THE FUNDAMENTAL PRINCIPLES OF MECHANICAL STABILIZATION

Norman W. McLeod, Department of Asphalt Technology,
Imperial Oil Limited, Sarnia, Ontario, Canada

When he wrote to request a paper on this topic, our secretary asked that it emphasize the practical aspects involved in the successful use of mechanical stabilization. The writer believes this can best be accomplished by presenting the paper under the two principal headings of

(1) Design,
(2) Construction,

which will deal respectively with,

(1) a brief review of the fundamental principles involved in the design of mechanically stabilized base courses,

(2) an outline of the basic principles of construction which must be followed to ensure the success of this type of construction.

PART I. DESIGN

A. INTRODUCTION

While this paper is to deal essentially with the design and construction of mechanically stabilized base courses, it cannot be stressed too emphatically, that the design of a successful base course or pavement, begins with the design of the subgrade upon which it is to rest. The writer would like to digress for a moment therefore, to consider very briefly the design of the subgrade under the headings of

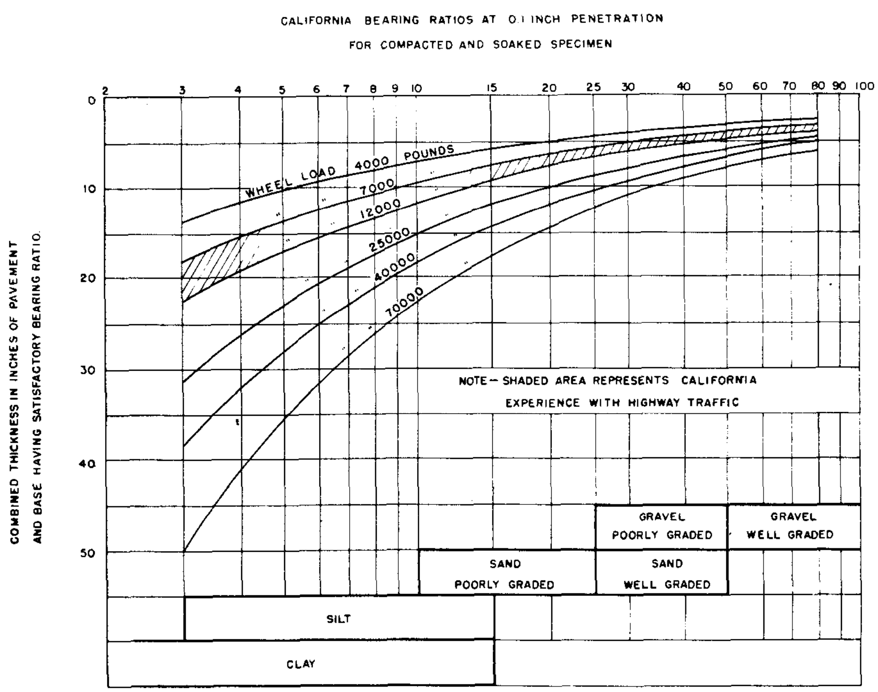
(1) Soil Classification
(2) Principles of Subgrade Construction
(3) Fundamentals of Soil Drainage

(1) Soil Classification

Every asphalt paving technologist should be vitally interested in the topic of soil classification at the present time, for the California method of classifying soils is being proposed for use on a wide scale for the design of thickness of flexible pavements for both highways and runways. This method classifies soils on the basis of their rating in the California subgrade bearing test, heavy clay soils rating very low (5 or less), while well-graded gravels rate very high (60 and above). A single chart of curves, purportedly applicable to every field and climatic condition, has been prepared by extrapolation from curves derived from California experience with traffic loads on highways, wherein the thickness of base plus surface required for aeroplane wheel loads up to 70,000 pounds, are plotted against the various possible subgrade soil ratings in the California subgrade bearing test, Figure 1.

The writer believes that both the California subgrade bearing test, and the empirical approach to the problem of pavement thickness implied in the extrapolated California chart, have a great deal of merit. The California bearing test requires simple small-scale equipment, it can be rapidly performed, and a large number of samples can be tested at the same time. Like most other tests, greater experience with it on a wide scale may indicate the need for certain improvements in either apparatus or testing procedure. The 7,000-and 12,000-pound curves represent the results of California highway experience in the field over a number of years, and were not derived from considerations of theoretical soil mechanics. The current confusion concerning the correct interpretation of the results of large scale load tests on highways and runways, makes the soil mechanics approach to the solution of the problem of pavement thickness unsatisfactory at present. The empirical approach therefore, based upon actual experience with pavement thickness in the field in various localities, seems to provide the soundest basis of design for the thickness of flexible pavements at the present time.

It seems to the writer, however, that the proposed universal use of a single chart of curves for thickness of flexible pavements, (base plus surface), has certain very serious drawbacks. If the California chart is applicable to subgrade soils under the worst possible conditions, (compacted and saturated), it would seem quite unreasonable to require the same thickness of base plus surface in localities where subgrade soils do not even approach their worst possible condition. Mr. Porter's reported experience in the Imperial Valley of California to the contrary, it is not reasonable to require the same thickness of base plus surface over a given subgrade soil, (a clay for example), regardless of whether the water table is deep or near the grade line, and whether the climate is arid or wet. The fact that many highways and airports with flexible pavements, which are seriously underdesigned on the basis of the California chart,



NOTE RANGES FOR ABOVE SOIL TEXTURES ARE APPROXIMATE, ACTUAL DESIGN BASED UPON TEST RESULTS (CALIFORNIA BEARING TEST, PROCEEDINGS HIGHWAY RESEARCH BOARD DECEMBER 1938)

DESIGN CURVES FOR OVERALL THICKNESS OF BASE PLUS SURFACE FOR FLEXIBLE PAVEMENTS ON SUBGRADES OF VARIOUS BEARING RATIOS.

FIG. 1

have performed without sign of distress for many years, is reasonable proof that the California method leads to serious overdesign in many localities where field conditions are average or better.

The California method of classifying soils for designing thickness of flexible pavements, has the weakness of every other attempt to classify soils on the basis of one or two tests. All such attempts lack the flexibility required for the classification of such a varied material, occurring under such varied conditions, as soil.

At the present time there is only one method for classifying soils which has the flexibility required to take all of the variations associated with this material into account. That is the agricultural or pedological system of soil classification.

The pedological system of soil classification divides the soils of a country first of all into groups of soils called soil series, on the basis of differences in one or more of the five principal soil forming or soil modifying agencies, climate, vegetation, geological origin of the parent soil material, topography and drainage, as reflected in the soil profile. Each soil series in turn, is subdivided on the basis of the texture of the top several inches into smaller units called soil types. Thus a soil series may include soil types which range in texture all the way from heavy clay to coarse gravel, but usually only a part of the possible range of soil types occurs in any one soil series.

The soil type is the unit used in soil mapping, and agricultural soil maps present the results of soil surveys made according to the pedological system of soil classification. These soil maps indicate the exact area or areas occupied by each soil type in any given locality, township, county, state, or province.

The value of these agricultural soil maps to the highway and airport engineer, lies in the fact that the same sequence of soil layers from the surface of the ground to as far below the surface as the engineer is interested, and the properties of each soil layer, are substantially the same at every point throughout the whole area or areas occupied by each soil type, but are different for different soil types. Therefore, the same engineering subgrade and drainage problems are presented at every point throughout the whole area or areas occupied by each individual soil type, but are also different for different soil types.

Thus, agricultural soil maps provide a key to the nature of the drainage, subgrade, and other soil engineering problems to be expected in any locality, and by showing the exact boundaries between the areas occupied by different soils, indicate the exact location where the engineering treatments required for each soil should begin or end.

Every engineer who studies the remarkable development of the pedological system of soil classification which has been made by the Michigan State Highway Department for the solution of highway location, design, construction, and maintenance problems, cannot fail to be impressed with the outstanding utility of the pedological system of classifying soils, to both highway and airport engineers. (Major Stokstad, who addressed us yesterday on the utilization of the pedological system of soil classification, was formerly Engineer of Soils for the Michigan State Highway Department, and was largely responsible for developing the highly commandable utilization of this system of classifying soils for the solution of highway engineering problems in Michigan.)

Anyone familiar with the pedological system of soil classification, realizes that theoretically at least, <u>a set of curves</u> similar to those in the California chart, giving the thickness needed for base plus surface over each subgrade soil to carry different wheel loads, would be required <u>for every soil series</u>. In actual practice, the number of such charts would be smaller than this theoretical number, because of the similarity between many of the charts for different soil series. The writer is not prepared to suggest the number of such practical charts that might be necessary, but it is probable that from three to six would be needed to cover every soil series. Each chart would be specifically tied in with the agricultural or pedological system of soil classification, by listing on each all of the soil series to which it was to apply.

The creation and adoption of several design charts to cover every soil series, would represent a much more logical approach to flexible pavement design, than the current attempt to employ a single chart of curves for thickness of base plus surface, (California chart), intended to apply to all soil series and to every field and climatic condition under which they may be found.

The millenium for most administrative highway and airport engineers would be reached, if it were possible to design highways and airports accurately and economically, even for localities they had never seen, by merely withdrawing master design charts from pigeon-holes in the walls of the central office. The combining of the pedological system of soil classification with the California method of design for flexible surfaces, in the form of several master design charts on which the various soil series were listed as outlined above makes such an objective possible, for a soil survey (by the pedological system) of the locality in which each project was situated, to locate the boundaries of each soil type present, would in general be the only important field information required in addition to the usual profile and cross-section data.

Without the use of the pedological system of soil classification *in this way, such a series of accurate master design* charts is not possible, and a vast, unnecessary, costly duplication (more probably multiplication), of observation and soil testing is required to accomplish even reasonably accurate design for projects scattered over an area as large as the U.S.A. In the absence of these master design charts, the design of each project must be worked out as an individual problem largely divorced from experience elsewhere, and must be left essentially to the good judgment of field engineers based upon their visual inspection and the carrying out of many field tests, neither of which may give particularly accurate information unless performed over the annual cycle of weather conditions in the locality. While this process eventually builds up considerable experience in the mind of each engineer, it is unorganized experience, for apart from the pedological system of soil classification, no other common medium of comparison exists whereby this experience can be made available to engineers in general. Duplication of observations and soil testing is unavoidable unless the pedological system of soil classification is adopted, for otherwise, engineers in different localities have no means of knowing whether their projects occur on the same or different soils. On the other hand, if the pedological system of classifying soils is utilized, engineers on projects where Miami clay loam occurs in Indiana, Ohio, and Michigan for example, have the key whereby the experiences of each engineer with construction on this soil become available not only to each other, but to all engineers. Thus, the pedological system of soil classification provides an *articulate medium for storing and expressing the accumulated* soil experience of engineers on every project, and is economically valuable for it removes the necessity for the multiplication of costly observations and tests which must otherwise be made.

The preparation of several design charts on which were listed the names of the soil series to which each chart was to apply, would not be a difficult task in the U.S.A., for the U.S. Department of Agriculture has prepared soil maps in considerable detail for most of the counties in the United States. When once prepared, these master design charts for thickness of base plus surface for flexible pavements would be of permanent value. They would make possible the intelligent design of airports and highways at the central office, or at least the intelligent checking in the central office of designs submitted by field engineers, they would eliminate the present costly duplication of tests on the same soil in different localities, and could be readily revised if necessary, as field observations of the performance of projects on each soil become available over the years.

Under the stress of war, essential highway and airport projects must be rushed to completion, and construction would have to be carried on during the time required for the preparation of these master design charts. For the construction which would have to proceed during this interregnum period, some of the flexibility of design required to cover the wide range of conditions actually found in the field, could be introduced into the California chart by either of the following two modifications,

(1) The subgrade soil in many localities does not attain the saturated condition required for the California bearing test. By testing the subgrade soil in these localities at the moisture content and density actually found for existing projects, a higher California bearing ratio would be obtained than from the standard test, and a correspondingly smaller thickness of base plus surface would be read off the present California chart.

