The Design and Construction of Low-Volume Roads in the Northwestern Sahara

JOSE CARLOS DE O.S. HORTA

Funding for low-volume roads is usually restricted. This is true in the Sahara, the greatest desert in the world. Long distances, scarce population centers, and low traffic levels accentuate the need for low-cost roads in the Sahara. Road engineers in the northwestern Sahara have met the challenge of building good roads with little money by taking advantage of specific features of the desert environment and questioning widely accepted specifications and construction practices. Infrequent rainfall and high evaporation rates represent the major advantage of desert environments for road engineers. Dry soils display high bearing capacities and require light pavement structures. A very wide range of natural materials, including highly plastic clays, can be used as pavement materials. Recommendations are provided for the selection and implementation of base materials in the northwestern Sahara. These recommendations are based on 25 years of experience in the Algerian Sahara and might prove useful for similar environments in other parts of the world. Eolian sand represents the major difficulty facing road engineers in desert environments. It forms dunes and sand seas called ergs that usually have awkward reliefs. Uniformly graded eolian sands display the lowest bearing capacities among the subgrade soils of bituminous paved roads in desert environments. Sand drifts should be controlled to prevent roads from being cut off and to maintain trafficability. Experience gathered in the Sahara and other deserts on sand drift control is reviewed. Design recommendations, simple maintenance structures, and practices are mentioned in connection with this problem. A discussion is also provided of the problems raised by eolian sand in connection with the construction of bituminous wearing courses. Other points discussed are drainage and shallow water tables, the effect of soluble salts on bituminous pavements, and possible savings of compaction water.

The Sahara covers an area of about 9 million km^2. In this huge country with a scarce, scattered population, the mostly very long roads represent considerable investments. Low-cost roads are a main requirement in this region perhaps more than anywhere else. The usually low traffic level of the Sahara does not justify high costs.

This situation is a challenge for road engineers concerned with building good roads in the Sahara. In the northwestern Sahara, the challenge was met by questioning widely accepted specifications and construction practices to take advantage of local materials and the specific features of the desert environment.

The bituminous paved roads that were constructed in the last 25 years, mainly by French engineers in Algeria, add up to a few thousand km and provide favorable evidence of the low-cost road technology developed in the northwestern Sahara. The technology discussed here is believed to apply to the region of the Sahara bounded by the Tropic of Cancer in the south and the Atlas mountains in the north, and extending from the Atlantic coast to Libya.

Louis Berger S.A.R.L., 71 Rue Fondary, 75015 Paris, France.

THE DESERT ENVIRONMENT

Climate

The desert environment may be defined by the annual mean precipitation. In northwest Africa, the isohyets of 100 or 50 mm are usually considered the boundary of the desert. These lines are close to each other and run along the foot of the Atlas mountain ranges. The very low precipitation allows substantial simplification of drainage. Costly appurtenant works, such as lining of ditches, herringbone and French drains, and pervious subbases that are of great importance in humid environments, are not necessary in deserts.

However, deserts are not simply characterized by the mean annual precipitation. The interannual variability of precipitation increases with a decrease in the average rainfall. In some parts of the desert, some years may be dry and one single shower may reach values as high as the mean yearly rainfall. The monthly precipitation usually falls in one single shower. As a result of concentrated precipitation and lack of vegetation, surface run-off may be as high as 30 to 40 percent and cause flash floods. Episodic surface run-off is difficult to predict.

It follows that it is not possible to do without drainage, even in deserts. Sufficient camber should be given to the pavement and shoulders in order to drain off precipitation rapidly. Run-off should not be obstructed, and culverts should be provided at every small channel or gully. Flash floods are particularly fierce at the foot of mountains; many case histories of road stretches being swept away have been reported. Bridges can be replaced in deserts by low-cost fords. However, both fords and culverts should have appropriate protection against scour.

The direct result of the extremely low yearly precipitation is the scarcity of water. Surface waters and shallow water tables are exceptional in desert environments. Ground water is usually very deep. Soaking of the subgrade does not occur except at a few particular places, such as depressions and basins with shallow water tables. Some of these places can be avoided by the road alignment and, if not, the pavement can be constructed on an embankment of suitable height.

The extremely low rainfall in the Sahara coincides with long periods of sunshine that cause extremely high potential evaporation. Evaporation ranges from 2000 to 6000 mm, which represents about 20 to 500 times the corresponding precipitation. As a result of high potential evaporation, desert soils exhibit very low water content and high strength. High evaporation concentrates salts in water and soil.

The relative humidity of the air in the northwestern Sahara drops to about 20 percent in the hot season and slightly exceeds 50 percent in the cool season. An additional peculiarity of the desert climate is the wide range of variation of temperature between day and night. This has implications on the bituminous binders that should have low thermal susceptibility. The development of thermal cracking has been witnessed in several instances, namely on a soil-bitumen pavement near Tamanrasset.

Vegetation

The scarcity of water and the low air humidity (except along the Atlantic coast) result in a very sparse plant cover of small shrubs that are usually dried out. Weeding and uprooting before earthworks is easily performed in the desert. Shrubs can be removed by hand or mechanically by blading. No topsoil needs to be removed.

Soils

The chemical weathering of rocks is negligible in deserts because of the scarcity of water. Mechanical weathering is caused by the wind and changes in temperature. Wind is the primary erosion and transportation agent in desert environments. It carries fine particles in suspension, and continuously shifts sand by saltation and surface creep.

Desert soils are lithosoils without humic horizon or topsoil. There is no clay neoformation in desert soils, but there is an accumulation of salts, which may have negative and positive effects. Calcium carbonate ($CaCO_3$) in Saharan soils is mainly inherited and formed during the pluvial periods of the Quaternary. Calcium carbonate is actually slightly soluble and requires significant amounts of water to be appreciably mobilized.

Gypsum ($CaSO_4{\cdot}2H_2O$) accumulates in most of the desert soils and is found in a more or less hydrated state called hemihydrate ($CaSO_4{\cdot}O{\cdot}5H_2O$), depending on the air and soil humidity. Gypsum is practically ubiquitous in desert soils. This salt has a relatively low solubility, and certain types of gypsum soils (gypcrete and gypcalcrete) can be used as pavement materials, if drainage is good. However, other soluble salts, namely halite or sodium chloride (NaCl), which is the most widespread, may damage the pavements, as is reported later. The soluble salts accumulate in shallow water tables and undrained basins and form crusts.

Other soils typical of deserts have an eolian origin. The wind may erode existing soils and carry away sand and fines. The remaining soil will show a high concentration of coarse elements on the surface. This type of soil is known as reg or desert pavement.

Eolian sand is present practically everywhere in desert soils. When pure, eolian sand forms dunes and sand seas, or ergs, which take up about 20 percent of the surface of the Sahara. Eolian sand is calibrated by the wind. Its size is a function of the wind velocity. Usual values lie between 0.15 and 0.30 mm. The grading curve of pure eolian sand is almost vertical. Desert soils are usually mixtures of different types of soils with eolian sand. They generally show an oversanded, gap-graded granularity with a characteristic sand hunch.

Terrain Morphology

Desert environments include all the types of relief found in more humid climates. The terrain surface of desert countries is to a great extent inherited from humid Quaternary paleoclimates. The terrain morphology changes very slowly under desert conditions. The wide development of dunes is typical of but not exclusive to deserts. The scarcity of water accounts for the stability of desert morphologies other than dune relief. The cohesion of dry desert soils is high, except for eolian sand. As a result, cuts can be constructed with vertical slopes and earthmoving costs can be decreased. However, eolian sand poses difficult problems for the road engineer. The problem of sand drift control will be discussed later.

The problem of wind erosion or deflation is not as acute as the former in the northwestern Sahara. Strong, sand-free winds might occur in very special conditions and could erode cohesionless sand embankments. Unprotected sand embankments could migrate under the action of wind, but this would not happen to cohesive or coarse materials. The latter represent a suitable protection against deflation when spread over sand slopes and surfaces.

