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REPORT OF SUBCOMMITTEE ON SUBGRADE STUDIES

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Present information indicates that subgrade efficiency is dependent upon the magnitude and uniformity of support afforded to the various pavement surfaces This magnitude and uniformity of support are dependent upon the moisture content of the subgrade, and this moisture content, in turn, seems to be dependent upon many factors, among which are climatic conditions including frost action, topography, soil type, soil structure, and, to some extent, type of pavement

Subgrade research, therefore, has been confined mainly to the development of fundamental laws for: (1) Soil identification, (2) the behavior of soils when subjected to various moisture conditions, (3) the improvement of subgrades having unsatisfactory or varying support, and (4) the compensation for undesirable subgrade conditions with variation in pavement design

The present status of information developed by subgrade research subdivided into groups representing the various phases of the problem is given below. In addition to the four divisions noted above, there is included, also, a chapter on Landslides.

I SUBGRADE SOIL IDENTIFICATION

A. FIELD MAPPING

The purpose of field mapping is to present a picture of the soil type and structure in the field, together with topography and other pertinent information, to those concerned with the design of road and drainage features For agricultural purposes, the classification of soils used in this work, that based primarily on the clay, silt and sand contents has been fairly satisfactory. From the field operations of the United States Bureau of Soils which have extended over many years, it can be concluded that one experienced in field identification of soils can, with a fair degree of precision, define the limits of the particular types and layers of the various soils From the engineers' viewpoint, the names given these various types and layers, such as Penn Silt Loam, horizon B, Iredell clay, horizon A, etc, are of assistance. The prime essential is that the soil having the same name should be practically the same wherever shown on the field maps.

B LABORATORY TESTS AND THEIR SIGNIFICANCE

The purpose of laboratory tests is two-fold: (1) To determine the relative properties of the various soils, under the same climatic and drainage conditions, to the end that the great number of classes now used for agricultural purposes can be grouped into a relatively small number of classes, with numerical limits for engineering purposes (identification tests), (2) to determine the influence of the different physical factors on which the behavior of the subgrade depends, such as temperature and humidity changes, freezing, permeability, etc (physical research tests).

The following are tests for identifying soils:

1 Mechanical analysis, which determines the amount of clay, silt and sand in a soil and forms the basis of a classification of soils (for agricultural purposes) with regard to the varying percentage of these fractions

2 The mechanical analysis supplemented by determination of the finer clay fractions—suspensoids and colloids

3 Simplified physical tests, such as plasticity, water-holding capacity, shrinkage and slaking value which concern the behavior of a soil when subjected to varying water contents.

4. Comprehensive tests which concern the engineering properties of a soil, such as compressibility, elasticity, and permeability

Which of these groups of tests most readily gives results on which a practical subgrade classification can be based can be determined only when the results from the subgrade and pavement surveys now in progress become available

Any set of standard routine tests can be considered satisfactory (from the identification standpoint) if it can be demonstrated that they give practically the same test results on soils that are essentially the same with regard to the effect of subsequent wetting and drying, the effect of frost action and the behavior of load at the extreme conditions produced by the aforementioned factors.

FACTS ESTABLISHED

1. The results of tests performed on disturbed samples of soil in the laboratory can yield information only about the properties of the raw material of which the soil in the field consists, irrespective of field conditions. Hence, their purpose is limited to determining the character of the raw material of the soils, which is merely one of several variable factors on which the quality of the subgrade depends The other factors, such as structural, climatic and ground water conditions, may have an importance equal to or greater than that of the properties of the soils in themselves; but their investigation cannot possibly be carried out except by direct observation in the field.

This was indicated by consistency tests (Ref 1) and also by tests in the field (Ref 2) In the latter instance laboratory tests on disturbed samples showed that an admixture of water gas tar reduced the volume change in the soil in the field, however, the slabs laid on water gas tar treated soil heaved more during slight frost than did the slab laid on natural soil

2. No general conclusions can be drawn from the mere knowledge that a certain method of treating the subgrade has proved to be beneficial in one isolated locality In order to take advantage of such knowledge it is necessary to make a systematic study of the individual physical factors which have led to the observed results (physical research tests) and to determine the relative importance of the factors responsible for those results.

In one locality (California) an admixture of Portland cement (1 20) reduced the soil shrinkage but little and was not considered an advisable subgrade treatment (Ref 3)

In (Arlington, Virginia) an admixture of Portland cement (1 14 and 1 28) considerably reduced the shrinkage in the subgrade and increased the resistance of concrete slabs to impacts from 50 to 65 per cent (Ref 4)

3. There is a moisture transfer taking place in frozen soil which tends to increase the amount of water held in the upper layers.

4. A soil loses its identity by dilution in suspension as soon as the concentration of the soil is small enough for the larger particles to participate.

