The effects of temperature, frost, sunshine, wind, humidity, precipitation, run-off and evaporation upon various phases of highway activities are interestingly discussed by Professor Eno. To this long list of climatic factors one more should be added namely, the influence of atmospheric pressure

IMPORTANT DEVELOPMENTS WITH RESPECT TO SUBGRADE INVESTIGATIONS

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Among the important developments disclosed by subgrade investigations during the past year are the following.

1. A conception of the physical laws controlling the stability of subgrades
2 A conception of the detrimental effects produced by elasticity in subgrades
3 A conception of the physical laws controlling the occurrence of frost heave
4 An understanding of the benefits which may be furnished by treating subgrades
5 Suggested tentative grouping of subgrades based upon their performance
6 The use of relatively few and comparatively simple laboratory tests which serve (a) to identify the dominating constituents of subgrade soils, (b) to disclose the important characteristics possessed by subgrade soils, and (c) to suggest the proper corrective measures to be used in pavement construction

STABILITY OF SUBGRADES DEPENDS UPON BOTH INTERNAL FRICTION AND COHESION

(a) Internal friction or that portion of the resistance to shear which is dependent upon the external force applied, and

(b) Cohesion or that portion of the resistance to shear which is independent of the external force applied

The significance of the term internal friction is illustrated by the performance of two pieces of sand paper when pressed together. Under these conditions they exert no resistance to being pulled apart.

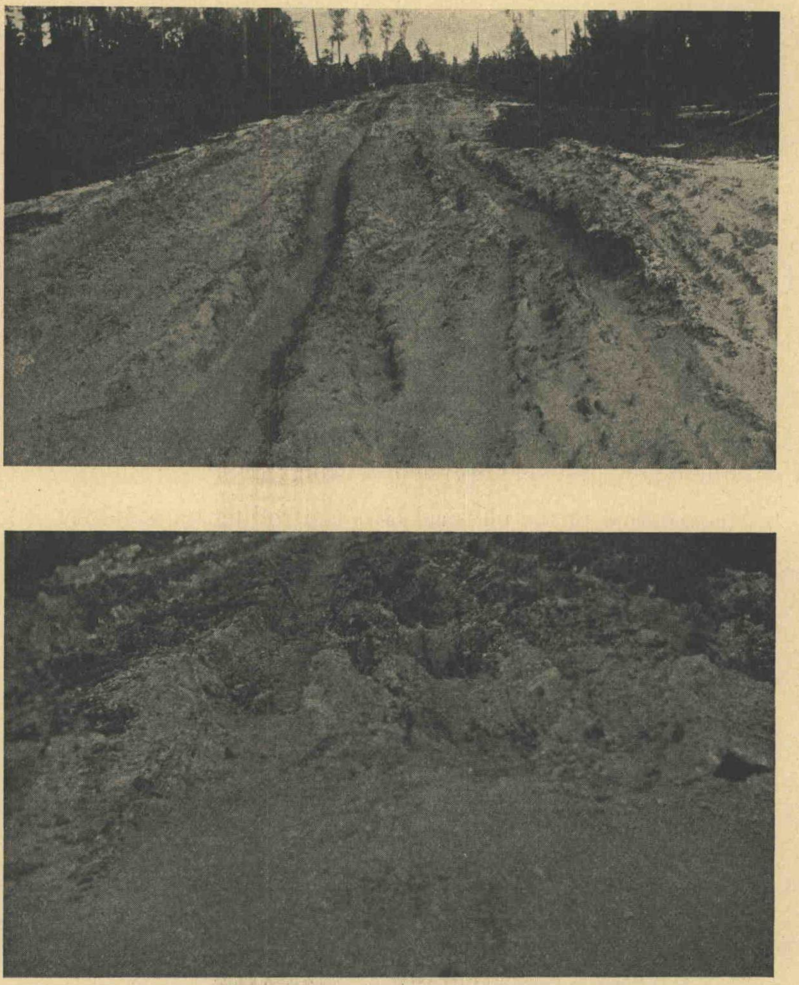


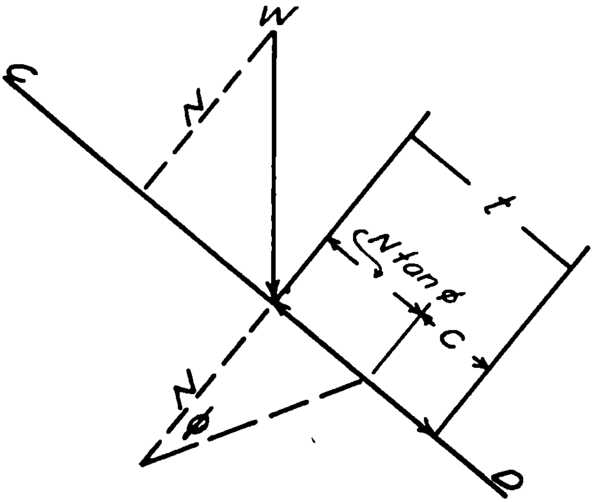
Figure 1. Unstable Road Surface Materials

Upper: Cohesionless sand
Lower: Soft cohesive clay

They exert resistance to sliding over each other, however, dependent upon the pressure with which they are pressed against each other.

