Durability Aspects of Chemically Stabilized, Weathered Basaltic Materials for Low-Volume Road Base Construction

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The occurrence of premature distress of a lime-stabilized, weathered basalt that was used in the construction of a strategic low-volume road in northeastern Botswana prompted a comprehensive investigation by the Roads Department. The main objectives of this investigation were to determine the probable causes and mechanisms of the unexpected base failures and to assess the overall structural integrity of the road. The main findings of the investigation, which included pavement and surface condition surveys, in situ and laboratory materials evaluations, and a petrographic study of the weathered base course aggregate are presented in this paper. A significant finding of the study was that although the weathered basalt satisfied the standard classification and strength criteria for a stabilized base, the pavement was not durable enough to retain its structural integrity in the project environment. Factors that contributed to this shortcoming included: (*a*) the presence of altered or secondary clay minerals in the aggregate in excess of the recommended critical limit for the project climate, and (*b*) the occurrence of carbonation of the lime, which resulted in apparent reversion of plasticity and a lack of significant strength development in the material.The major conclusion of the investigation is that special attention should be paid during the design process to the assessment of durability, including the mineralogical composition and carbonation potential, of weathered basaltic materials, which could significantly influence their in-service performance.

Road network planning in Botswana is influenced to a great extent by the country's large size (582 000 sq km, which is approximately the size of France), its low population of 1 million (it is one of the least densely populated countries in the world), its central, land-locked location in southern Africa, and its physical characteristics (predominantly flat, sandy terrain, semi-arid subtropical climate, and erratic rainfall).

Road communications are still poor between the eastern and western parts of the country. However, the provision of a basic transport infrastructure has been a high priority for the Government. This policy is aimed at providing an adequate road network to enable the scattered and often remote rural communities to contribute to and participate in the country's development process.

In spite of the rapid increase in the length of bituminous-surfaced roads in recent years, unsurfaced roads still represent a very large proportion (about 80 percent) of the total gazetted road network of just over 8000 km. Many of the unsurfaced roads carry light (<200 vpd) but nationally important traffic and require four-wheel drive vehicles, particularly in the sandier areas in the west of the country.

Maintenance of the unsurfaced roads is inordinately high because of the paucity of suitable, naturally occurring gravels in much of the country. This factor, coupled with the very high costs of vehicle operation on such roads, often makes it cost-effective to surface them at relatively low traffic levels (<200 vpd).

Thus, because of Botswana's large size, the geographic distribution of its small population, and the generally poor quality of road construction materials, per capita expenditure on the provision of an adequate road network is relatively very high. Such an expenditure has consistently absorbed, and will continue to absorb, a large proportion of the country's annual development budget (*1*). Under such circumstances, the greatest social and economic benefits at the least cost would be achieved by the construction of low-volume bituminous surfaced roads with proper regard to the prevailing traffic and climatic conditions and the availability of local resources and materials.

Road Construction Materials

The surface geology of Botswana is generally characterized by rather poor road construction materials. In the western and central areas of the country, kalahari sands and calcrete (a pedogenic material of variable quality) predominate, and along the eastern edge, ancient metamorphic and volcanic rocks are exposed in a broad belt (see Figure 1). The latter rocks are believed to be some of the oldest in the world with ages estimated between 2,700 and 3,500 million years; not surprisingly, they exhibit varying degrees of weathering (*2*).

Local Design Methods

Design traffic levels hardly exceed 0.5 million equivalent standard axles (E80s) in low-volume road construction. The Botswana Road Design Manual (BRDM) specification for pavement layer requirements for low-volume roads is based on the well-established United Kingdom Transport and Road Research Laboratory's (TRRL) Road Note 31 and the South African TRH4 methods (*3, 4*). The BRDM also includes less stringent criteria for design of traffic volumes below 0.2 million E80s based on experimental work performed by TRRL and others on calcrete bases (*5, 6*). The design criteria that were specified for a selection of basic pavement layer requirements are listed in Table 1.

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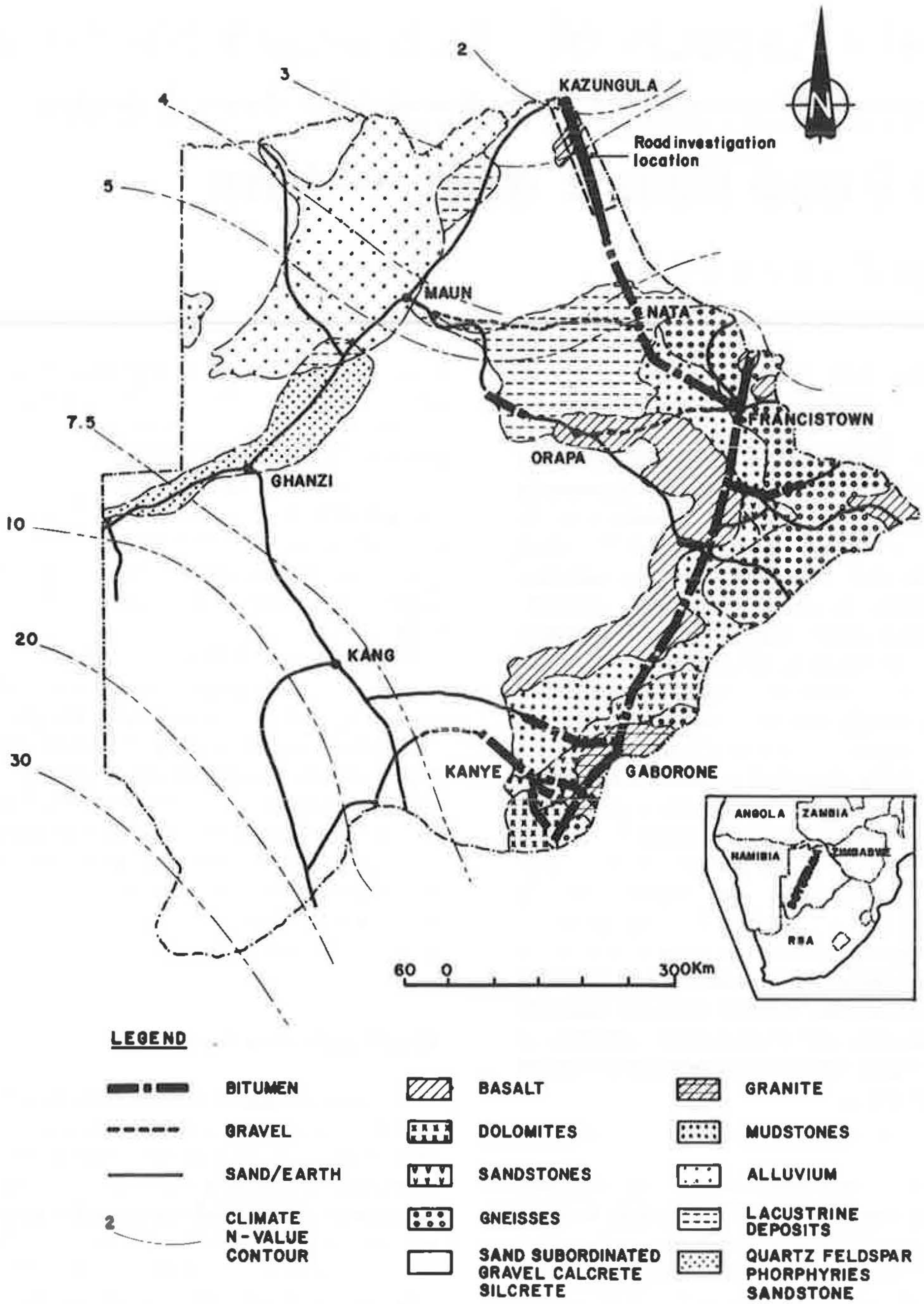


FIGURE 1 Simplified geological map of Botswana including road network and climatic N-values.