5 The size and shape of particles determine the concentration of the suspension at which precipitation and segregation take place

6. The finer particles, especially those with colloidal properties, largely determine the physical properties of the soil The following soil phenomena are directly dependent on the amount and activity of the colloids in the soil · attraction for water or its hygroscopic content, adhesion, heat of wetting, freezing-point depression, water-holding capacity, capillary movement, percolation, plasticity, soil structure, shrinkage, etc.

7 The mechanical analysis of soils by the wet method or a combination of wet and dry methods will give a useful indication of the moisture content allowable at minimum concentration in solution This analysis should include the colloidal fraction.

8 Slaking value is an indication of the resistance of the soil to water erosion.

9 Flow pressure graphs may be used to determine the absolute condition necessary for plastic flow with colloidal solutions

10. The colloidal fraction of a soil differs from the other fractions primarily only in the size and shape of its grains.

The colloidal fraction of the Bentonite group, was found to consist of an accumulation of scale like and of bulky mineral grains (Ref 30) There is no evidence that these grains differed from coarser grains of the same minerals except by their size

Atterberg found that the finest fraction of powders obtained by grinding certain minerals (Kaolin, Talcum, Chlorite, Muscovite, Biolite, Hamalite) exhibit the physical characteristics of typical clays (high plasticity index, volume change, cohesion, etc) Ref 31 Here again, size of grain, constituted the only difference between coarse grained and fine grained powders of the same minerals

11. Some of the most conspicuous properties of the clays and of other soils rich in colloids are due to the fact that the physical properties of the water contained in the narrow voids of such soils (adsorbed water) are not identical with those of normal water The viscosity and the surface tension of the absorbed water are greater (Ref 31, page 124-125), its density is greater (Ref. 32, pp 64-70), and its freezing point is lowered (Ref 16 and 33). The passing of the water from the normal into the adsorbed (semi-solid) state is associated with the development of heat (heat of wetting and heat of swelling).

12 The volume change which is intimately associated with the moisture changes in the subgrade soil depends not only on the colloidal

NOTE—References 5 to 29 inclusive are given as support for facts 3 to 9 inclusive fraction of the soil, but also on the composition of the coarser soil fractions, silt and sand (Ref 34)

13 Climatic and topographical conditions being equal, the resistance of a subgrade against deformation depends on the purely mechanical properties of the soil, viz., compressibility, elasticity, and permeability (Ref. 35, pp 395-397).

14. The compressibility and elasticity of soil specimens is practically identical with the compressibility and elasticity of coarse-grained mixtures of bulky and of scale-like grains (Ref. 36, pp 41-43). The only one difference between the behavior under load of coarse-grained and of colloidal soils consists in the speed with which the volume changes occur (Ref 36, pp 43-44)

15 The tests required for determining the purely mechanical properties of the soils (comprehensive soil tests) are too elaborate to be carried out as routine tests Their value resides in their furnishing a well-defined standard for the interpretation and calibration of the results of simple routine tests, regarding the mechanical properties of the material and its permeability (Ref 34).

16 In general, the nature of a soil cannot possibly be expressed by a single figure, because two soils may have any two essential properties in common and yet be different in another essential respect. Hence, any routine program for identification purposes must include tests furnishing several independent coefficients (Ref 34, 36 and 37)

17 The soil coefficients furnished by different soil tests are apt to be connected with each other by statistical laws, valid for the average of the values obtained from testing a great number of samples from different parts of the country The deviation of the individual coefficients from the corresponding average depends on the degree of relationship between the properties to which the statistical laws apply (Ref 34).

18 The slaking value test furnishes an excellent measure of the destructive or non-destructive action of the free water upon the road shoulders and ditch and cut embankments (Ref. 37, 38 and 39).

19 A simple percolation test may indicate what soils may or may not be drained by tile or broken stone subdrains (Ref. 37 and 38)

Strong Indications

1. Certain laboratory tests identify properties in subgrade soils which influence the behavior of pavements laid upon them.

In a survey of the California roads the pavements with no breakage were laid on sands, those with a slight amount of breakage were laid on loams, and those containing the greatest amount of breakage were laid on clays (Ref. 40). In New York the Gansevoort-South Glenns Falls Road laid part on clay and part on sand showed a strikingly better condition on the latter soil (Ref 41). The classes of clays, loams and sands are based on results of mechanical analysis test.

A conclusion from the Rio Vista experiment was that the suitability of a soil for subgrade purposes or the merits of the various methods of soil treatment can be determined by relatively simple laboratory tests (Ref. 3).

In the Pacific Northwest it was concluded that a lineal shrinkage value of 5 per cent forms the dividing line between good and bad subgrade soils (Ref. 42). This conforms in general to a lower liquid limit of 25, a lower plastic limit of 15, and a volumetric change of 13, above which limits, in Ohio, the soils are viewed with suspicion (Ref. 37, 38 and 39).