The significance of the term cohesion is illustrated by the performance of two pieces of fly paper when pressed together. Under these conditions they exert high resistance to being pulled apart due to stickiness or cohesion possessed by glue-like materials brought in contact with each other. The resistance which the pieces of fly paper exert to resist sliding over each other is furnished by surface stickiness instead of surface roughness as was furnished by the sand paper

When a soil flows latterly, whether it pushes out from beneath a pavement edge or up into the interstices of a macadam, sliding occurs along either one or more planes existing in the soil. Furthermore this sliding occurs only because the force which produces sliding exceeds the shear resistance existing in the soil along the sliding plane or planes.



Assume for instance that the line *CD* represents any plane in the soil upon which a unit soil weight *w* is acting. A unit shear resistance *t* acting along the plane *CD* holds the soil (weight *w*) in equilibrium and prevents it from sliding

The shear resistance *t* is composed of two parts: That furnished by the resistance of the soil grains to sliding over each other (sand paper effect) and that furnished by the cohesion (fly paper effect) existing between the soil particles The resistance to sliding is dependent upon the angle of internal friction ϕ: that angle whose tangent equals the frictional resistance divided by the pressure normal to the sliding plane The cohesion existing between soil particles is designated as cohesion in pounds per square feet, kg per sq cm, etc, existing between the soil particles

When

ϕ = angle of internal friction.
N = component of w, normal to CD.
$t = N \tan \phi + C$

On this basis the Bureau of Public Roads, in its publication "Public Roads," vol 10, No 3, May, 1929,[1] * suggested a formula by means of which some conception could be obtained with respect to the influence exerted by both internal friction and cohesion upon stability

TABLE I

VALUES OF c AND ϕ FOR DIFFERENT SOILS AND THEIR INFLUENCE UPON THE SUPPORTING VALUE, q FOR SEVERAL ASSUMED CONDITIONS
($b = 0.71$ FOOT AND $s = 100$ POUNDS PER SQUARE FOOT)

Soil	Cohesion, c, pounds per square foot	Angle of internal friction, ϕ Degrees	Supporting value, q,* pounds per square foot
Clay, almost liquid	100	0	400
Clay, very soft	200	2	864
Clay, soft	400	4	1,857
Clay, fairly stiff	1,000	6	4,982
Clay, stiff	1,500	8	8,050
Clay, very stiff	2,000	12	12,528
Silts, wet †	0	10	43
Sands, dry	0	34	768
Sand predominating with some clay	400	30	6,035
Sand-gravel mixtures, cemented ‡	1,000	34	17,838

* The values of q serve for demonstration purposes only and should not be used as a basis of pavement design

† In silty soils, the angle of internal friction may vary between 10 and 30 degrees but the cohesion may be almost 0

‡ In properly graded soils, depending upon the extent of their compaction, the angle of internal friction may exceed 34° and the cohesion may be considerably less than 1000

According to Table I, the stability of clays may be increased enormously by reducing their moisture contents Furthermore the stability of wet clays may be very appreciably increased by mixing sand with them and the stability of sands may be very greatly increased by mixing clay with them

The supporting value of sand, for instance, possessing no cohesion and internal friction in amount represented by $\phi = 34°$, is 768 pounds per square foot The supporting value of soft clay possessing cohesion in amount equal to 400 pounds per square foot and internal friction in amount represented by $\phi = 4°$, equals 1857 pounds per

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* Numbers refer to reports listed in the attached bibliography

square foot These two materials properly combined, however, are apt to furnish support exceeding in amount 6000 pounds.