TABLE 1 PAVEMENT LAYER REQUIREMENTS FOR LOW-VOLUME ROADS IN BOTSWANA

	100,000 E80s		200,000 E80s		500,000 E80s	
Test	Base	Sub-base	Base	Sub-base	Base	Sub-base
Minimum grading modulus	1.1	-	1.5	-	2.0	-
Maximum plasticity index (%)	25	20	15	20	6[a]	15
Minimum of 4 days	50	25	60	25	80	25
Soaked CBR (%)	98	95	98	95	98	95
At minimum field density	MOD AASHTO	MOD AASHTO	MOD AASHTO	MOD AASHTO	MOD AASHTO	MOD AASHTO

[a]In low rainfall areas, an increase in the plasticity index is permitted provided the specified plasticity modulus is complied with.

Utilization of Materials

Because of the marginal quality of materials along the road corridor, it is normally considered a cost-effective and expedient practice in low-volume road construction to resort to in situ chemical stabilization. This practice has already been adopted on more than half of the road network in Botswana. In recent years, however, there has been growing concern, and indeed evidence, not only in Botswana, but elsewhere in southern Africa, of the lack of durability of lime-stabilized pavements, which has often resulted in the occurrence of premature distress in many roads (*7*). However, the main reasons for this distress have never been fully ascertained.

Objective of Paper

The main objective of this paper is to report on the investigations of the premature failures that occurred on a recently constructed low-volume, lime-stabilized road in Botswana in which a weathered basalt was used. Attention is drawn to various factors associated with the construction of stabilized roads that can affect pavement durability and that should be carefully considered at both the design and construction stages.

PROJECT DETAILS

General

The 75-km section of road under consideration is located in northeastern Botswana and serves as part of the strategic north-south transit link that provides access to the northern part of the country, as well as to Botswana's northern neighbors (see Figure 1). Construction of this road was completed between October 1982 and November 1983. The existing gravel road was upgraded by the provision of a new base course and the addition of a wearing course of double bituminous surface treatment.

Climate

The average daily temperatures in the project area are a mean maximum of 33° C and a mean minimum of 20° C in summer and a mean maximum of 28° C and a mean minimum of 6° C in winter. The mean annual rainfall in the project area varies from approximately 585 to 685 mm, which places the road in an area of maximum rainfall for Botswana (350 to 700 mm range). Based on the contour map of climatic *N*-values for Southern Africa developed by Weinhert the road is located in a climatic region where *N* varies from 2 to 3.5 (*8*). These *N*-values are a quantitative expression of the "weathering climate," which greatly influences the mode and rate of weathering of igneous rocks.

Topography and Geology

The topography of the project area is generally flat and lies between 900 and 1000 m above sea level. The road alignment traverses mostly kalahari sands interspersed with deposits of calcrete at its southern end. At its northern end, sand-clays are interspersed with sections of expansive clays and numerous outcrops of basalt in varying states of decomposition.

Design and Construction Details

The dimensions of the road cross-section are shown in Figure 2. The pavement structure was designed according to the well-established TRRL Road Note 31 method to carry a traffic loading in one direction of 0.50 million E80s with an associated 20-yr nominal design life (*3*).

The suitability of the weathered basalt for use as base course was assessed on the basis of conventional classification and strength testing, including the effect of varying percentages of lime on the material's properties. Neither a petrographic study nor a durability test of the weathered aggregate was included in the testing program.

Selected, typical results obtained from the preconstruction laboratory testing program are given in Tables 2 to 4 as background information against which the results of the postconstruction investigations can be compared and evaluated.

Road Performance

Within 18 months after the road was opened to traffic, localized shallow base failures occurred in the outer wheel path (OWP) of the road at a number of locations apparently because the lateral shear was deformed. This was cause for concern in such a new road and prompted comprehensive investigations by the Materials Section of the Roads Department.

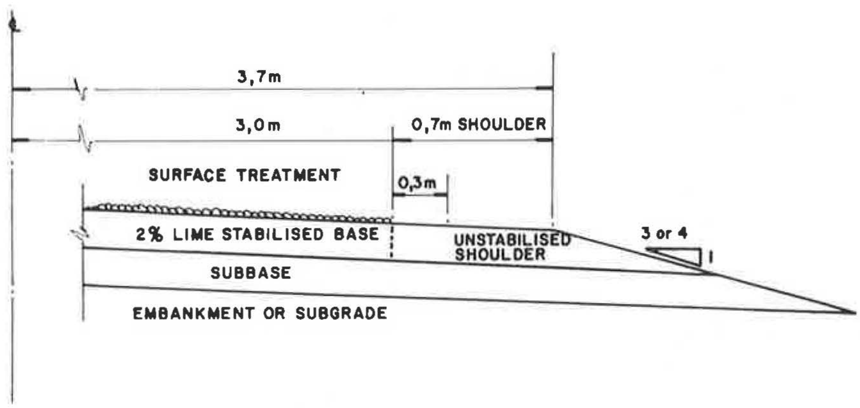


FIGURE 2 Road cross-section design and construction details.

TABLE 2 EFFECTS OF 1.75 PERCENT LIME OR PLASTICITY CHARACTERISTICS OF WEATHERED BASALT

Curing Period (days)	Liquid Limit			Plasticity Index			Linear Shrinkage		
Untreated	24	21	21	10	6	5	4.5	2.5	2.5
2	27	23	25	6	4	5	3.5	2.5	2.5
4	26	22	24	7	6	10	3.5	3.5	4.0
6			24	SP	SP	5	1.5	2.0	2.5

TABLE 3 EFFECTS OF LIME ON STRENGTH CHARACTERISTICS OF WEATHERED BASALT

	Strength (CBR %)/MC		Lab Compaction Data		
Percentage of Lime	4 days soaked	After 7-day cure	Mod AASHTO Dry density (kg/m^3)	Percentage of Compaction	MC
0.0	22/8.4		2,224	99.6	8.1
1.5	172/9.2	207/8.8	2,172	97.3	8.2
2.0	256/8.0	277/8.4	2,184	97.8	7.8
2.5	249/8.6	211/8.6	2,166	95.5	7.9

TABLE 4 TYPICAL PARTICLE SIZE DISTRIBUTION OF NATURAL SAMPLES AND SAMPLES TAKEN AFTER COMPACTION

Sample Condition	Sieve Size (mm) 19.0	13.2	4.75	2.00	0.425	0.150	0.075
Before compaction	100	94	72	55	39	28	30
After compaction	100	98	83	64	45	30	32

INVESTIGATIONS PERFORMED

Objectives

The main objectives of the road investigation were to

- Determine the nature and extent of the road failures,
- Identify the probable causes and mechanisms of failure,
- Assess the overall structural integrity of the road, and
- Recommend appropriate short- and long-term remedial measures to prevent or minimize the recurrence of failure.

Investigation Program

The main objective of the field investigation and laboratory testing program was to assess the general condition of the entire 75-km section of road pavement in terms of measurable parameters. This quantitative information was evaluated in relation to more comprehensive and detailed testing that was performed in the failed areas of the road and provided the basis for determining the most probable causes, mechanisms, and extent of pavement distress.

For logistic and economic reasons, the general field investigations were confined to the outer wheel path of the road and to the base layer of the pavement. However, in the failed sections investigations were performed over the full width of the carriageway extending to the subgrade.