(2) Flexibility could be introduced by the use of several different California charts, in which the thickness of base plus surface required over a subgrade soil of any given bearing ratio, was made to vary from a minimum for arid regions with a deep water table, to a maximum for regions of high rainfall and high water table. For this alternative, the California bearing test would be made on the compacted soaked specimen as required by present procedure, but the curves would have the flattest slope and the minimum thickness requirements on the chart for conditions of arid climate and deep water table, and their slope and the corresponding thickness requirements would both increase for succeeding charts, to a maximum on the chart for conditions of high rainfall and shallow water table.

The writer believes that neither of these two alternative methods of design should be considered of more than stop-gap value. Both have serious limitations, but they possess a certain degree of flexibility which is quite foreign to the present California design, and when used in conjunction with observations of the performance of existing highway and airport projects in a locality, they should be capable of reasonably satisfactory service, until the master design charts based upon the California design and the pedological system of soil classification previously described, could be prepared.

(2) Principles of Subgrade Construction

Apart from provision for adequate drainage, the most important principles of subgrade construction are,

(1) Proctor compaction of the subgrade,
(2) The relation of grade line to soil water table,
(3) Elimination of frost heaving and frost boils,
(4) Removal of peat and muck from under the subgrade.

Proctor compaction of subgrade soils makes use of the principle that for a given method of compaction, there is one moisture content for each soil (optimum) at which that soil can be consolidated to its highest density (maximum density). Earth fills should be constructed in approximately 6-inch layers and consolidated at optimum moisture, preferably with sheepsfoot rollers, to the specified density, which usually varies from 90 to 100 per cent of maximum density as the subgrade material varies from coarse sandy or gravelly soils to heavy clays. Water is added to the soil before it is hauled to the fill, or by sprinkling the soil layers as they are placed. The upper 9 to 12 inches of soil in cuts should be ploughed, brought to optimum moisture, and consolidated to the required density. The advantages of Proctor compaction are, elimination of subgrade settlement, high bearing capacity at a low deflection under applied loads, and resistance to the entrance of capillary moisture thereby tending to preserve a more uniform subgrade bearing capacity.

Practical experience has indicated that the water table should be kept at least 4 feet below the finished grade for highways, and 5 feet below the finished grade for runways. Where the water table is close to ground level, an embankment from 4 to 5 feet high should be constructed, unless the water table can be economically lowered by drainage.

Frost heaving and frost boils are usually caused by the presence of pockets of silt soil or fine sand in the subgrade. Pockets of these materials favour the formation of ice lenses under certain moisture and low temperature conditions. The amount of heaving is related to the combined thickness of the ice lenses in the subgrade underlying the point of heave. Frost boils are formed under the action of traffic, by the large volume of water set free in the spring, when the ice lenses near the surface melt while the underlying soil is still frozen, thereby preventing drainage of the released water downward. Frost heaving and frost boils cannot be prevented by the installation of drains in these pockets of silt and fine sand. They can be cured by excavating the pockets to a depth of about 4 feet or to the depth of frost penetration, and backfilling with a nonfrost heave soil, either a dense clay or coarse sand or gravel. A heavy thickness of granular material (of the order of 2 feet), is sometimes recommended as a blanket over subgrades affected by frost action. This indiscriminate blanketing of good and bad sections alike, usually runs into excessive cost for the granular material required, and the excavation and backfilling of the actual areas affected is generally a much more economical and more positive treatment.

Deposits of peat and muck are very undesirable under a subgrade, partly because of their compressibility, and partly because they may suddenly become displaced leading to partial or complete loss of the grade. Subgrades over these materials may undergo large settlement which occurs slowly but steadily over long periods of time, thereby causing the failure of every pavement constructed over them for years. Peat and muck should be completely removed from under the subgrade by excavation, displacement, jetting with water, or dynamiting.

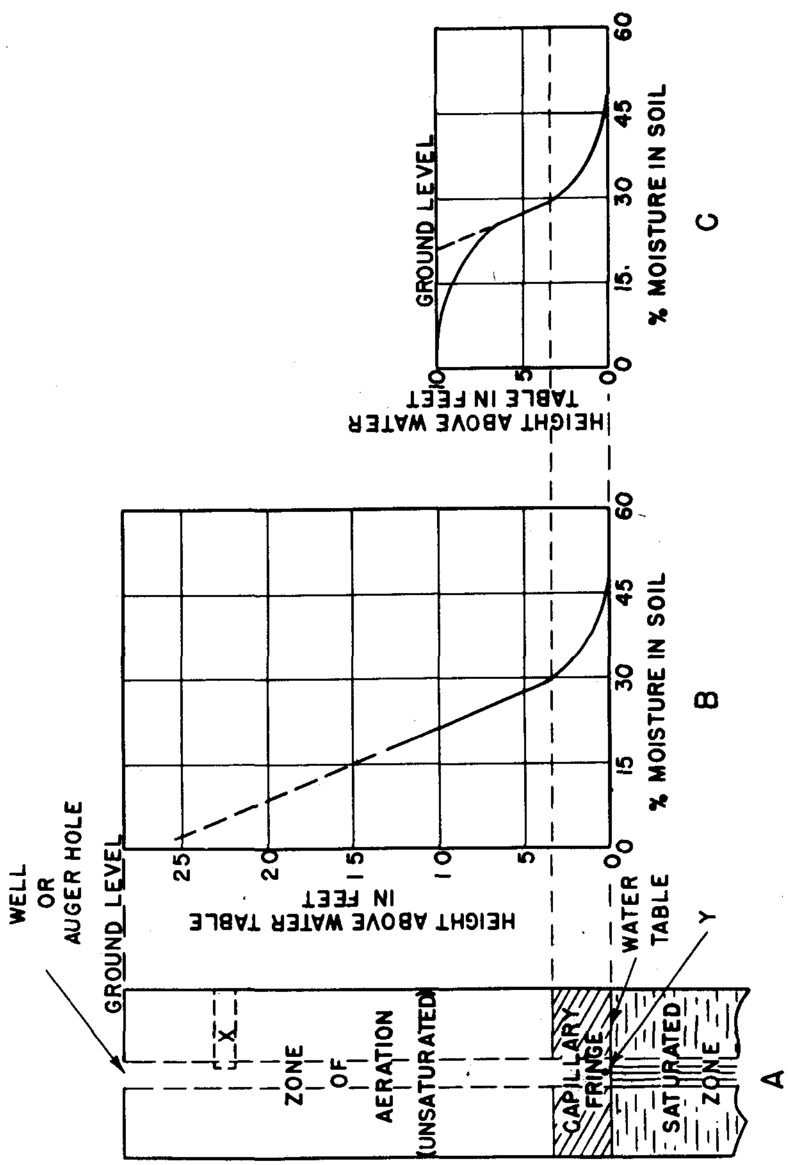
(3) Fundamentals of Soil Drainage

1. Capillary Water Cannot Be Drained

The principles of drainage involved in the removal of surface water from a pavement or right-of-way are usually well understood, and require no special comment here. On the other hand, the principles of drainage pertaining to the removal of ground water from a soil by subdrainage do not appear to be well understood. In the following paragraphs therefore, the fundamentals which should serve as a guide to the installation of any system of drains for removing sub-surface moisture from a soil are briefly discussed.

In Fig. 2A, a diagram of the vertical cross section of the moisture conditions in a soil extending from the surface of the ground to below the water table, is presented. The water table is the highest elevation in the soil profile at which free water is found under equilibrium conditions. In digging a hole with a soil auger, the water table has been reached when the soil sample withdrawn glistens due to the free water it contains, and water can also usually be observed on the auger. In a small hole which has been bored below the water table, water will rise in the hole to the level of the water table in a short time.

Below the level of the water table, the soil pores are completely filled with water, and this portion of the soil profile is called the saturated zone.



THE CHARACTERISTICS OF SOIL MOISTURE
FIG. 2

Soils can raise water many feet against the force of gravity by virtue of their capillarity, and immediately above the water table is a zone known as the capillary fringe, which may vary in thickness from a fraction of an inch to several feet, as the texture of the soil varies from gravel or coarse sand to the finest clay, respectively. The soil pores in the capillary fringe are filled with water, for the thickness of the capillary fringe is governed by the height above the water table to which the capillary forces can raise sufficient water to completely fill the pore space in the soil.

Above the capillary fringe, the capillary forces are unable to lift enough water against gravity to completely fill the soil pores with water, and they are therefore, partly filled with air The proportion of air to water in the soil pores increases with increasing height above the capillary fringe. The portion of the soil profile above the capillary fringe is known as the zone of aeration, or the unsaturated zone.

The decrease of moisture content with increasing height above the water table for a loam soil is illustrated in Fig. 2B.

From this description, it should be evident that two types of water may be found in the soil profile,

(1) free water, which under equilibrium conditions is found only below the water table,
(2) capillary moisture, which is lifted and maintained above the water table by virtue of the capillary forces of the soil.

Only the free soil water can be drained, and in order to remove water from a soil, drains must be placed below the level of the water table. Drains placed at any elevation above the water table, even in the capillary fringe, cannot remove any part of the soil moisture, for capillary moisture cannot be drained.

That capillary water cannot be drained from a soil can be proven theoretically. This theoretical proof is based upon the first law of thermodynamics, which states the principle of the conservation of energy. One of the implications of the first law of thermodynamics is that perpetual motion is impossible.

Suppose that an engineer believes that capillary moisture can be drained from a soil, and provides a system of tile drains for this purpose at elevation X in Fig. 2A. Let the outlet to this drainage system project out into the well or auger hole. If capillary moisture can be removed from the soil by these drains, in falling from the drainage outlet to the bottom of the well, it could be utilized to drive a pelton wheel or water turbine placed at Y just above the water table. After being again raised to the drainage system by capillarity, and removed from the soil by drains, the water is again available for driving the pelton wheel in falling to the bottom of the well. This process, however, would result in perpetual motion, since work would be performed without any energy being put into the system, and the scheme is therefore impossible.

A moment's consideration indicates the exact point where the fallacy in reasoning has occurred. It is an easily observed fundamental fact of nature that water can be raised many feet above the water table in a soil by capillary forces. Consequently, there is capillary moisture in the soil about the drainage system at X. It is also a fundamental fact of nature, that if any water gets into the drainage system at X, and makes its way to the outlet, it will drop to the bottom of the well, for the law of gravity takes care of that. The break-down in logical reasoning occurs therefore, when it is assumed that the drains at X are capable of removing capillary water from the soil.

Owing to the failure on the part of some engineers to realize that capillary water cannot be drained from a soil, many hundreds of thousands of feet of drains have been installed at elevations in the soil profile where they are as useless for the purpose of removing water from the soil, as if they had been suspended above the grade line by cables from barrage balloons.

2. Accumulation of Capillary Moisture after Pavement Construction

Fig. 2C illustrates a condition which has occasionally led to the failure of pavements. The ground level is only 10 feet above the water table, and either Fig. 2B or C indicates that the moisture content of the soil just at this ground level may be raised to 21 per cent by capillarity. When used as an earth or gravel road, the moisture content of the subgrade just at the road surface may be reduced to only 5 per cent because of evaporation, as shown by the full curve of Fig. 2C. If an impervious pavement is constructed, this evaporation is shut off and capillarity soon raises the moisture content of the subgrade just below the pavement to its equilibrium value of 21 per cent, illustrated by the broken line of Fig. 2C. At this high moisture content, the bearing capacity of the subgrade may be so low that the pavement will fail.

Consequently, a subgrade surface which has high bearing capacity when used as an earth or gravel road, may have a much lower bearing capacity when covered with an impervious surface, due to the increased moisture content induced by the capillary action of the soil.

Since capillary moisture itself cannot be drained from a soil, it should be evident from Fig. 2B that the capillary moisture content of a subgrade beneath an impervious surface can be reduced by only one or the other of the two following methods.

(1) lowering the water table by drains placed below the level of the water table, which would give a downward displacement of the curve in Fig. 2B, and therefore a smaller moisture content at any point above the original level of the water table.

(2) raising the grade line by the construction of an embankment, which gives the lower moisture content corresponding to a greater distance above the water table.

The second of these two methods, namely, constructing additional embankment, is to be preferred, since it is a more positive treatment. There is always the danger of any subsoil drainage system being inadequate, or becoming partly or completely inoperative with time or at certain critical seasons of the year, due to freezing, silting, etc. Apart from the desirable drainage features, the higher grade line resulting from additional embankment, assists in keeping highways clear of snow.