2. Some tests, notably the moisture equivalent and the shrinkage tests based on the moisture equivalent are considerably influenced by grains larger than .005 mm. in size This is not true, however, for the plasticity tests (Ref. 34).

3. The moisture content at which soils begin to flow plastically when loaded (laboratory specimens) has been found to be approximately as follows:

Plastic soils—at Atterberg's lower plastic limit.

Friable soils—at 75 per cent of Atterberg's lower liquid limit (Ref. 43).

4. The results of plasticity and shrinkage tests seem to disclose a greater variety of independent aspects of the soil (influence of size of grain, shape of grain, colloidal content, uniformity and chemical composition) than do the results of any other tests made with equal expenditure of time and labor (Ref 34).

5. The Atterberg tests combined with one or two other routine tests may furnish adequate information about the elastic properties and the permeability of the soils with a sufficient degree of accuracy.

6. The amount of colloids may be measured indirectly by the ratio method of absorption of water vapor or heat of wetting

7. The activity of the colloids may be measured either by the absorption of water vapor or by the heat of wetting.

8. The amount of suspensoids may be measured directly by the hydrometer method of Boyoucas.

RESEARCH IN PROGRESS

1. Efforts to exclude the personal equation from the liquid limit test[1]

2. Effort to improve the slaking value test.[1]

3 A study of the errors connected with the present form of the standard swelling test[1]

4 A study of the relation between the mechanical properties of the soils and the results furnished by the different routine tests.[1]

5 A study of the freezing of water in the voids of the soils and within soil cracks, as a preliminary to an investigation of differential heaving due to frost[2]

6 An exhaustive investigation of the effect of the different soil constituents (sand—angular and rounded grains of different sizes, mica flakes—different sizes, organic matter, different electrolytes, different colloids) on the results furnished by routine soil tests, final soil tests and colloidal determinations[3]

7 An exhaustive investigation of the effect of the size, shape and uniformity of coarse material on the results of routine and final soil tests.[4]

SUGGESTIONS FOR FURTHER RESEARCH

1 A more exhaustive study of the statistical laws between the coefficients furnished by different tests, including determination of quantity and activity of soil colloids.

2 Investigation for the possibilities of a subgrade soil classification based on the moisture content at which plastic flow begins coupled with the total volume change up to this point The basis for this classification is the assumption that an ideal subgrade is one whose bearing capacity is at all times sufficient for carrying the loads imposed upon the overlying pavement and whose volume change is insufficient to affect the structural integrity of the pavement.

3 Determination of the amount of water various soils can hold without segregation

[1] Massachusetts Institute of Technology, the U S Bureau of Public Roads cooperating

[2] University of South Carolina, the U S Bureau of Public Roads cooperating

[3] U S Bureau of Public Roads

[4] Ohio State University, the U S Bureau of Public Roads cooperating

4 Development of flow pressure graphs of soils at varying moisture contents by the capillary tube method

5. Correlation of colloidal quantity and activity with its various physical manifestations

II THE BEHAVIOR OF SOILS WHEN SUBJECTED TO VARIOUS MOISTURE CONDITIONS

Drainage has been considered the most important factor which influences road behavior (Ref 44) One author has pointed out that desiring and obtaining good drainage in subgrades are two entirely different things Experiences with roads and research have demonstrated that the relation between soils and moisture contents is very complex.

Under certain conditions soils are loath either to take up moisture or to release it Under other conditions the reverse is true

Research has thrown light on these items by demonstrating that only part of the water is free to respond to the laws of gravitation, while the remainder, whose percentage increases as the grains of soil grow smaller, does not respond to the laws of gravitation, and, therefore, cannot be removed by artificial drainage This unfree water content may not cause serious trouble in the summer time, but during frost action it may be gradually drawn from the small capillaries, become free and freeze, increasing the thickness of the ice cakes on the surface of the subgrade This withdrawal of the water from the small capillaries reduces the moisture content of the soil below normal, so that the free water liberated by the melting of the ice cakes may quickly saturate the part of the subsoil which has melted, while below this point, where thawing has not occurred, an impervious frozen layer exists, which temporarily prevents the free water from escaping into the drains Therefore, it can be seen that under normal conditions ditches and tile drains can remove only a portion of the water from the soil, this amount ranging from very small to large percentages, depending on the character of the soil During and following frost action this amount of drainage water may be materially reduced

A. THE OCCURRENCE OF FREE AND UNFREE WATER IN SOILS

Facts Established

1. Subgrade soil moisture exists in three different states as follows.

a. Free water which responds to the laws of gravitation b Capillary water which does not respond to the laws of gravitation, and

c Adsorbed water and combined water which is not influenced by gravitation nor directly does it respond to the laws of freezing and of evaporation (Ref. 44, 16, 45, 46, 36, 47).