Because conventional classification and strength tests are unable to assess the durability of pavement materials, which is governed by their mineralogical composition, particular emphasis was placed on this aspect of the laboratory testing program as well as on carbonation testing of the stabilized base. The field investigation and laboratory testing program are summarized in Figure 3.

RESULTS AND FINDINGS

Preliminary Investigations (Stage 1)

Traffic Loading

The results of the axle load surveys are summarized in Table 5 and Figure 4, respectively.

Although traffic volumes on the road are quite low, the incidence and magnitude of overloading are very high, a feature that is not uncommon on rural roads in many developing countries. More than 60 percent of all commercial vehicles were found to exceed the legal 8.2-tonne single-axle load limit and to account for more than 95 percent of all standard axles on the road. However, despite the disproportionately severe damage caused by commercial vehicles (mean E80/commercial vehicle of 21.8), this factor was not the primary cause of pavement

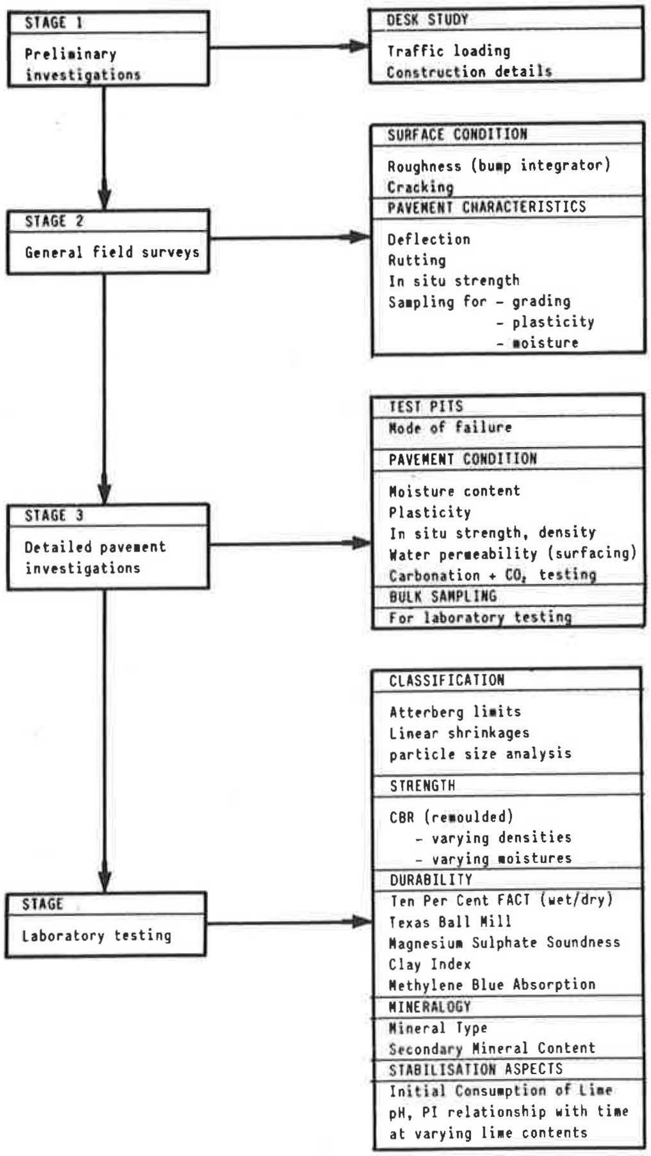


FIGURE 3 Field investigation and laboratory testing program.

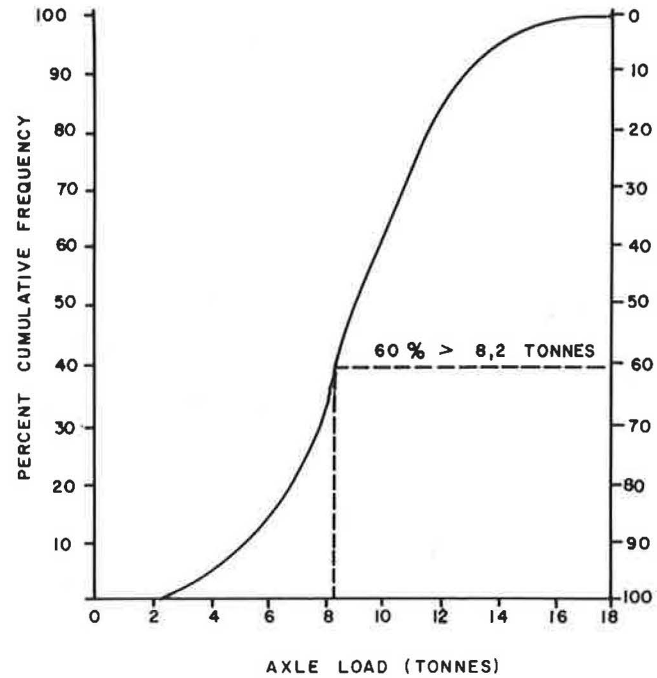


FIGURE 4 Distribution of axle loads.

failures in the lime-stabilized weathered basalt section of the road. Traffic and environmental conditions were similar on adjacent sections; however, when other base materials were used, there were no such failures.

General Field Surveys and Measurements (Stage 2)

Plasticity

The results of the plasticity index determinations performed in the outer wheel path of the road base are summarized in Figure 5 together with those obtained at the time of construction. Comparison of these results indicates that a dramatic reversion in plasticity of the lime-stabilized base course had occurred with more than 80 percent of all values exceeding the maximum specified limit of 8 percent. Such reversion of plasticity was contrary to the indications of the laboratory testing program (see Table 2).

Moisture Content

The results of the moisture content determinations performed in the outer wheel path of the road base are summarized in Figure 6. More than 35 percent of all such determinations were found to be higher than the equilibrium moisture content ratio (field moisture content (FMC)/optimum moisture content

TABLE 5 SUMMARY OF TRAFFIC COUNTS FROM 1982 TO 1985

	Annual Average Daily Traffic		
Year	Non-Commercial Vehicles[a]	Commercial Vehicles[b]	Total
1982	13	28	41
1983	22	36	58
1984	34	47	81
1985	34	59	93

[a]<5 tonnes gross vehicle weight.
[b]>5 tonnes gross vehicle weight.

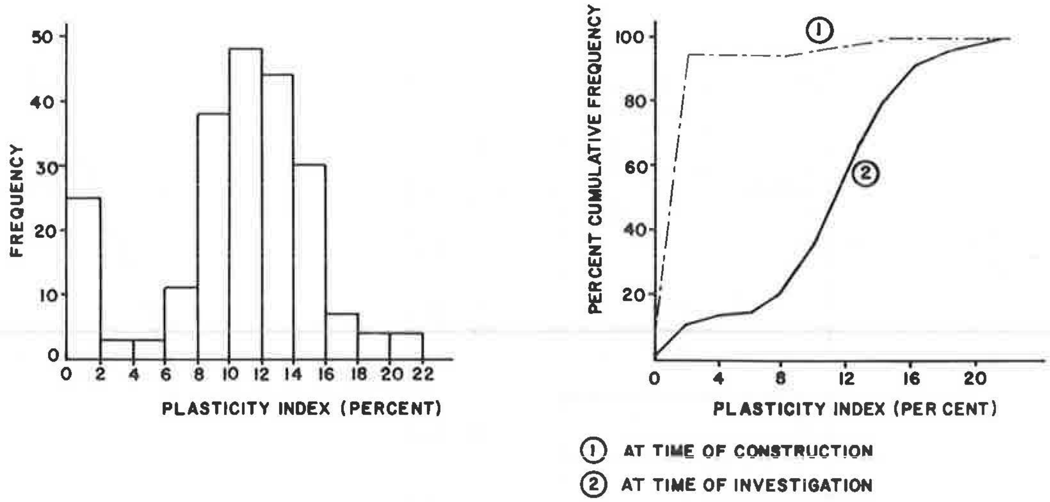


FIGURE 5 Results of PI determinations in weathered basalt base course.