By use of the formula referred to it can be demonstrated also that with equal cohesion furnished by the clay, the stability of the subgrade increases with increase of internal friction furnished by the sand and for equal internal friction furnished by the sand the stability of the subgrade increases with increase of cohesion furnished by the clay

Thus for instance when the cohesion equals 400 pounds per square foot the supporting value of the subgrade will equal either 2554 or 7596 pounds per square foot depending on whether the angle of internal friction equals 12° or 34° And when the angle of internal friction equals 34° the supporting value of the subgrade will equal either 4182 or 17,838 pounds per square foot depending on whether the cohesion equals 200 or 1000 pounds per square foot

According to available information sands possess a relatively high degree of internal friction The greater the degree of angularity, sharpness or roughness possessed by the sand grains the greater is apt to be the degree of internal friction furnished by the sand Silts possess internal friction in amounts varying between $\phi = 10°$ and $\phi = 30°$ depending upon the moisture content of the soil Silts possess practically no cohesion Clay and colloids furnish cohesion but possess internal friction in relatively small degree

Practically this information suggests that:

1 Admixtures which serve to prevent the soil from taking up moisture, serve to prevent the soil from losing cohesion and therefore should serve to increase the stability of clays when used either as binders or subgrades.
2 Admixtures possessing cohesion should serve to furnish cohesion additional to that possessed by the soil Admixtures of this type therefore should serve to increase (a) the stability of cohesionless silts when used either as binder or subgrades and (b) the stability of sands when used as subgrades
3. Admixtures of granular materials possessing high resistance to sliding are apt to furnish stability in much greater amount than admixtures of granular materials possessing relatively small resistance to sliding

ELASTICITY A DETRIMENTAL SUBGRADE CHARACTERISTIC

The ability to distort in a jelly like fashion (1) instead of permanently compacting when loaded, causes soils possessing elasticity to

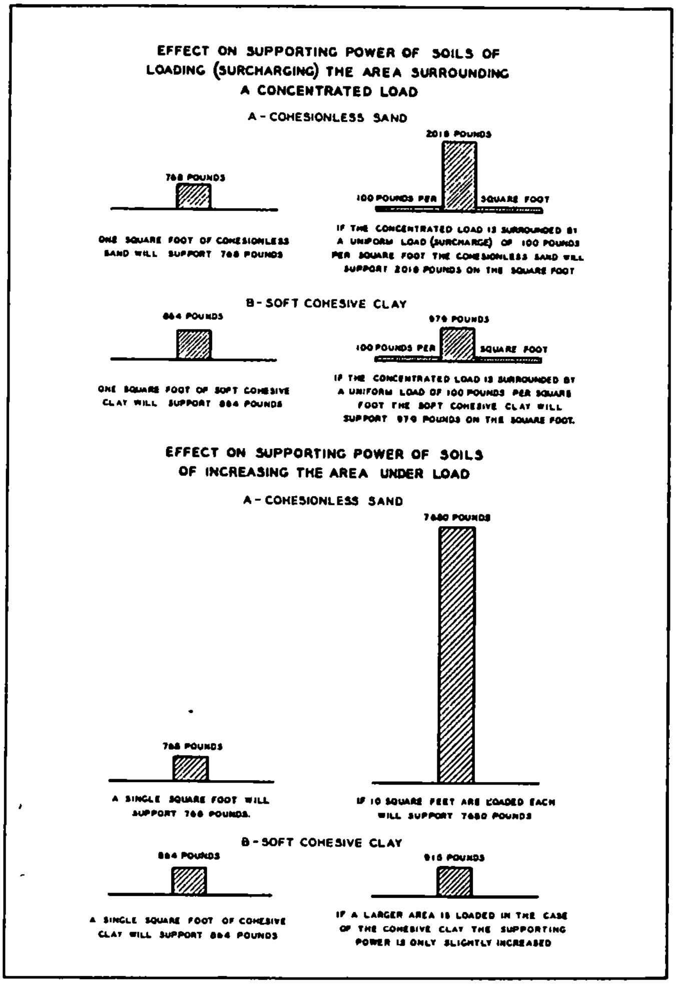


Figure 2 Sketch Illustrating How Cohesionless Differ from Cohesive Soils When Used as Subgrades

Upper: The appreciable increase in the unit support that is furnished by cohesionless soils when surcharged adjacent to the loaded area is not furnished by soft cohesive soils under the same conditions.

Lower: The appreciable increase in unit support that is furnished by cohesionless soils when the loaded area is increased in width is not furnished by soft cohesive soils under the same conditions. (Public Roads, Vol. 10, No. 3, May, 1929.) Also, the safe slope of cohesionless soils is constant irrespective of both the height of fills and depth of cuts. The safe slope of cohesive soils in contrast decreases as either the height of fills or the depth of cuts increases. (Public Roads, Vol. 10, No. 10, December, 1929) rebound upon the removal of load. This performance is caused by the presence of soil constituents such as mica and organic matter which possess abnormally high porosity when dry. Furthermore, the pores of these materials when wet are apt to contain air in appreciable amounts and this also is productive of elasticity. Clay soils flocculated due to the presence of certain chemicals also are apt to possess elastic properties under certain conditions.

