SOIL SCIENCE RELATING TO FLEXIBLE TYPE ROAD SURFACES

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SYNOPSIS

The theory of stability of soils and the methods used to produce stabilization of subgrade soils are presented The essential features of stabilization include prevention of clay and silt soils from becoming deterimentally wet, incorporation of granular materials in clay soils and furnishing granular soils with cohesive binder General methods are enumerated as follows

1 Selection of natural soils with granular material and binder which furnishes high stability
2 Adding soil binder to granular materials, or adding granular material to clays
3 Treating graded soils with deliquescent materials
4 Waterproofing soils with surface treatments of bituminous materials
5 Densification of natural soils by special manipulation in combination with admixtures of physical or chemical materials other than soil to eliminate permanently those clay and colloidal properties productive of volume change

Since comprehension of the practicability of permanently densifying soils is facilitated by understanding the performance of materials when in films of molecular thickness, the discussion deals especially with the theory of matter in the film phase, the wetting of solids by liquids, adsorption as affected by electrolytic properties, and the densification of soil at optimum moisture content

The rôle of soil science in the design of flexible type road surfaces may be pictured by reviewing briefly the relative contributions of both subgrade and constructed surface structure to the total load capacity of the road

Our discussion deals with raindrops, ruts, and relativity It begins with the theory of stability, advances to the effect of soil character and density, scrutinizes the influence of adsorbed films of air and moisture on the surface of soil colloids, and concludes with the application of surface chemistry in laboratory test and construction practice

We draw largely from the research by Terzaghi, the practice of Proctor and the general theory of "Applied Colloidal Chemistry" as presented by Bancroft in his book published by McGraw-Hill Book Company, Inc , 1932 All quoted passages are from Bancroft's treatise

THEORY OF STABILITY

Loss of stability or rutting may be illustrated by means of Figure 1 Here it is assumed that the load is applied for an indefinite length over a width of 2 b as shown in Figure 1-A.

In order that deformation under the load can occur, the section "A" must shear along some plane such as S and displace laterally as indicated in Figure 1-B But for this to occur, the adjacent section marked "C"

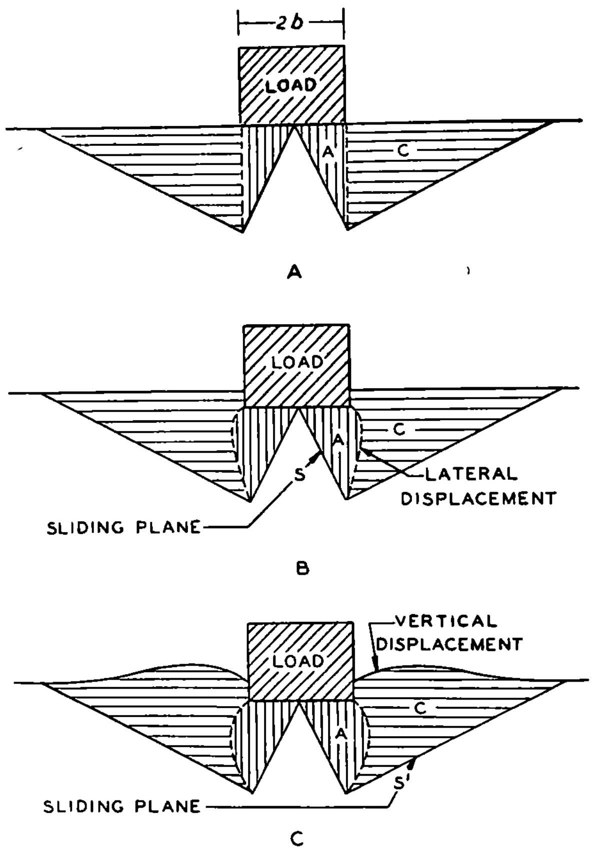

Figure 1. Illustrating Shear Planes along Which Lateral Displacement of Soils Occurs.

must shear along some surface as S' and, in consequence, displace upwards forming a bulge adjacent to the loaded area as shown in Figure 1-C

