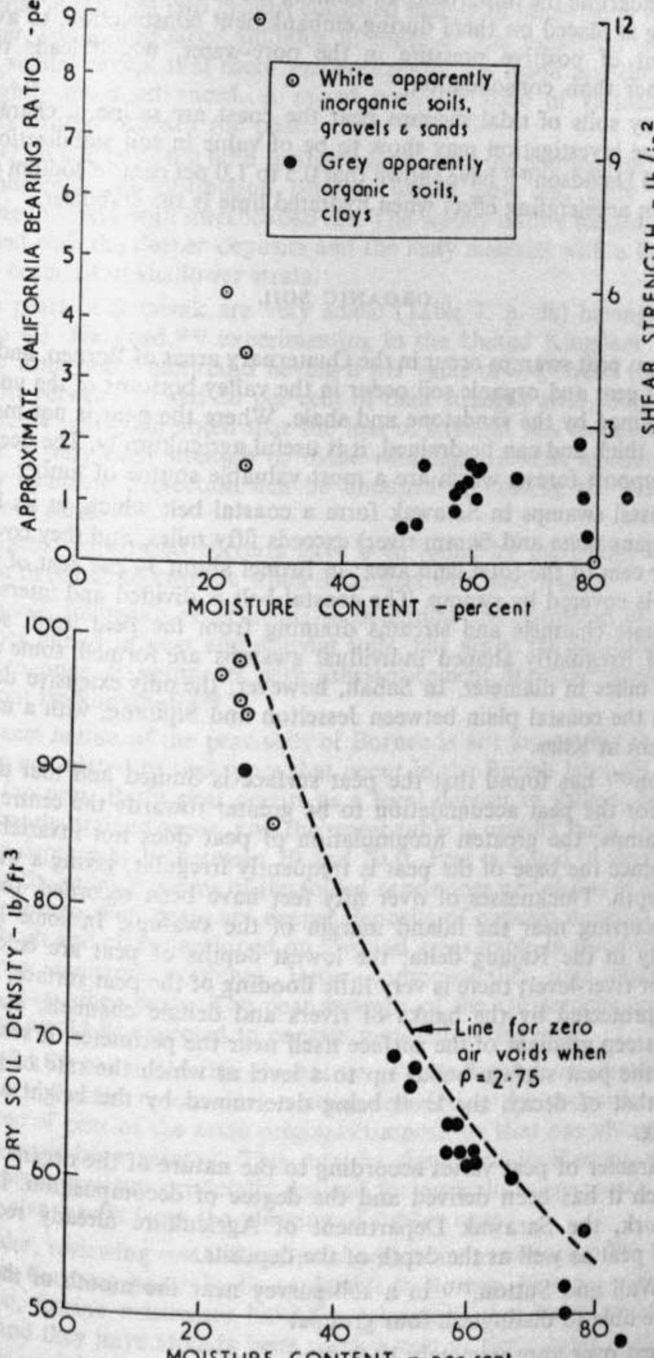


FIG. 24. Natural moisture contents, dry soil densities and strength of undisturbed core samples of alluvial soils in Kuching port, Sarawak

maintain them in a drier condition, and compact them. The low undisturbed strengths underline the importance of limiting the rate at which they are loaded when filling is placed on them during embankment construction, to avoid the development of positive pressure in the pore-water, which leads to shear failure rather than consolidation.

Some grey soils of tidal swamps near the coast are saline, a characteristic which future investigation may show to be of value in soil stabilization, since Mateos and Davidson[65] have shown that 0.5 to 1.0 per cent of sodium chloride can have an accelerating effect when hydrated lime is the stabilizer.

ORGANIC SOIL

Peat

Numerous peat swamps occur in the Quaternary areas of Borneo, and smaller deposits of peat and organic soil occur in the valley bottoms of the undulating country formed by the sandstone and shale. Where the peat is not more than 6 or 7 feet thick and can be drained, it is useful agriculturally. The deeper peat deposits support forests which are a most valuable source of timber.

The coastal swamps in Sarawak form a coastal belt which, at its broadest (in the Rajang delta and Baram river) exceeds fifty miles, and they cover more than 8 per cent of the total land area; in Brunei about 14 per cent of the total land area is covered by swamp. The coastal belt is divided and intersected by rivers, deltaic channels and streams draining from the peat itself, so that a number of irregularly shaped individual swamps are formed, some of which exceed 10 miles in diameter. In Sabah, however, the only extensive deposit of peat is on the coastal plain between Jesselton and Sipitang, with a maximum development at Klias.

Anderson[66] has found that the peat surface is domed and that there is a tendency for the peat accumulation to be greater towards the centre of individual swamps; the greatest accumulation of peat does not invariably occur centrally since the base of the peat is frequently irregular, giving a wide range of peat depth. Thicknesses of over fifty feet have been recorded, the greater depths occurring near the inland margin of the swamps. In some localities, particularly in the Rajang delta, the lowest depths of peat are below mean sea-level or river-level; there is very little flooding of the peat surface, however, which is protected by the banks of rivers and deltaic channels, and by the relatively steep gradient of the surface itself near the perimeter. It seems probable that the peat surface builds up to a level at which the rate of growth is equal to that of decay, the level being determined by the height above the water-table.

The character of peat varies according to the nature of the organic material from which it has been derived and the degree of decomposition. In its soil survey work, the Sarawak Department of Agriculture already records the texture of peat as well as the depth of the deposits.

Thus, Wall and Sutton,[67] in a soil survey near the mouth of the Sadong river, were able to distinguish four groups:

(a) Peat over approximately 10 ft deep

(b) Peat between approximately 6 and 10 ft deep

(c) Peat between 3 and 6 ft deep

(d) Mainly mineral soil, containing mixed silty clay and peat.

Material in the first two groups consisted mainly of imperfectly rotted leaves and litter, containing large amounts of more or less preserved wood; group (c) was similar except that there was apparently less wood and decomposition was slightly more advanced. A mixed peat/clay zone of variable thickness probably existed beneath the peat.

In another survey of flat land farther inland along the Sadong river, Sutton[37] again observed this distinction between woody peat and leafy peat, often occurring in layers with interbedded silt. The woody nature tended again to be associated with the deeper deposits and the leafy material with a high mineral content occurred in shallower strata.

Some peats in Sarawak are very acidic (Table 7, p. 38) having pH values down to 4.1. Halstead,[68] experimenting in the United Kingdom with water draining from peaty moorland having a pH value of 4.4, found that concrete cubes lost between 30 and 50 per cent of their strength after being in contact with it for 4 years. He noted that the loss of strength was markedly less with concrete of very high strength or made with high-alumina cement, and that virtually complete protection can be obtained by coating the concrete with bituminous paint.

Corrugated galvanized culverts have been found by the Public Works Department in Sabah to corrode when in contact with acid waters.