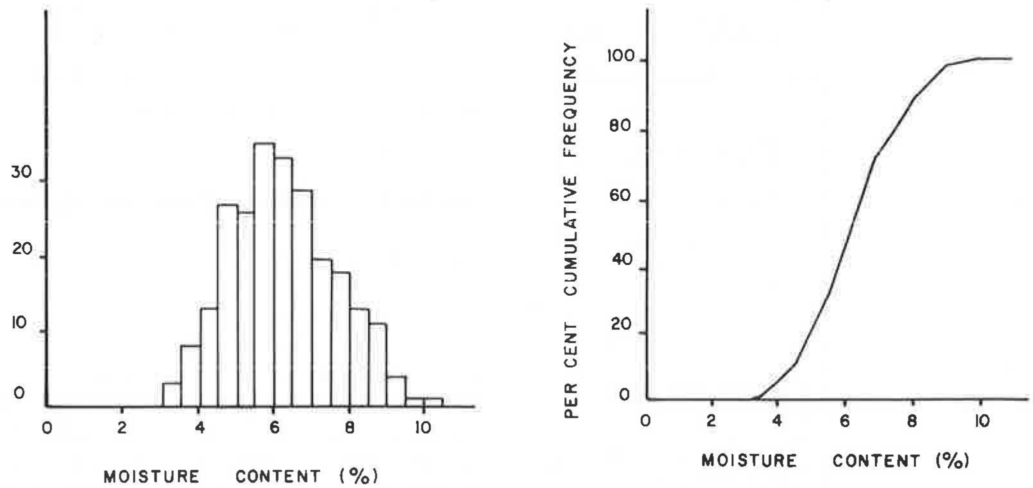


FIGURE 6 Results of moisture content determinations carried out in outer wheel path of road.

(OMC) of 0.6 to 0.7) that would normally be expected in the base layer of a pavement located in the project environment (*9*). In keeping with the particular suction/moisture content relationship that applies to the project climate, the higher moisture contents were generally found to occur at locations in which the material also exhibited high plasticity.

In Situ Strength

The results of a DCP survey that was performed to obtain a comparative indication of in situ pavement strength in the outer wheel path of the road base are shown in Figure 7. In situ values of CBR at the prevailing moisture content were obtained using the well-researched correlation between DCP and CBR (*10*). These results indicate that at more than 60 percent of all the locations tested, the in situ CBR of the base layer was below the specified service design value of 100 percent.

Summary of Results

For ease of comparison all the road performance parameters obtained from Stage 2 of the field investigation were plotted on a longitudinal strip plan of the road, as illustrated in Figure 8. The following general findings can be summarized from this figure.

1. The plasticity index, plastic modulus (PI times the percentage that passed the 0.475-mm sieve), and in situ strength (DCP CBR) of the pavement materials were highly correlated with pavement condition. These parameters all reflect the way in which the pavement layer responds to traffic in the project environment. The magnitude of the values obtained therefore closely reflects the degree and extent of pavement distress.
2. Pavement deflection was not found to be a sole, reliable indicator of pavement condition. This parameter was found to be more sensitive to subgrade support conditions than to the state of a particular layer in the pavement. In other words, it reflected the elastic state of the total pavement layer rather than the deformation state of a particular layer within the pavement.
3. Transverse deformation (rutting) was found to be highly correlated with, and hence a very reliable indicator of, pavement condition because it reflected the extent of layer deformation within the pavement.
4. Variation in surface roughness generally did not coincide with the variation in the structural condition of the pavement.

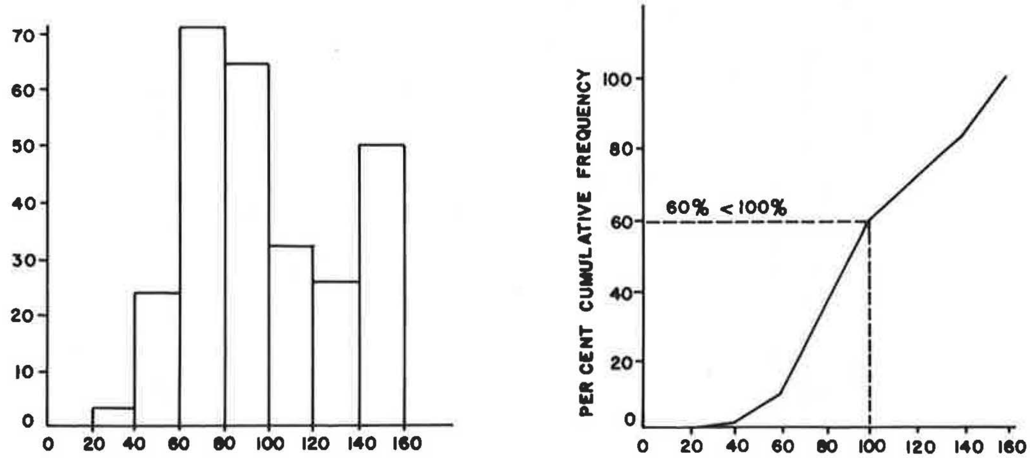


FIGURE 7 Results of DCP CBR determinations carried out in outer wheel path of road.