The terrain morphology of the northwestern Sahara is generally tabular. As a result, alignments with small horizontal radii are exceptional and there is great latitude as to the location of the road alignment. This should be put to profitable use to bring the alignment nearer to the available deposits of road-building materials. Materials investigations should be performed sufficiently in advance of the final design toward this end.

EOLIAN SAND

Dunes and Ergs

Eolian sand in deserts forms individual dunes and dune seas, or ergs. The surface of ergs is relatively stable, but mobile dune fields exist in some places that are usually formed by barchans, or crescent dunes. These dunes may attain a height of 10 m and a diameter of 30 to 50 m. The barchans appear where the wind always blows in the same direction, and the wing tips indicate the wind and migration direction. In the course of their migration, barchans can cut off roads (Figure 1) if they are not readily fixed or destroyed.

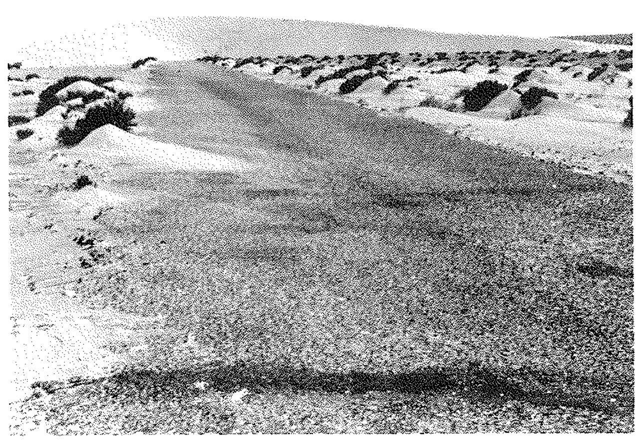

FIGURE 1 A migrating barchan has cut off the road from Laayoune to Bojador, 31.5 km from Laayoune.

Longitudinal undulating dunes appear where the wind blows from more than one direction. They are called siouf, which is the plural of seif. Small dunes form against obstacles. The nebkha, or shrub coppice dune (Figure 2), is smaller than the rebdou. The latter is more than 1 m in height and may grow 3 to 4 m high and 2 to 5 m long. Spaces free of dunes are called sahane if they are equidimensional and feidj if they are elongated like corridors. Many other types of dunes and dune assemblages have been described (*1, 2*).

The surface of the sand seas corresponds to a precarious aerodynamic equilibrium that should not be disturbed by earthworks if the road is to be kept free of sand drifts. However, winds loaded with sand blow everywhere in the desert and problems with sand drifts are not limited to the ergs and dune areas. Because wind energy is incommensurable with human capabilities, sand drift control should be based on the understanding of sand transport by the wind, the knowledge of the particular situations (topography and prevailing winds), and experiments (*3*). The problem of sand drift control should be studied at the design stage to minimize the number of drift-susceptible spots and later the maintenance costs. The techniques of sand drift control and snow drift control are basically the same (*4*). However, unlike snow, sand will not melt in the spring and under certain conditions can stockpile indefinitely.

Rules for Sand Drift Control

In order to avoid sand drift, the design should be based on a few rules. However, some situations will not permit compliance with some of the sand drift control rules; sand control structures and maintenance will have to intervene for these particular road stretches. Neglecting the sand drift control rules could have a significant effect on maintenance costs. The annual maintenance costs would rise and might exceed construction costs, as in the case of a road from the town of Laayaoune to its port.

The following rules should be observed for the location of the road alignment:

- Keep the disturbance of the ground surface to a minimum. The design speed should therefore be decreased to about 75 km/h in the dune areas.
- Preferably locate the road in regions that are free of dunes (sahanes and feidj), and bypass important sand massifs.
- Avoid mobile dune fields.
- Locate the road on regs and coarse sands instead of on surfaces that are covered with eolian sand.
- Avoid crossing dunes and, when unavoidable, select large passes, and locate the road alignment on ground normal to the length of the dune.
- In dune areas, locate the road close to the windward side and far away from the leeward dune slope. If possible, the distance between the road and the dune should be greater than two to three times the dune height.
- Cliffs should be climbed where they are free from sand and exposed to the wind.

The profile of the road should comply with the following rules:

- The gradeline should be raised 0.2 to 0.5 m above the adjacent ground level; soils can be borrowed along the alignment for this purpose.
- Avoid embankments that are higher than 2 to 3 m.
- Avoid cuts; cuts and transitions from cuts to embankments are most susceptible to drifting.

The wind accelerates and sand bounces easily above low embankments and hard pavement surfacing. However, if the embankments are high, the eddies at the windward slope will drop sand on the road. In the past, it was believed that the embankment height should be raised to the crest level of the highest dune, but this resulted in an increase in sand drift, namely in Algeria at National Road 1 between Ghardaia and El Golea.

Trenches and cuts tend to be invaded by sand, especially if they are oblique to the wind direction (Figure 3). Where cuts are unavoidable, their cross-section should be appropriately designed.

Aerodynamic cross-sections should have slopes $H : V \geq 4 : 1$ for embankments and $H : V \geq 6 : 1$ for cuts. Rounding the intersection of the slope with the shoulder would change these limits to 2 : 1 and 4 : 1, respectively. Aerodynamic cross-sections are supposed to be blown clear of sand.

Some authors have stated that cuts deeper than 6 to 8 m are not subject to snow drift (*5*). Deep cuts are usually not necessary in the topography of the northwestern Sahara. Where cuts are unavoidable (cliffs, for instance) the slope may be cut vertically

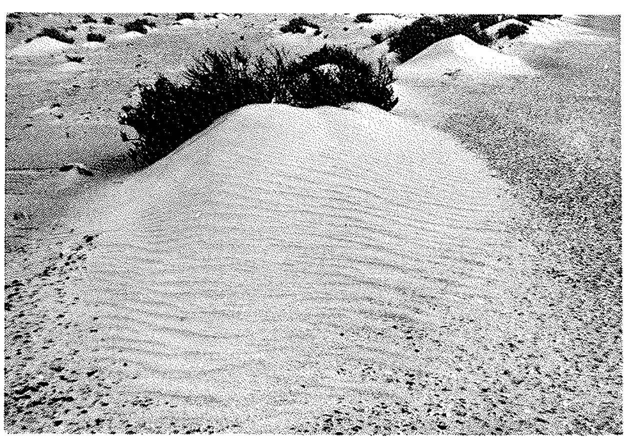

FIGURE 2 Nebkha dunes along the road from Laayoune to Bojador, 130 km to the south of Laayoune.

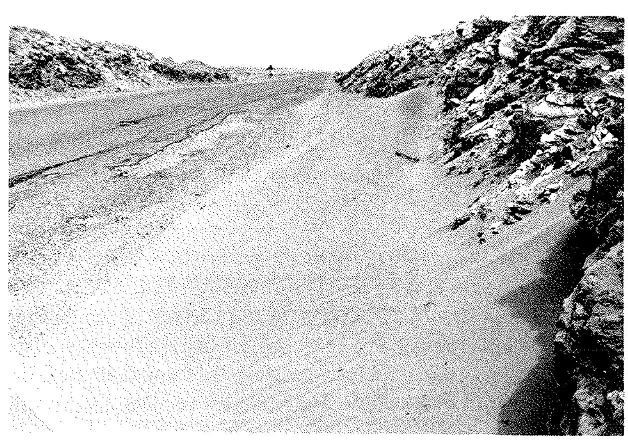

FIGURE 3 Cut section invaded by sand on the road from Tan-Tan to Laayoune, 150 km to the south of Tan-Tan.

and a platform for sand deposition may be provided at the foot of the windward slope. If H is the height of the slope, the width of the platform should be more than $1.2H$. High embankments on curved alignments should not have a downwind camber (*6*).

Another rule in connection with the cross-section is that the width of the road should be increased to a minimum of 10 m in dune areas. A large cross-section will allow traffic to pass, even after sand has drifted over one lane.