Romanoff, following experiments to determine the corrosion of galvanized steel pipes buried in peat and alluvial soils, has noted the usefulness of bituminous coatings. Experiments with asbestos-cement drainage pipes were also carried out by Romanoff.[69]

The exact nature of the peat soils of Borneo is not known but it is believed that they are related to two types that occur in the British Isles: (i) basin peat and (ii) fen peat. Basin peat occurs as a local deposit in valleys, hollows and similar poorly-drained areas, and the water-table is usually fairly near the surface. The depth may be between 10 and 20 ft. Peat is found in similar circumstances in the valley bottoms of the folded sandstones and shales in the Tertiary areas of Borneo. Fen peats are deeper deposits of organic material contaminated with silt and clay, developed on lowland areas liable to flooding, and they have lower moisture contents, lower compressibility and slightly higher strength than other peats. The peat swamps of the Quaternary coastal areas of Borneo would be expected to contain material of this type.

Markwick[70] has noted that the nature of peat depends on climate and that when it is subjected to seasonal wetting and drying the properties will differ from those of peat of the same original composition that has always been wet and has never been aerated. This may be significant in Borneo, where peat swamps are sometimes artificially drained for agricultural purposes and where drainage also results from the planting of rubber trees.

Tresidder, reviewing methods of road construction over peat,[71] notes three techniques that may generally be applicable in Borneo. In areas with abundant vegetation, fascine mattresses have the advantage that local material is employed, and they have already been used in two or three cases in Sabah; they should be used below the water-table (to hinder rotting) to support filling for embankments and are satisfactory for lightly-trafficked roads. Near sawmills it may be possible to use pressure-baled wood shavings in place of fascines, as a lightweight raft for a road, as has been done in Indonesia.[72] On more heavily-trafficked routes where the expense is justified, such as in towns, concrete roads may be carried on timber piles. Flynn has recorded that in Florida, where in some ways foundation conditions are analagous to those on the Borneo coast, creosote-treated wooden piles 55 ft long and 12 in in diameter were used to carry reinforced concrete road slabs over marshy areas 40 to 50 ft deep.[73] The third technique, applicable particularly to more heavily-trafficked routes and shallower peat depths, is to construct an embankment of suitable filling material and remove underlying peat by blasting with explosives, as has been described by Duncan, Dalzell and Williams.[74] This procedure has been found experimentally to be more economical than other methods of excavation, and would probably be more convenient in Borneo, where the topography and nature of the ground may place difficulties in the way of the operation of mechanical earthmoving plant.

Hydrated lime has been used in newer methods of road construction over swampy ground. In the U.S.A., it has been employed to stabilize an organic 'muck' soil to provide a working surface during reconstruction of a road a few feet above sea-level.[75] The lime was observed to have a 'drying' effect on the soil which helped to maintain stability in wet weather. For the more permanent type of agricultural road construction in the coastal marshlands of North Germany, Otto has obtained satisfactory results in three experimental roads over peat, the thin layer of overlying organic clayey silt being stabilized with 6 to 8 per cent of lime.[76] The stabilized soil replaced gravel, which is expensive to import.

Burmister[77] has noted that in the field the engineering properties of organic soils are much affected by their environment and by any changes that may be imposed on them during construction, for example, of embankments. Similarly, the kind of test procedure used in the laboratory markedly influences the results, and better correlation between laboratory and field is needed. Fundamentally, a better understanding of the influence of the internal structure of peat and organic soils on their mechanical properties would be helpful.[78] However, as far as Borneo is concerned, a useful first step would be to characterize the various organic soil types more closely, and to compare their engineering properties with those of similar soils elsewhere whose performance under roads is better known.

CONSTRUCTIONAL CHARACTERISTICS OF SOILS

The character of the land in much of northern Borneo is such that properties of soils and fill materials that are exhibited in earthmoving are of particular interest to the road engineer. Indeed, when discussing the soils they have encountered in their work, engineers in this territory almost invariably start by referring to the ease, or otherwise, with which these materials can be excavated and placed in embankment construction. The information given in Table 10 has been compounded from their observations.

Care is taken by the Departments of Public Works to select the best materials for embankment construction, particularly for the 1 to 2 ft directly below subgrade level. Evaluation of soils in this respect follows that given in the Civil Engineering Code of Practice on site investigations.[79] Excessively wet material is avoided and slopes of $1\frac{1}{2}$:1 are used, variations being made as necessary to

Table 10

Characteristics of fill materials available for embankment construction in Borneo

Material	Colour	Excavation and/or extraction	Compaction characteristics	Characteristics as an unsealed surface	Characteristics as a pavement foundation	Susceptibility to erosion
Sandy gravel	White	Readily extracted; buff colour *in situ*	Heavy rolling is undesirable initially, as this breaks the stone; changes colour to white after compaction and drying out	Very good; said to be self-cementing	——	——
Sand	White	Readily extracted; abrasive to tracks	Readily compacted	Good when wet; poor when dry	Good, well-drained	Very susceptible
	Brown		Should be compacted at the natural moisture content and not allowed to dry first	Very good; said to be self-cementing	——	Not susceptible after hardening
Clayey silts and sand (podzolic soils)	Yellow	The natural moisture content of clayey sands *in situ* is often above the optimum for compaction possibly because of low natural densities; readily excavated when moist, but plastic and difficult after rain	Good when available damp and rolled in thin layers; needs to be handled quickly to avoid wetting by rain	Good after compaction and drying out	Good as a sub-base, stabilizes well with cement for base construction	Moderately susceptible; dependent on clay content
	Red		Better fill material than yellow variety, characteristics otherwise similar			Less susceptible than yellow variety
Silts	White	Difficult to excavate; usually wet and plastic, softness increasing with depth; the soils take a long time to dry and often have to be discarded as filling	Difficult to compact because of unstable condition	Very poor; may not carry even a Land-rover	——	Not very susceptible
Clays	Orange		Orange clays intermediate in properties between white silts and red shales; sometimes acceptable as filling			
Shale	Red and Brown	The most widespread and useful filling material in Sarawak; can be extracted at its natural moisture content even in wet weather, and is relatively easy to handle; red varieties usually workable by bulldozer, but may need loosening by ripper; black may need explosives	Natural moisture content is near the optimum for compaction; compacts well in thin layers	A well-compacted surface is strong and carries traffic well, but may be slippery; sheds water well	Good; little softening if well-drained; useful sub-base material	Resists erosion well
	Grey		Grey varieties are less widespread; engineering properties similar to red, but said to be more brittle			
	Black		Black variety absorbs water less readily than the red			
Weathered sandstone	Yellow/brown	Usually extracted readily	Readily compacted, but gravel may break down into sand	Good when wet	Good sub-base	Fairly susceptible

suit soil conditions. Inverts are shaped to reduce silting and scour, and particular attention is paid to providing adequate drainage outlets.

As far as possible fill material is compacted in layers not exceeding 12 in in thickness, particular attention being given to the top 2 to 3 ft of the embankment. Rain falls all the year round in Borneo and on most days, and earthmoving is hampered accordingly. There are, however, periods of more than and of less than average rainfall, and during the earthmoving for the Sarikei to Binatang road, Bosward[45] has found that earthwork production increases significantly during the slightly drier months (Fig. 25). The recognition of the existence of such periods during the year may help in pre-planning new road construction.