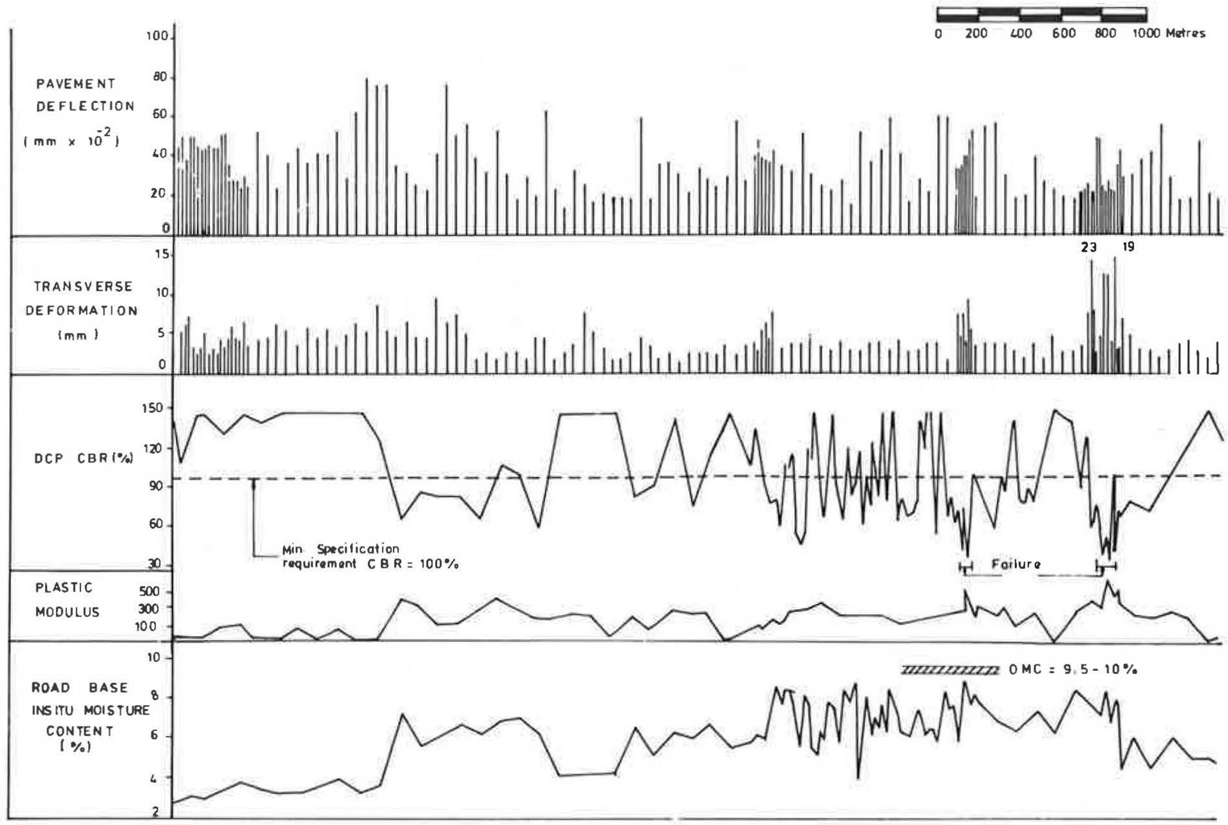


FIGURE 8 Longitudinal plot of results of field investigations.

Detailed Pavement Investigations (Stage 3)

Plasticity, Moisture Content, In Situ Strength, and In Situ Density

In order to compare and contrast in situ pavement conditions across the full width of the carriageway of the road, in both sound (middle section between inner wheel paths (IWP)) and failed (OWP) sections of the road, a full range of material properties were investigated in detail at a number of locations. These investigations were performed over 100-m sections along a 10-m by 1-m grid and the results are plotted in Figure 9.

A marked variation in pavement condition was found to exist between the center and edge of the road. Moisture conditions in the sound, middle section of the road were found to be approximately 50 percent drier than in the failed, outer wheel path and to mirror the variations in the road base strength for material that had a similar density and plasticity. The higher equilibrium moisture content (FMC/OMC) ratios of the failed outer wheel path sections are close to unity (i.e., optimum moisture content) and indicate an excess of moisture and a corresponding low strength below the specification requirement.

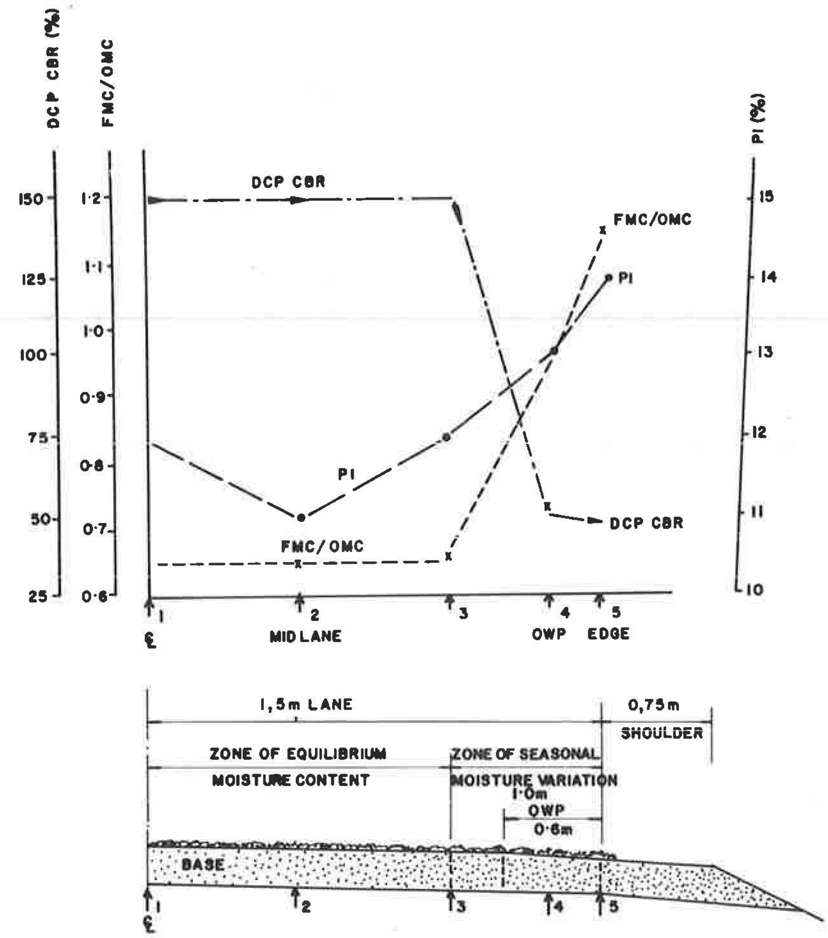


FIGURE 9 Effects of variation in moisture content on strength of decomposed basalt section.

Water Permeability

Falling head permeability measurements were performed to determine the extent of moisture penetration into the road pavement, either through the surfacing (double bituminous surface treatment) or in the shoulders. The results, which follow, are typical of those obtained from failed sections of the road in which the surfacing was still intact.

Permeability rating (litres/hour):

Surface	*Base*	*Shoulder*
0	1.0	0.4

The permeability results indicate that the surfacing is generally impermeable and that any moisture penetration into the outer wheel path of the road and zone of seasonal moisture variation was probably by way of the road shoulders.

Carbonation and Carbon Dioxide

In view of the suspected link between carbonation of stabilized bases and the associated lack of pavement durability, carbonation tests were performed in accordance with the rapid field procedure developed at the South African National Institute for Transport and Road Research (NITRR) (*11, 12*). In this method, the relationship between color changes of a phenolphthalein solution and the pH of stabilized soil was outlined to detect whether lime was present or not.

In all the sections tested, there was no change in color of the phenolphthalein solution that was sprayed over the full depth of the layer. This indicated that the pH of the material in this layer was less than 8.3 and, consequently, that the lime that was originally added had become carbonated. In other words, carbon dioxide from the atmosphere or the soil had reacted with the lime (calcium hydroxide) to form calcium carbonate. The presence of carbonate in the lime-stabilized base, which was not detected from chemical analysis of the natural (unstabilized) material, was confirmed by its effervescence with dilute hydrochloric acid. The results of numerous pH determinations that were performed in a number of failed sections are shown in Figure 10.

Carbon dioxide (CO_2) measurements were also performed at various depths in and below the road pavement in accordance with procedures developed at NITRR. The typical results are shown in Table 6.

The extraordinarily high CO_2 values that were recorded in the failed sections of the road base (up to 100 times higher than atmospheric CO_2) were all associated with carbonated material in a highly weakened state.

An important finding of this aspect of the investigation was that carbonation had occurred from the surface of the base

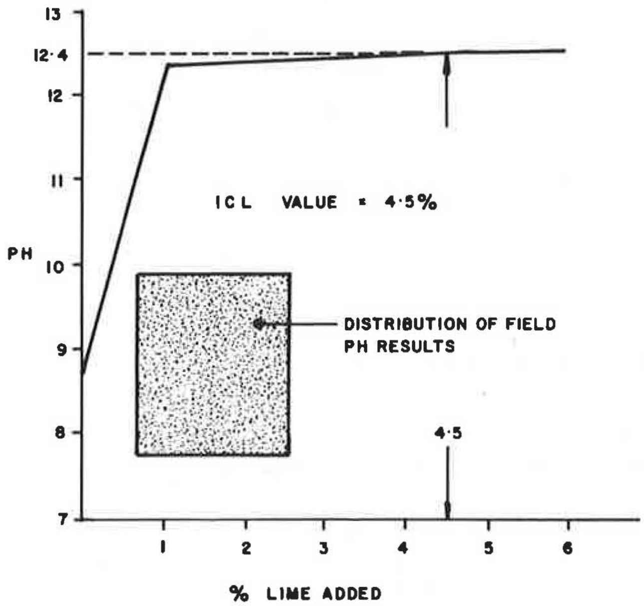


FIGURE 10 pH of lime-stabilized material in relation to its ICL value.

downwards and/or from the bottom of the base upwards, and that the entire 150-mm lime-stabilized base layer had become totally carbonated within 18 months, and probably well before.