Two other sand drift control rules should be implemented during construction. In dune areas, materials should preferably be borrowed from the nearest dunes in such a way as to level them. After construction is completed, a strip 50 m wide along the road should be cleaned and leveled to eliminate any obstacles. If the wind blows from one side only it will be enough to level the windward side. If this rule is ignored, nebkhas and rebdous will invade the road (Figures 2 and 4). As shown in Figure 4, the roadsides have not been cleaned and leveled since completion, and rebdou dunes have formed against obstacles and are now invading the pavement.

Structures and Maintenance Practices to Control Sand Drifts

The maintenance practice for sand drift control comes down to transposing sand with earth-moving equipment. It is very simple, but the costs are high. It requires the use of permanent teams that are ready to intervene after each sandstorm or continuously in areas of migrating dunes. Some methods to stabilize and divert sand are needed to minimize maintenance costs.

Dunes can be stabilized by planting. This is an excellent method, but it requires a water supply. It could be contemplated locally where water is available at a low cost. Spraying the sand surface is another method of stabilization. Salt water can be used to form salt crusts. Bitumen emulsions would form a brittle, thin crust that would not bond with the underlying sand and that could be broken by animals and vehicles. Undermining and exposure of sand would result. Some other types of binders penetrate deeper, build flexible and self-healing protection, and allow vegetation to grow. Stabilization by spraying is expensive. It decreases the roughness of the surface, accelerates migration, and hinders the deposition of sand. Paving with gravel, stones, and cohesive soils is equivalent but cheaper.

The usual methods that are employed to stop sand are trenching, fencing, and panelling. Pannels can also be used to increase the wind velocity and divert sand, but after some time panels usually become covered by sand. However, they can allow maintenance to be programmed independently of sand storms. Trenches should also be cut periodically. Fences are relatively cheap and can be built with local materials, such as palm fronds (Figure 5). Kerr and Nigra recommended a three-fence system to guard against sand drifting (*6*).

The above-mentioned methods and structures can also serve to destroy migrating dunes when they are far enough from the road to be protected. Trenching disrupts the dune temporarily. Movable panels lead to the same result, but the panels must be watched and adjusted to avoid toppling (*7*). Differential stabilization of the dune surface by spraying or paving is the most effective procedure to scatter migrating dunes (*6*).

SUBGRADE SOILS

All the types of subgrade soils that are found in humid climates are also found in desert environments. Calcareous soils and gypsum soils, namely calcrete gravels (GE) and sands (SE) and gypsum sands (SY) and silts (MY), are very widespread in the northwestern Sahara (*8*). Chemical tests are required for the geotechnical identification of soils in this region. The carbonate content should be determined by reaction with hydrochloric acid and expressed as calcium carbonate content (calcium carbonate equivalent). The soluble sulphates content should be determined by reaction with barium chloride and expressed as gypsum content. These identification tests are run together with the Atterberg limits tests on the fraction passing the No. 40 sieve.

The main property of desert subgrade soils is the low water content. The natural water content is a function of the soil type. It is practically nil for cohesionless sands and gravels, around 2 percent for the most common soils, and up to 5 percent for high-plasticity clays (CH). With the exception of sections with water tables shallower than 7.5 m in some depressions and basins, the desert subgrade soils are practically dry and display high California bearing ratios (CBRs). The desert subgrade soils can be grouped in two classes: those with bearing ratios in excess of 20 percent, and eolian sand or uniform poorly graded sand. It is clear that the CBR of Saharan subgrade soils should not be determined on laboratory specimens after soaking.

FIGURE 4 Road from Tan-Tan to Laayoune, 132 km to the south of Tan-Tan.

FIGURE 5 Fences of palm fronds protecting gardens from sand drifts in the oases of In Salah.

Some authors recommend that the CBR be determined at the optimum moisture content (*9*). However, this still appears to be unrealistic in regard to Saharan climatic conditions. Actually, after compaction at the optimum moisture content, the subgrade dries and its bearing capacity increases. Hunt investigated water contents beneath two existing paved desert roads in Libya (*9*). The values found were considerably less than optimum, namely less than 1 percent in the region of Tripoli, and between 2 and 4 percent in the region of Kufra.

Design bearing ratios for desert subgrade soils can either be determined on laboratory specimens molded at low water contents or on specimens molded at the optimum water content and then dried. For this purpose, the drying time is usually 48 hrs, either in the ambient atmosphere or in an oven at 55 to 60°C.

As a result of the high bearing ratios of the Saharan subgrade soils, the total pavement thickness seldom exceeds 20 cm, and a subbase is not required. Another important result for low-cost roads is that any type of soil can be used for the subgrade. In order to decrease construction costs, both the embankment materials and the subgrade materials can be borrowed along the alignment and in the close vicinity of the road, without any previous selection. In this way, the pavement can be easily constructed on a shallow embankment without previous blading of topsoil, and cuts can be avoided.

BASE MATERIALS

Taking Advantage of Natural Materials

Many authors have stressed the importance of taking advantage of local materials. Tobin has stated that "the biggest financial savings in road construction can probably be made in the selection of pavement materials" (*10*). Humarau said that "the art of the engineer consists for a good part in discovering technologies that will make possible the use of the materials that he finds in the vicinity of the road works" (*11*). However, force of habit, inadequate specifications, and some negative experiences have opposed the use of local materials.

Experience in the previously French, but now Algerian, Sahara indicates that well-selected natural materials can perform as well as, and in some cases better than, stabilized materials such as sand-bitumen and sand-cement. Of course, the natural materials of the Sahara seldom meet the usually accepted base course specifications. But is it surprising that specifications developed under the conditions of humid countries would not work in the environment of the Sahara?

The natural road-building materials that are available in the northwestern Sahara will be reviewed and recommendations that were developed for these materials will be provided in the following sections.

Natural Gravels

Natural gravels in the northwestern Sahara are found as alluvial fans and slope debris. The former are usually rounded and the latter angular. Both usually have a certain amount of eolian sand and an over-sanded, gap-graded granularity. Well-graded natural gravels are exceptional. Natural gravels are usually hard and have a wide range of plasticity indexes.

Calcrete

Calcrete has been studied from the geotechnical point of view by Netterberg in Southern Africa and Horta in North Africa; it is known as caliche in America (*12, 13*). It is formed by the precipitation of calcium carbonate in soils under semi-arid climates.

Calcrete gravels are usually gap-graded and cannot be properly characterized by the Atterberg limits. They exhibit a very wide range of hardness values and their hardness is a function of the grain size. They have the property of self-cementation by dissolution and recrystallization of calcareous fines (*14*). Calcrete materials selection and specification should be based on the carbonates content determination and hardness tests such as the Los Angeles abrasion test (*13*).

Silcrete

Silcrete results from precipitation of silica in soils under particular climatic conditions. It may develop as concretions (Figure 6) and crusts. The former and the latter supply hard gravels upon dismantling that can be specified in the same conditions as natural gravels without any particular problem.

Gypcrete

Gypsum precipitation above shallow water tables results in soft, massive crusts known as gypcrete. Young gypcrete in contact with the water table is not suitable as a road-building material in the northwestern Sahara, but old gypcretes formed during past quaternary times have partially lost their hydration water in contact with the dry atmosphere and are in fact natural plaster mortars.

Old gypcretes may be borrowed as sands (gypsum sand or SY) or silts (gypsum silt or MY) and are composed of eolian quartz sand and gypsum fines. The plasticity index is not significant for proper selection and specification and the gypsum content should be determined. After compaction they provide very stiff pavements with deflections as low as 0.5 mm under a 130-kN wheel axle (*15*). In some regions calcrete and

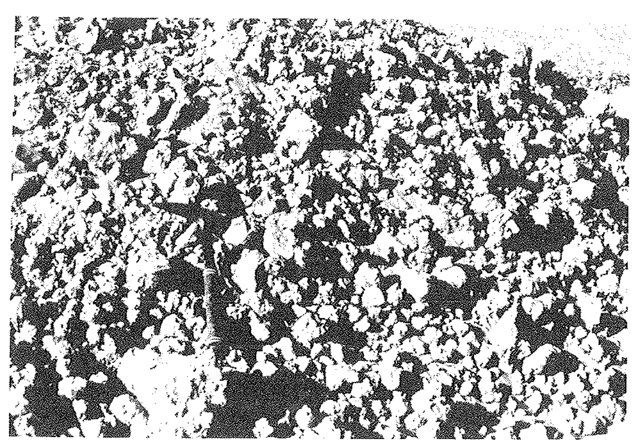

FIGURE 6 Concretionary silcrete gravel on National Road 1, about 75 km to the south of El Golea.

gypcrete are associated or superposed to form gypcalcrete. This type of material is as soft as gypcrete and should be specified by means of the previously mentioned chemical tests (*16*).