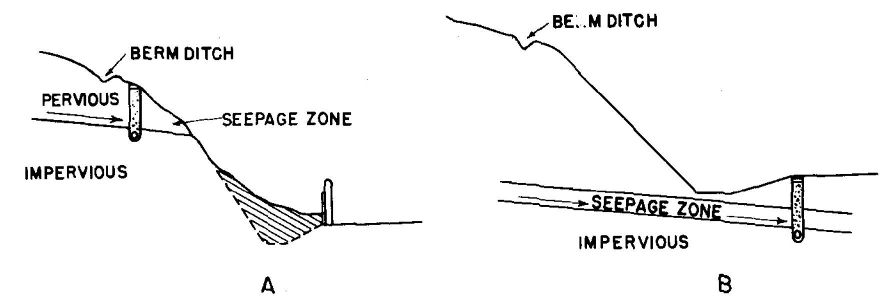
For soils which are of a loam to sand texture, the slope of the curve of moisture content versus height above water table is much flatter than for the curve shown in fig. 2B, which is for a clay loam soil. Consequently, for the light textured soils, (loams and sands), a few feet of difference in elevation above the water table will give a much more pronounced change in moisture content than that illustrated by the curve in Fig. 2B.

There is a third method for assisting the control of the amount of moisture that a soil can take up by capillarity. That is Proctor compaction, which was discussed briefly in the previous section. Because the soil pores of a Proctor compacted soil are nearly filled at the optimum moisture required for obtaining maximum density, the tendency of the compacted portion of the subgrade to absorb further capillary moisture is appreciably reduced.

3. The Installation of Sub-drains

There is not space to give any detailed discussion as to how and where sub-drains should be installed, but in Fig. 3, two elementary examples are given of the correct installation of subdrains for the purpose of eliminating the damage to a roadway caused by moisture conditions rather frequently encountered.

In Fig. 3A, the placing of a drain as shown, to intercept the water flowing down a seepage zone, eliminated the unsightly



DRAINAGE FOR ELIMINATING DAMAGE DUE TO SEEPAGE ZONES

FIG. 3

oozing of mud down the slope, where it filled the ditch and moved out onto the roadway before the retaining wall was built. In Fig. 2B, a drain placed as shown, intercepted water in the seepage zone which had been flowing under the subgrade and causing damage to the road surface.

It should be observed that both of these examples emphasize the fundamental principle of drainage, namely, that drains should be placed only in locations where they can intercept or collect free soil water.

In concluding this section, it should be added that owing to the failure to recognize and understand these fundamental principles of drainage, there have probably been more engineering *atrocities committed in the name of drainage, than of any* other phase of highway and airport construction.

B. THE DESIGN OF MECHANICALLY STABILIZED BASE COURSES

It may be worth while to consider for a moment, the place of base courses in modern highway and airport construction, and why they are necessary.

A highway or runway usually consists of three principal inter-dependent units, the subgrade, the base course, and the wearing surface, as illustrated in Figure 4.

The subgrade provides the foundation for the highway or runway, while it is the primary function of the wearing surface to resist the abrasion of traffic.

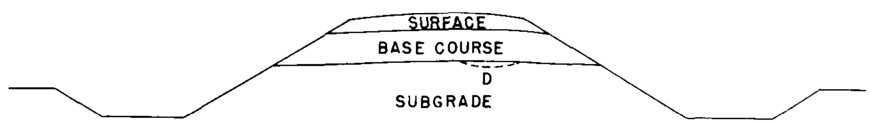


DIAGRAM OF TYPICAL HIGHWAY CROSS-SECTION

FIG. 4

There are few subgrades which in themselves have the bearing capacity required to support the heavier wheel loads of traffic. While in the past, and also at the present time unfortunately, the surface course has been constructed of considerable thickness in order to provide the additional load carrying capacity required, this is not economically desirable because of the relatively high cost of wearing course materials. Consequently, there is a fundamental need in the modern highway and runway for an intermediate course which is capable of providing high bearing capacity, and is at the same time relatively inexpensive. This intermediate coarse is generally known as the base course.

It is the fundamental function of the base course therefore, to supply the additional bearing capacity required for supporting wheel loads, which is not inherent in the subgrade itself.

Base courses can be of many types. There are bases of crushed stone, pit run gravel, consolidated gravel, oyster shell, penetration and waterbound macadam, portland cement concrete, the various types of black base, and the most recent development, stabilized base courses.

For a given bearing capacity requirement, the most economical base course in a great many localities is the stabilized base course if it is properly constructed, and it is to soil stabilization that highway and airway engineers must look for any worth-while reduction in the cost of adequately constructed highways and runways in the near future, because soil stabilization employs a maximum of cheap locally available materials, and a minimum of the more expensive prepared or manufactured products.

Since stabilized base courses are of quite recent development, and so much confusing literature has been published concerning them, an attempt will be made to present in a logical manner, some basic information concerning their characteristics and design.

(1) Soil Stabilization Defined

As far as this paper is concerned, soil stabilization might be defined as "the treatment of soil or soil aggregate mixtures to produce highway or runway base courses which are structurally stable under all conditions of field moisture and weather."

While the term "soil stabilization" has been very loosely applied to various operations of highway and runway construction, the writer is in complete agreement with those who believe that this term should be discontinued as far as the subgrade is concerned, and should be reserved for the types of base courses covered by the definition which has just been given.

For example, the compaction of subgrades to maximum density at optimum moisture either in the top layer of the subgrade in cuts or throughout the full depth of an embankment, to which the term "stabilization" has been frequently applied, is simply modern subgrade construction at its best, and does not require any descriptive term other than that generally applied, namely, subgrade consolidation, or subgrade densification.

(2) The Types of Soil Stabilization

All types of soil stabilization fall into one or the other of two principal divisions,

(1) First, the type generally known as "mechanical stabilization," which is formed from a scientifically designed mixture of gravel, sand, and clay binder, to which as a quite recent development from 1 to 2 per cent of liquid asphalt has been incorporated as a waterproofing admixture to give "waterproofed mechanical stabilization." For this type of stabilization therefore, it is usually necessary to obtain all of the aggregate required, gravel, sand, and clay binder, from nearby deposits.

(2) Second, the soil material naturally occurring in the upper few inches of the subgrade, frequently modified by the addition of granular or other soil material, is treated with from 5 to 15 per cent of asphalt, tar, portland cement, bituminous emulsion, or other admixture, which hardens the soil and reduces its susceptibility to the effects of weather and moisture.

As a first impression, it might seem that stabilized bases produced from the second of these two principal types of stabilization would be the cheaper, because it utilizes the upper few inches of the soil in the subgrade as the aggregate, and little or no outside aggregate may be required.

However, the cost of the 5 to 15 per cent of bitumen, portland cement or other admixture which must be used, plus the relatively high cost of processing in order to get the admixture uniformly distributed throughout the fine soil particles, has made this the more expensive of these two types of stabilization at the present time as far as Canada is concerned. On the other hand, due to the fact that the materials required for mechanical stabilization are not readily available, and to other local conditions, there are areas where this second type of stabilization is the more economical, and it is being developed on a considerable scale in certain sections of the United States.

Canada has been so highly glaciated that adequate quantities of the gravel, sand, and clay binder required for mechanical stabilization are usually found within a short distance of any project, and this type of stabilization has so far proven to be both more economical and more satisfactory for Canadian conditions. Since the Northern United States has also been well glaciated, it is apparent why mechanical stabilization has also been developed there on a large scale.

The following paragraphs are therefore devoted to a discussion of the characteristics and properties of mechanical stabilization, and of the very promising recent development, "Waterproofed mechanical stabilization."

(3) The Bearing Capacity of Gravel Base Courses Can be Increased By the Addition of Binder

Fig. 5 shows a thoroughly compacted 6 x 6 inch cylinder of well-graded gravel, and Fig. 6 demonstrates that this cylinder collapses under the weight of a hand placed on it. Figures 5 and 6 illustrate the well-known fact that granular materials have no bearing capacity apart from the lateral support supplied by the confining influence of adjacent material. At the same time, it should be remembered that bearing capacity derived from the confining influence of lateral support is common to every base course material in place on a roadway or runway.

There are areas where deposits of gravel are so plentiful that it is probably the cheapest base course material that can be used. In localities where granular materials are scarce and

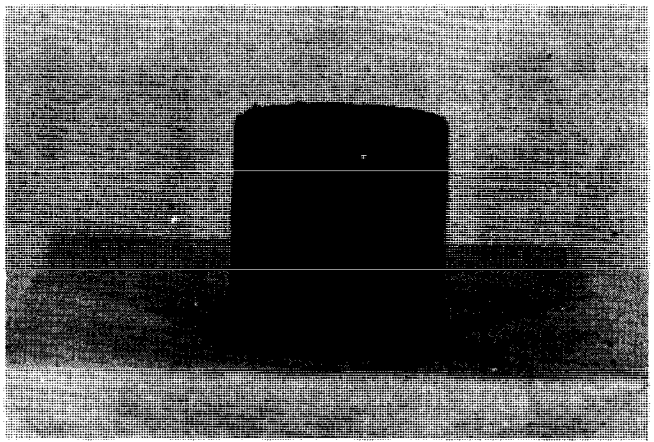


Fig. 5. 6 x 6 inch cylinder of compacted gravel.

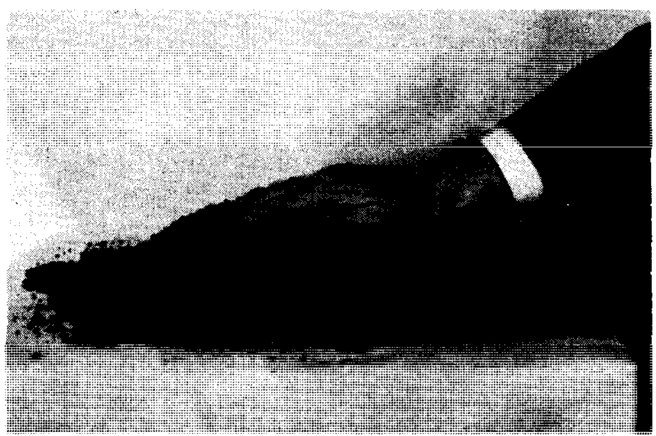


Fig. 6. Cylinder of compacted gravel of Fig. 5 collapses under the weight of a hand placed on it.

costly on the other hand, engineering ingenuity endeavours to find some inexpensive process for treating them to obtain the maximum load-carrying capacity from their use, thereby increasing their efficiency.

From Figs. 5 and 6, it should be evident that the load-carrying properties of gravel as a base course material could be increased by the addition of a suitable binder, whereby the resulting mixture would have inherent load supporting capacity apart from the bearing capacity derived from lateral support. That is, an unconfined cylinder of the mixture would have a measurable load supporting capacity, whereas a cylinder of unconfined gravel, (Figs. 5 and 6), has none.

(4) Clay as a Binder

The cheapest binders for granular materials available to highway and airport engineers are clays. That clay is a binder is demonstrated by Fig. 7, where two brass discs cemented together with clay are withstanding a 25-pound weight in tension. In some tests these discs have carried a 75-pound weight for 1/2 hour.

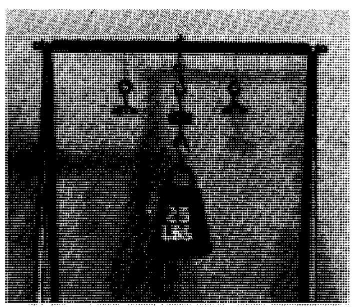


Fig. 7. Clay can function as a cement.

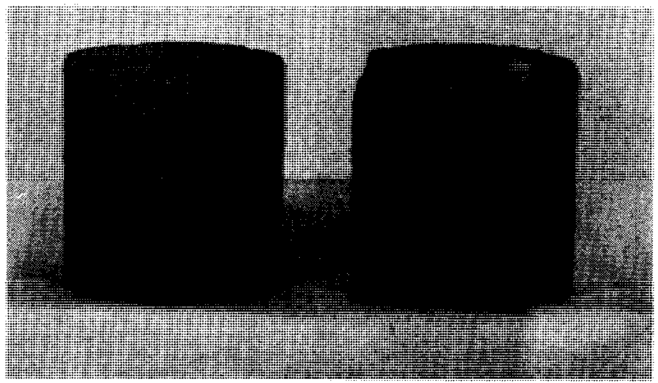
When clay binder is mixed with gravel and fine sand in the proper proportions, the resulting material is known as a "mechanically stabilized mixture."