2 The proportion of free and capillary water which exists in a soil depends, in part, on size of pores or capillaries, and consequently on grain characteristics (soil type) as determined by mechanical analysis and on the results of correlated tests.

The per cent of unfreezable water varied from 2 per cent in quartz sand to 80 per cent in Minnesota clay (Ref 46) and from zero in quartz sand to 30 per cent when standard Ottawa sand was ground to flour (Ref 45)

A study of the data in Table 1 (Page 6) Ref 45, shows it is indicated that the percentage of free water is statistically related to the moisture equivalent values and the clay content (grains less than 0 028 mm) decreasing as the above values increase (from Table 1, Page 6, Ref 45) Therefore it should be related statistically to the generally related soil tests (Ref 34)

3 Surfaces of exposed soils change moisture content quickly from 2 to 124 per cent of the dry weight of the soil due to rain, thawing and drying weather (Ref 37, 38, 39, 48, 49).

B. MOISTURE CONTENT OF A SOIL AS INFLUENCED BY ARTIFICAL DRAINAGE

Facts Established

1 Only free or gravitational water can be removed by ditches and drain tile

2. Water, capillary and adsorbed, cannot be reduced by drain tile or trenches directly. Thus tile drain laid in dense soil, free from stratification, cracks and other openings is not always useful.

3. Practically all of the water in gravel is gravitational and can be removed by drains (Ref 44).

4 The capillary and adsorbed water in clays cannot be removed by drains. This may amount to 50 per cent by volume of the clay. Tile drains might lower the water table and thus reduce the capillary moisture, but moisture contents of 30 per cent by volume have been found more than 10 feet above the ground water (Ref. 44).

At the University of North Carolina it was found that drains were not efficient for removing capillary moisture from the subgrade Ref 53

On one section of the Bates Road 200 feet long tile drains were laid under the side edges of the pavement 24 inches below the subgrade, the trenches were back filled with cinders and free outlets were provided for the tile Observations covering a period of three years, showed no measurable difference in moisture contents of the subgrade where the tile was used and in adjacent sections where no drainage was provided Ref 54

On the Chatham Road (Illinois) in a soil different from that on which the Bates Road was laid, tile drains were installed 42 inches deep under each edge of the pavement for a distance of 1000 feet Extended observations showed that throughout the period, the moisture content of the drained subgrade was from 2 to 10 per cent greater than that in the undrained sections Ref 54

Observations on experimental sections at Arlington, Va, did not show that side ditches with drain tile were effective for reducing the moisture content of the subgrade nor for reducing the heaving of the pavement slabs during frost Ref 2

5 The normal capillary moisture content at least of some soils cannot be increased by flooding the side ditches.

On adobe soil rolled in successive layers, flooding the side ditches from January 30 to March 15, failed to appreciably increase the moisture content of the subgrade Ref 50

Flooding the side ditches surrounding slabs at Arlington, Va, for various periods failed to appreciably increase the moisture contents in the subgrade Ref 55

Water standing in the trenches at subgrade elevation for six weeks during the summer did not cause a perceptible increase in the moisture content of the subgrade at a sampling station 30 inches away Ref 54

6. Soils containing both air and moisture will take up water to a greater degree than the same soils which contain moisture alone

On the Bates Road it was found that under certain sections, which were laid on a dry subgrade, the moisture content at subsequent times was near the saturation point, while on other sections which were laid on a wet subgrade, future moisture contents were not in excess of the normal capillary moisture contents Ref 54

7. In railroad work tile drainage has been effective for removing or intercepting free water under all conditions where the resistance to flow through the tile is less than that of the material to be drained In stratified soils tile drainage is ineffective unless it is placed in a favorable position for receiving and delivering the flowing water (Ref 56, 57, 58, 59 and 60).

8. On all slopes water may be diverted from or concentrated toward parts of the roadway by small details of topography, such as a miniature valley or ridge, by soil stratification or by a combination of surficial and structural details of the contiguous terrace (Ref 61, 62 and 63).

9 A section of a subgrade located at or near the floor of an aquifer or water-bearing stratum is in the most favorable position possible for receiving the water from such source. The ratio of flow depends upon

the hydraulic gradient and coefficient of friction in the aquifer. The volume of flow depends upon such factors as:

(a) Rainfall
(b) Area of water shed
(c) Permeability and slope of the surface
(d) Thickness of the aquifer

Aquifers occur in sedimentary subsoils in the form of strata of widely different porosities, but in rock they take the form of openings, such as joints, fissures, bedding planes, solution openings, etc. In residual subsoils the aquifers follow the joints and other opening of the parent rock, but weathering frequently produces horizons of widely different textures (Ref. 62, pp. 152-159, 166-192; Ref. 63, pp. 284-288).