Gypsum is soluble and gypsum sand pavements cannot withstand soaking and flooding. The gypcrete pavement of National Road 48 in the Souf region of Algeria was flooded and collapsed once in 1968 to 1969. However, such floods are rare.

Highly Plastic Clays

Clays light in plasticity are not suitable as pavement materials because they are relatively pervious and may soak in a short time after showers. However, highly plastic clays have been used as base courses of bitumen-paved roads and runways (Figures 7 and 8). The calcareous, lateritic clay in the red clay borrow pit shown in Figure 7 was used in the base course of pavements of the airport of Reggane, including runways.

After excavation, the clay appears like a gravel composed of clay mottles of different sizes. This gravel should be quickly mixed with water and compacted with light rollers to avoid crushing. Time is insufficient to soak the mottles deeply after wetting and before the water evaporates. The soaked superficial shell binds the material.

Laboratory CBR tests indicate that the clay specimens that compacted immediately after wetting exhibit higher bearing ratios than the samples kept in plastic bags for 48 hrs after wetting and before molding in spite of lower dry densities (Figure 9). The optimum water content is lower for the former.

Clay bases require good drainage of run-off; for this purpose, the camber of the surfacing should be increased to 3 to 4 percent. This type of material, of course, performs less well than others.

FIGURE 7 Red clay borrow pit in Reggane.

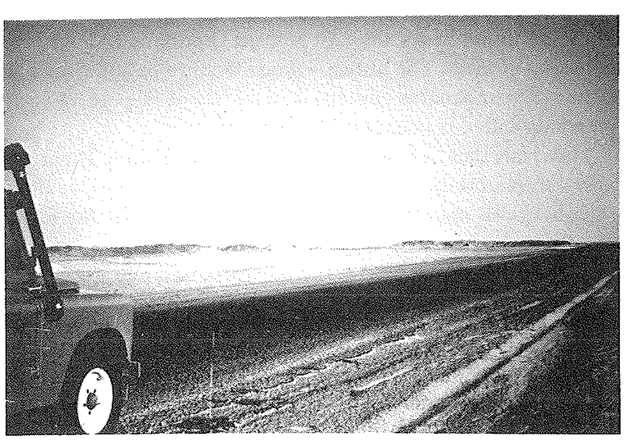

FIGURE 8 Red clay base course and borrow pit on National Road 6 in the vicinity of Sbaa and Adrar.

Classification and Selection of Base Materials

The classification and selection of natural base materials in the northwestern Sahara are based on the following laboratory tests: sieve analysis, Los Angeles abrasion test, carbonates content, soluble sulphates content, and Atterberg limits, W_P and W_L. The last three tests are run on the minus No. 40 fraction. The Los Angeles test should always be run on a specimen of grading A (*17*). Results on other gradings may not be comparable because the hardness of natural materials may be a function of the grain size.

The first selection criterion that should be taken into account is granularity, but this criterion is not restrictive. Materials of any granularity may be accepted as base course materials, provided that certain other conditions are met. The plot of the sieve analysis should be compared with the grading limits of Figure 10. These grading limits delineate three different areas that correspond to three geotechnical families. The grading limits given in Figure 10 are known as the Beni-Abbes grading limits and were introduced by a workshop on the Saharan roads held at that town (*18*).

Family II groups materials whose plots fall within the limits. Families I and III group materials whose plots fall below the lower limit and above the higher limit, respectively. If the plot intersects the lower limit, the material will be considered to belong to Family I. If it intersects the higher limit or both limits, the material will be considered to belong to Family III.

Family I Materials

Materials that belong to Family I do not require further testing. These materials always exhibit satisfactory hardness. Materials of this family are either debris and alluvial gravels with hard cobbles and boulders or calcrete with hardpan.

Gravels with boulders will require previous crushing or screening. Gravels with flat boulders and Los Angeles abrasion losses in excess of 25 percent, such as hardpan calcrete, can be crushed at a low cost by grid rolling. Some gravels without boulders will exhibit hollow granularities because sand fractions are lacking, and will intersect the lower grading limit. If the lack of sand is not compensated by an excess of fines, compaction and priming will be problematic. Gravels without boulders and with a lack of fines should be rejected if they show a sand hunch and are gap-graded. If they are well-graded, they are comparable to hollow-graded materials.

Family II Materials

Materials that belong to Family II are usually gap-graded because of an excess of sand. If the fines have a binding action,

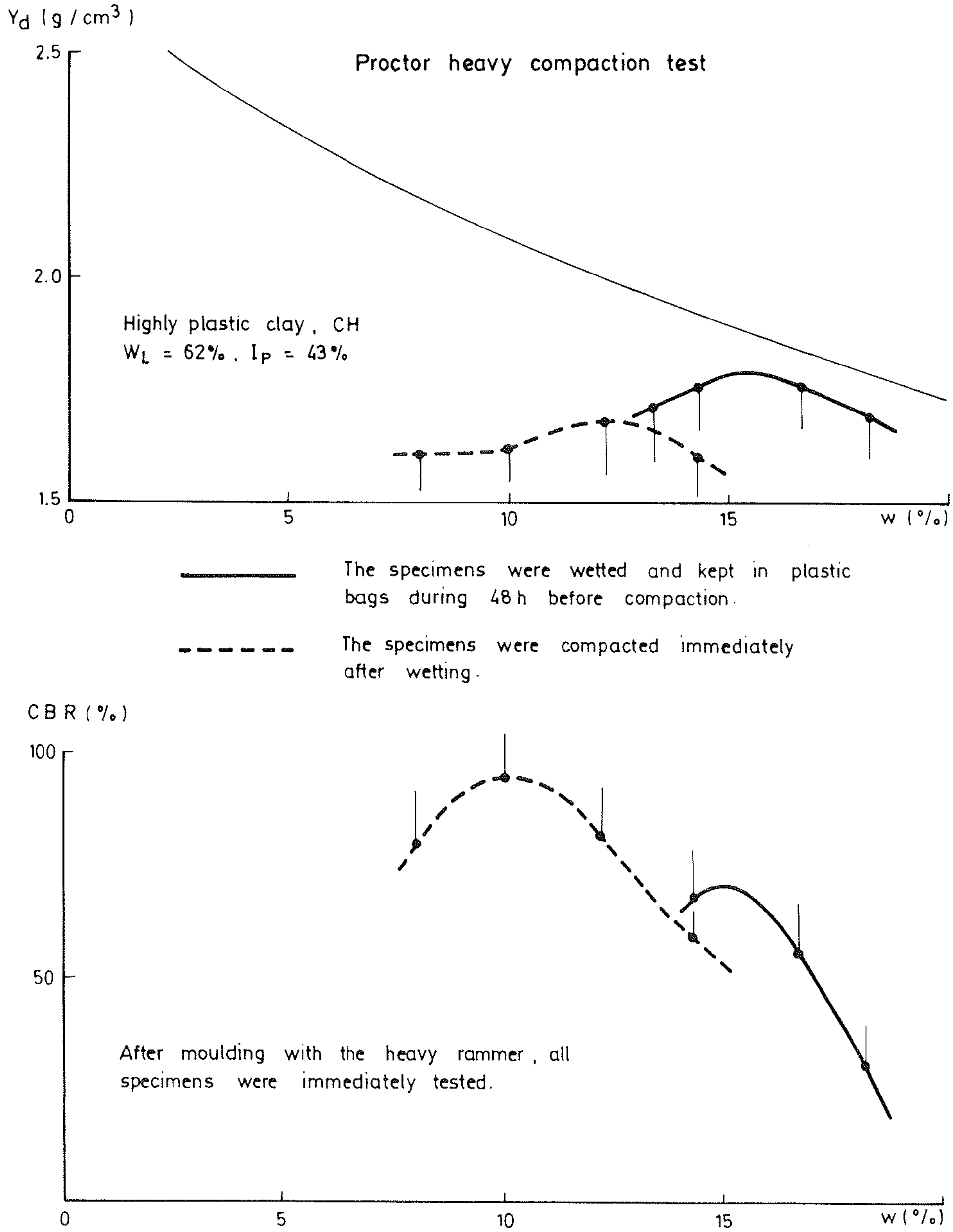

FIGURE 9 CBR of a highly plastic clay for different conditions of wetting.

the excess sand is not harmful. In the case of cohesionless fines, over-sanded and gap-graded gravels are unsuitable as base materials because they loosen after compaction upon drying.