Cuttings are normally made with side slopes of 1:1, and in poor soils they are benched to reduce erosion. In the wet environment in northern Borneo such slopes would be expected to be unstable in almost all soils. Slips on a small scale are fairly common, and one or two movements on a large scale have also occurred. Both here and in Malaya it is claimed to be cheaper to use steep slopes and to repair slips as they occur, rather than to construct a

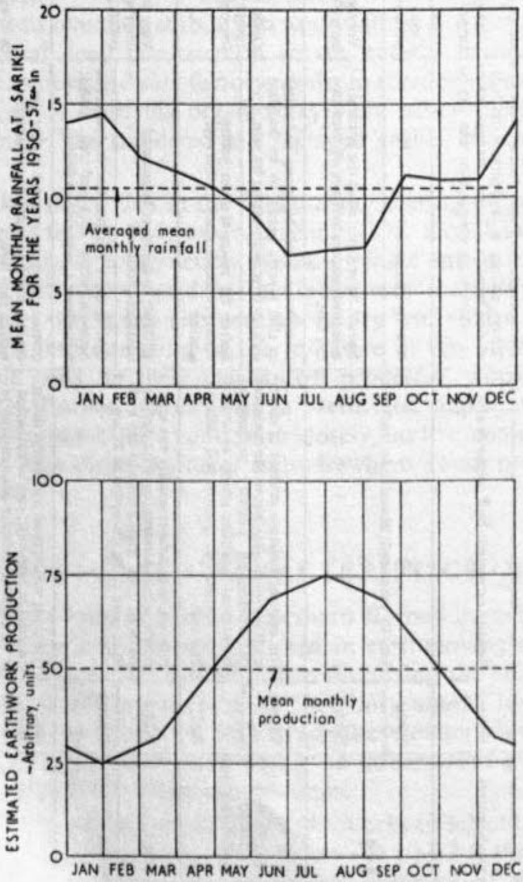


FIG. 25. Rainfall and earthwork production on the Sarikei to Binatang road, Sarawak (Bosward [45])

stable slope initially. Certainly some soils remain stable at quite steep slopes, possibly a reflection of a structure of some kind in the soils.

In the past with roads built slowly and to rather a low standard, it may well have been cheaper and more convenient to use steep slopes and repair where slips occurred. Nowadays the increasing importance of road transport is leading to the rapid construction of roads to a higher standard and with larger cuttings and embankments. In this situation more certainty is needed that slopes will remain intact. Methods are available for predicting from laboratory tests the slopes suitable for cuttings through isotropic and homogeneous soils, and it may be found that these can be applied in certain cases in Borneo. At many other sites, where the material is stratified or has a structure, modifications to the existing methods will be needed, or new ones may have to be evolved. A complementary line of investigation would be to systematize knowledge about the types of soil and geological environment most frequently associated with slip failures; Malaysia is a region offering scope for field work of this kind.

SOIL LOCATION BY VEGETATION AND AERIAL PHOTOGRAPHY

Northern Borneo is covered with a thick blanket of tropical vegetation, and timber is a major export. Forestry Departments have investigated the factors influencing forest type and distribution, and information is available which makes it possible to infer the nature of the soil from the characteristics of the vegetation it supports.

Thus, Browne and Roe[80] found that the forests on humus podzol soils ('kerangas') in Sarawak contain several typical species, principally *Casuarina sumatrana* (vernacular 'ru ronang'), and *Shorea pachyphylla* and *S. scabrida* as well as *Agathis* spp. ('bindang'), *Dacrydium beccarii* var. *subelatum* and *Shorea albida* ('alan').

In Brunei, Ashton[81] has studied forest species in relation to soil type and Table 11, prepared with his collaboration, shows the trees that can be regarded as indicative of the subsoil. The types listed were chosen as indicator species because they are relatively abundant and widespread in northern Borneo and, where they have been studied in Brunei, they are specific to the soil type. It is expected that these trees will also identify the same soil groups in Sarawak and Sabah. To utilize this information, engineers making preliminary soil surveys for roads in areas of primary forest could make visual observations of the tree species from the ground or from the air, or fallen leaves could be collected at each site preferably from dipterocarps ('kayu dammar') and transmitted to the Forestry Department for identification.

Where land on 'kerangas' soils has been cleared, cultivated and later abandoned, the secondary forest often consists of dense thickets of *Ploiarium alternifolium* (=*Archytaea vahlii*) ('somah') alone, or in association with *Cratoxylon glaucum*. Where secondary forest fails to establish itself, the ground becomes covered by scrambling fern, *Gleichenia linearis* ('salingkawan') or by *Imperata cylindrica* ('lallang' grass), although lallang does not really thrive on 'kerangas' soils.

Wood[54] has studied the tree species associated with different soil types in the more limited Bintulu area of Sarawak. He confirms that the species most

Table 11

Forest species indicative of subsoil types in Brunei (after Ashton[82]*)*

Soil type		Species specific to soil type
Lithosols	High sand content	Limited extent in Brunei; not examined
	High clay content	*Shorea angustifolia* ,, *ferruginea* ,, *superba* ,, *leprosula* ,, *faguetioides* ,, *fallax* *Parashorea smythiesii*
Red podzolic soils	High clay content	*Shorea isoptera* ,, *laevis* ,, *maxwelliana* ,, *macroptera* *Dryobalanops beccarii* *Dipterocarpus confertus*
	Medium clay content	*Anisoptera grossivenia* *Dipterocarpus crinitus* ,, *geniculatus* *Shorea faguetiana* ,, *kunstleri* ,, *ovalis*
	Low clay content	Not examined; probably as yellow podzolic soils
Yellow podzolic soils		*Dipterocarpus globosus* ,, *sarawakensis* *Dryobalanops aromatica* *Shorea flemichii* ,, *geniculata* ,, *laxa* ,, *rugosa*
Alluvial soils	Sand present	*Dipterocarpus apterus* *Shorea havilandii*
	Sand absent	*Dipterocarpus exalatus* *Shorea macrophylla* ,, *myrionerva*

Table 11—*continued*

Shallow humic podzols	*Cotylelobium malayanum* *Shorea scabrida* ,, *venulosa* *Vatica mangachapoi*
Giant humic podzols	*Agathis borneensis* *Cotylelobium burckii* *Dipterocarpus borneensis* *Hopea micrantha* *Shorea materialis*
Bog soils	*Dryobalanops rappa* *Shorea albida* ,, *pachyphylla* ,, *platycarpa* ,, *teysmanniana*

characteristic of humus podzol soils is *Casuarina sumatrana*; *Whiteodendron moultonianum* ('kawi') is also a good indicator of such soils in low-lying sites. At higher elevations most characteristic are the conifers indigenous to Sarawak, *Agathis* spp. and *Dacrydium beccarii* var. *subelatum* ('sempilor'). Tree species particularly associated with the alluvial soils of the river banks are *Eusideroxylon Zwageri* ('belian') and *Shorea seminis* ('tegelam'); *Tristania* spp. ('selunsor merah') and *Dipterocarpus oblongifolia* ('ensurai') along river edges are especially characteristic.

Ashton's experience[82] with some of the above species in Brunei is somewhat different. There, *Whiteodendron moultonianum* occurs on yellow podzolic soils and on poorly-drained alluvium in freshwater swamps, but not on humus podzols. *Eusideroxylon Zwageri* is typically a tree of the heavy-textured yellow/red podzolic soils on low hills, rather than of alluvium. *Tristania clementis* is found typically on sandbanks, sandy alluvium and sandstone rock on river banks, and *Dipterocarpus oblongifolius* is invariably found on clay soils overlying shale, near fast-flowing rivers, and only rarely on alluvium.