STRONG INDICATIONS

1 With respect to the type of topography, in roads whose lateral drains do not extend below the lower surfaces of the pavement, major pavement failures due to subgrade weakness are frequently found:

(a) On transverse slopes
(b) At or near the foot of hills
(c) On low level plains contiguous to higher ground

Likewise the fewest pavement failures occur on the tops of ridges.

Springs can occur only at points where aquifers reach the ground surface. It is, therefore, obvious that this can occur only on sloping ground unless the direction of the aquifer changes to an upward direction, in which case it ceases to flow under gravity and can then flow only under hydrostatic pressure (Ref 64, 65 and 66).

2. From investigations primarily of railways it was found that the best conditions were usually on fills (settlement and slide not considered). Likewise, the poorest conditions were found in cuts and on transverse slopes, unless the inflow of gravitational water has been intercepted A cut increases the probability of encountering springs or seepage, while a fill decreases such probability (Ref 60, p. 657; 62, p 192, 65, p 83, 67, p 514, 68, pp 45-51; 69, pp 53-57; and 70, pp. 639-664)

3 In railways "soft spots" result from seepage, impervious underlying layers or uneven soil structure, and are most frequently found on transverse slopes, at or near the change of the road grade, at points where water-bearing strata reach the subgrade sometimes

on fills near the mouth of a cut on a higher elevation and in fills containing water pockets (Ref 56, pp. 917-918, 57, pp. 64-66, 66, p 625; and 67, pp. 514-15).

4. " Frost boils " occur under conditions similar to those favorable to " soft spots," but are, of course, confined to sections where considerable freezing occurs (Ref 60, 71, pp. 14-20, 72, p. 67, and 64, p 144).

5. The viscosity of water or water containing soil suspensions is materially affected by temperature Low soil and water temperature greatly retards the percolation of water through fine-textured soils or impedes the flow of water on shoulders or in drains which are flat and covered with grass, weeds, etc

The fluidity of percolating cold water is still further decreased by a greater accumulation of soil suspensions due to lowered temperature (Ref 73, p. 541; 74, p 75, 75, pp 410-411).

Current Research

1. Detailed studies of conditions surrounding " frost boils," both with and without artificial drainage [5]

2. Tabulating of results obtained on locations of roads in service where various methods of artificial drainage have been installed [5]

Suggested Research

1. Determine and correlate conditions of seepage on highways.

2. Determine minimum depth of open lateral drains in sands, loams and clays

3 For statistical and research purposes, investigate the possibilities of a classification of drainage conditions surrounding highways, which shall be based on the following factors:

(a) Permeability of the soil on the water shed
(b) Topography
(c) Road cross section
(d) Uniformity of drainage
(e) Width and condition of shoulders
(f) Depth and condition of lateral drains.

[5] U S Bureau of Public Roads, U S Bureau of Soils, and various state highway departments (Minnesota, Iowa, Missouri, Rhode Island) cooperating

C. FROST ACTION

Facts Established

1. The total moisture content of the subgrade does not freeze in accordance with the physical laws for free water

Unless stirred or agitated, soils can remain supercooled unfrozen indefinitely to —4° C Agitating below —1 5° C, or supercooling below —4° C, quickly freezes the soils This is true for sands as well as clays (Ref 45 and 46) Free water or that responding to the laws of gravity can be frozen at slightly below 0° C (—1 5° C) Capillary water can be frozen at slightly below 4° C while adsorbed water fails to freeze at —78° C (Ref 45)

2 The formation of ice in clay and sand is different.

Freezing in sand continues downward thus cementing the grains together In clay, ice of fibrous texture gradually increased in thickness because of water that slowly reached the localities of freezing of the clay through the small capillary openings Ref 77 On second freezing the percentage of unfrozen water is not reduced in sands and sandy loams but is reduced in clays Ref 46

3 The behavior of sand and clay subgrades during freezing is different.

Noticeable heave from frost is confined to clays and other soils with very small voids Ice forms first in the larger openings, along planes of cleavage and other weak planes Thickest layers of ice are found under objects which radiate heat rapidly Ref 76 On cold nights weights on wet clay were lifted through the gradual formation of pure ice between the weights and the clay Weights similarly placed on wet sand were not lifted, although the water in the voids in the sand was frozen Ref 77 Observations covering a period of one year on two road slabs showed first that appreciable heaving occurred only during freezing weather and second that both sides and center of the slab laid on sand and the center of the slab laid on clay heaved the same (20 mm) while the sides of the slab laid on clay heaved twice as much (40 mm) Ref 78

4. The difference in behavior of soils upon freezing is dependent upon the proportions of free and unfree water and the number of successions of frost and thaw.