Natural well-graded gravels are exceptional in the northwestern Sahara, but well-graded crushed stone can be produced with adequate equipment. Well-graded materials should have Los Angeles abrasion losses lower than 40 percent. Well-graded natural materials usually comply with this specification and the rocks and boulders subject to crushing should be selected on the basis of this requirement.

Over-sanded, gap-graded materials should also be tested for hardness. If the Los Angeles abrasion loss is 40 percent or more, they should be tested for the carbonates content and rejected if it is not in excess of 70 percent. This is the same criterion that applies to Family III materials. Its application to soft, evolutive gravels is equivalent to considering these as belonging to Family III.

Hard, gap-graded, over-sanded materials with Los Angeles abrasion losses lower than 40 percent should be tested for the cohesion of fines. The fines are considered to be cohesive when either the carbonates content is in excess of 20 percent or the plasticity index is in excess of 6 percent.

Materials that belong to the geotechnical Family II perform best. If materials that belong to this family are available together with materials that belong to Family III, the former should be preferred.

Family III Materials

Family III mainly groups sands and fine soils. Of the soils that belong to this geotechnical family, the following four types can be used as base materials:

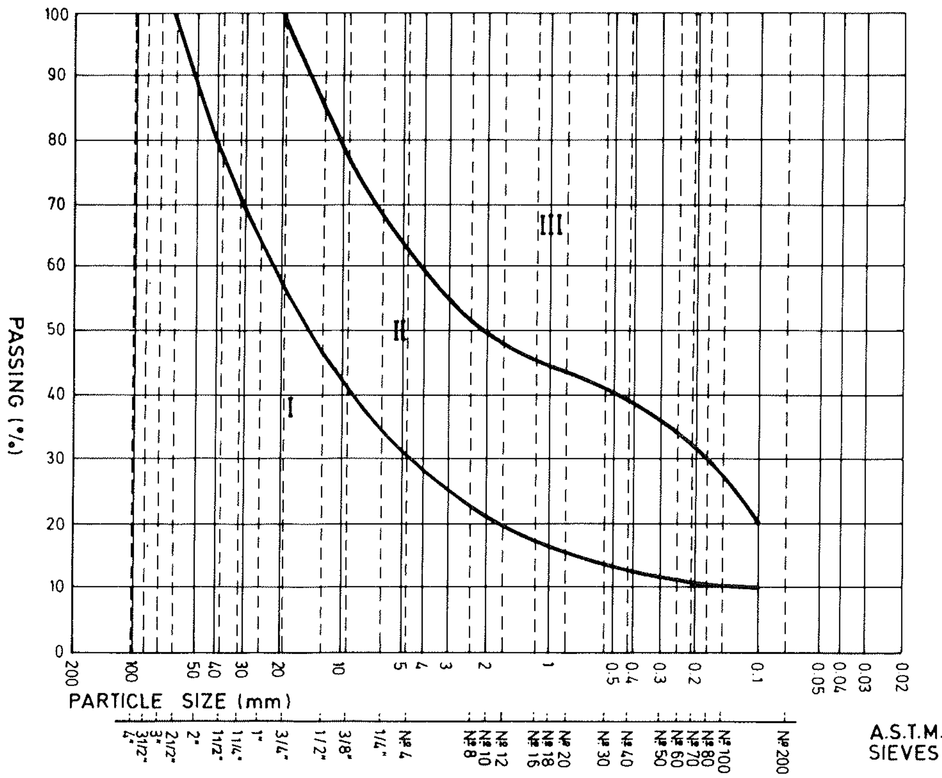

FIGURE 10 Grading limits for base course materials in the northwestern Sahara (Beni Abbes, 1965).

- Calcrete gravels and sands and calcareous fine soils (clays and silts) in which a carbonates content in excess of 70 percent is required;
- Gypsum sands and silts in which a gypsum content in excess of 70 percent is required;
- Gypcalcrete, in which case a total content of carbonates and soluble sulphates in excess of 70 percent is required; and
- High-plasticity clays (CH) that exhibit liquid limits in excess of 50 percent.

Checking the Strength

Some countries have specifications for the bearing ratio of base materials. The CBR should be in excess of 80 or 100 percent, depending on the traffic. The bearing ratios of materials that belong to Family II are usually not problematic. The strength of materials that belong to Family III may be checked by this test. However, the CBR test is not adapted to highly cohesive, stiff materials. In the Sahara, the strength of materials that belong to Family III is usually tested by means of the unconfined compression test on specimens 50 mm in diameter. The unconfined compression strength of materials of Family III should be in excess of 2.5 MN/m^2 after oven drying at 55 to 60° C for 48 hrs and in excess of 2.0 MN/m^2 after drying in the ambient atmosphere for 48 hrs. This recommendation should be considered as a check after selection by other tests as was recommended earlier.

The criteria for the selection of base course materials are summarized in Table 1 and their application is illustrated by the flowchart of Figure 11. The sieve analysis results should be plotted on the graph of Figure 10. Materials that belong to Family I can be accepted without further testing. If well-graded, materials that belong to Family II should exhibit a suitable hardness (Los Angeles abrasion loss <40 percent). As was previously stated, well-graded gravels are very uncommon in the Sahara. Family II materials generally exhibit a more or less accentuated sand hunch; in order to be accepted as base course materials, they should either be hard enough (Los Angeles abrasion loss <40 percent) or contain highly carbonated fines (carbonate equivalent >70 percent). The second condition eliminates sandstone gravels, not soft calcrete gravels. Hard, gap-graded gravels should be tested further for the binding action of fines. Materials that have a calcium carbonate equivalent of 20 percent or less and a plasticity index of 6 percent or less should be rejected.

Materials that belong to Family III should be tested for calcium carbonate and gypsum. Highly cohesive materials with more than a 70 percent calcium carbonate plus gypsum equivalent should be accepted. Materials that exhibit lower values of carbonate plus soluble sulphates content should only be accepted if their liquid limit is higher than 50 percent (highly plastic clays).

It should be emphasized that no upper limit is set to the plasticity index of base materials. Alluvial gravels with plasticity indices in excess of 18 percent have been successfully employed, but sometimes nonplastic gravels could not be used because of an excess of sand.

THE WEARING COURSE

All types of bituminous surfacings have been successfully used in the Sahara, including hot-mix, cold-mix, sand asphalt, and surface dressing. Wearing course thicknesses seldom exceeded 5 cm.