A 6 x 6 cylinder of such a clay bound stabilized mixture is shown in Fig. 8A, and a cross section of the mixture in Fig. 8B. In Fig. 9 the cylinder of Fig. 8A is shown supporting a heavy man, and depending on moisture content and other properties will actually carry from 1 to 12 tons, - quite a different material from the gravel cylinder which collapsed under the weight of a hand. Because of the proper quantity of clay binder it contains, this mechanically stabilized base course mixture, in contrast to gravel which has none, possesses inherent bearing capacity apart from lateral support.

Two detrimental characteristics of clays must always be kept in mind when using them as binders -

(1) their tendency to shrink and swell,
(2) their susceptibility to absorption of water, which decreases their strength as a cement or binder.

When designing a mechanically stabilized mixture, the tendency of the clay binder to shrink and swell can be reduced to a negligible degree by requiring the addition of the correct proportion of fine sand. The effectiveness of sand for reducing the swelling and shrinkage of clay is illustrated in Fig. 10.



A B

Fig. 8. A - 6 x 6 inch cylinder of clay bound mechanically stabilized mixture.

B - Cross-section of 6 x 6 inch cylinder of mechanically stabilized mixture.

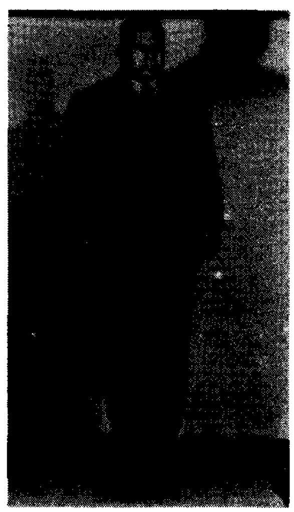


Fig. 9. 6 x 6 inch cylinder of clay bound mechanically stabilized mixture (air dried) easily supports the weight of a man. Depending upon moisture content and other variables this cylinder can actually support from 1 to 12 tons in a compression test.

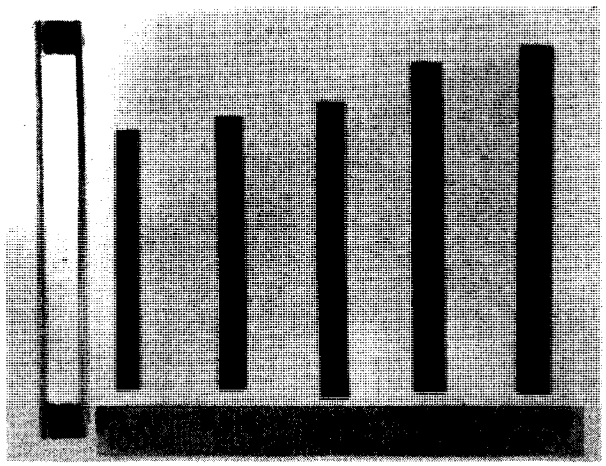
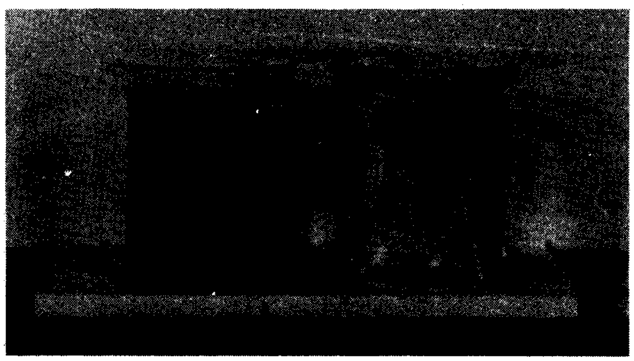


Fig. 10. The detrimental shrinkage properties of a clay binder can be eliminated by adding the proper proportion of fine sand.

The susceptibility of clay binder to water absorption and loss of bearing capacity can be minimized by requiring the incorporation of a small quantity of liquid bitumen into the stabilized mixture as a water-proofing material. The effectiveness of bitumen for this purpose is demonstrated in Figs. 11 and 12, pictures taken of a slaking test, wherein one briquette has been treated with liquid asphalt. The untreated briquette collapsed completely in about 1/2 minute, Fig. 12.

The effectiveness of a small quantity (1 to 2 per cent) of liquid asphalt as a waterproofing material is further demonstrated in Figs. 13 and 14. Two air-dried 6 x 6 cylinders of a well-designed mechanically stabilized mixture are shown in a water bath, Fig. 13, just before immersion in water. Both cylinders are identical in every respect, except that the cylinder on the right contains 1 per cent of liquid asphalt (by weight of the mixture) uniformly distributed throughout the mixture as a waterproofing material. The cylinders were completely covered with water and allowed to stand overnight. The picture shown

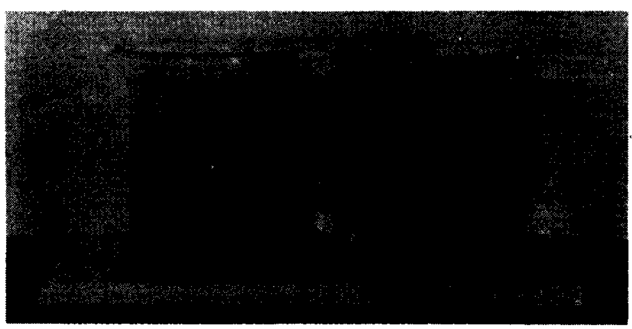


A B

At beginning of slaking test.

Fig. 11. A - briquette of clay binder.

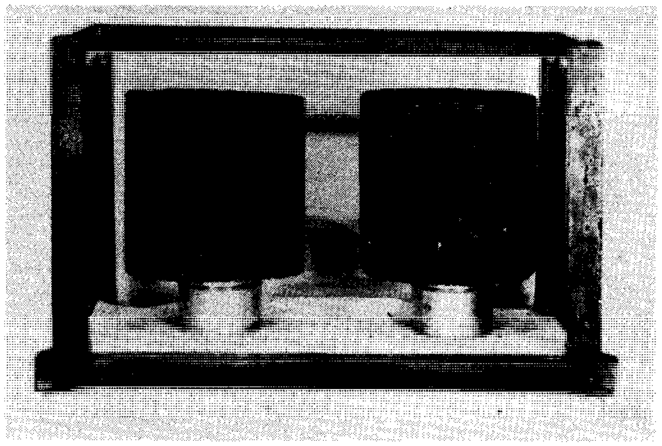
B - briquette of same clay binder waterproofed by the incorporation of a small quantity of liquid asphalt.



A B

Fig. 12. Slaking test of Fig. 11 - after standing overnight. Note - the untreated briquette A, collapsed completely in less than 1/2 minute.

Figs. 11 and 12 demonstrate that the detrimental effect of water on the cementing power of a clay binder can be eliminated by the incorporation of a small quantity of liquid asphalt as a waterproofing material.

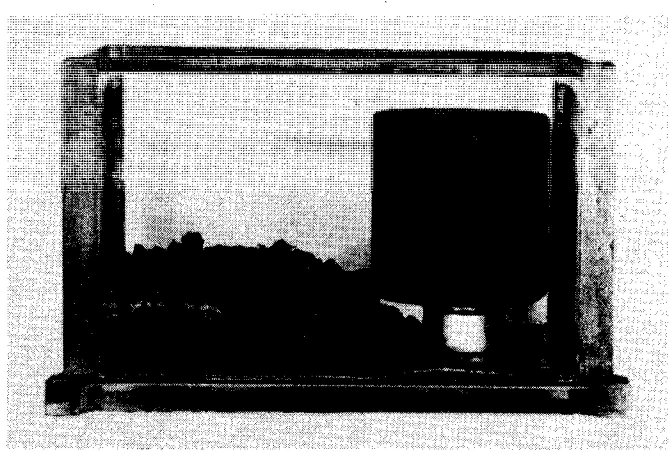


A B

Before immersion in water.

Fig. 13. A - 6 x 6 inch cylinder of non-waterproofed mechanically stabilized mixture.

B - 6 x 6 inch cylinder of same mechanically stabilized mixture as "A", which has been waterproofed by incorporating 1 per cent of liquid asphalt R.C.1.



A B

Fig. 14. Same as Fig. 13 but after being immersed in water overnight.

Note that the cylinder of non-waterproofed material has collapsed, while cylinder of waterproofed mechanically stabilized material is essentially unaffected.

in Fig. 14 was taken the following morning. The cylinder of ordinary mechanically stabilized mixture has collapsed, while the cylinder of waterproofed material is essentially unaffected.

(5) Cooperative Investigation Provides Quantitative Data Required for Design

So far, this discussion of the characteristics of mechanically stabilized base course mixtures has been entirely qualitative. For actual intelligent design, quantitative information is required. To obtain the much needed quantitative data regarding the effect of the many variables which should be considered in the design of a mechanically stabilized mixture, a cooperative investigation was undertaken 3 years ago by five organizations, the Highway Departments of Quebec and Ontario, Queen's University, L'Ecole Polytechnique of Montreal, and Imperial Oil-Research Laboratories at Sarnia.

The affect of the different variables was studied by means of the compression test, Fig. 15, and the water absorption test Fig. 16. Some of the most important results were discussed in the paper by Baskin and McLeod before the A.A.P.T. meeting two years ago. Other results have been published by the cooperating laboratories. Only the results of greatest importance to the design of mechanically stabilized base course mixtures will be touched upon here.

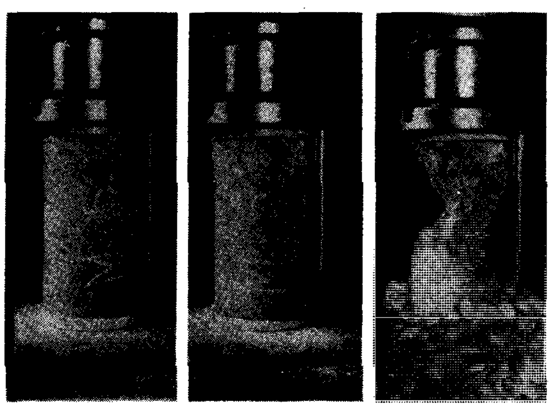


Fig. 15. Behaviour of 6 x 12 inch cylinders of mechanically stabilized mixture at different stages during a compression test.

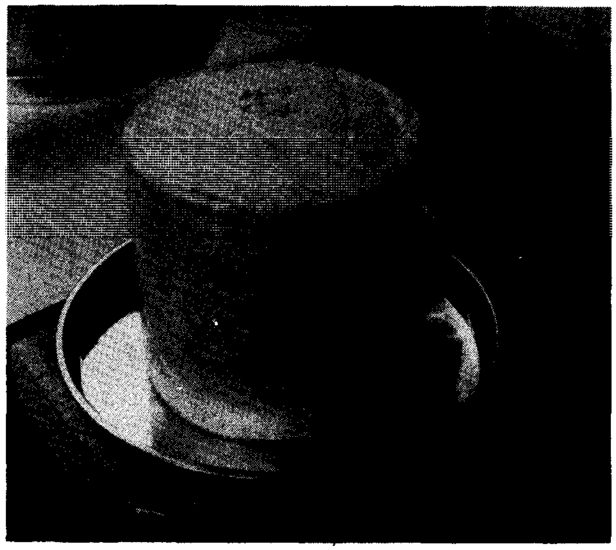


Fig. 16. 6 x 6 inch cylinders of mechanically stabilized mixture in water absorption test. Sides and tops are waxed to prevent evaporation, thereby simulating field conditions. The waxed layer contains pinholes on top to permit escape of displaced air. The bottoms are covered with filter paper and rest in 1/2 inch of water.