Actually the surfaces S and S' may be parts of a continuously curved surface, but for mathematical treatment they may be considered as separate plane surfaces without introducing a prohibitive error

If rutting is to be prevented, the prism C must resist displacement enough to prevent the lateral bulging of the prism A This may be accomplished by two means, separately or in some combination. The shear strength along the plane S and S' must be sufficiently high to prevent sliding of the prisms or sufficient weight must be placed adjacent to the loaded area to prevent the upward bulging of the prism C

Friction between the granular particles, combined with the stickiness or cohesion furnished by clay or water films in the binder, control the shear strength of the soil The road surface furnishes the weight adjacent to the loaded area

Consequently the design problem of flexible surfaces includes determination of

1 The required load capacity

2. The components of the total load capacity to be furnished by (a) the shear strength of the soil and (b) the effective weight of the road surface

TABLE I

INFLUENCE OF INTERNAL FRICTION AND COHESION UPON THE STABILITY OF SOILS

Soil Types	Cohesion c	Angle of internal friction ϕ	Supporting value q[1]	Cohesion c required to increase q to 2,500 lb per sq ft
	Lb per sq ft	*degrees*	*lb per sq ft*	*lb per sq ft*
Clay, liquid	100	0	400	
Clay, very soft	200	2	860	
Clay, soft	400	4	1,850	
Clay, fairly stiff	1,000	6	4,970	
Clay, very stiff	2,000	12	12,490	
Sands, dry	0	34	270	131
Cemented sand and gravel	1,000	34	17,340	

[1] Computations on assumptions that weight of the soil equals 100 lb per cubic foot and width of loaded area equals three inches

3 The complex combination of thickness and capacity for load distribution required to furnish the desired weight of road surface

CURRENT METHODS OF STABILIZATION UTILIZE PROPER GRADING AND CONTROL OF MOISTURE CONTENT OF THE SOIL

For the conditions of load as shown in Figure 1, Terzaghi (*Public Roads*, May 1929) developed a formula which furnishes numerical values indicative of how stability is influenced by (a) the granular fraction, the binder fraction and the moisture content of the soil, and (b) the weight and the capacity for load distribution of the road surface

Purely theoretical values of this kind, which illustrate only the effect of internal friction and cohesion (see Table I) disclose that the supporting value of clay soils may drop from as much as about 12,000 lb per sq ft to less than 400 lb. per sq ft with change from the dry or damp to a soft or almost liquid state

While the stability of a cohesionless sand may be less than 300 lb per sq ft and that of a fairly stiff clay about 5,000 lb per sq ft, these two materials properly combined might have a supporting value of more than 17,000 lb per sq ft

As a matter of fact, only the cohesion of an almost liquid clay, about 130 lb per sq ft, is required to increase the supporting value of cohesionless sand from but 270 to 2,500 lb per sq ft

Accordingly, the essential features of stabilization include (a) prevention of clay or silt soils from becoming detrimentally wet, (b) incorporation of granular materials in clay soils, and (c) furnishing granular soils with cohesive binder

To provide a definite basis for flexible surface design, the support of subgrades should be of more or less constant value At least there should be definite minimum values which can be determined quantitatively

General methods suggested for producing such subgrade support are enumerated as follows

1 Selection of natural soils with granular material and binder of the character and proportions to furnish high stability

2 Change of grading by adding soil binder to granular materials, and gravel, crushed stone, slag or sand to clays

3 Stabilization of the moisture content by treating graded soils with deliquescent chemicals

4 Stabilization of the moisture content by waterproofing soil with surface treatments of bituminous materials

5 Densification of natural soil material by means of special manipulation in combination with admixtures of physical or chemical materials other than soil, to eliminate permanently those clay and colloidal properties productive of volume change

STABILIZATION OF COHESIVE SOILS WHEN GRANULAR MATERIALS ARE NOT AVAILABLE

Where granular materials and binder are readily available for furnishing stable soil mixtures, satisfactory measurable subgrade support is assured Only for graded mixtures has treatment by means of deliquescent chemical substances thus far been advocated