Anderson[66] has studied the peat-swamp forests of Sarawak and Brunei, and has found that each vegetation species has a certain radial range of distribution which is rarely discontinuous, and is repeated in different localities. Each species seems to have a range of tolerance to the increasingly infertile conditions that are encountered towards the centre of the swamp, and invariably the average size of the tree decreases with distance from the perimeter. Thus, *Dactylocladus stenostachys*, which is a dominant species, near the edge of swamps often has a girth of ten or twelve feet there, whereas in the centre of most highly-developed swamps it is abundant as a small tree or shrub ten feet high or less. Anderson notes, however, that although vegetation types tend to occur in concentric zones, a peat-swamp forest is fairly uniform in species composition and the extent can be defined through aerial photography, the crowns of *Shorea albida* being clearly visible. A satisfactory correlation of vegetation and depth of peat has not been found but the surface structure of the peat and drainage conditions are felt to be important factors governing the distribution of vegetation.

Dense stands of *Shorea albida* are indicative of deep peat, in excess of 10 feet and frequently exceeding 30 feet in depth. The distribution of all the larger areas of peat swamps and of the forest types dominated by *Shorea albida* is shown on the Land Use Map of Sarawak (Fig.26).

Brown[83] has examined forests in the Tawau area of Sabah; Plate 2 shows three types noted by him to be indicative of the nature of the subsoil supporting them.

Movement over the land surface of Borneo is not easy, but it is possible to obtain an idea of the vegetation and hence the soil, by studying aerial photographs, which cover a good deal of the country. Thus, Brunig[84] has developed a classification scheme for the forests of Sarawak based on their appearance in aerial photographs. The Department of Lands and Surveys in Sarawak has prepared a Land Use Map of the territory, based on the appearance of the natural and cultivated vegetation visible from the air. A key for this map (Fig. 26) shows how soil characteristics of engineering interest may be inferred for the areas delineated; this map is particularly useful in relation to the transported and organic soils.

'Kerangas' soils are of special interest to the road engineer, since they provide good, generally level, foundations. Because of their infertile nature the vegetation they support is often thin and stunted by comparison with that covering the adjacent yellow/red podzolic soils. Thus, with some experience in the field and in the interpretation of aerial photographs, it is possible to identify 'kerangas' forest under the stereoscope. A typical photograph is shown in Plate 3, in which the area of 'kerangas' forest is outlined. Dr. Brunig observes that terraces often show up as irregular low tables, surrounded by an erosion landscape sometimes rather compact in form. Raised beaches can be seen running parallel to the coast in narrow, more or less straight, dunes and flat ridges which may open on to small tablelands. The forest canopy on such terraces is more irregular than that on other podzol soils, and the crowns of the emergent trees are larger; the whitish crowns of *Shorea albida* trees are often conspicuous. Large, compact terraces sometimes have a small-crowned stunted forest in the centre, if the drainage is not particularly good. 'Kerangas' vegetation on flat sandstone strata may look similar to that on terraces, but there is usually some slope which can be detected under the stereoscope, and the transition to the surrounding forest is often less abrupt than that occurring with terraces. Undulating terraces, and those surrounded by cultivation, are difficult to detect.

Another type of soil identifiable from the air is the poorly-drained infertile clay formed on basalt ('plateau clay') or on sandstone with shale layers embedded (as on the Merurong plateau). Infertile clay also occurs at low altitude in 'kerangas' and 'kerapak' and terraces on other sites, and *Tristania* spp. ('selunsor') are frequently common in such forest. Plate 4 shows a deposit of this type noted by Whittle[25] in the area of the upper Plieran river, in Sarawak. The poor drainage and vegetation cover are evident, revealing some small-scale irregularity in the ground surface. Further associations of soil and vegetation in Sarawak are given in papers by Smythies[85] and by Brunig;[86] both contain useful glossaries of Malay names for trees and plants

(From Sheet No. 4, Land Use map of Sarawak and Brunei. Lands and Survey Dept., Kuching, Sarawak, April 1956)

VEGETATION	TOPOGRAPHY	SOIL TYPE	DRAINAGE	FOUNDATION RATING *
Settled cultivation (Wet padi, rubber)	Flat, gentle slopes	Silty, clayey sands	Poor to fair	2
Shifting cultivation (Dry padi, pepper)	Hill-and-valley	Clayey silts and sands; clays	Good	4
Mangrove and Nipah palm	Flat	Saline and organic silts	Fair, but subject to flooding, and to differences of <10 ft tidal water-table	5
Mixed swamp forest	Flat	Organic silts; some alluvial sands	River levees and old river banks are well-drained	3
'Kerangas' forest	Flat, plateaux, raised beaches	White silty and sandy soils, with gravel occasionally	Good; liable to erosion	1
Alan forest	Flat	Deep peat	High water-table but isolated areas of dry land	6
Padang Paya forest	Flat	Deep peat	Badly-drained	7
Other forest, mainly lowland Dipterocarp, sometimes old Secondary forest	Hilly	Probably clays, clayey silts and sands	Well-drained	Probably about 4

* In foundation rating, 1 is the best, 7 the worst

† This group appears in the Land Use map, but not on the area illustrated

FIG. 26. Engineering information available from the Land Use Survey map, Sarawak and Brunei

The experience of the Department of Agriculture in Sabah, however, is that the primary forest type as seen on air photographs is only exceptionally a guide to the soil types there. The Geological Survey Department has used the vegetation pattern shown on air photographs to distinguish different rock types in Sabah.

TIMBER

Forest covers a large part of the land surface of northern Borneo, and timber is one of the principal natural resources of the country. The tree-felling necessary for site clearance often provides the road engineer with abundant timber, and the nature of the country provides him with ample scope for its use.

Piling is a characteristic feature of much constructional work on the western coast. Concrete culverts under urban roads in Sibu are carried on a grid of 30-ft timber piles driven through soft alluvial mud. The improvement in bearing strength is such that the road surface over the culvert is sometimes many inches higher than that of the road on the adjacent soil, and it might be worth while using concrete slabs supported on piles for some of the more heavily-trafficked urban roads. On trunk and feeder roads in Sarawak, culverts are normally constructed of reinforced concrete pipes, but the Public Works Department has found that in the swamps timber culverts of belian (*Eusideroxylon Zwageri*)* may be easier to construct. Belian can be expensive, however, for example in Sabah, probably owing to difficulties of extraction.

Timber is a suitable material for the construction of various types of bridge capable of carrying light to medium traffic, and Sarawak, with its multiplicity of small streams and rivers, offers exceptional scope for structures of this kind. Many of the smaller bridges are of belian; on the proposed feeder road between Lundu and Serayan, the 140-ft long superstructure will have belian timber beams and decking, resting on braced belian piles and protected by wing walls constructed with anchored belian sheet piling. Similar single-lane timber bridges are envisaged for other feeder roads.

Standard designs for belian bridges and culverts are being prepared by the Public Works Department in Sarawak. Constructional methods used in India have been described by Harrison[87] and those in Burma by Lloyd.[88]

In road pavements, wood is used as fascines or in 'corduroy' construction. These uses would be particularly applicable to forest roads in Sarawak. At present most of the timber is extracted from swamps adjacent to the rivers, which are used to transport it to one of the major ports; in future, more timber may be drawn from inland sources, in which case feeder roads may be needed.