TABLE 1 CRITERIA FOR THE SELECTION OF BASE MATERIALS IN THE NORTHWESTERN SAHARA

Granularity		Los Angeles abrasion (%), grading A	Carbonates content, $CaCO_3$ (%)	Soluble sulphates content, $CaSO_4 \cdot 2H_2O$ (%)	Atterberg limits		Unconfined compression strength σ_R (MN/m^2)
					W_L (%)	I_P (%)	
Family I		n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
Family II	Well-graded	< 40	n.a.	n.a.	n.a.	n.a.	n.a.
	Over-Sanded Gap-graded	< 40	> 20	n.a.	n.a.	n.a.	n.a.
			⩽ 20	n.a.	n.a.	> 6	n.a.
		⩾ 40	> 70	n.a.	n.a.	n.a.	n.a.
Family III		n.a.	> 70	n.a.	n.a.	n.a.	>2.5 after 48h in the oven at 55–60°C
			n.a.	> 70	n.a.	n.a.	>2.0 after drying in the ambient atmosphere during 48 h
			$CaCO_3 + CaSO_4 \cdot 2H_2O > 70$		n.a.	n.a.	
			n.a.	n.a.	> 50	n.a.	

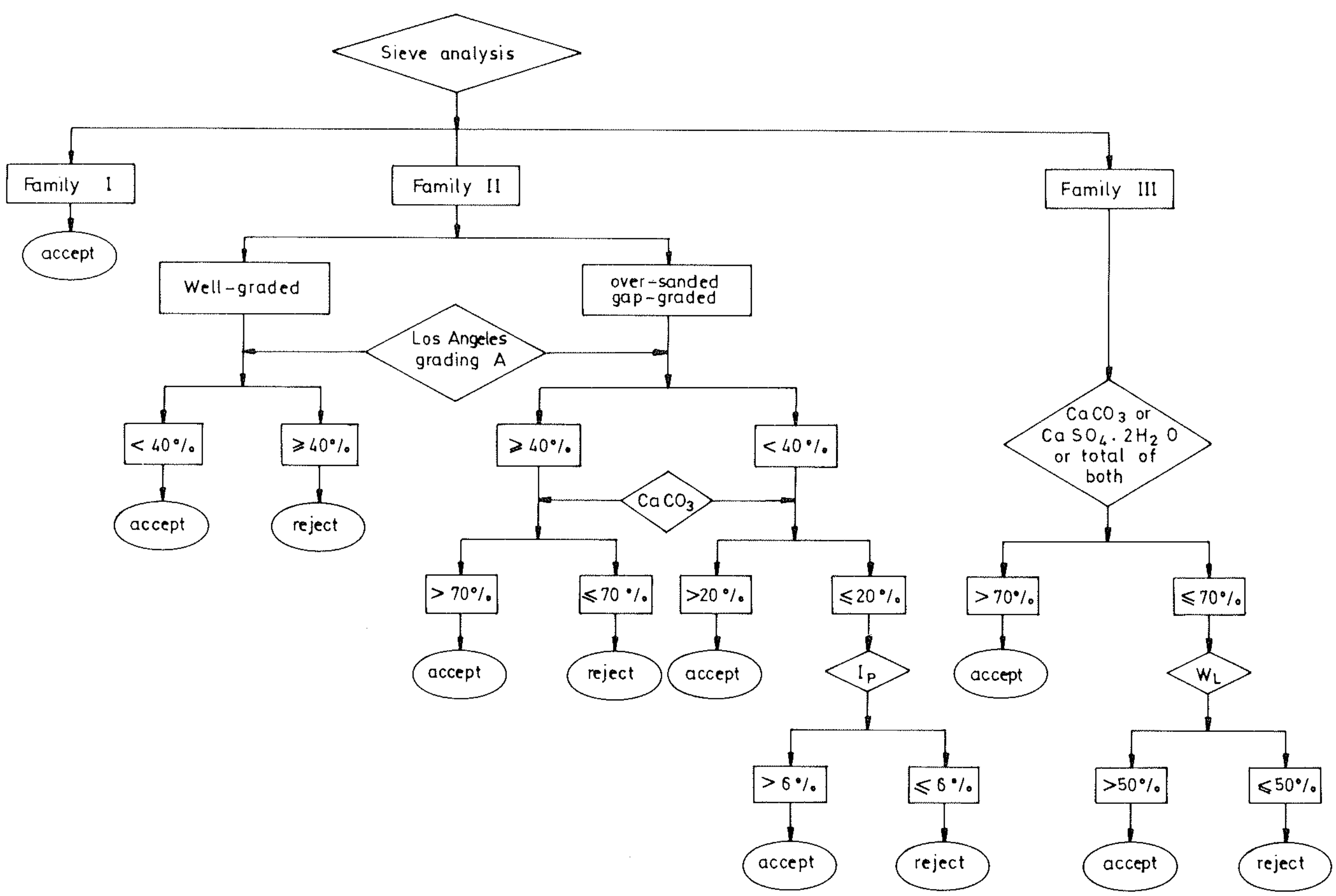

FIGURE 11 Flowchart for the selection of base course materials in the northwestern Sahara.

As a provision for the absorption of sand and dust carried by the wind, it is recommended that the bitumen content be increased. As a result, the surfacing will have the advantage of being flexible. Another advantage is the lower aging rate. Bleeding is not an important problem in the Sahara, because sand is available everywhere. Cold-mix wearing courses do not require seal coats in the Sahara. Their surface will be swiftly sealed by eolian sand.

An adequate binder for surface dressing is penetration bitumen. The viscosities of cut-back bitumens may be too low under the high temperatures of the Sahara and should only be used in the cool season. Emulsions risk premature setting because the chips are usually covered with dust and mixed with eolian sand. The successive sprayings of binder and spreadings of chips should be done without interruption to avoid pollution by sand.

The wearing courses of the desert roads are exposed to heavy erosion by sand-loaded wind. The differential erosion of softer bitumen exposes the harder chips to stripping by the traffic. Deflation over bituminous pavements may cause higher rates of wearing than traffic alone.

PAVEMENT STRUCTURES AND PERFORMANCE

The pavement structures in the northwestern Sahara are usually very light. Depending on the traffic, total pavement thicknesses of 15 to 25 cm are required by current design methods (*19*). The pavement full depth is generally constructed with materials that comply with the criteria discussed earlier. The embankment is compacted at natural water content, except the top layer. This layer usually has a high strength and, as previously discussed, a subbase is not required.

The road network of the Algerian Sahara, including more than 7000 km of bitumen paved roads is shown in Figure 12. Distance and some other problems prevented consistent monitoring of the Saharan road pavements. However, the prevailing opinion on the performance of the Saharan road pavements in Algeria is very positive (*20*). Maintenance has been restricted to sand drift control and resealing. In spite of traffic growth, pavement strengthening has not been contemplated.

Recent traffic figures of the Saharan roads in Algeria and the dates of construction, pavement materials, and visually surveyed condition are given in Table 2. The roads and count stations referred to in this table are shown in Figure 12.

The traffic on the Saharan roads is generally heavy to very heavy. About 80 percent of the traffic count stations display heavy traffic levels in excess of 30 percent; this rate exceeds 50 percent in a third of the count stations. It should be emphasized that the legal axle load in Algeria is 130 kN. Calcrete and natural gravels perform best as pavement materials and are able to carry high volumes of traffic.

In spite of hygroscopical cracks, the behavior of gypcrete pavements is good, provided that the subgrade water content remains low (*8*, *15*). This is not always the case for Road N3.