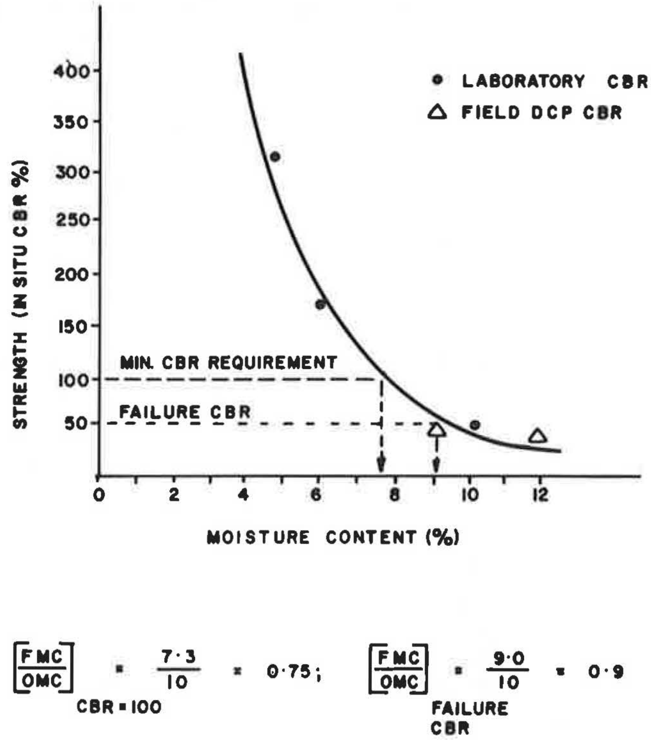


FIGURE 11 Strength/moisture content relationship for remolded base course samples.

Laboratory Testing (Stage 4)

Moisture Content and Strength Relationship

The effects of moisture changes on the bearing strength of representative base course samples were investigated at their field densities. The results of the CBR determinations at varying moisture contents (soaked OMC, 0.75 OMC, 0.5 OMC) are illustrated in Figure 11 and clearly confirm the sensitivity of the strength of remolded base course samples to moisture, as indicated by the results of Stage 2 of the investigation (see Figure 8).

Durability

A range of durability tests was performed to assess the soundness of the road base aggregates, particularly in the presence of moisture. Typical results of the wet/dry 10 percent Fines Aggregate Crushing Test (10 percent FACT) and the Texas Ball Mill (TBM) tests are given in Table 7.

The results of the 10 percent FACT and TBM tests together indicate the susceptibility of the weathered basalt aggregate to break down in the presence of water and to produce plastic fines.

Mineralogy

A petrographic study was performed on a number of representative samples of aggregate from both failed and sound sections of the road (*13*). This study included an examination of thin sections of the aggregates and x-ray diffraction analysis to determine their mineral type, secondary mineral content (SMC), and secondary mineral rating. In this analysis, secondary minerals were defined as those deleterious clay or clay-like minerals that originate from alteration of primary minerals and that are believed to be a principal cause of poor engineering properties (*14*).

The results of the petrographic study of the weathered basalt aggregates are summarized in Table 8 and indicate the presence of a large proportion of secondary or alteration minerals,

TABLE 6 RESULTS OF TYPICAL CO_2 MEASUREMENTS IN THE ROAD PAVEMENT

	Inner Wheel Path (CO_2 %)		Outer Wheel Path (CO_2 %)			
Pavement Condition	Base (Stabilized)	Subbase (Unstabilized)	Base (Stabilized)	Subbase (Unstabilized)	0.5m	1.0m
Failed	3.5	4.6	1.1	2.0	1.5	4.2
Failed	3.0	4.5	0.1	2.5	1.5	1.3
Sound	0.2	0.2	0.2	0.2	0.2	0.8
Sound	1.3	0.8	1.4	1.3	0.5	1.3

Note: Atmospheric CO_2 content is approximately 0.03 percent.

TABLE 7 RESULTS OF SELECTED DURABILITY TESTS

				TBM Values					
	10 Percent FACT (kN)			Original Sample		Dry Ball Mill		Wet Ball Mill	
Sample No.	Dry	Wet	Wet/Dry	P425	PI	P425	PI	P425	PI
A	265	165	0.62	30	10	34	15	34	14
B	290	145	0.50	26	11	31	12	33	12

TABLE 8 RESULTS OF PETROGRAPHIC STUDY OF WEATHERED BASALT AGGREGATE

	Secondary Mineral Content (%)				
Mineral Type	Sample No. (Sound Pavement)		Sample No. (Failed Pavement)		
	1	2	3	4	5
Primary					
Feldspar	11	14	9	9	9
Augite	6	10	5	5	4
Olivine					
Opaque ore	9	1	2	6	2
Glass/isotropic groundmass	48	59		9	7
Secondary					
Altered feldspar (clay minerals/chlorite)	7		14	5	13
Altered augite (clay minerals)	5	1		2	4
Altered olivine (clay minerals)	2	6	9	1	7
Devitrified altered (glass/groundmass)	8	8	54	56	52
Chlorite				1	
Geothite/limonite		1	1	3	1
Clay minerals	4		5	3	1
Secondary silica/chalcedony					
Voids			1		1
Percentage of secondary minerals	26	16	84	71	78
Secondary mineral rating	50	40	458	121	225

Note: Secondary Mineral Rating RSM = $[\Sigma(P.M)]\ T_R$ where P = percentage of secondary minerals; M = stability rating (2.0 for calcite to 10.0 for pure smectite); and T_R = textural or mineral distribution.

particularly from the failed sections of the road. The secondary mineral ratings of the aggregates in the failed sections were generally over 140, which, on the basis of investigation work performed on Australian basalts (*15*), would be considered to indicate a potentially unsound aggregate.

Stabilization Aspects

Initial Consumption of Lime and pH of Material The initial consumption of lime (ICL) value of the unstabilized material and the pH of the stabilized road base were determined for a number of representative samples. The results of these determinations are shown in Figure 10 and indicate two significant findings.

1. The ICL value of the material is comparatively high; it exceeds the critical value of about 3, which, for weathered basic igneous rocks, generally indicates a potential lack of durability and the need to satisfy the ICL value to achieve durability (*16*).

2. The amount of lime added (a nominal 2 percent), apart from being less than the ICL value of the material, was as a result insufficient to create a pH of about 12.4, which is necessary to sustain the strength-producing, lime-soil pozzolanic reaction (*17*).

Effects of Curing on PI and pH of Lime-Treated Samples The effects of curing on the plasticity of the lime fraction (passing a 0.425-mm sieve) of the weathered basalt were assessed at the nominal construction lime content of 2 percent and also at 5 percent lime, which was just above the ICL value of 4.5 percent for the natural material. The lime used in this aspect of the investigation was obtained from the same source as that used during construction.