In sands and gravels practically all of the water is free and is frozen near 0° C with only the expansion due to freezing water Ref 45 and 33 The growth of amorphous or needle ice in clays during continuous freezing is caused by the fact that water in the larger capillaries, upon freezing, draws upon itself by the force of crystallization the water from the finer and smaller capillaries and films around the soil particles and grows at their expense Ref 17 Repeated freezing and thawing also liberates for freezing, unfree water Ref 33

5 The moisture content of the soil in some instances influences its behavior during freezing

Greater percentage of water failed to freeze when 5 cc were added to 25 gms of soil than when 10 gms were added, the difference being 0 for sand and increasing in the clays Ref 46

Soils with low moisture contents could not be supercooled without freezing any further than soils with very high moisture contents Ref 46

When a soil with a *low moisture* content is frozen (under laboratory and field conditions) small droplets or particles of ice occur mainly in the most porous places or in the largest capillary spaces between the soil particles When, however, the soil is very moist and the freezing process is not too rapid, the moisture freezes at the surface of the soil in the form of ice capillary columns or long needle-like crystals Ref 17

6 Heating very plastic soils to 800 or 1000° C. destroys the plasticity Heating up to 600° C and subsequent cooling does not reduce the time of freezing but does eliminate the necessity for agitating before freezing begins (Ref 45).

7 Pavements can heave under continuous frost action or with repeated freezings and thawings

One investigator finds detrimental heaving occurs with freezing following a thaw Ref 79 In Duluth heaving was found to be steadily progressive over the period with temperature below zero Ref 80

Research in Progress

1 Field studies of pavement heaving, soil temperature and soil moisture with and without drains and subbases [6]

2 See *Research in Progress* No 5, Laboratory Tests, this report

III COMPENSATION FOR UNDESIRABLE SUBGRADE CONDITIONS BY SUBBASES AND SUBGRADE TREATMENT

Subbases and subgrade treatments have been used for drainage purposes, for increasing the magnitude of support and for decreasing the variation in support Insulating layers of sand, gravel, crushed stone, slag, cinders, etc, varying in thickness from 2 to 18 inches have been commonly used for drainage purposes

Sand clay soils, bank run gravels, slags, field stones and crushed stones have been, by proper manipulation, used as foundations for supplying adequate supporting value for various road surfaces

Subgrade treatments have had for their object the stabilization of the subgrade and have been varied depending in many instances on the local material available and the correction needed By means of admixtures of Portland cement, lime, sand and bituminous materials attempts have been made to reduce the shrinkage and water capacity

[6] U S Bureau of Public Roads, Massachusetts Institute of Technology, and the state highway departments of New Hampshire and Massachusetts cooperating

of a soil and increase the bearing value Where pure sand existed, admixtures of clay were used for stabilization purposes.

The value of subbases, foundations and certain subgrade treatments has been amply demonstrated for various flexible type surfaces The benefits to be derived from their use with rigid pavements have not as yet been established

A. SUBBASES

Facts Established

1. In locations subjected to extreme moisture conditions well drained subbases of stone, gravel, slag, etc, may be efficient for reducing the heaving, cracking and breaking up of pavements

Experimental slabs laid at Arlington, Va, on gravel subbases (3-inch and 6-inch) heaved less during light frost than did the slab laid on natural soil Ref 2

One 4-inch section on the Bates Road laid on a rolled stone base (8-inch) developed several cracks as soon as they appeared on sections of equal thickness laid on natural soil It resisted further breakage, however, and was serviceable long after other 4-inch sections had failed Ref 54

Michigan has found less cracking in roads laid on well-drained gravel subbases than in roads laid on natural soil Ref 41 and 81

Observations on the Rio Vista, Calif, Road led to the conclusion that a sand or gravel layer is an efficient and economical method of minimizing damage to pavement resulting from swelling of the subsoil Ref 3

It has been found in New England that a satisfactory method of reducing the heaving and breakage in pavements is to remove pocketed water by means of gutters, catch basins and pipes, to remove free water both surface and underground (porous strata, springs, etc) by deep ditches and drains placed along side of the road and to provide insulating layers of broken stone, gravel, etc, of thickness depending on the demands for reducing the heaving from capillary water and for reducing the effects of this heaving Ref 71 and 82

2 Subbases in all cases have not been beneficial.

The section of the Pittsburgh Experimental Road laid on an undrained gravel subbase, failed before the comparable section laid on natural soil (adobe) Ref 50

Undrained gravel bases in Michigan have been found to be unsatisfactory Ref 41

In some of the older roads in New York State, sections laid on subbases with and without drainage showed more breakage that those laid on natural soil There was the possibility here that the drainage systems had failed to function Ref 41

Subbases of sand, gravel and broken stone beneath the Union County road in Ohio showed no benefit over the heavy clay natural soil after two years of service French drains were used in conjunction with these subbases Ref 37 and 38.