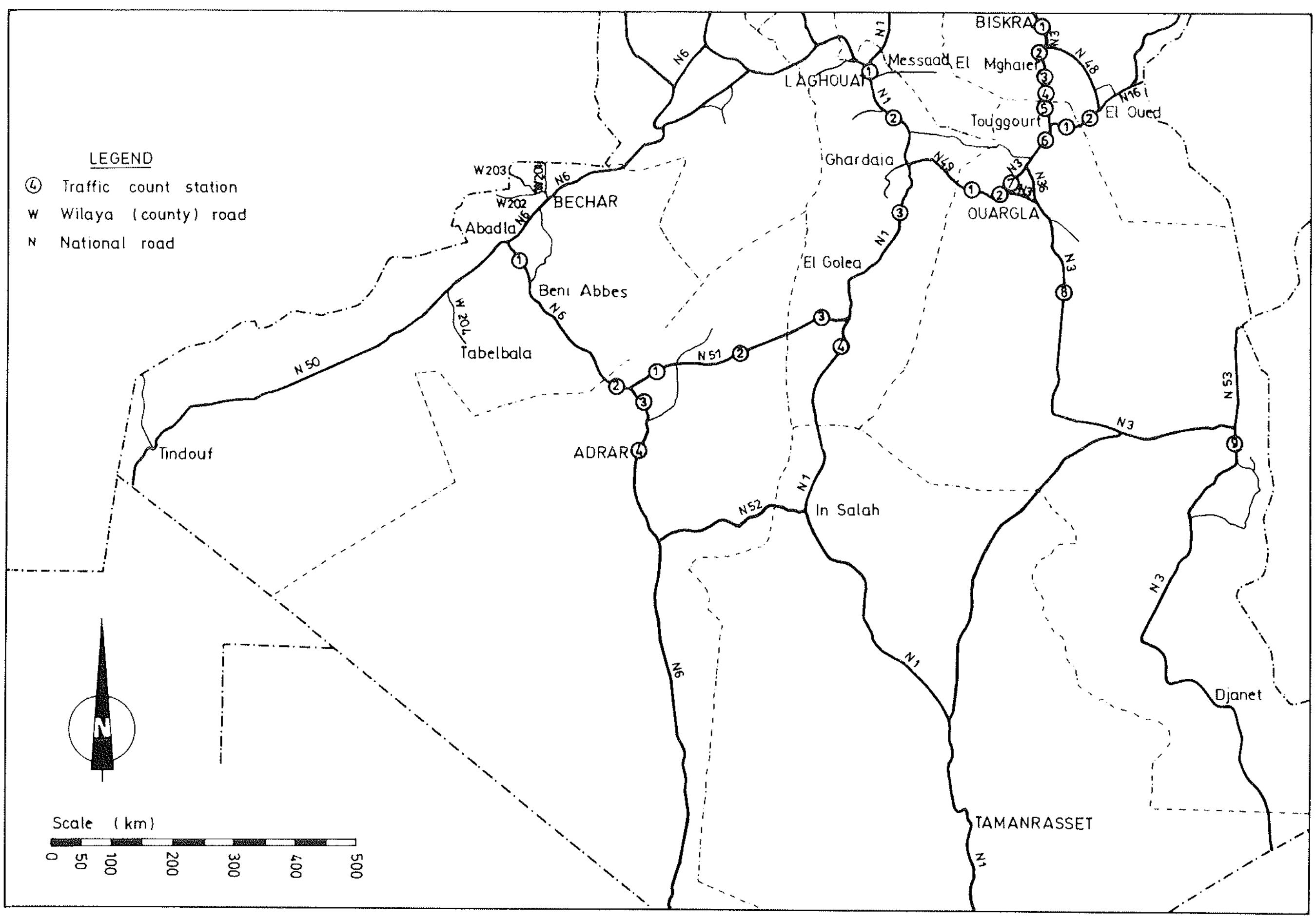

FIGURE 12 Algeria's Saharan roads.

TABLE 2 TRAFFIC FIGURES (1985) AND PAVEMENT PERFORMANCE IN THE ALGERIAN SAHARA

Road	Wilaya	Count station	Average daily traffic	Heavy traffic (%)	Date of construction	Pavement materials: Wearing course	Pavement materials: Base course	Pavement condition	Date of last survey
N1	Laghouat	1	1106	32	1960-62	hot mix	II, III (calcrete)	local shear: water entrappment	1979
		2	1724	45	1958-59	idem	II	good	1979
		3	360	69	1956-59	surf. dress.	binder, II	good	1979
		4	-	-	1974	cold mix	non standard	failed	1982
N3	Biskra	1	2844	-	1957	surf. dress.	II	good	1979
		2	3187	31	1957	hot, cold mix, sand asph.	III (gypcrete)	fair	1979
		3	2720	29	1957	idem	idem	fair	1979
		4	1388	45	1957	idem	idem	fair	1979
	Ouargla	5	1192	28	1958-59	idem	idem	fair	1979
		6	863	62	1958-59	idem	III (gypcalcrete)	good	1976
		7	1798	38	1958-59	idem	idem	good	1979
		8	729	40	1958-59	sand asphalt	chem. stab. soil	failed	1969
		9	128	64	1962-63	surf. dress.	II	good	1969
							III (clay)	good	1969
N6	Bechar	1	258	83	1960-62	surf. dress.	II	good	1969
		2	184	65	1963-64	idem	II	good	1969
		3	221	62	1965-66	idem	II	good	1969
		4	663	26	1966	idem	III (clay)	good	1969
N16	Ouargla	1	1124	30	1963-64	idem	III (gypcrete)	good	1976
	Biskra	2	1000	24	1963-64	idem	idem	good	1976
N36	Ouargla		747	33	1958-59	idem	III (gypcalcrete)	good	1969
N48	Biskra		756	67	1957	hot mix	III (gypcrete)	fair, flooded 1968-69	1976
N49	Laghouat	1	715	48	1958-59	cold mix	pen. macadam	good	1976
							II	good	1976
	Ouargla	2	821	58	1958-59	idem	III (gypcalcrete)	good	1976
N50	Bechar		327	95	1965-67	idem	I, II	good	1969
N51	Adrar	1	161	58	1967-68	idem	I, II	good	1982
		2	92	64	1968-69	idem	I, II	good	1982
						idem	soil-bitumen	failed : salt damage	1982
	Laghouat	3	115	20	1968-69	idem	I, II	good	1982
						idem	non standard	rutting	1982
N52	Adrar		41	46	1980 (?)				-
N53	Ouargla		74	40	1963-64	surf. dress.	II	good	1969
W201	Bechar		984	55	1975 (?)		II		-
W202			1040	42	1975 (?)		II		-
W203			610	21	1975 (?)		II		-
W204			40	0	1975 (?)		II		-

The pavement of this road developed settlements and alligator cracks along some oasis stretches with shallow water tables. Clay base courses may be able to carry low volumes of traffic for a few years.

DRAINAGE AND SHALLOW WATER TABLES

In wide, small valleys, the drainage of run-off at the pavement level is usually preferred to save the cost of culverts. In this case, the shoulders should be surfaced for protection against scour. The pavement of these sections should be constructed with materials of a low susceptibility to water. Natural gravels with a low clay content and calcrete can be used. The pavement should be designed on the basis of soaked CBR. However, these sections are exceptional and the general situation is that of low embankments and deep water tables very much in excess of 7.5 m, without any influence on the subgrade water content.

In some places, such as oases and salt dry lakes (sabkhas), the water table is shallow. In order to provide efficient protection against soaking and salt migration, the pavement should be placed on embankments of sufficient height and constructed with clean, coarse soils such as eolian sand.

Some of the base materials used in the Sahara, for instance gypcrete, are very susceptible to moisture. For fast draining of run-off, the surface camber should be about 3 percent and the surfacing impervious. The latter requirement is usually met because bitumen proportioning is increased to account for sand absorption.

DAMAGE BY SOLUBLE SALTS

The easiest test to detect soluble salts is tasting. Tasting is a very sensitive way to detect the amount of salt that would be harmful to the pavement, such as a 0.5 to 1.0 percent sodium chloride equivalent. Soluble salts are able to migrate through menisci of soils provided the liquid films are continuous. In this way they get at the pavement. Upon evaporation of the pavement moisture, salt crystals grow at the surface or between the base and wearing courses, and cause heaving of the latter and subsequent damage to the pavement (*21*).

Sometimes the salts come either from the compaction water or from the base materials. In these conditions they can be easily eliminated by sweeping after compaction and drying. Difficult situations arise where the salts originate in shallow water tables. Impervious membranes or very pervious cut-off layers are necessary to stop salt migration (*20*).

COMPACTION AT NATURAL WATER CONTENT

Water is a scarce commodity in the desert. It not uncommonly has to be pumped from deep aquifers in drill holes several tens of meters long and transported over distances of several tens of kilometers. In addition, evaporation of compaction water may be as high as 50 percent in hot, windy weather. This is why dry compaction of embankments has been implemented in the Sahara for a long time. Actually, dry compaction means compaction at natural water content, usually in the range of 0.5 to 2.0 percent, without additional wetting.