This leaves but two types of stabilization suitable where only cohesive soils abound They are The use of waterproof surfacing and stabilization of the moisture content by mechanical or chemical means

The blotter type tar and asphalt surface treatments of the heavy gumbo soil roads of western Minnesota and eastern North Dakota[1]

[1] Lang, F C Blotter Treatment of Gravel Roads in the State of Minnesota Eighth Annual Asphalt Paving Conference, 1929

indicate the beneficial effects to be furnished by waterproofing highly plastic soils. Figure 2 shows the condition in the spring of a road west of Ada, Minnesota, prior to the first treatment in 1924. Gravel used for surfacing was found to have penetrated to a depth of as much as three feet. Figure 3 shows the condition of the same road in the spring

Figure 2. Typical Untreated Minnesota Gumbo Road Surface in the Early Spring.

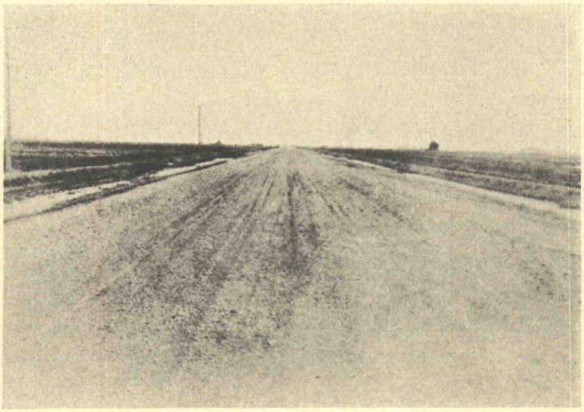

Figure 3. Typical Condition of Minnesota Gumbo Road Surfaces Stabilized with Surface Treatment of Bituminous Materials Covered with a Thin Layer of gravel.

after receiving a surface treatment of bituminous material with gravel covering. On inspection in 1932 the total thickness of the surface treatment was found to be slightly less than one inch.

The flexible type road surface, if constructed without interstices in the base course, which serve as storage space for free water or which can be penetrated by the subgrade soil, naturally waterproofs the subgrade and consequently furnishes all the advantages of this type of treatment.

Full comprehension of the practicability of permanently densifying soils is facilitated by some understanding of the remarkably unusual performance of well known materials when in films of molecular thickness

MATTER IN FILM PHASE

"All solids tend to adsorb or condense upon their surface any gases or vapors with which they are in contact Adsorption is specific and varies with the nature of the gas and of the absorbing solid Two plane surfaces placed closely together will adsorb a good deal more gas than the same surfaces spaced farther apart With the same solid and the same gas the amount of adsorption is greater the higher the pressure of the gas and the lower the temperature "

Hardy and a Miss Nottage in 1928 found that a pressure of 14 lb per sq ft reduced the air films between two plane surfaces to a thickness of about 160 millionths inch, or 1,500 molecules

Some conception of the character of gas films can be had if we subscribe to the thought—again drawing from Bancroft—that the transition of a pure liquid to its own vapor is not abrupt, but that over a narrow range all the densities intermediate between those of vapor and of the liquid actually occur Baker estimates the transition film for carbon dioxide at 20° to be 3 molecules of about 3 ten-millionths of an inch thick

The importance of matter with submicroscopic dimension to the understanding of hitherto well-known but unexplained phenomena is being recognized in all fields To illustrate, let us digress for a moment to the realm of medicine and draw upon a discussion by Sir Henry Dale published in Science, October 19, 1934

According to this authority, infections such as small pox, infantile paralysis, measles, common colds and the like, transmitted by viruses in which no organisms could be cultivated or seen, include a whole series with infective particles of diminishing size, until, as in the case of the virus of foot and mouth disease, they approach the dimensions of protein molecules in solution Smaller even than these organisms are the tiny charges of chemical substance now believed responsible for the transmission of the effect of nerve impulses There is evidence that every motor nerve impulse to the fiber of our voluntary muscles is due to the liberation of charges of acetylcholine from the nerve fiber ends, which stimulate the muscle fibers to contraction