(6) <u>The Serious Loss of Bearing Capacity Caused by Water Absorption</u>

The data illustrated graphically in Fig. 17 (each point on the curve is the average for three 6 x 12 inch cylinders), emphasize the rapid decrease in compressive strength which occurs as the moisture content of a mechanically stabilized mixture is increased. This is a fundamental characteristic of all mechanically stabilized mixtures, and is due to the fact that the clay binder progressively softens and loses cementing power as its moisture content is increased, just as happens with another well-known binder, glue.

From Fig. 17, a number of important considerations emerge which should influence the design and construction of mechanically stabilized mixtures.

(1) At the moisture contents of from 4 to 7 per cent which have been frequently measured for non-waterproofed

mechanically stabilized base courses in the field, their compressive strengths and corresponding bearing capacities are very low, and the stabilized base course is not an efficient load supporting medium at these moisture contents.

(2) In the interest of good bearing capacity, every reasonable precaution should be taken to keep the moisture content of these stabilized base courses as low as possible.

(3) All admixtures with a strong affinity for water, which tend to maintain a high moisture content in stabilized base courses, should be avoided.

(4) Stabilized base courses should be constructed in layers not exceeding 2 inches compacted thickness, and after being properly consolidated at optimum moisture, should be allowed to dry to as low a moisture content as prevailing conditions permit, before a succeeding layer is placed. This procedure develops the higher bearing capacity possessed by these mixtures at lower moisture content.

(5) However, even if ordinary mechanically stabilized mixtures are dried to a low moisture content during construction, they may readily absorb moisture from the subgrade or other sources, and their bearing capacity becomes seriously impaired at the 4 to 7 per cent moisture content often found for them in the field.

(6) Fig. 17 makes quite clear the advantages which would result from the waterproofing of mechanically stabilized base course mixtures to maintain them at a low moisture content.

(7) The Waterproofing of Mechanically Stabilized Base Course Mixtures

The cheapest waterproofing materials are the bitumens, and the data illustrated graphically in Fig. 18, demonstrate the effectiveness of from 1 to 2 per cent of liquid asphalt as a waterproofing material, when compared with the controls which are otherwise the same but not waterproofed.

Each point on these water absorption curves is the average for two 6 x 6 inch cylinders, waxed on sides and top to represent field conditions of no evaporation from sides or top, and with bases immersed in 1/4 inch of water. Pin holes were made in the waxed tops to permit the escape of displaced air. Water absorption data are on the basis of the weight of the cylinder.

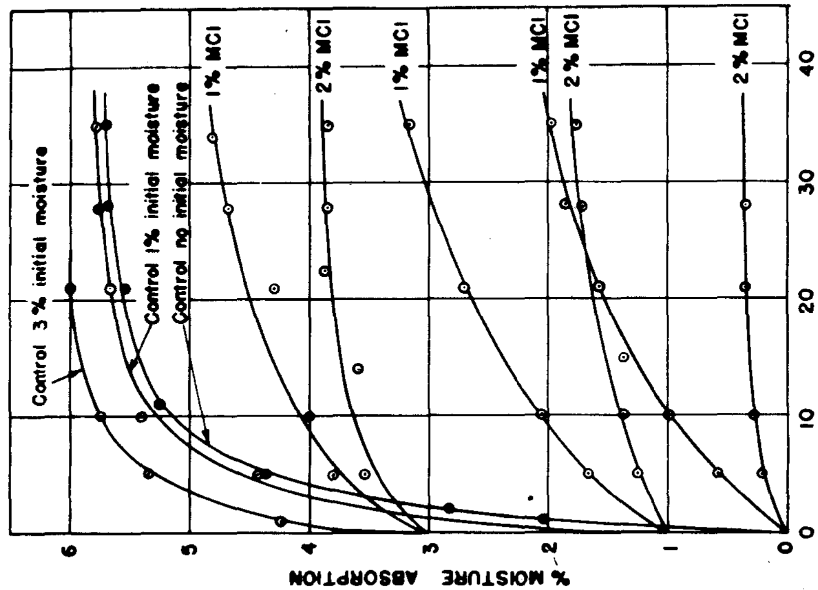

Control 3 % initial moisture
Control 1% initial moisture
Control no initial moisture
1% MCl
2% MCl
1% MCl
1% MCl
2% MCl
2% MCl
% MOISTURE ABSORPTION
TIME IN DAYS
0
10
20
30
40
0
1
2
3
4
5
6

FIG. 18

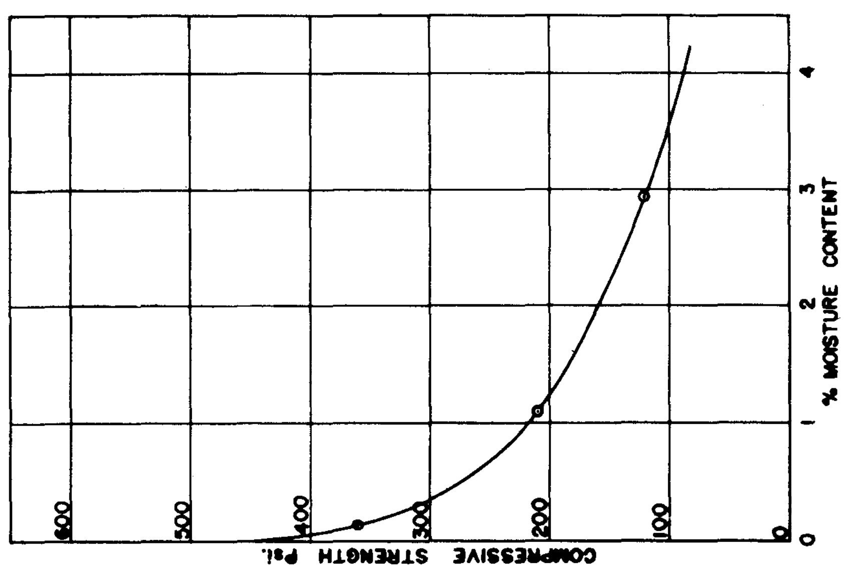

COMPRESSIVE STRENGTH Psi.
% MOISTURE CONTENT
0
1
2
3
4
0
100
200
300
400
500
600

FIG. 17

No mechanically stabilized base course can ever become or remain thoroughly dry in the field. Moisture studies on waterproofed mechanical stabilization which has been in service for several years, indicates an equilibrium moisture content for this type of about 2 per cent in drier regions, and of about 5 per cent in wetter climates, the water table being deeper than 5 feet in all cases.

The following items of information may be obtained from a study of Fig. 18,

(1) If the equilibrium moisture content of a waterproofed stabilized base course is from 1 to 3 per cent, the small quantity of liquid asphalt it contains is nearly as effective a waterproofing material, as when the mixture is initially thoroughly dry. That is, the presence of an initial moisture content up to 3 per cent does not greatly increase the rate of water absorption about that shown when the initial moisture content is zero.

(2) The rate of water absorption is very high for the controls which are not waterproofed, but very slow for the cylinders of waterproofed material. This is of important practical significance, for it demonstrates that water making its way through a cracked or porous area in a wearing surface down to an ordinary mechanically stabilized base course, would be rapidly absorbed, with a correspondingly rapid deterioration of the bearing capacity of the base course over the area affected. For a waterproofed mechanically stabilized base on the other hand, water absorption would be practically nil during a normal period of rainfall, the water in the cracked or porous area of the wearing surface would evaporate when the rainfall ceased, and no appreciable strength reduction in the base would occur.

(3) The slowness with which water is absorbed by waterproofed stabilized base courses, compared with the rapidity with which it is absorbed by non-waterproofed stabilized bases, is one of the great advantages of the former type over the latter in providing efficient and reliable base course performance.

(4) Because of these characteristics, a smaller thickness of a waterproofed mechanically stabilized base course would generally have the same load supporting value as a greater thickness of non-waterproofed stabilized base.

At the present time, 1 per cent of liquid asphalt is considered to be sufficient waterproofing material for incorporating in mechanically stabilized base courses in drier climates, and 2 per cent for regions of higher rainfall. Experience in the field over a long period of years may indicate that a greater percentage of liquid asphalt is required for this purpose, or that even a smaller quantity would suffice.

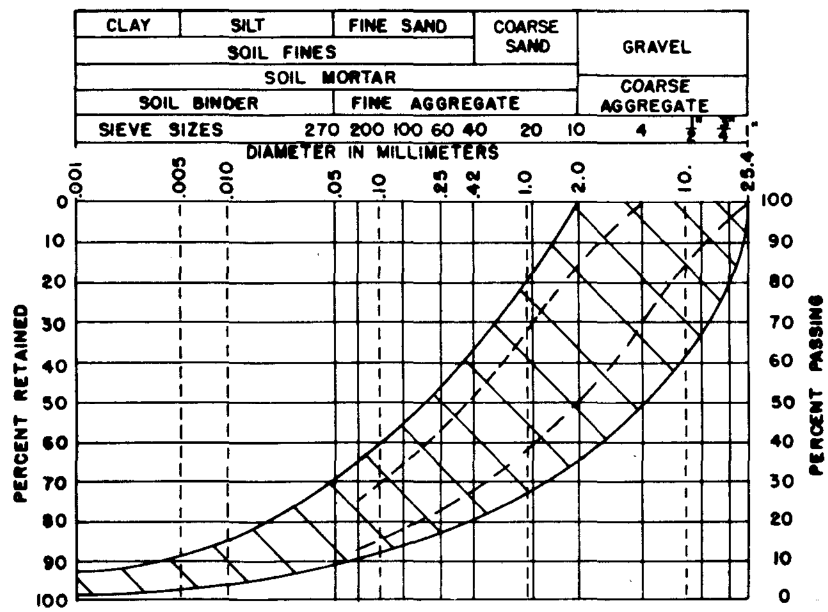
The type of liquid asphalt which has been most satisfactory for waterproofing is RC.1. From field experience thus far, it is believed that the viscosity of the liquid asphalt used for this purpose should not exceed 100 seconds Saybolt Furol at 122°F. If a higher viscosity material is used, difficulty is experienced in obtaining uniform distribution.

(8) Gradation

In Fig. 19, the recommended limits for the gradation of mechanically stabilized base course mixtures are presented graphically, for stabilized mixtures in which the maximum particle size ranges from 1 inch to No. 10 sieve. The recommended optimum gradings appear as broken lines - the lower broken line for stabilized mixtures containing coarse aggregate (1-inch maximum size), and the upper broken line for stabilized mixtures made from fine aggregates (No. 4 sieve maximum size). The recommended curves for optimum grading are the result of both laboratory studies and field observations, and were arrived at on the basis of harshness of the mix, tendency to segregate, workability, ease of compaction, etc. The broken curves do not actually stop at the 200 sieve, but continue on down to particles of colloidal size. They are stopped at the No. 200 sieve in Fig. 19, partly to avoid confusion, and partly because it is unusual to use a smaller sieve than the No. 200 when designing a stabilized mixture.

It should be observed that the top of the broken curve for 1-inch maximum size, leans toward a minimum content of course aggregate. This results from laboratory tests which indicate that a large percentage of coarse aggregate is not necessary for the high bearing capacity of a stabilized mixture. This is very important economically for keeping down the cost of mechanically stabilized base courses, for the coarse aggregate is usually the most expensive ingredient of a stabilized mixture.

It is a point in favour of mechanical stabilization that excellent stabilized base course mixtures, which contain no material larger than fine gravel or coarse sand (No. 4 sieve), can be designed with bearing capacities apparently equal to those



GRADING BAND FOR MECHANICALLY STABILIZED BASE COURSES

FIG. 19

made with gravel or crushed stone. This is important from the point of view of the cost of stabilized base courses in localities where much coarse sand is locally available, since sand is usually much cheaper than gravel or other coarse aggregates. It is to be observed that without the addition of a binder, granular materials smaller than a No. 4 sieve, do not ordinarily make satisfactory base courses.