After the lime was added, the soil mixture was brought to its approximate OMC by adding water and sealing it tightly in plastic bags to prevent loss of moisture. At intervals up to 90 days the PI, linear shrinkage (LS), and pH were carefully determined in triplicate. The results of this investigation, which

are shown in Figures 12 and 13, indicate the unstable nature of the modification reaction at the lime content below the ICL value of the material. The initial reduction in PI after curing for about 2 to 3 days to about 35 percent of the untreated value was followed by a subsequent increase that leveled out at about 60 percent of the untreated value. In contrast, at the lime content above the ICL, the PI was reduced to a slightly plastic condition that was maintained throughout the 90-day test period.

The interesting feature of these results is that in the case of 2 percent lime, the "initial state" PI value, which would have been obtained from the field quality control testing the day after compaction (i.e., after 2 to 3 days of curing), would have yielded acceptable values, which were in fact reported. However, these values would have been misleadingly low compared to the longer-term "equilibrium" plasticity of the material.

ANALYSIS, DISCUSSION, AND CONCLUSIONS

General

When the various results of the road investigation are considered, it is apparent that a number of interrelated factors were

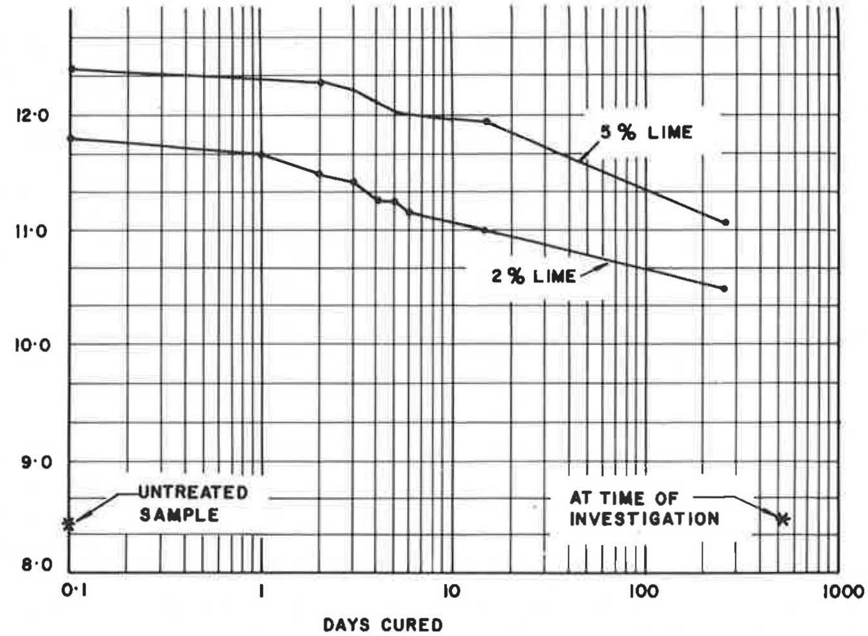


FIGURE 12 Effects of curing at various lime percentages on plasticity and linear shrinkage of weathered basalt sample.

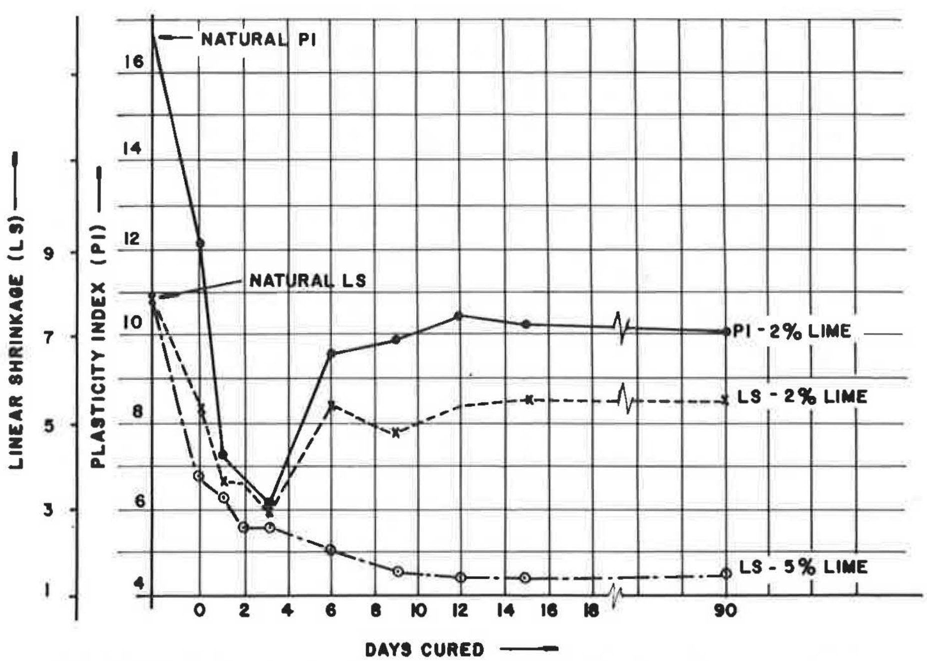


FIGURE 13 Effects of curing at various lime percentages on pH of weathered basalt sample.

contributing to the lack of pavement durability and consequent distress exhibited by the lime-stabilized, weathered basalt base course. These factors are discussed in the sections that follow.

Materials Properties

Mineralogy

The results of the petrographic study clearly confirmed that the basaltic base course material was highly weathered. Many of the alteration minerals that were identified, such as swelling chlorite, are highly unstable in the presence of moisture and would degrade to hydrophilic, montmorillonitic clays. As verified by the Texas Ball Mill test, such degradation would be expected to produce moisture-sensitive fines. In service, these hydrophilic fines would attract more moisture and thereby set up a chain reaction effect.

The mineralogical and chemical composition of the deleterious secondary minerals would also account for the high ICL value of the material in view of their high cation exchange capacity.

As indicated in Figure 14, the secondary mineral content of the basaltic base course material exceeded the recommended critical limit for the project environment. Thus, because of the moisture and temperature balance in the base layer, in which chemical activity is favored, weathering would be expected to proceed at a comparatively fast rate in the absence of effective cementation of the clay particles (*8*).

Plasticity

Despite the initial reduction in PI of the basaltic base course material that was indicated in both the laboratory investigations and quality control site tests, it is apparent that complete modification of the material was not achieved. This can be attributed to two factors: the high lime demand (ICL) value of the weathered basalt and the superimposed effects of carbonation.

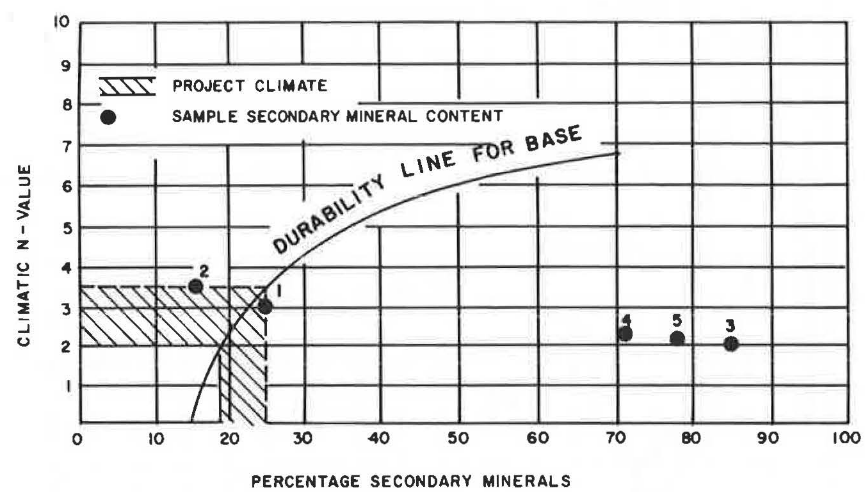
The gradual but sustained decrease in pH of the soil-lime mixture indicated in Figure 13 reflects the continued absorption of lime by the "degraded" clay minerals under laboratory conditions. It is evident that the high cation exchange capacity of the soil-lime mixture was not satisfied by the addition of only 2 percent lime relative to the "lime-fixation" or saturation value of 4.5 percent. Thus, full modification of the clay minerals could not have been achieved.