The estimated weight of this chemical required to transmit the effect of a single nerve impulse to a single muscular cell is of the order of sextillionths of a gram Can you imagine a dimension so small that a row of 20 naughts is required to the right of a decimal point before a significant figure is reached? Thirty thousand billions of impulses for each and every one of the one billion minutes comprising the Christian era would be required to liberate one ounce of the motivating chemical

Wetting of Soil Particles due to Displacement of Air Films by Moisture Films

"If a liquid is adsorbed at a solid surface, it forms a liquid film there and we say that the liquid wets the solid For a liquid to wet a solid in the presence of air the liquid must be adsorbed more strongly than the air and must displace it

"During a period of drought, drops of rain will often roll along the dust without wetting it Even in the case of a shower the dust may be only wetted to a depth of less than ¼ inch This is shown by Ehrenberg and Schultze to be due to the adsorbed air on the surface of the solid Any treatment which cuts down the amount of adsorbed air makes the dust more easily wetted.

"Water wets glass; mercury does not Therefore, to be strictly logical, we must conclude that a column of mercury in a glass tube does not touch the glass at any point and that it stands alone surrounded on all sides by a film of either mercury vapor or something that is not glass "

A special case of non-wetting which depends upon volatility was observed by Dewar, 1878, when pieces of solid carbon dioxide were dropped into water The dioxide did not become covered with ice although it was at a temperature considerably below that of the Arctic regions It was in reality coated with a layer of gas constantly renewed, which prevented the solid from actually coming in contact with the water

A drop of water, as from an oar of a boat or paddle of a canoe, may fall on a sheet of water, become submerged and then emerge with the upper portion of the drop apparently unwetted by the liquid with which it has been covered.

We can oil the meshes of a fine-mesh sieve and carry water in it because the oil prevents the water from wetting the wires Consequently, surface tension prevents the water from passing through the holes

All campers are familiar with the unpleasant fact that touching canvas with one finger will cause a tent to leak in the rain It matters not whether the touching is from the inside or the outside It either contracts or expands the air spaces In the first case, air is driven out and water enters when the finger is removed If the air spaces are expanded, water runs in Either way air is displaced at that point and water enters.

Adsorption Affected by Electrolytic Properties

"Siebel, 1921, found that electrical resistance increases with increasing adsorption, and Leonard, 1922, found that mercury wets platinum only when a current is flowing At other times there is evidently an air film "

"A vertical jet of water or any liquid slows up and breaks into drops when the head is sufficiently great relative to the diameter of the jet These drops scatter because they rebound when they strike one another " This is because an enclosing film of adsorbed air prevents two drops from coalescing when they collide Again, a feebly electrified body brought close to the jet causes the stream to become coherent because when the drops are electrified the air film is removed to such an extent that the drops come more nearly in contact and coalesce In the absence of the electrical charge the water particles apparently collide and bounce away from each other without really coming in contact

Soap bubbles, which are merely hollow drops, behave in like manner "It is possible to press two soap bubbles together with considerable force without causing them to coalesce, but if they are electrified slightly they coalesce readily without bursting "

The influence of electrolytes on the rate of wetting may greatly affect the speed at which dry soils slake in the presence of free water Dr F E Hance has observed that samples of soil which resist slaking indefinitely when immersed in distilled water may disintegrate almost instantaneously when immersed in drinking water from the faucet.

Properties of Materials in Films Different from Properties of Same Materials in Bulk

Attention is called also to the difference in density of gases in film and in bulk phase. "Williams, 1920, believes that the first layer of an adsorbed gas vapor may be considered to be under a pressure of about 10,000 atmospheres, graded then from the corresponding density to that of the liquid in bulk in the outermost layer " Because of this extreme condensation a cubic foot would contain far more gas in film than in bulk phase

A nitrogen cylinder filled with dry cocoanut charcoal will discharge far more nitrogen on equal reduction of pressure than a similar cylinder containing no charcoal "Briggs, 1921, considers that the sudden outbursts of gas in collieries involve gaseous adsorption, the gas is held in the coal in a state available for discharge when the pressure is released These outbursts are characterized by an almost instantaneous discharge into the mine of thousands, and in some cases of millions, of cubic feet of fire damp "

In like manner, the character of water changes with the size of the particle Drops $\frac{1}{40000}$ of an inch to about 1 millionth inch suspended in the air form fog if you walk through them and a cloud if you look at them from a distance Under electrical stress they coalesce to form the raindrops at sizes of about $\frac{2}{1300}$ inch to $\frac{1}{4}$ inch, which eventually become moisture films in soils.