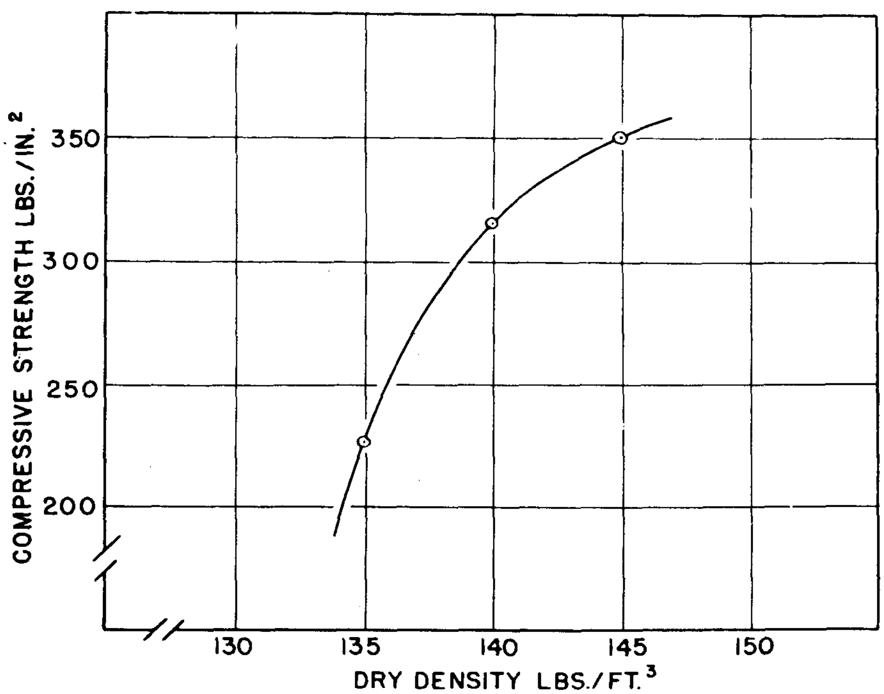
(9) Effect of Plasticity Index

For ordinary mechanical stabilization, a P.I. less than 6 is specified for base courses at the present time.

It is an advantage of waterproofed mechanical stabilization that its properties are to a large degree independent of the P.I. of the finished mix, because water in detrimental amounts is kept from the clay binder. An upper limit of P.I. beyond which trouble would begin, cannot be stated with certainty at the present time, but a limit as high as 10 or 15 appears reasonably safe. A waterproofed stabilized base course having a P.I. of 25 which could not be lowered except at excessive cost, has been giving excellent service since its construction several years ago.

(10) Compacted Density Required in the Field

Fig. 20 emphasizes the importance of rolling mechanically stabilized mixtures to high density in the field. Bearing capacity falls off quite rapidly if densities are low. For mechanically stabilized mixtures containing gravel, the specified density should be between 140 and 145 pounds per cubic foot. For stabilized mixtures containing no particles larger than a No. 4 sieve, the specified density should be from 130 to 135 pounds per cubic foot.



EFFECT OF DENSITY ON COMPRESSIVE STRENGTH

FIG. 20

(11) Thickness of Stabilized Base Course Required

There is considerable controversy at the present time over the design of base course thickness required for supporting any given wheel load on a highway or runway.

One of the most rational methods of design which has so far been proposed for this purpose, is that brought out by Professor Housel several years ago. Using Fig. 21 for illustration, two sample calculations for thickness of base course will be worked out using his method.

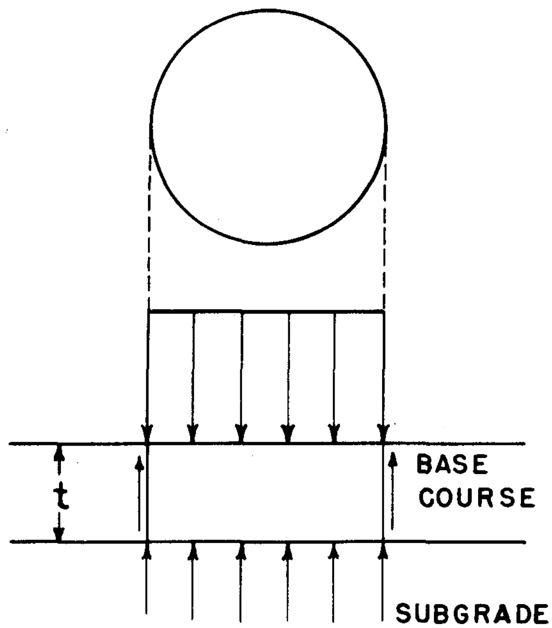


DIAGRAM ILLUSTRATING THE FORCES INVOLVED WHEN DEVELOPING THE LOAD CARRYING CAPACITY OF BASE COURSE AND SUBGRADE

FIG. 21

The Housel formula is

$$t = \frac{(r)\ (p - n)}{2m}$$

where t = thickness required in inches
r = radius in inches of contact area (where contact area is wheel load divided by tire pressure)
p = tire pressure in p.s.i.
n = subgrade support in p.s.i.
m = shearing resistance of base course in p.s.i. (punching shear)

Example 1

Suppose wheel load = 15,000 pounds
tire pressure = 90 p.s.i.
subgrade support = 25 p.s.i.
shearing resistance of stabilized base = 40 p.s.i.

Note - a shearing resistance of 40 p.s.i. appears to be a reasonable value for waterproofed stabilized base courses in the field, on the basis of compressive strength tests made on these mixtures at 3 per cent moisture content in the laboratory. A reasonable factor of safety is contained in this value, since it does not include the effect of any lateral support.

$$\text{Thickness required} = t = \frac{(7.3)\ (90-25)}{(2)\ (40)}$$

$$= 5.93 = 6 \text{ inches}$$

Example 2

Suppose wheel load = 75,000 pounds
tire pressure = 75 p.s.i.
subgrade support = 25 p.s.i.
shearing resistance of stabilized base = 40 p.s.i.

$$\text{Thickness required} = t = \frac{(17.8)\ (75-25)}{(2)\ (40)}$$

$$= 11.1 \text{ inches.}$$

(12) Advantages of Waterproofed Mechanically Stabilized Base Courses Versus Relatively Porous Bases

(a) Myth of the "Capillary Break"

There are countless references in our technical literature to the use of a layer (subbase or base course) of porous sand or gravel on top of the subgrade and below the pavement, for the purpose of acting as a "capillary break." The theory behind its recommended use in this manner, is that capillary water cannot enter the pore space of the granular material, and the pavement or any other layer above is therefore protected from the rise of capillary water from the subgrade. It can be easily proven by the first law of thermodynamics that this theory is entirely a myth, and Fig. 22 will be used for this purpose.

Let A at the left of Fig. 22 consist initially of a column of dry soil with the water table as shown, and containing a central well. Water will continue to rise through the soil up to

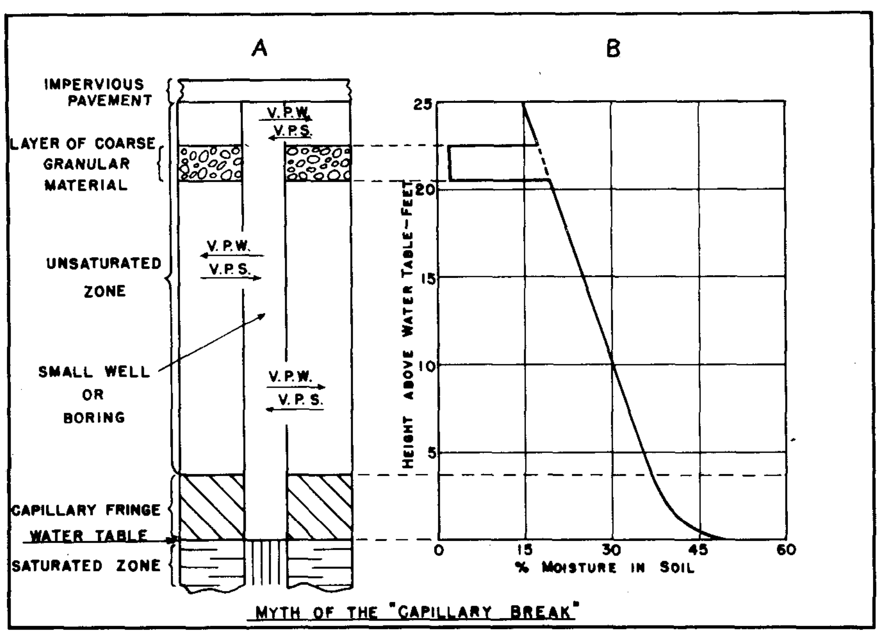


FIG. 22

the porous layer by capillarity, until the maximum capillary moisture content is attained at each elevation above the water table. In the well itself, the vapour pressure of water vapour decreases with height above the water table because of the influence of gravity. When the soil has taken up its maximum moisture by capillarity, the vapour pressure of moisture in the soil, and vapour pressure of water vapour in the well must be exactly the same at each elevation above the water table. Otherwise a steam engine could be set up and driven by the difference in vapour pressures. Since this would result in perpetual motion, and is therefore impossible, the two vapour pressures must be the same when equilibrium conditions are established in both soil and well.

It is true that capillary moisture cannot rise through the porous layer, but the fact that is usually forgotten is that water vapour from the top of the well will enter the soil above the porous layer. Since at equilibrium the vapour pressure of moisture in the soil must equal the vapour pressure of moisture in the well at the same elevation above the water table, water vapour will distill from the well into the soil until it has absorbed enough moisture to establish this equilibrium. When this equilibrium is reached, the amount of moisture in the soil layer will be the same as that which it would have attained by capillarity if the porous layer had not been there, Fig. 22 B.

To anyone who objects that such wells are not normally a part of a roadway or runway structure, it can be pointed out that millions of such wells exist in every soil in the form of its pore space in which water vapour is always present and through which it travels. This pore space can be of considerable size in a porous layer.

In the design of roadway or runway structures therefore, it is well to remember that moisture equilibriums can be established through the vapour as well as through the capillary phase.

Consequently, as far as keeping capillary moisture out of a pavement is concerned, a porous base course has no advantage over a dense mechanically stabilized base course.

(b) General

(1) Porous base courses are frequently recommended because their porosity is supposed to enable them to function as a drain under a pavement. In criticism of this conception, it can be pointed out that a small depression formed in the surface of the subgrade for any reason (D in Fig. 4) causes a porous base to function as a reservoir, and leads to failure of the pavement when the subgrade is clay.

Because of their very small pore space, mechanically stabilized base courses cannot become water reservoirs.

(2) Porous base courses transmit water to the subgrade during surfacing operations, if rains occur during construction, and may require frequent removal of the porous base to allow the subgrade to dry.

Waterproofed mechanically stabilized base courses shed water, and reduce construction delays.

(3) Porous base courses may yield during surfacing operations because rain has penetrated and softened the subgrade, and this makes consolidation of the pavement difficult.

Because they protect the subgrade, waterproofed mechanically stabilized base courses provide firm support for surfacing operations.

(4) No wearing surface is entirely impervious to moisture. Water will flow through a crack or porous area in a pavement quite rapidly during a rain if there is any reservoir of pore space in the base course below to accommodate it. If such a crack or porous area occurs in the pavement over a porous base near the centre of a roadway or runway, the water flowing through during a rain, or from melting ice or snow, has a distance of many feet to travel to a side drain or ditch. Much of this water would be absorbed by a clay subgrade on its way to the drain, or might be caught in a subgrade depression or other area where drainage was blocked, leading to serious softening of the subgrade with resulting surface failure.

This mechanism of pavement failure is not possible for a waterproofed mechanically stabilized base course. Water entering through cracks or porous areas in the wearing surface is stopped when it reaches this type of base below. After the cracks or porous areas fill, the remaining water is unable to enter and is shed to the edges of the pavement. The water in the cracks or porous areas in the surface course evaporate after the rain, and no damage results because neither base course nor subgrade has been affected.

(13) <u>The Cost of Waterproofed Stabilized Base Courses</u>

The contract prices for plant-mix waterproofed stabilized base course construction for highways in Canada, have varied quite consistently between about 35 and 60 cents per square yard of 6 inches compacted thickness. Included within this price range is one project where the gravel required was hauled 85 miles by rail. As would be expected, the contract price has varied with the distance the various materials have had to be transported, and with the method of haulage used.

On many highway projects, the contract price for waterproofed stabilized base courses, apart from the bitumen for waterproofing, has not been much higher than the cost for consolidated gravel bases of the same thickness would have been.