SOIL STABILIZATION

In 1954, Roe[89] noted that the lack of good roadmaking aggregate (by inference mainly igneous rock) was an obstacle to development along the coast of Borneo. New quarry sites have since been found, but as these are small and widely scattered, there is scope for methods such as soil stabilization, in which locally-available soils are used instead of stone in the road structure. This is particularly so in the Third, Fourth and Fifth Divisions of Sarawak,

*This timber is referred to as 'billian' in the United Kingdom, and is sometimes known as 'Borneo ironwood' where hard natural stone is available only in the few places where the geology differs from the general pattern in the region.

The presence of oilfields in northern Sarawak and Brunei with conveniently accessible sandy soils (see 'beach sands', p. 42) resulted in the early application of sand-bitumen mixtures for road construction in those areas. Methods developed in 1947 and 1948 have led to a successful technique and, up to the end of 1959, 42 miles of wet sand-mix roads 15 to 18 feet wide had been laid round Seria in Brunei (Plate 5) and a further 20 miles had been laid round Lutong in Sarawak.

The technique employed is to remove topsoil and bring sand from the seashore by sand-pump, or other means, to form an embankment at least 2 ft above the highest level of the water-table.[90] Beach sand intended for the sand-bitumen mixture is stockpiled on the seashore immediately behind the mixers. Hydrated lime, bitumen and sand are mixed in proportions of 4: 5:91 by weight in double-paddle batch-type asphalt mixers, a battery of four producing about 160 tons/day. A 5-in thick loose layer is compacted between timber kerbs, giving a 4-in final thickness. No traffic is allowed on the road for a week, to enable the mixture to harden. Four or five months later road oil or cutback 80/100-penetration bitumen is applied and blinded with sand or $\frac{3}{4}$-in maximum size stone. This suffices for lightly-trafficked and residential roads; for heavier traffic a premixed bituminous surfacing, using $\frac{1}{4}$-in maximum size crushed stone (Limbang gravel, Hong Kong granite, etc.) is laid to thicknesses between $\frac{3}{4}$ in and 2 in. Wearing courses of this type are reported to last for 4 to 5 years before a surface-dressing is needed. Such roads have carried successfully the 40-ton vehicles used to transport oil prospecting equipment.

In 1955, soil-cement construction was introduced in Brunei, where yellow/red podzolic soils were successfully stabilized with 8 to 10 per cent of cement using mix-in-place machinery, processing the soil to a depth of 6 in. Myles[34] has described the material produced as one of the most satisfactory for base construction in Brunei. By 1958, more than 28 miles of road with a soil-cement base-course had been laid in the State.[49] By 1960, the emphasis had changed because of the discovery within the State of increased supplies of gravel. The soil-cement process, however, could well be applied in those areas of Borneo where transport costs render the use of imported gravel excessively expensive.

At Krokop, a satellite town of Miri, the headquarters of the Fourth Division in Sarawak, a start has recently been made with the construction of 100 000 yd^2 of residential roads, mainly using locally-available material. Both bitumen and cement stabilization are being employed, a wet sand-bitumen surfacing being laid on a soil-cement base. The base is 6 in thick, 18 ft wide (Fig. 27) and laid

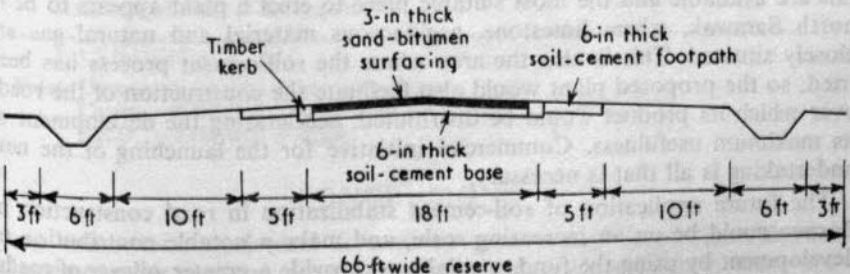


FIG. 27. Section of stabilized soil residential road, Krokop, Sarawak

on compacted sand. The yellow/red podzolic soil used, imported from high ground near Miri, has a plasticity index of about 6 per cent. The maximum dry density in the British Standard normal compaction test is 115 lb/ft^3. The compressive strength in the laboratory after the addition of 4 per cent of cement was found to be 200 and 280 lb/in^2 at 7 and 14 days respectively. In the field, 5 per cent of cement is added, in a double-paddle batch-type asphalt mixer of 7 ft^3 capacity (Plate 6). The material is spread by hand between timber kerbs, and compaction is carried out using a smooth-wheeled roller; the soil-cement is primed with M.C.0 grade cutback bitumen, at a rate of about 5 yd^2/gal. The wet sand-mix surfacing is laid 3 in thick over the soil-cement on the carriageway only. It is produced under contract by the Shell Sarawak Oil Fields Ltd., from sand found at Lutong, the mix proportions being similar to those used in Seria and Lutong.

Table 12 gives details of some of the costs found in work carried out so far at Krokop. The largest item in the unit cost of the pavement is that of the wet sand-bitumen surfacing, followed by that of the soil-cement base. Any development which would materially reduce the costs of these two items would help to achieve greater economy in construction; the present specification is already said to be cheaper than methods of pavement construction previously available in the area. Abundant supplies of beach sand suitable for sand-bitumen surfacings occur along the coastal strip where development is now proceeding, and are available where removal will not jeopardize the stability of the shore.

Experimental and full-scale soil-cement stabilization has also been carried out in the Sandakan area of Sabah. Following successful tests at the Road Research Laboratory(35) with a locally-available silty sand, two trial lengths were laid on Leila road in 1961. Two-layer mix-in-place construction was undertaken using a rotary hoe to add 3 and 7 per cent of cement to the lower and upper layers respectively. A nominal 2-in thickness of crushed-stone regulating course was then placed, followed by a double surface-dressing.

The trial sections behaved satisfactorily and the cost indicated a saving over a block stone construction traditional in the area, and the method was used for laying the rest of the road in 1962. To obtain the benefits of better quality and higher output, the soil-cement was mixed in a specially modified Barber-Greene continuous mixer with an output of 20 tons/hour, and this mixer was later also used to prepare the premixed bituminous surfacing. The work is deemed so successful that it is hoped to extend it further afield.

The more extensive use of the soil-cement process would be encouraged by the availability of locally-produced cement. Fitch(91) has reviewed the possibility of cement-making in the Borneo territories; he has concluded that materials are available and the most suitable place to erect a plant appears to be in north Sarawak, where limestone, argillaceous material and natural gas are closely situated. This is also the area where the soil-cement process has been tried, so the proposed plant would also facilitate the construction of the roads over which its product would be distributed, accelerating the development of its maximum usefulness. Commercial initiative for the launching of the new undertaking is all that is necessary.

The future application of soil-cement stabilization in road construction in Borneo could be on an increasing scale, and make a notable contribution to development by using the funds available to provide a greater mileage of roads. Newill(92) has shown that soils from many places in northern Borneo harden satisfactorily when only 5 per cent of cement is added (see Appendix 2, p. 69), and further experiments in the field would help to establish the minimum proportions needed in practice.