So long as the soils are in the liquid or the plastic state, the films have in general the evaporation and freezing characteristics and the surface tension of water in bulk. When drying or mechanical compaction reduces the density of the soil below that at the plastic limit, the boiling point of the film rises, the freezing point lowers, the surface tension increases so that these films become properties somewhat tougher than water in bulk (Public Roads, Oct 1926, p 154) This causes the soil to change from a plastic to a semi-solid material In thicknesses below two millionths of an inch, the films behave, according to Terzaghi, 1920, like semi-solid substances

The very fine vapor films have an adhesive power so great they cannot be removed from glass by heating at temperatures up to 500° Centigrade This high tenacity is utilized in the manufacture of frosted glass for use in office doors and windows Rather thick glass is first coated with gelatine or glue As the glue loses moisture it contracts, and the power of the gelatine is so great that it tears away the surface of the glass itself, chipping it into characteristic fern-like patterns A brittle glue will give a different pattern from a tough glue, and the addition of salts also modifies the patterns

The whole theory of adhesives depends in part on the fact that the cementing material adheres strongly to the two surfaces and hardens there For a given adhesive and given materials the thinnest film gives the strongest joint The thickness of films depends upon both the adhesive and the materials to be cemented A slight change in the electrolytic properties of the latter alone is sufficient to cause a considerable variation in the thickness of the adhesive film and consequently in the strength of the resulting mixture of adhesive and aggregate.

Skidding of motor cars in wet weather is due to moisture films adsorbed so strongly on either the tires or the pavement that the rubber is separated from the riding surface by films sufficiently thick to have the mobility of free water

Research on means for eliminating this serious traffic hazard should include search for chemical treatments which could so electrolyze the tires or the pavement surface that the thickness of the separating moisture films would be reduced below that required for lubrication, in other words, to within the range of thickness where the films have properties more like solids than liquids

"Pettijohn, 1919, found about 5 millionths of an inch for the maximum thickness of a water film on pearls made from one type of glass and 10 millionths of an inch for pearls made from another type With river sand the estimated thickness varied from 20 millionths with 10 mesh sand to 5 millionths of an inch with 60-mesh sand"

Wetting Power Disclosed by Simple Apparatus

Bartell distinguishes between the wettability and the wetting power Wettability represents the tendency of a solid to be wetted and may be expressed in terms of work Wetting power represents the attractive force which the liquid exerts on the solid and may be expressed in terms of attractive force. Various means for determining this force have been suggested.

Jamin, Askenasy, and Wiedenburg, as early as 1896, described different forms of apparatus in which water evaporates through a porous tube or a porous cup of plaster into dry air. As the water evaporates off, mercury is drawn up into the tube, reaching a height of 90 cm without difficulty If bubbles of air did not form, water or mercury could be drawn up into incredible heights, limited by the tensile strength of the

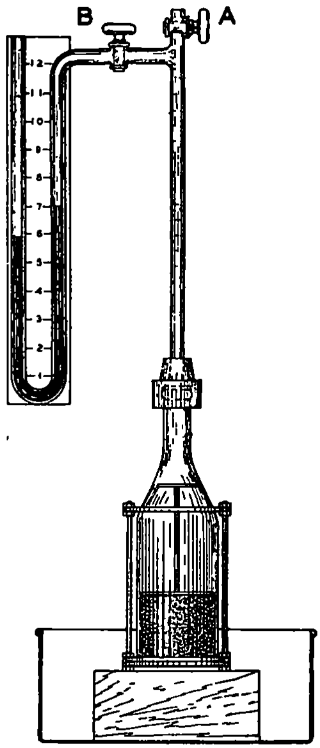

Figure 4. Combined Permeameter and Capillometer for Testing Soils

liquids. It is this type of evaporation which is now believed to account for the rise of sap in trees and not osmotic pressure