The results after three years of service, of 2285 feet of porous subbases, 2-inch 4-inch and 6-inch depth, on Route 26, Washington County, Ohio, show a crack ratio of 0 75 feet per lineal foot of pavement as against 1 31 feet of crack per foot of pavement upon 1984 feet of pavement built upon the natural soil adjacent Ref 37 and 38 In this road, in which the subbases were undrained, it was indicated that additional depth over 2 inches in porous subbases is detrimental as well as more expensive Ref 37, 38, and 39 The slag porous bases gave the best results Five hundred feet of 2-inch 4-inch and 6-inch bases gave a crack ratio of 0 46

In Duluth (Minn) the worst heaving occurred where the pavements were laid on subbases Ref 80

B SUBGRADE TREATMENTS

1 The benefits of subgrade treatments have yet to be determined.

Observations on slabs at Arlington, Va , indicated that admixtures of Portland cement considerably increased the supporting value of the subgrade Also that there was little difference in the increase as afforded by mixes of 1 14 and 1 28 Ref 82a

Observations on the Rio Vista Experiment led to the conclusion that soil adulteration with cement or lime compounds was not an efficient or economical method of securing stability in heavy soils Ref 3 It was found that adulterating the subgrade with a lime compound or sand to a depth of 1 foot reduces shrinkage in the portion adulterated, but the subsoil beneath this treated layer would continue to swell and shrink and displacement of the upper layer and of the pavement would doubtless continue but to a less degree Ref 3

In soils containing a large amount of sulphates, treatment with a heavy coat of asphaltic oil, sprinkled with sand seemed satisfactory Ref 83

Tarred paper laid on highly adsorptive soil in Iowa reduced cracking in concrete slabs Ref 84

Cement-clay and lime-clay admixtures for subbases beneath high type roads are impracticable due to the impossibility of securing a reasonably good admixture with a sticky, tough, clay soil during any continued rainy weather conditions Ref 37, 38, and 85

The results of three years service of 2-inch 4-inch and 6-inch depths of an admixture of 5 per cent by weight of cement with a heavy clay soil indicate by the crack ratio but a small advantage over untreated bases adjoining Ref 37 and 38

The average crack ratio of three two hundred feet sections of heavy clay mixed with 7 per cent cement subbase beneath a concrete road in Union County, Ohio, after two years of service, indicates about two-thirds as many cracks as upon the natural soil base adjoining, or a ratio of 0 24 to 0 36

IV COMPENSATION FOR VARIATION IN SUBGRADE BY VARIATION IN PAVEMENT DESIGN SUPPLEMENTED BY RESORT TO DRAINAGE, SUBGRADE TREATMENT, SUBBASES OR FOUNDATIONS

Before attempting to design a pavement so as to utilize full advantages of support offered by the varying subgrades it is pertinent to consider the character of various pavements and the manner in which they fail Generally this can happen in just two ways—either by disintegration beginning with surface wear or by structural failure developing in the body of the pavement Also it must be learned whether the failure extends generally throughout the pavement or just in certain locations which in length might amount to only a small percentage of the total.

If it is a case of surface weakness and the structure is adequate, then the remedy obviously is to supply only a wearing surface which adequately resists abrasion from traffic If this wearing surface reduces the evaporation of moisture from the subgrade then a factor enters which must be given considerable attention. For instance, a top soil or a gravel surface whose subgrade contains only unfree water (capillary or adsorbed) with attendant conditions of evaporation might have a surface structure adequate for the loads imposed. It is possible however that adding an impervious surface layer and thus reducing the evaporation might so increase the moisture content in the top soil or gravel foundation that the structure becomes weakened and failure results.

Therefore, if it is contemplated to take advantage of this existing structure by laying on it a bituminous or brick wearing course it might be advisable to determine the effect of stopping evaporation by giving the surface a bituminous coating sometime prior to laying the final surface

As concerns structural behavior, pavements can be divided into flexible and rigid pavements The flexible surfaces deform with the subgrade and thus at all times utilize the full support afforded by the subgrade, and by their confining action might develop higher support than could be acquired by a rigid pavement So long as they have adequate support, they can adapt themselves to variation in elevation without serious structural defect They require, however, greater support than is required for rigid pavements and when this support is not adequate they break up badly and require replacement

Rigid pavements crack because of several reasons Longitudinal cracking in the main seems to be caused by variation in subgrade support. Tranverse cracking is influenced by variation in subgrade support and on the roughness of the subgrade in conjunction with temperature changes Corner cracking seems to depend upon thickness of slab Faulting and spalling of slabs seem to be due to lack of adequate support Low supporting value, if well distributed is not detrimental to rigid pavements nor is heaving by frost if uniform

With these things in mind it can be seen that if a flexible pavement fails throughout its length and width greater thickness or foundation must be supplied or change made to a rigid surface If it fails only by settlement along the edges then horizontal or vertical curbs for confining the subgrade seems to be a remedy If they fail only in certain cuts then resort to subbases and drainage for these locations will probably be all that is necessary If they occur in fills it is probable that the trouble is due to the material or the manipulation of the soil used and therefore subbases would not correct the trouble.