Table 12

Costs of items of carriageway construction on stabilized soil residential roads, Krokop (1960)

Item	Details	Quantity (yd^2)	Cost ($\$/yd^2$*)
Clearing grass	66-ft wide reserve	13000	0·03
Earthmoving	66-ft wide reserve	5660 (yd^3)	0·25
Shaping and compaction of formation and verges	18-ft carriageway and two 5-ft footways	15000	0·05
Timber kerbs	Contract labour and materials inclusive	3900 (ft)	0·32
Soil-cement base	Including materials, plant, haulage and labour by contract	1773	2·14
Priming of stabilized soil base	18-ft carriageway including labour, plant and materials	1280	0·33
Wet sand-bitumen surfacing	18-ft carriageway including labour, haulage and materials by contract	940	4·06
Total cost of 1 yd^2 of carriageway			7·18

* 1 \$ (Malay) = 2*s.* 4*d.*

Note: Cement – \$ (Malay) 95/ton from Japan
Cement – \$ (Malay) 108/ton from Hong Kong } May, 1960
S.R.O. – \$ (Malay) 1·36/gal

CONCLUSIONS

Young sedimentary geological formations predominate in northern Borneo and consequently resources of good quality roadstone are limited. More emphasis is placed on the soil as a roadmaking material; factors influencing soil characteristics are the parent rock and, to a lesser extent, the topography. Residual, transported and organic soils occur and 15 types having potentially distinctive engineering differences have been recognized; many of these are found in systematic sequences and in particular landscapes which simplifies the appreciation of their influence in road building.

Red and yellow clayey sands and silts, weathered shales and sandstones are the types of soil most commonly encountered, and when compacted and well-drained, California bearing ratio values of 10 per cent or more may be expected from them. Experience suggests, however, that under some site conditions a value of 7 per cent may be more appropriate. The clay minerals in them are not expected to cause foundations to swell if they become wet. The lighter-textured sandy and silty soils are promising for cement stabilization. Firm, well-drained dark brown clays having a crumb structure occur in the volcanic area in Sabah. In the coastal areas of development in the region, beach sands and alluvial gravels are found which give good road foundations and which can be stabilized satisfactorily with bitumen and cement. Silty alluvial soils are encountered; these need particular attention when used as road foundations. Peat occurs in extensive swamps which also contain sulphate-bearing clays that are potentially corrosive to concrete. In some areas, individual types of soil support specific types of vegetation, whose presence can therefore be used to locate soils in unsurveyed areas, either by inspection of individual trees, or by studying the types of forest seen on aerial photographs.

The application of methods of soil stabilization has been increasing in recent years, using both cement and bitumen, and there should be considerable scope for this type of construction in the future.

ACKNOWLEDGEMENTS

Most of the information presented in the Paper derives from road engineers, geologists and other scientists working in northern Borneo. Thanks are due to them, and particularly to the Directors of Public Works in Sarawak and Sabah, and the State Engineer in Brunei, whose co-operation made the field work possible; the authors are also indebted to the officers in charge of the various materials laboratories who have made the results of their work available; these are Mr. C. K. Gray in Jesselton, Mr. N. Dharmapalan in Kuching, and Mr. D. B. Watson and Mr. J. Bosward of the laboratories on the Serian-Simanggang and Sarikei-Binatang roads respectively.

APPENDIX 1

THE MINERALOGY OF THE CLAY FRACTION IN SOILS FROM NORTHERN BORNEO

by

M. J. Dumbleton, Ph.D., A.Inst.P.

Thirty-four samples of cohesive soil collected during the field survey were examined by X-ray diffraction and differential thermal analysis to determine the mineralogy of the clay particles.

Experimental technique

The samples, at their natural moisture contents, were dispersed in water. Particles less than 1·4μ in equivalent spherical diameter were separated by sedimentation, and brought to a moisture content in equilibrium with a relative humidity of 55 per cent. X-ray photographs were taken using CoKα radiation from a fine-focus tube; a 114·83-mm powder camera, fitted with a special collimator and beam trap, allowed low-angle reflections to be recorded. Characteristics used for identifying minerals in the clay fraction are as given by Brown.[93]

Approximate percentages of goethite and gibbsite were estimated by taking the peak areas on the differential thermal analysis curve to be proportional to the weight of material producing them, using values obtained from artificial mixtures as a calibration. The differential thermal analysis apparatus used is a modified form of that described by Mitchell and Mackenzie.[94] The apparatus, which was made at the Road Research Laboratory, uses nickel alloy sample-holders, and a controlled atmosphere of nitrogen is employed. The heating rate was 10°C per minute.

Results of mineralogical examination

The results given in Table 1A show that in the residual soils formed on igneous rocks, the clay fraction contained mainly disordered kaolin minerals often including some hydrated halloysite, sometimes vermiculite or chlorite, and montmorillonite in one profile on a basaltic rock. Goethite was also present, accompanied occasionally by gibbsite, but both in small proportions only, the maxima being 12 per cent of goethite in the Stebun sample and 6 per cent of gibbsite in that from Sebuyau.

The soils formed on sedimentary rocks, which were mainly shales, differed from those formed on igneous rocks in that they contained considerable amounts of illite or muscovite. Kaolinite was present, often as a major constituent, with varying proportions of chlorite and vermiculite. In the white clayey silt profile on the Serian-Simanggang road, chlorite and vermiculite appeared to be forming at the top by weathering of the illite, confirming the observations of Wood and Beckett,[29] and a similar trend could be seen in the top ten feet of the yellow/red podzolic soil profile from Sarikei.

The one transported soil examined contained mainly illite, with some kaolin mineral also present. It was thus similar to the residual soils formed on the sedimentary rocks, from which it was probably derived in the first place.

Relation between soil minerals and physical properties

The plastic properties of the soils could be explained by reference to the particle size distribution, and the mineralogical composition of the clay fraction.

Table 1A

Mineralogy of the clay fraction in soils from northern Borneo

Soil group	Location	Depth (ft)	Soil type	Clay content (%)	Quartz Q	Mica Mu=Muscovite I=Illite	Kaolin minerals: Kaolinite P=partially ordered D=disordered	Kaolin minerals: Halloysite Me=Meta-halloysite H=Hydrated halloysite	C=Chlorite V=Vermiculite Mo=Montmorillonite	Go=Goethite Gi=Gibbsite He=Haematite
	Sebuyau, Sarawak	4	Developed on granite	46	Q t	—	D ***	H *	C t	Go * Gi *
	Stebun, Sarawak	4	Developed on tuff	41	Q *	—	D ***	H *	V t	Go ** Gi t
	Serian, Sarawak	4	Developed on vitreous trachyte	20	Q t	—	—	H * Me***	C * V *	Go ** Gi t
	Quoin Hill, Sabah (a)	9	Developed on basaltic lava	87	—	—	D ***	H *	—	Go *
	,, ,, ,, (b)	—	,, ,, ,, ,,	78	—	—	D ***	H ***	—	Go *
Residual	Tawau, Sabah	2	Developed on volcanic ash	47	—	—	D ***	—	—	Go *
soils on	,, ,,	3	,, ,, ,, ,,	29	—	—	D ***	—	—	Go *
igneous and	,, ,,	4	,, ,, ,, ,,	48	—	—	D ***	—	—	Go t?
volcanic	,, ,,	5	,, ,, ,, ,,	72	—	—	D ***	—	—	Go *
rocks	,, ,,	6	,, ,, ,, ,,	69	—	—	D ***	—	—	Go * He *
	,, ,,	11	,, ,, ,, ,,		—	—	D ***	—	—	Go t
	Apas road, Sabah	2	Developed on basaltic rock	66	—	I t	—	Me **	V ** Mo **	Go t
	,, ,, ,,	3	,, ,, ,, ,,		—	I t	—	Me **	V ** Mo **	Go t