The drainage indicator described before this body in 1931 utilized this principle, as does also the modified form shown in Figure 4. It consists of a glass container with perforated metal bottom, manometer, graduated glass tube, and valves arranged as shown. Water introduced through the valve A passes down the graduated tube into the glass container, to the soil sample held between a perforated plate above and the perforated bottom of the glass container below

With the valve A open and the valve B closed, the device serves as a simple permeameter by means of which the coefficient of permeability of the sample may be determined With the valve A closed and the valve B open, the device serves to disclose the attractive force which the soil exerts as moisture escapes from the bottom of the sample by evaporation. This indicates the capillarity of the sample.

DENSIFICATION OF SOIL AT OPTIMUM MOISTURE CONTENT

The great possibilities for the application of surface chemistry in soil stabilization are indicated by the studies of Winterkorn, Reagel and Schappler, of the Missouri State Highway Department They disclose that some bases have greater affinity for bitumen than for water and that the reverse is true for other bases Ions from some bases increase while those of other bases decrease the shrinkage, the plasticity, and the

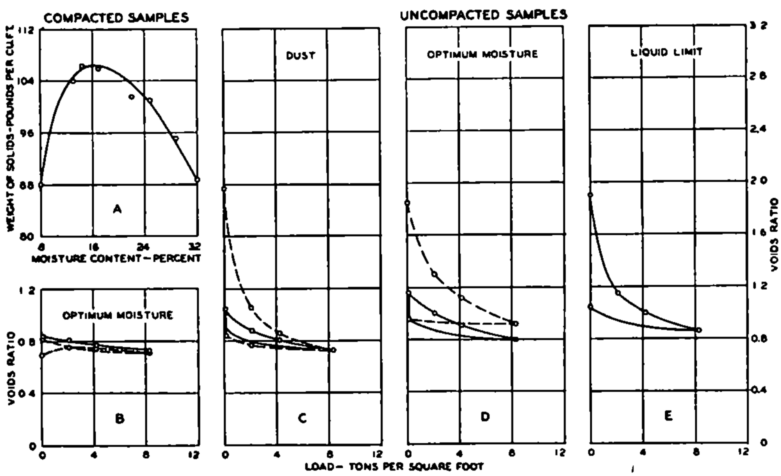

Figure 5. Data Furnished by Compaction and Compression Tests Performed on Samples of Iredell Clay.

other properties on which the stability of soils depends For every soil it is possible to select a cation for exchange which will adjust the properties of the subgrade as desired

The use of chemical flocculents or deflocculents whose sole purpose is to furnish the electrolytic state which facilitates the wetting of the soil particles with moisture films of minimum thickness also presents attractive possibilities What can be done with mechanical compaction alone with the soil at different moisture contents is quite spectacular.

Reports by Proctor (Engineering News-Record, August 31, September 7, September 21, and September 28, 1933) disclose that for every soil there is a moisture content at which maximum compaction can be obtained by means of a sheepsfoot roller in practice The extent of this compaction is readily ascertained by compacting samples at different moisture contents under impacts of a standard tamper in the laboratory

The results of such tests are shown in Figure 5, upper left The sample in this case is representative of one of the most troublesome of subgrade soils—due to shrinkage and plasticity—the highly colloidal, sticky, tenacious soil in zone B of the Iredell series

The curve in this figure shows that maximum density is obtained at a moisture content equal to about 16 percent of the weight of the dry soil At this moisture content a density indicated by a dry weight of 106 lb per cu ft is obtained A sample of soil compacted at this moisture content tested for compressibility and expansion furnished the results shown in Figure 5, lower left

The load was applied first in increments up to 8 2 tons per sq ft and then reduced to 0 05 ton per sq ft when the sample did not have access to water This is shown by the broken line Water was then allowed to enter the testing apparatus, after which the load was again increased