If a rigid pavement cracks longitudinally and transversely at distances not less than about fifteen feet apart it is probable that this cracking can be controlled by longitudinal and transverse grooves and joints Thus it will not be a structural defect unless there results a faulting or spalling of the resulting slabs For the prevention of this trouble, steel reinforcement should be used If corner breaks occur, the edges of the pavement should be thickened If tranverse cracks develop less than 10 feet apart and more than one longitudinal crack occurs, the slab should be thickened throughout

Facts Established

1. For equal superimposed loads the pressure on the subgrade when exerted through a concrete slab is distributed over a larger area and is of considerably less maximum magnitude than when exerted through a broken stone surface

A 4000-lb load on an 8-inch concrete slab at Arlington exerted a maximum pressure of 0 8 of a lb per sq inch on a wet clay subgrade while the same load on 8 inches of broken stone exerted a maximum pressure of 6 4 per sq inch (8 times as much) on the subgrade Ref 55

A 7130-lb wheel load on the Bates Road through concrete slabs was considerably more distributed and was of considerably less magnitude (3 to 5 lbs) than when exerted through an 8-inch macadam based with a brick top and mastic cushion (30 lbs plus or 6 to 10 times as much) Ref 86

Note—These relations are subject to change by such factors as condition, compaction and thickness of the stone layer

2 Excluding all other variables the warping of rigid slabs due to moisture or temperature changes in the concrete prevents uniform subgrade support and at times prevents actual contact between the slab and the subgrade.

Observations on a concrete slab (18 feet x 30 feet x 8 inches) in Arlington, Va, disclosed the fact that in a period of 24 hours the corners had no contact with the subgrade for 4 hours, the pressure exerted by the ends of the slab on the subgrade varied from 0 to 6 lbs, that exerted by the side edges varied from 0 to 3 lbs, and that at the center of the slab was fairly uniform, varying from 0 5 to 1 lb per square inch (The weight of the slab was about 0 8 lbs per sq in) Ref 55

The difference in the corner elevations between night and day in Illinois was found to be as much as 0 1 or 0 2 of an inch A 6000-lb wheel load on 7- and 9-inch corners at night did not depress them to their unloaded daylight positions For two-thirds of a 54-hour period, a 6000-lb wheel load did not depress a 9-inch corner to its unloaded afternoon position Ref 54

Observations on a concrete slab (18 feet x 25 feet x 7 inches) at Purdue University laid on a 4-inch layer of coarse gravel held in an impervious wooden base, showed a vertical movement at the extreme corner of 0.2 of an inch in a month due to non-uniform moisture distribution in the concrete Ref 87

3. Separations which cannot be accounted for by warping of the pavement occur between rigid slabs and the subgrade

Several thousand observations of subgrade pressures made during the period of a year on the Bates Road showed that the support under a rigid surface is extremely variable owing to the fact that the slab rests on portions of the subgrade having little support on other portions These portions are variable with regard to their positions at different times Ref 86

Observations made throughout the year on brass discs laid on the subgrade of the Bates Road showed separations which could not be accounted for by slab warping They were as much as ½ inch and extended over areas of considerable magnitude A separation occurred at all observation cylinders at one time or another Ref 54

4. Rigid slabs laid on soft and yielding subgrades of very low, but uniform, supporting value might develop fewer cracks than those laid on firm, unyielding subgrades, especially if rough

Slabs laid on firm subgrades such as old road bed and rolled stone base course, might develop cracks before slabs laid on softer bases Firm bases, however, seemed effective against breakage and surface unevenness in the slabs Ref 41

5 Reinforcement has proved beneficial in slabs laid on subgrades of low or variable supporting value

From the time of laying its first concrete pavement in 1919 the state of Washington has made yearly surveys of all pavements of this type Reinforcement was not used as part of the primary design but only in such slabs as were subjected to the worst conditions of support as

(A) Across trenches excavated for the purpose of placing culverts

(B) At bridge approaches wherein one end of the slab rests on the solid concrete abutment and the other end is supported by the adjacent embankment

(C) On overhanging pavement laid on narrow embankments which are widened just prior to pavement construction

(D) In some cases on high fills

(E) Over soft subgrades

A report on the result of these pavements made in 1925 stated that "notwithstanding the adverse condition to which they were subjected, reinforced slabs (mesh and bar) showed less cracking than the plain concrete sections" Ref 88

Research in Progress

1 Road and subgrade surveys, Michigan State Highway Department.

2. Investigation of the influence of soil type, soil structure, topography, climatic conditions and pavement design on road failures

3. The use of mesh reinforcement laid between the slab base and tarmacadam top at places where weak subgrades were encountered—Worcester-Alcester Main Road, England, constructed 1923.

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