Inasmuch as the lime-stabilized, basaltic base course layer was shown to have carbonated, and to have reduced in pH to that of the natural material, it seems most probable that the eventual loss of lime was due, at least in part, to the effects of carbonation. As a result, the originally achieved partial modification of the weathered basalt would have been nullified. Consequently, a reversion to the basic characteristic properties of the clay would be expected in which high plasticity would be a dominant feature. This reversion of plasticity, which would appear to have occurred in the field, is considered to be directly responsible for the lack of stability that occurred because of the adverse environmental (moisture) conditions in the outer wheel path of the road.

Strength

Although the results of the laboratory soil-lime mixture showed the potential for an appreciable gain in strength of the weathered basalt at comparatively low lime contents, it is apparent that those results were generally not obtained or sustained in the field. As was the case with lack of achievement of permanent modification of the material, the two main factors probably responsible for this are insufficient lime and the effects of carbonation.

As was indicated earlier, because a small amount of lime was



NOTE : SAMPLES 1, 2 FROM SOUND PAVEMENT
SAMPLES 3, 4, 5 FROM FAILED PAVEMENT

FIGURE 14 Durability line for base course as related to climatic N-value and secondary minerals [after Weinhert (8)].

added to the base course, relative to its ICL value, insufficient stabilizer remained at the end of the modification reaction to achieve the strongly alkaline environment (pH>12.4) required to sustain the strength-producing pozzolanic reaction.

Even if there was sufficient lime for cementation purposes, if for example pockets of less weathered material were used, because of the time delay required to develop the pozzolanic reaction (which may be as much as a year (*18*)) and associated strength gain, the intervening occurrence of carbonation would retard, if not prevent, the development of such strength.

Durability

The potentially degradable, nondurable mineralogical characteristics of the natural weathered basalt were revealed by the results of the petrographic study and verified by its high ICL value. The lack of durability of this material in the presence of moisture was also verified by the results of the wet/dry 10 percent FACT in which there was a large degree of breakdown between the wet and dry strength values. Consequently, the material would be unlikely to be able to retain stability and integrity over years of exposure to the destructive forces of weathering in the project climate unless adequate means were adopted to ensure long-term cementation of its weathered soil constituents. That such means were not successful is therefore considered to be a primary factor associated with a lack of durability of the basaltic base course layer in the pavement. In addition, the effects of carbonation have exacerbated the durability problem that is often associated with weathered, basic igneous rocks.

Mechanism of Failure

Traffic loading and the effects of moisture are considered to be two of the most influential factors that affect the performance of the road for the given characteristics of the weathered basalt in the project environment.

Because the pavement failures were material-dependent, traffic is considered to have been subordinate in influence to the effects of moisture. Moisture conditions in the zone of seasonal variation, which unfortunately coincided with the outer wheel path of the 6-m road, are therefore considered to be the key factors controlling its performance.

The effects of moisture were detrimental to the performance of the base layer in a number of ways. Moisture acted as a weathering agent on the aggregate particles. It effectively lubricated interparticle contact, thereby causing large strains to occur in the material, and ultimately, at an FMC/OMC ratio above about 0.9, it caused a decrease in the shear strength of the base layer to a value below that required to resist the traffic-imposed stresses. Failure consequently occurred, which resulted in characteristic shallow base failures often associated with the use of degraded igneous materials such as basalt and dolerite (*19-21*).

Future Performance

Future performance of the road is primarily a function of time in relation to the effects of moisture on the basaltic base course layer. Because of the hydrophilic and expansive nature of the clay minerals in the base course, and their moisture-sensitive characteristics, it seems probable that progressive road failures will occur. Indeed, since completion of the investigations and the intervening rainy season, additional failures have occurred in those sections of the outer wheel path in which the FMC/OMC ratios were comparatively high.

The rate at which further failures will occur can be estimated from the prevailing moisture condition in the outer wheel path of the road. Field measurements indicated that approximately 15 percent of the road length was in a "critical" condition at the time of the investigation (i.e., at an FMC/OMC ratio associated with failure). Progressive failures along a further 12 km can therefore be expected in the near future. It is also probable that even the existing sound sections of the road are likely to eventually degrade as a result of gradual and sustained increases in the moisture content of the outer wheel path of the road. It is concluded, therefore, that a substantial proportion of the 75-km section of the road is unlikely to attain its 20-yr design life. Continual minor reconstruction and comparatively high maintenance expenditures will be required to keep the road serviceable.

Remedial Measures

Maintenance of a stable moisture condition in the outer wheel path of the road, at a moisture content below the "critical" value, will be necessary to ensure that adequate strength of the basaltic base course is sustained during its design life. Such a condition could have been achieved by sealing the shoulders at construction to ensure that the vulnerable zone of seasonal moisture variation fell outside the outer wheel path of the road.

In its present condition, a significant proportion of the basaltic base course in the outer wheel path is already above the critical moisture content value at which it can provide adequate shear strength. As a result, sealing the shoulders would only prove to be a successful measure if the existing high moisture content were to dry out and to remain below the critical value before the onset of any irrecoverable shear deformation. Whether this will occur or not is difficult to predict and should best be investigated by constructing trial sections of sealed shoulders and monitoring moisture content changes in the outer wheel path of the road. If the road dries out, then such remedial measures are likely to be successful in prolonging the life of the road; if not, then there is little else that can be done other than to drastically reduce the magnitude of axle loads on the road.

CONCLUDING SUMMARY

The results of the investigation have highlighted a number of factors of fundamental importance to the durability aspects of lime-stabilized, weathered materials, which can be summarized as follows:

1. Standard acceptance criteria that are based on classification and strength tests are insufficient to assess the durability of lime-stabilized, weathered materials, which is governed by their mineralogical composition.
2. Supplementary petrographic analysis and appropriate soundness tests, including the wet/dry 10 percent FACT and Texas Ball Mill tests, correlated well with performance. These

tests provided a reliable indication of service durability of the weathered basalt aggregate in the project climate and should be included as a required part of any laboratory testing program aimed at evaluating the durability of basic igneous rocks.

3. The effects of carbonation on the stabilization process were shown to have far-reaching consequences on the durability of the stabilized materials, particularly because they were weathered and of marginal quality. The occurrence of carbonation interfered with and largely nullified both the modification and cementation stabilization reactions, which resulted in a reversion of plasticity and a lack of significant strength development.

4. Unless special precautions are taken to minimize the effects of carbonation, the achievement of pavement durability is unlikely. Such precautions, which might include sealing the membranes of the stabilized layer to minimize ingress of carbon dioxide, will significantly increase construction costs but should nevertheless be taken into account during the design process.

5. Whenever moisture-sensitive materials, particularly weathered materials, are used in road pavements, the shoulders of such roads should be sealed to a sufficient width to ensure that the outer wheel path is kept away from the edge zone of seasonal variation. This practice will ensure that, other than in extreme environmental conditions, the entire carriageway width of the road base will be maintained at the comparatively low equilibrium moisture content ratio at which higher soil strength will prevail.

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