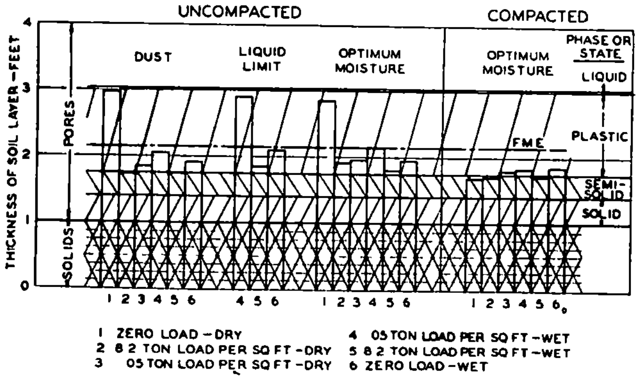

Figure 6 Thickness of Layers of Iredell Clay Soil at Different Conditions of Test, Figure 5, per Layer of Solids Equal to One Foot in Thickness

to 8 2 tons per sq ft and then reduced to 0 05 ton per sq ft These results are indicated by the full lines

Figure 5-C shows results of similar tests performed on a sample of the same soil in dust phase, figure 5-D at optimum moisture content but uncompacted, and figure 5-E the results of application and removal of load on a sample wetted to about the liquid limit

The very small volume change of the compacted sample as compared with that of the same soil in the other states is very striking This is further emphasized by Figure 6 which shows the same test results in terms of thickness of soil layer per unit thickness of solids in the layer

The results shown in Figure 6 indicate that by means of manipulation at properly selected moisture contents alone subgrades comprised of the highly plastic soils, such as the black waxies, the adobes and the gumbos, can be constructed at relatively high densities which remain fairly constant under widely changing conditions of load and access to water

Indicated consolidations were produced by load periods of 72 hours on samples about one cm thick. Expansions were measured after loads had been removed for periods of 24 to 48 hours For an equal degree of consolidation to occur in soil layers thicker than one cm., the duration of the load would have to equal the product of 72 hours into the square of the thickness, in centimeters, of the layer of subgrade affected

SUMMARY

Subgrade soils may be arranged with respect to supporting value into general groups as follows

(a) Graded materials of the A-1 and A-2 soil groups, including the topsoils, sand-clays, natural gravels, better grade shales and the like, which have high supporting values and thus eliminate the necessity of a foundation course under the flexible wearing surface

(b) The better grade A-4, A-6 and A-7 soils which may serve excellently as subgrades for flexible surfaces provided adequate flexible base courses are used

(c) The highly elastic soils of the A-5 group, the mucks and peats of the A-8 group and the frost heave varieties of the A-4 group which are not suitable as subgrades for flexible pavements, without special treatment

By incorporating certain elements of the Proctor tests in a modified compression and permeability test, it seems possible to predetermine densities indicative of the supporting value of soils in the confined state which can be produced by current methods of manipulation and compaction and maintained under prevalent climatic and load conditions

The maintenance of such densities in subgrades requires that the road surfaces be constructed in such a manner as to prevent (a) loss of moisture from the subgrade by evaporation, and (b) intrusion of the subgrade soil into the interstices of the road surface or base course

The effect of the size of the loaded area and of lateral flow upon deformations of the soil must be determined before the densities thus attained can serve as a quantitative measure of subgrade support Nevertheless, the recently acquired ability to prepare a soil so that its maintenance at a fairly constant density can be assured should greatly facilitate the determination of the structural properties which leads to the ultimate formulation of rules of procedure for the rational design of flexible road surfaces

In conclusion, however, let me point out that as yet we have no more than scratched the surface in this direction What Mr Proctor has been able to accomplish by means of manipulation at optimum moisture content alone suggests that determination of the possible additional benefits to be furnished by supplementary methods of stabilizing the interfacial colloidal films by proper utilization of the bitumens, the portland cements, and the sodium, the potassium and the calcium ions, comprises the most promising field of endeavor in the realm of highway research today