Experience has shown that dry compaction is feasible with heavy compactors. Recent studies by the Laboratoire des Ponts et Chaussées of France confirmed this observation (*22*). Excellent results can be achieved with heavy dynamic compactors and nonplastic coarse soils, namely eolian sand. Dynamic compaction is effective to a depth of 40 cm but the upper layer of about 10 cm remains loose. This layer should be compacted through the next layer or by static rollers after wetting at the optimum moisture content. Silty and clayey coarse soils are more difficult to compact at natural water content, but it is still possible to achieve satisfactory results for earthworks.

The compaction of base materials at natural water content would therefore be possible for cohesionless materials that belong to Families I and II and dry bound macadam. However, compaction is excluded for cohesive materials such as calcrete and gypcrete. The strength of these materials is mobilized by water.

Cisse provided some figures for savings that resulted from dry compaction of the Tahoua-Arlit road in the Saharan region of the Republic of Niger (*23*). The water supply may amount to 10 percent of the total construction cost in some stretches. The saving in relation to the total cost of earthworks was 38.8, 38.6, and 14.4 percent for the three different stretches of this road.

CONCLUSIONS

The specific characteristics of the desert environment and the distinctive features of road-building technology in the northwestern Sahara have been discussed. The feasibility of taking advantage of the characteristics of the desert environment to decrease road-building costs has been shown. Long distances and scarce economic activity do not contribute to low construction costs. However, the stable terrain relief with few obstacles and the scarce number of towns to serve result in a large degree of freedom in the location of roads and to build roads of shorter length. These conditions also permit roads to be located closer to road-building materials deposits, which decreases hauling costs.

The aridity of the desert should also be considered as a remarkable advantage to road engineers. Bridges can be replaced by fords. The drainage of pavements is simplified as a result of the absence of springs and the low frequency of shallow water tables. A further advantage that results from aridity is the usually dry state of the subgrade soils, which exhibit high strength. Strong soils require light pavements even when the traffic level is relatively high.

The very low water contents that result from high evaporation rates enable the use of a wide range of natural materials in the base course. Some of these materials contain important amounts of relatively soluble minerals, such as gypsum, that would dissolve under the humid climates of Mediterranean northwest Africa, with subsequent collapsing and formation of hollows and caves. Most of the base course materials used in the Sahara contain significant amounts of clay and practically all of them have or should have a plasticity index in excess of 6 percent.

However, the desert environment also has some disadvantages and presents some difficulties that were mentioned earlier. If these disadvantages are not considered, it is not possible to speak of low-cost roads in the Sahara, and maintenance costs will increase to prohibitive levels.

Eolian sand drift is a very difficult problem that should be considered at the design stage and carefully studied and experimented with by trial and error in sections that are exposed to drifting.

As a result of aridity, the water supply is very expensive, which is why dry compaction has been experimented with and studied. Compaction of the earthworks and a few base materials at natural water content is feasible.

Inattention to soluble salts, which may be contained in materials and compaction water, would also result in higher maintenance costs because these salts may cause damage to bituminous surfacings.

REFERENCES

1. R. U. Cooke and A. Warren. *Geomorphology in Deserts*. B. T. Batsford Ltd, London, 1973, 394 pp.
2. J. Tricart and A. Cailleux. *Le Modèle des Régions Sèches*. Societe d'Editions d'Enseignement Supérieur, Paris, France, 1969, 472 pp.
3. R. A. Bagnold. *The Physics of Blown Sand and Desert Dunes*. Chapman and Hall Ltd, London and New York, 1954, 265 pp.
4. F. W. Cron. Snowdrift Control Through Highway Design. *Public Roads*, Vol. 34, No. 11, Bureau of Public Roads, 1967, pp. 227-234.
5. T. R. Schneider. *Snowdrifts and Winter Ice on Roads*. Technical Translation 1083. National Research Council of Canada, Ottawa, 1962, pp. 1-61 and 142-193.
6. R. C. Kerr and J. O. Nigra. Eolian Sand Control. *Bulletin of the American Association of Petroleum Geologists*, Vol. 36, No. 8, 1952, pp. 1541-1573.
7. A. Coursin. Observations et Expériences Faites en Avril et Mai 1956 sur les Barkhanes du Souehel el Abiodh (Région de Port-Etienne). *Bulletin de l'Institut Français d'Afrique Noire*, Série A, No. 3, Dakar, Senegal, 1964, pp. 989-1022.
8. J. C. O.S. Horta. Calcrete, Gypcrete and Soil Classification in Algeria. *Eng. Geol.*, Vol. 15, No. 1, 1980, pp. 15-52.
9. T. Hunt. Geotechnical Aspects of Road Design in Libya. *Ground Engineering*, Oct. 1979, pp. 15-19.
10. M. P. Tobin. Factors Influencing Road Design, Construction and Maintenance in the United Arab Emirates. *Proc., Institution of Civil Engineers*, Part 1, No. 68, London, England, Feb. 1980, pp. 27-38.
11. P. Humarau. Les Problèmes Posés aux Entreprises par la Construction des Routes et de Pistes d'Envol au Sahara. *Fourth International Roads Federation World Meeting*, Madrid, Spain, Oct. 14-20, 1962.
12. F. Netterberg. *Calcrete in Road Construction*. CSIR Research Report 286, NIRR Bulletin 10, Council on Scientific and Industrial Research, National Institute for Road Research, Pretoria, South Africa, 1971, 73 pp.
13. J. C. O. S. Horta. Les Encroûtements Calcaires et la Construction de Chaussées en Afrique du Nord. *Tecnica, Revista de Engenharia*, Vol. XLII, No. 460, pp 9-22 and No. 461, pp. 61-72, 1980.
14. F. Netterberg. Self-Stabilization of Road Bases: Fact or Fiction? *Proc., 6th Regional Conference for Africa Soil Mechanics and Foundation Engineering*, Vol. 1, Durban, South Africa, 1975, pp. 115-119.
15. J. C. O. S. Horta. Les Chaussées en Sables Gypseux du Sahara. *Tecnica, Revista de Engenharia*, No. 447, 1978, pp. 417-430.
16. E. Fenzy. Particularités de la Technique Routière au Sahara. Revue générale des routes et des aérodromes, No. 411, June 1966, pp. 57-71.
17. Standard Test Method for Resistance to Degradation of Small-Size Coarse Aggregate by Abrasion and Impact in the Los Angeles Machine. *Annual Book of ASTM Standards*, ASTM Designation C 131-81, Vol. 04.02, American Society for Testing and Materials, 1985, pp. 94-97.
18. E. Fenzy. L'Etat Actuel de la Technique Routière au Sahara, Deuxième Séminaire Routier, Béni-Abbès, March 22-25, 1965, *Rév. d'Inf. O.T.M.V.R.S.S.*, Nos. 14 and 15, 1965.
19. *A Guide to the Structural Design of Bitumen-Surfaced Roads in Tropical and Sub-Tropical Countries*. Road Note 31. Fig. 3, Pavement Design Chart for flexible Pavements. Transport and Road Research Laboratory, Crowthorne, England, 1977, p. 9.
20. Routes en Milieu Désertique. *International Roads Federation, Fourth African Road Conference*, Nairobi, Kenya, Abdelghani INAL, Jan. 20-21, 1980.
21. J. C. O. S. Horta. Salt Heaving in the Sahara. *Géotechnique*, Vol. 35, No. 3, 1985, pp. 329-337.
22. M. Froumentin and G. Morel. Le Compactage à Faible Teneur en Eau des Remblais et des Chaussées. *Routes et Développement, C. R. du Colloque Int.* Paris, France, May 22-25, 1984, Vol. 2, 1984, pp. 935-940.
23. A. Cisse. *Compactage à Sec des Remblais et Assises de Chaussées*. Rapport de recherche LPC No. 112, 1982, 94 pp.