Approximately five million square yards of plant-mix waterproofed mechanically stabilized base courses have been constructed on highway and airport projects across Canada. Consequently, this base course material has passed well beyond the experimental stage, and must now be looked upon as an important addition to standard base course construction.

(14) Some Don'ts for the Successful Construction of Waterproofed Mechanically Stabilized Base Courses

Don't use waterproofed mechanically stabilized base course construction,

(1) where rainfall is so high and regular that the periods of dry weather would not be sufficient to lower the moisture content of the base course to the 3 or 4 per cent required for developing reasonable bearing capacity, without causing construction delays.

(2) where it would be in perpetual contact with free water (because the water table is near the elevation of the grade line), which would keep it saturated or nearly saturated, and therefore weak, (Fig. 17).

(3) where the subgrade is not firm. It will fail like any other type of base course under this condition.

(4) unless adequate field laboratory control is provided over every phase of construction, to ensure proper proportioning of ingredients at the mixing plant, adequate mixing, and ample control of the density being obtained during rolling operations.

PART II. CONSTRUCTION

The successful construction of waterproofed mechanically stabilized base courses requires,

(1) Proper selection of materials.

(2) Adequate mixing.

(3) Proper consolidation when laid on highway or runway.

(4) Adequate and active field laboratory control over every phase of construction operations.

(1) Selection of Materials

(a) To obtain the grading required, it is usually necessary to employ three ingredients, gravel or crushed stone, sand or stone screenings, and clay binder. While occasionally two ingredients, aggregate and clay binder, will provide a satisfactory stabilized mixture, the use of three ingredients has the advantage of providing greater flexibility of control over the grading required.

(b) The clay binder should preferably have a P.I. between 10 and 20, and should be pulverized until 85 per cent passes a No. 4 sieve.

There is room for considerable improvement in the performance of existing clay pulverizing equipment on the part of road machinery manufacturers, particularly in devising equipment which will satisfactorily shred moist clays.

(2) Adequate Mixing

(a) While road-mixing and travelling plants have been used for mixing operations, central mixing plants are to be preferred, for much better control of the mix is possible.

(b) Mixing equipment should preferably be of the pugmill type, but concrete mixers are also quite satisfactory. Either continuous-mix or batch-mix plants may be used.

(c) The gravel, sand, clay binder, water, and liquid asphalt are usually added together in batch plants, and mixing is continued until all ingredients are uniformly distributed throughout the mix. This requires a minimum of 1-minute's mixing for concrete mixers, and somewhat less for pugmill mixers.

(d) The moisture content of the finished mixture should be kept between 5.5 and 6.5 per cent, to facilitate later rolling operations on the highway or runway.

(3) Laying the Stabilized Base Course

(a) The finished mixture should preferably be laid with a self-propelled mechanical spreader.

(b) It should be laid in layers not exceeding 2 inches compacted thickness for each.

(c) Immediately after spreading, each layer should be rolled once with a self-propelled steel roller. This eliminates any rutting by the pneumatic tired rollers which follow, and removes any necessity for blading to smoothness with a motor patrol.

(d) All other rolling should be done with pneumatic tired rollers.

(e) During the entire rolling operation, each layer should be maintained at a moisture content between 5.5 and 6.5 per cent, by spraying the surface with water from a spray truck as required. Moisture contents much above 6.5 per cent cause the mixture to be plastic and difficult to roll. This may lead to the failure of short sections where a surface skin becomes dry, and cracks under the roller or traffic because the remainder of the layer remains plastic. Such plastic sections should be removed, otherwise they may cause the failure of succeeding superimposed layers in the same area. At moisture contents below about 5.5 per cent, the mixture does not consolidate rapidly. By judicial use of a water spray truck, it is a simple matter to control the moisture content between 5.5 and 6.5 per cent during rolling operations.

(f) When the required density is obtained, each layer of the stabilized base course should be allowed to dry to as low a moisture content as prevailing weather and construction conditions permit, before a succeeding layer is constructed.

(4) Field Laboratory Control

(a) The successful construction of mechanically stabilized base courses, requires comprehensive and vigorous laboratory control over every phase of construction.

(b) The stream of finished mix from the mixing plant should be sampled every half hour (5-pound sample), and the resulting composite sample tested for moisture content and sieve analysis for every four hours of plant operation.

(c) The density of the finished mixture being rolled in place must be measured as a guide to the amount of rolling required, and over an ample number of points to ensure that the density being obtained is uniform.

(d) Adequate active field laboratory control will cost approximately 4 per cent of the contract price of the work being constructed on a project, and inspection is almost certain to be inadequate if the cost of the field laboratory control is less than 3 per cent of the contract price.

SUMMARY

(1) Because of the lack of flexibility in the California design for thickness of flexible pavements, it is suggested that the desired degree of flexibility of design could be obtained by combining the California design with the pedological system of soil classification.

(2) Four fundamental principles of subgrade construction are briefly discussed.

(3) The most important fundamental principle of drainage for the removal of water from a soil is that capillary water cannot be drained.

(4) Mechanically stabilized base courses consist of a scientifically designed mixture of gravel, sand, and clay binder, in which as a recent development, from 1 to 2 per cent of liquid asphalt is incorporated to give "waterproofed mechanical stabilization."

(5) The detrimental characteristics of clay as a binder for granular materials can be controlled by,

(a) the addition of the proper proportion of fine sand to minimize its swelling and shrinkage properties,

(b) the addition of a small quantity of liquid asphalt as a waterproofing material, to keep out harmful amounts of water which reduce its cementing power.

(6) The compressive strength of a mechanically stabilized mixture decreases rapidly as its moisture content is increased.

(7) The incorporation of from 1 to 2 per cent of liquid asphalt into a mechanically stabilized mixture as a waterproofing material, keeps the equilibrium moisture content of waterproofed stabilized base courses in the field down to about 2 per cent in drier regions, and to about 3 per cent in wetter climates.

(8) The recommended range of gradation for mechanically stabilized base courses is specified.

(9) Waterproofed mechanically stabilized mixtures are largely independent of the P.I. of the finished mixture.

(10) The influence of density on compressive strength is illustrated, as a guide to the need for adequate compaction in the field.

(11) Sample calculations for thickness requirements are given, based upon the Housel formula.

(12) The cost of waterproofed stabilized base courses is discussed.

(13) Some don'ts for mechanically stabilized base courses are listed.

(14) The requirements for the successful construction of mechanically stabilized base courses are described.

There are two remarks the writer would like to add by way of conclusion,

(1) It is small credit to the ingenuity of man, in view of the remarkable technological developments in the use of soil materials in recent years, if our most efficient use of granular materials for highway and runway base courses still consists of merely pouring natural gravel on the subgrade as our forbears have done for several thousand years. Stabilization represents one attempt to use granular materials in a more efficient manner, and it is quite conceivable that still other probably superior processes will be developed.

(2) There is a current shortage of both transportation facilities and many construction materials. Furthermore, the asphalt, portland cement, and other manufactured or prepared products required for the construction of highways and airports, are relatively bulky substances. The quantities of these materials required, and the transportation facilities needed for transporting them both at home and abroad, can be reduced to a minimum, if the principles of soil engineering are applied to developing the maximum utilization of materials locally available in the vicinity of each project, for subgrades, base courses, and wearing surfaces.

DISCUSSION

CHAIRMAN ENDERSBY: Dr. McLeod's paper should be of special value to all interested in bituminous stabilization, for the reason that you cannot neglect the mechanical aspect of the soil in applying bituminous material. It is noticed that he bordered also on bituminous stabilization, and that is interesting for the reason that if the proper choice between different types is purely economic. If materials can be found for mechanical stabilization without the use of oil, which produce a satisfactory result as cheaply as you can do it with oil, then there is no good reason for applying the more complex method of oil stabilization. It is purely a matter of which is the cheapest method to produce the given result.

There has not been any formal discussion presented for this paper, so I will call first on some of those whose work bears on this, and then we will have more general discussion, but we cannot prolong it very much. Mr. McLeod set forth the proposition that in using the California Bearing Test, there should be a family of curves for each pedological soil classification. I would like to ask Mr. Porter to comment on that.

MR. STANTON: Mr. Porter is not here at present. However I can state that as far as the California Bearing Test is concerned, it relates to the soil in a particular degree of consolidation and with a certain moisture content. If we assume that that moisture will not accumulate to the extent of, we will say, the maximum or the worst conditions, then what Dr. McLeod states is perfectly true, and there is where the skill and experience of the engineer comes in. In other words, we start with the worst condition conceivable, which is represented by the particular series of curves, that were presented yesterday. Then as the conditions can be improved, there should be another set of curves for the improved conditions or the original curves should be modified, based on the judgment and experience of the engineer and the analysis fitting the particular case under consideration.

MR. PORTER (by letter): Dr. McLeod's suggestion may be practical in many sections of the country, but I believe that the matter should be given careful study, in each specific case, to properly evaluate the probable effect of additional load repetition on any roads or runways which are used to secure empirical data on which to modify the design curves. It should also be clearly determined from this study whether or not the subgrade has reached a state of equilibrium in regard to density and that a higher moisture content will not be present at some later date.

The main disadvantage of the pedological soil classification is that they bare no relationship to the engineering properties of the material and also that the soils cannot be compared on a nation-wide and world-wide scale. Although the same pedological classification of soil may extend over relatively large areas in some sections of the country, the types on even a state-wide scale, in a state such as California, become sufficiently voluminous to be meaningless to the average engineer. Only a relatively small area of the state has been mapped but somewhat over 300 soil series have already been classified. In many cases each soil series ranges in texture from sand to clay. As an example, the Rosamond series include sand, sand hummocky phase, sand well-drained phase, fine sandy loam, loam, silt loam, and clay loam. In all, there probably are well over 1000 soil types listed and these do not include the subsoils and soft bedrocks (more or less recent deposits which pulverize under grading equipment) which make up a large percentage of the subgrade materials encountered on most construction projects traversing rolling or hilly ground. To prepare curves for all of the pedological types encountered throughout the areas where our armed forces are now constructing highways and runways would be a mammoth undertaking even if the necessary factual information was available.

MR. OGDEN: I am not a member of this organization, I am just interested and I would like to ask a question. We have done a great deal of work in stabilization, Mr. McLeod, and when you speak of moistureproofing the particles, can you get a stabilized mix out of that, that will stand up? Have you had that experience?

DR. McLEOD: As I understand your question, you asked: when these particles are waterproofed, will the stabilized mixture stand up? The only real answer I can give is that there is something like 5,000,000 square yards of waterproofed mechanical stabilization giving excellent service in Canada.

MR. OGDEN: Let me finish my story. We have made a lot of experiments and we have found by simply waterproofing the particles and putting them to a water absorption test and then subjecting them to compression as the McKesson test is made, that the mixture does not stand up; it does not stand up much better than a mixture of ordinary materials containing no bitumen, because we find that we have to get away from capillary attraction. We have always figured that it was necessary to fill the voids in the mix. When we did fill the voids in the mix, we got marvelous tests, but with just waterproofing the material, we never got a test that was worth a snap of your finger, and I want to know what is wrong with our test.

DR. McLEOD: You bring up a matter on which there is considerable conflicting opinion at the present time, and that is the value of some of the arbitrary laboratory tests which have been proposed for stabilized mixtures as a criterion of their field performance.

We have found from actual field tests on mechanically stabilized base courses in which from 1 to 2 per cent of liquid asphalt has been incorporated as waterproofing material, that over a period of years these base courses appear to acquire an equilibrium moisture content which is quite uniform throughout the year regardless of changing climatic conditions. In drier areas, this equilibrium moisture content is from 2 to 2-1/2 per cent, and in areas of higher rainfall from 3 to 3-1/2 per cent. Without waterproofing, moisture contents as high as 7 per cent have been found in mechanically stabilized bases in the field. Since the strength of a mechanically stabilized base course decreases rapidly with increasing moisture content, the advantages of waterproofing based on these field results are obvious.

Based on some arbitrary laboratory test, from 1 to 2 per cent of liquid asphalt for waterproofing a mechanically stabilized base course mixture would probably seem insufficient, but this is not borne out by field experience up to the present time. I believe that this field experience provides the answer to the question you brought up.