Table 1A — continued

Residual soils on sedimentary rocks	Serian-Simanggang road, Sarawak	3	Yellow/red podzolic soil	15	—	Mu ***	*	—	—	Go t Gi t
	Kelupe, Sarawak (a)	3	White clayey silt	35	—	Mu ***	D **	—	—	—
	.. .. (b)	3	Yellow/red podzolic soil	38	—	Mu ***	D **	—	—	—
	.. .. (c)	3	Weathered red shale	23	—	Mu ***	*	—	V t	—
	.. .. (d)	3	Weathered grey shale	20	—	Mu ***	t	—	C **	—
	Selantek, Sarawak	3	Yellow/red podzolic soil	55	—	I *	*	—	V * Mo *	Go t
	Sarikei, Sarawak	3	Yellow/red podzolic soil	26	—	—	P ***	—	C **	Gi t
	.. ..	10	.. ..	35	—	I **	P ***	—	V *	—
	.. ..	15	.. ..	24	—	I ***	P ***	—	—	Go *
	.. ..	20	.. ..	26	—	I ***	P ***	—	—	—
	.. ..	23	.. ..	16	—	I ***	P ***	—	—	Go *
	Labuk road, Sabah	3	Weathered black shale		—	I ***	*	—	C **	—
	Muara, Brunei	2	Yellow/red podzolic soil		Q t	I ***	*	—	V *	—
	.. ..	5	.. ..		Q t	I ***	*	—	C t or V t	—
	.. ..	8	Weathered black shale		Q t	I ***	*	—	C * Mo *	—
	.. ..	14	.. .. ..	36	Q t	I ***	*	—	C t or V t	—
	.. ..	19	.. .. ..	32	Q t	I ***	*	—	C * Mo *	—
	Serian-Simanggang road, Sarawak	3	White clayey silt	20	—	—	D ***	—	C * or V *	Gi *
	.. ..	8	.. .. ..	8	—	I **	D ***	—	—	Gi t
	.. ..	12	.. .. ..	8	—	I **	D ***	—	—	—
Transported soils	Marudi, Sarawak	1	White/grey alluvium	47	Q *	I ***	**	—	V t	—

Key: t = trace, * = some, ** = considerable *** = much

Of the soils plotting above the 'A'-line on the Casagrande classification chart (the region in which the results for many clay soils fall), the soils from Apas road, which contained considerable montmorillonite, had the highest values of liquid limit and plasticity index. The yellow/red soils from Sarikei, which contained both kaolinite and illite, had the lowest values of liquid limit and plasticity index, while the soil profile from Muara, which contained mainly illite, gave intermediate values. This is as would be expected from the values usually quoted for pure clay minerals. However, the profile from Tawau, which contained mainly kaolinite, gave values which tended to be higher than those of the profile containing illite, perhaps because the kaolinite in this case was of the disordered type.

Silty soils and soils containing hydrated halloysite plotted below the 'A'-line of the Casagrande classification chart, as is usual with such materials. The samples from Quoin Hill had high contents of clay comprising disordered kaolinite with hydrated halloysite, and gave a plastic limit of about 70 per cent and a liquid limit of about 105 per cent. These soils are of interest because of their similarity to the red clays of the Kenya highlands; both are fertile and well-drained, and have stable crumb structures. Both form on igneous rocks and contain disordered kaolin minerals which may be in the hydrated form.

The soils from the Serian-Simanggang road and from Kelupe contained considerably more silt than clay, and plotted below the 'A'-line. In the Kelupe soils the dominant clay mineral was in each case muscovite. The two soils from this location, which were found by the materials engineers working on the adjacent Sarikei-Binatang road to be lower grade materials than the two weathered shales (see Table 10, p. 53), had relatively higher clay contents, including a considerable proportion of disordered kaolinite.

A fuller description of the mineralogy of the soils and its relation to their physical properties is given elsewhere.[28]

APPENDIX 2

SUITABILITY OF SOILS FROM NORTHERN BORNEO FOR STABILIZATION WITH PORTLAND CEMENT

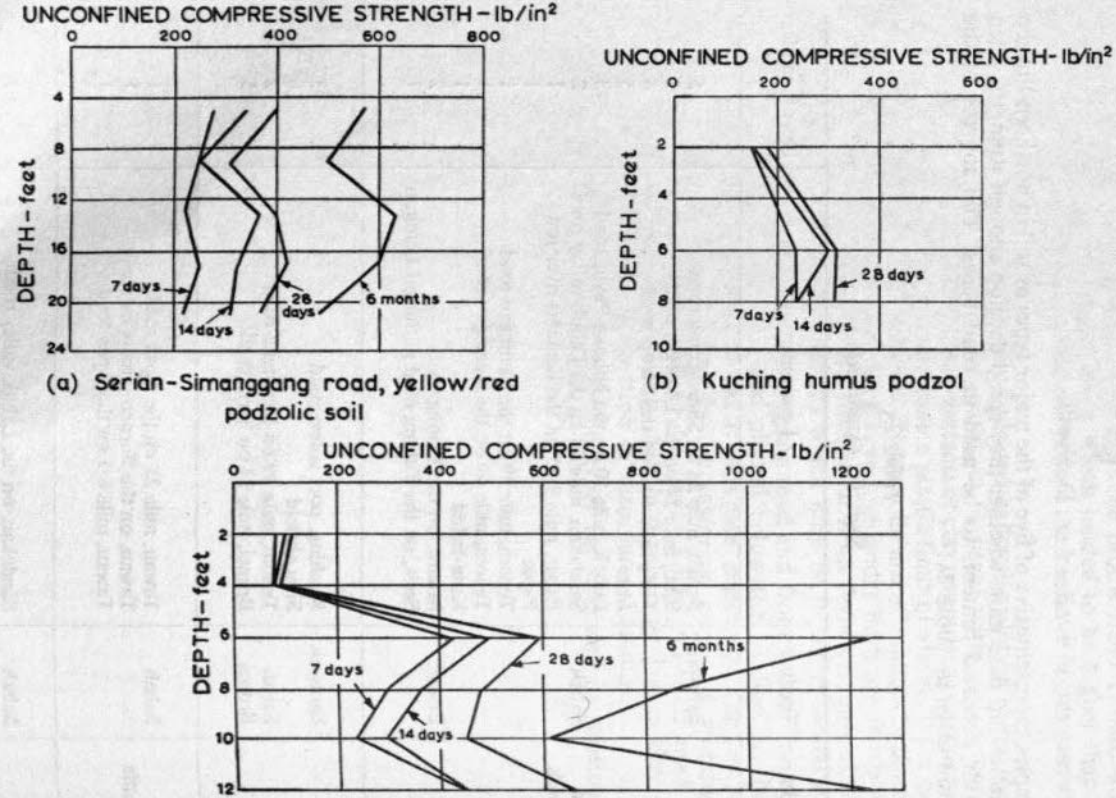
by

D. Newill

Fifty samples representative of five of the major types of soil in northern Borneo were examined to determine whether they could develop enough strength, when mixed with Portland cement, to be used in road bases. The sources of the samples are given in Table 2A.

Table 2A
Samples examined

Soil type	Territory	Location	No. of samples
Yellow/red podzolic soils	Sarawak	Serian, mile 24 on Simanggang road	5
		Sibu, mile 24 on the Ulu-Oya road	1
		Miri, mile 10·5 on the Berop road	4
		Miri	5
		Lubok, mile 10 on the Nibong-Puyut road	3
	Sabah	Sandakan, mile 30 on the Labuk valley road	2
		Papar, mile 9·25 on the Kimanis river road	1
		Papar	1
		Tenom, mile 39 on the Keningau road	1
		Tenom, mile 40 on the Keningau road	1
		Kota-Belud	1
	Brunei	Muara, on the Tutong road	2
		Seria, on the Tutong road at Sungei Liangon	1
Humus podzols	Sarawak	Kuching, port access road	3
		Sibu airfield	6
	Sabah	Tenom, mile 39 on Keningau road	2
	Brunei	Brunei, mile 34 on Seria road	5
Soils on volcanic tuffs	Sabah	Tawau, mile 21 on the Apas road	1
		Tawau, on the Borneo Abaca Estate	1
		Tawau, mile 8·5 on the Apas road	1
Lithosols	Sabah	Sandakan, on the Labuk valley road	1
	Brunei	Muara, on the Tutong road	1
Alluvium	Sabah	Lahad Datu	1



(a) Serian-Simanggang road, yellow/red podzolic soil

(b) Kuching humus podzol

(c) Sibu humus podzol / white silty sand

FIG. 1A. Variations of unconfined compressive strength with depth at different ages for three of the profiles examined

Experimental technique

Soil-cement mixtures were prepared containing 5 per cent of cement by weight, and at moisture contents giving the optimum values for compaction, judged by the consistency of the mix. From each mix of approximately 400 g, 6 to 8 specimens (1 in in diameter and 2 in high) were prepared. The specimens were compacted at dry densities chosen to give air contents of 5 and 10 per cent for the clayey and sandy soils respectively. The specimens were coated in wax and stored at 25°C. Unconfined compression strength determinations were made at ages of 7, 14 and 28 days, and in most cases also at an age of 6 months. Progressive increase in strength with age was taken to indicate satisfactory hardening, and the numerical values of strength were judged in the light of previous experience with similar soils elsewhere.[95]

Results and discussion

Yellow/red podzolic soils. Twenty samples from five profiles were examined, together with individual samples from eight other sites. Twenty-five samples were found to develop adequate strength; four of the five profiles contained suitable soils at all levels, in one case down to a depth of 21 ft (Fig. 1A). Particularly satisfactory results were obtained with a sample from a pit on the Seria to Tutong road in Brunei, from which material has been used in successful soil-cement road construction.[34] A good 7-day strength was recorded, and hardening progressed at least up to an age of 6 months (Fig. 2A). Two samples from a profile in Brunei developed on shale gave low strengths. They had plasticity indices of 45 per cent, suggesting that difficulties might be encountered when mixing cement with soil in the field. A third sample giving a low strength was obtained from immediately below a humus podzol soil on the Tenom to Keningau road in Sabah, which may have been contaminated with deleterious organic matter.

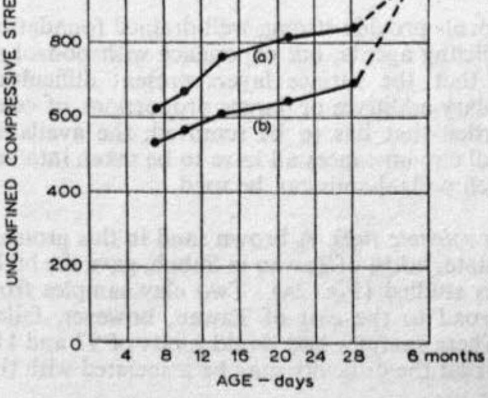


FIG. 2A. Strength/age relations for (a) a brown sand from Borneo Abaca Estate, Sabah, and (b) a yellow/red podzolic soil from Seria-Tutong road, Brunei

Gray[35] has earlier shown that yellow/red podzolic soils from two sites in Sabah develop adequate strengths when stabilized with cement, and the present results indicate that the suitability of this type of soil extends widely throughout the region.

Humus podzols and white silty soils. Sixteen samples from four profiles were examined. At only two sites—the port access road in Kuching and the airfield at Sibu—was soil found that was suitable for stabilization, and that was at depths of 6 ft and below. The unsuitability of the soil above this level is almost certainly caused by the presence in it of organic material which can retard or prevent the hardening of cement. Sherwood[96] has found that this contamination extends to a depth of about 4 ft in podzol soils in the United Kingdom.

With samples from a profile on the Brunei to Seria road, no hardening occurred at any level down to the 10 ft examined, and contaminating organic matter may also be present here. The soil is a uniformly-graded fine sand (Table 3A), difficult to compact to a high density, and hence it would be expected to yield a low strength on this score also.

Table 3A

Texture of humus podzol soils

Location	Sand (%)	Silt (%)	Clay (%)
Sibu airfield, Sarawak	65	20	15
Port access road, Kuching, Sarawak	40	50*	< 10*
Tenom to Keningau road, Sabah	30	50	20
Brunei to Seria road, Brunei	95	5*	—

* Total silt-clay contents measured, individual values estimated

The humus podzols provide strong, well-drained foundations and should mix readily with stabilizing agents, but experience with podzol soils in the United Kingdom shows that the surface layers present difficulties in stabilization, even when secondary additives or larger proportions of cement are used. The depth of overburden that has to be removed, the availability of alternative materials and local circumstances all have to be taken into account in assessing the extent to which podzol soils can be used.

Soils formed on volcanic tuffs. A brown sand in this group, from a pit on the Borneo Abaca Estate, north of Tawau in Sabah, gave the highest 7-day strength of all the samples studied (Fig. 2A). Two clay samples from different points along the Apas road to the east of Tawau, however, failed to develop any useful strength. These samples had liquid limits of 97 and 117 per cent respectively, suggesting that the difficulty may be associated with the very fine texture of the soil.

Lithosols. Two samples of black weathered shale were examined; because the rate of hardening when cement was added was very slow, the materials are not regarded as being potentially suitable for stabilization. Whether the red weathered shales and weathered sandstones can be hardened satisfactorily remains to be established.

Alluvial soils. A brown silty sand from Lahad Datu showed no progressive hardening, probably because of the presence of deleterious organic matter, and is not considered suitable for stabilization.

Other experiments

A fuller account of the tests described above has been given elsewhere,[92] in which a description is included of measurements made of the velocity of ultrasonic pulses through soil-cement specimens.

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