MR. OGDEN: I would like to have that answered, because in our tests we have worked out a formula where we can make and figure out absolutely accurately a stabilized mix. We have found, as you say, that if you put more than enough asphalt in it, it is not any good; if you put too little, it isn't any good. There is a range of material you must have, but that material, we find, must fill the void; you must have your mix arranged so that it fills the void. Have you had that experience?

DR. McLEOD: No. Based upon our own laboratory studies and field experience, we do not feel it is necessary to add sufficient bitumen to completely fill the voids in a stabilized mixture. Because of the large amount of bitumen required, and the resulting tendency toward instability, we believe such a practice would be actually detrimental, and far too costly.

MR. OGDEN: Has anybody here had that experience? Thank you, Dr. McLeod.

DR. McLEOD: Does the type of stabilization that you refer to consist of the mechanically stabilized type, or would it be the type that Mr. McKesson and Mr. Klinger are going to describe?

MR. OGDEN: My dear sir, I know so little about it, I don't know what type. All I know is what we have done. I couldn't tell you the technical term of a thing.

DR. McLEOD: It is my understanding that there are these two types of stabilization: first, the mechanically stabilized type, which is a scientifically designed mixture of gravel, sand, and,clay binder --

MR. OGDEN: That is what we do: we grade it and we grade it so that the voids will be within a certain percentage of the mass, so the voids will not exceed five to six per cent, or four and a half to six per cent, and those voids, when filled with a stabilizing material like asphalt, have all made good tests.

For instance, we took Texas black soil, of which ninety-eight per cent will pass through a 200-mesh sieve, and by putting any kind of aggregate in it, make perfectly beautiful tests, if we put the right amount of asphalt; but just to waterproof those particles alone, we never got any worth-while results.

DR. McLEOD: We waterproof the whole mixture, not just the fine particles.

MR. OGDEN: We tried that, too,

DR. McLEOD: I might add that we believe that whether 1 per cent or 2 per cent of liquid asphalt, or more, is required for adequately waterproofing a mechanically stabilized base course mixture cannot be answered by laboratory tests alone. We believe the answer to this will only develop out of our experience in the field over a period of years. Up to the present time however, very satisfactory results have been obtained with the use of only 1 to 2 per cent of liquid asphalt as waterproofing material for this type of stabilized base.

MR. CAMPEN: Dr. McLeod, I inferred from your talk, speaking on mechanically stabilized mixtures that you were not able to control the water holding capacities of these mixtures in the field. Is that right?

DR. McLEOD: No. I think I would say that we do control the water absorbing capacities of these stabilized mixtures, by the use of liquid asphalt as a waterproofing material.

MR. CAMPEN: Here is what I mean: Supposing that in a certain mixture you design, you wish to keep its water content to 4 per cent or less in actual use in order to get the desired load bearing value or strength from it. I get the impression from what you said that these mixtures might take up a total of 5 to 7 per cent of water and actually did it in the field.

DR. McLEOD: No. The mixtures which in our experience take up 4 to 7 per cent of moisture are those of the ordinary mechanically stabilized type which have not been waterproofed. We have never found these high moisture contents in the field for mechanically stabilized mixtures that have been waterproofed.

MR. CAMPEN: What was the optimum water content on a typical mixture?

DR. McLEOD: About 6 per cent.

MR. CAMPEN: Does this mixture have sufficient strength at that optimum water content?

DR. McLEOD: We have abundant laboratory evidence to prove that the compressive strength of these mixtures at 6 per cent moisture content is a great deal smaller than at lower moisture contents.

MR. CAMPEN: I wanted to be sure that I understood you, because I want to give an observation or two that I have made in the last six weeks on work which has to do with mechanical stabilization.

We have been able to take well-graded mixtures and found that after compacting them to maximum density at optimum water content that they do not take up any more water by capillarity than we put into them during construction. These mixtures are stable at that moisture content and in our work had sufficient strength to do what we wanted them to.

DR. McLEOD: It is our experience that a properly consolidated mechanically stabilized base course, which is not waterproofed, and which has become dry after construction, is capable of again absorbing water up to its optimum moisture content, which is usually about 6 per cent.

MR. CAMPEN: But not more than that?

DR. McLEOD: In general it will absorb more than its optimum moisture only if the stabilized mixture has not been compacted to the maximum density corresponding to this optimum moisture. Field moisture contents as high as 7 per cent, which we have occasionally observed for mechanically stabilized base course mixtures which have not been waterproofed, are probably the result of inadequate compaction.

MR. CAMPEN: The reason I am going into detail is because it is one of the fundamental principles involved in constructing these economical subbases and bases with these types of materials without using anything else. There is a use for asphalt and cement and many other mixtures for stabilizing solid, also a use for soil mixtures using nothing but water, clay, silt, sand and gravel. Construction of this latter type is suitable for a great many purposes and we should not get the impression that these mixtures are not stable, that is, that they might take up any amount of water depending on how much water comes in contact with them. The fact is, these mixtures can be so selected and compacted as to retain certain structural properties...I don't know for how long ... In my own experience for six years on jobs I have had contact with.

DR. McLEOD: I agree with Mr. Campen that non-waterproofed mechanically stabilized base course mixtures which have been properly consolidated, will not generally absorb water in excess of their optimum moisture. As previously pointed out, however, at their optimum moisture the compressive strength of these mixtures becomes very low, and they are not as efficient for supporting load as at a lower moisture content. The efficiency of mechanically stabilized base courses is greatly increased (that is, a given load can be supported by a thinner base) at very low cost by waterproofing with liquid asphalt. This waterproofing reduces water absorption, and preserves a high uniform bearing capacity on a project regardless of changing climatic conditions.

We believe there are definite advantages (outlined in the paper itself), in reducing the specified thickness of ordinary mechanical stabilization, by the small fraction required to affect the saving in aggregate materials for offsetting the small cost of the 1 to 2 per cent of liquid asphalt needed for waterproofing the remaining thickness. It is our observation, that engineers who have experienced the advantages of properly designed and constructed waterproofed mechanically stabilized base courses, do not care to return to the non-waterproofed type.

MR. E. H. SCOTT: Mr. Chairman, if you would allow me to make a few remarks in connection with this subject, I am going to rather take the liberty of censoring the asphalt technologists for their lack of appreciation of what Dr. McLeod has done and has proved. The whole thing comes down to this: He is using clay as a binder; he is not using asphalt as a binder at all. The stability which he gets from his mechanically stabilized mixtures comes from the cementing property of clay, certain clays under certain moisture content. He uses asphalt merely to maintain the moisture content of the clay binder and the asphalt acts as a waterproofer.

In our experience, we have found that unless you can control the water content of mechanically stabilized soils, you cannot get anything of a permanent result. I am referring to calcium and chlorides and that sort of thing, and let me go so far as to say probably emulsions.

The situation comes down to this: that when you construct an airport in the manner which is laid out by Dr. McLeod, you get something which approaches a very weak concrete, you get something which is even better than the soil cement stabilization which we hear so much about in commercial life. You can take a pick and you can hammer, and you won't dent it and it maintains its stability.

I have attended meetings of this organization for some years. I heard Dr. McLeod's original discussion, which was merely passed over, I don't know why, and I am trying to emphasize the point that you are missing something unless you look into this...you are absolutely missing something.

You may say it has nothing to do with asphalt. A gallon per square yard for 30,000 square yards means quite a bit of asphalt. We find on ordinary ports that we build, instead of paying $40,000 for asphalt we are paying $70,000 for asphalt. The extra money is for asphalt for a stabilized job. The men in the supply business must realize that while the percentage of asphalt is small, it is nevertheless sufficient and runs into good quantities.

I do wish to suggest to you that there are limitations to the use of mechanical stabilization. We lay it down as a standard when we have gumbo soils in areas that do not have too much rain. We also use it to handle certain very clean and fine gravels.

I was glad to hear Dr. McLeod mention Professor Housel. We are using the Housel method of soil compaction and we use a penetrometer, which is a mechanical thing that the contractors' superintendents use, and we have established that the penetrometer has to take fifteen to twenty blows before we will accept the soil. But, we run into certain soils which we call gumbo where you have a volumetric change of 60 per cent between wet and dry; we figure if you have your soil wet and it gets a little drier, you have cracks forming. So, we look for a semi-rigid base to put on that kind of soil, and those are the places where we use this mechanical stabilization, and I submit that we can show you results. We have a number of ports, quite a large number of ports constructed in that manner.

There is only one proviso I would suggest, that is, don't put it in a rainy area, because you make your mixtures at about 6 per cent of moisture and they have to dry out before you get the setting effect in your base course stabilization.

CHAIRMAN ENDERSBY: Mr. Scott has implied quite a criticism of the asphalt paving technologists -- but "implied" is not exactly the word. (Laughter) I think the easiest way to settle the question as to whether we are subject to criticism on that point or not, is to ask anyone here who works with asphaltic stabilization if he disagrees with any of the points raised by Mr. Scott.

MR. KLINGER: We would like to express general agreement with everything that has been said so far. As we pointed out at a previous paper by Baskin and McLeod, if you figure the amount of liquid asphalt on the basis of the material that needs the liquid asphalt, it comes to about 12 to 15 per cent. This is approximately the same percentage we would use for the binder soils and clay. In that respect we do not differ at all. In the total mix for conditions of our test, we would probably go to percentages of 3 to 4 per cent rather than 1 to 2 per cent, as mentioned by Dr. McLeod. That isn't a very great difference.

The point which he emphasizes is that waterproofing is obtained on the particles which need it most, which are the fines and particularly the clay that is added. For his particular method, this is the correct amount required for complete waterproofing.

MR. MIDDLEBROOKS: I agree with Dr. McLeod on most of his points, particularly on his drainage, and there is no doubt that increased compressive strength has an advantage in bases. However, I think he has passed over granular materials too lightly which, when confined, do have considerable bearing capacity. Just because that particular material would not have a high unconfined compressive strength does not mean that confined under a reasonable thickness of pavement it would not give good bearing. We have cases of clean sand where five inches of sand asphalt carrying 20,000-pound wheel load, the sand underneath that would have zero compression strength if you put it under a test like Dr. McLeod described

I think in most cases clay as a binder is unnecessary. It is not essential as long as you have a pavement or surface over it which will confine it sufficiently to develop its proper bearing capacity. We have other cases where five inches of good, well-graded gravel base material, over a uniform sand, has carried up to 20,000-pound wheel load. That is not due to compressive strength but to the development of the frictional strength of this granular sand by the applied and confining load. That is the main point on which I differ with Dr. McLeod. You can utilize clean granular material, including all types of sand as a base course material, to great advantage.

In other words, we have places where we pumped in great fills of clean sand and gravel, and it is not necessary in those cases to go in and make an elaborate mixture in order to get an ideal gradation including clay as a binder. The main thing is to confine that granular material with a sufficient surface to hold it down and distribute and carry the load.

DR. McLEOD: As Mr. Middlebrooks has pointed out, when clean gravel or sand are properly consolidated and suitably confined, they develop good bearing capacity. In localities where gravel is abundant, it is probably the cheapest base course material that can be used.

It is a well-recognized property of granular materials, that they have no bearing capacity apart from the lateral support supplied by the confining influence of adjacent material, but it should also be recognized that bearing capacity derived from the confining influence of lateral support is common to all base course materials in place.

The bearing capacity of granular materials can be increased by the use of a suitable binder, which furnishes them with bearing capacity apart from lateral support. Both laboratory tests and experience in the field indicate that the addition of the proper proportions of fine sand and clay binder to gravel or coarse sand to give a mechanically stabilized mixture, provides a base course material, which at low moisture content, appears to have appreciably higher load carrying capacity for a given thickness than base courses of clean gravel. This low moisture content is maintained by waterproofing.

Stabilization, therefore, becomes particularly important in those areas where granular materials are scarce and costly, and where some inexpensive process must be applied to obtain the maximum value in load carrying capacity from their use. Because of the advantages of waterproofed mechanically stabilized base courses, when compared with base courses of clean aggregates, enumerated in the paper itself, I also believe that stabilized base courses of this type, when properly designed and constructed, have a place in base course construction even where granular materials are more plentiful.