Cohesionless soils possessing elasticity are apt to prove troublesome when both dry and wet. Cohesive soils of this group, in contrast, may exhibit elastic properties only when containing certain amounts of moisture.

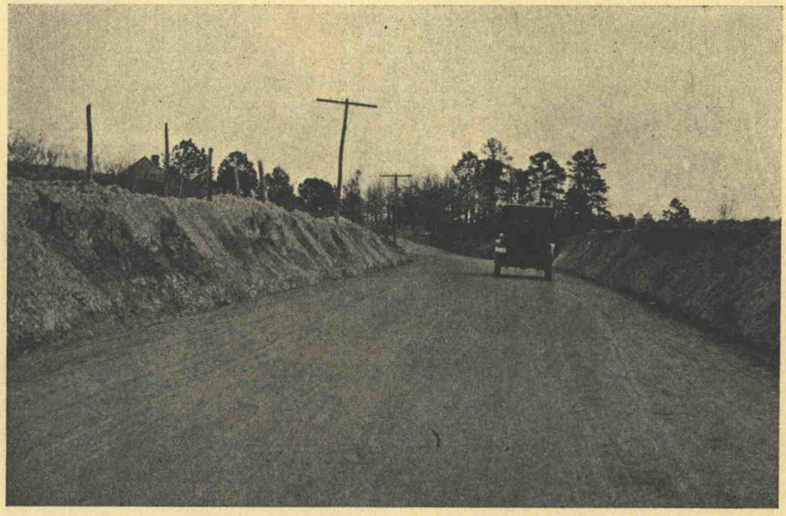


Figure 3. Highly Stable Mixture of Sand, Silt and Clay Possessing Both Internal Friction and Cohesion in Proper Amounts

A knowledge of the existence of elasticity in subgrades prior to pavement construction might be the means of saving the cost of either a concrete or a macadam pavement.

After thorough rolling according to the current procedure for instance, a subgrade of the elastic type if it possesses cohesion is apt to retain a certain degree of compaction. A slight wetting under these conditions such as is furnished by freshly deposited concrete may cause a non-uniform rebound of the subgrade. This combined with water loss from the concrete due to absorption by the soil may cause pavements to crack excessively during the setting period of the concrete.

Figure 4. Detrimental Effects of Elasticity in the Subgrade

Upper: Cracking apt to occur in concrete pavement during setting period. Note how cracks occurred apparently over ruts formed in the subgrade by the concrete mixer.

Lower: Alligator hide cracking apt to occur in macadam laid on elastic subgrade. After cracking of this type occurs, water enters the subgrade, softens it, and permits the subgrade soil to work into the interstices of the macadam. In this instance the subgrade soil has penetrated the road surface to within about an inch of the top. (Photograph furnished by I. B. Mullis.)

Likewise movements of both heavy material trucks and mixing apparatus adjacent to pavements laid on elastic cohesionless subgrades may cause distortions of the soil supporting the freshly laid concrete productive of pavement cracking Cracking of this character might remain in microscopic form for an appreciable period of time. Except during the setting period of the concrete, elastic subgrades may not be detrimental to concrete pavements

The presence of elasticity in subgrades may prevent macadam pavements from acquiring adequate bond during construction and from retaining it subsequently. Under these conditions macadams are apt to develop "alligator hide" cracking through which water may pass and cause the subgrade soil to soften and to penetrate the voids of the macadam thus causing the macadam to fail.

Practically this information suggests the following with respect to the preparation of elastic subgrades:

(a) Stabilize elastic subgrades by treatment as for instance stage construction before attempting to construct a macadam pavement.
(b) When absence of cohesion in the subgrade (highly micaceous sands, etc) interferes with the construction of pavements, admixtures of cohesive materials (clays) may prove beneficial.
(c) Make the subgrade both as uniformly dense and as uniformly moist as possible by breaking up all clods with a light weight roller (about 3 tons) harrowing, and possible sprinkling.
(d) Attempt to prevent excessive moisture change in the soil during the setting period of the concrete by either placing tar paper or similar material or applying bituminous coatings on the subgrade.

FROST HEAVE APT TO BE DETRIMENTAL IN PERMEABLE SILTS

Frost heave which is due to the formation of well defined ice layers [3] instead of to the expansion during freezing of the moisture originally contained in the frozen soil layer is due to three physical phenomena:

(a) The ability of water particles contained in soil pores larger than about capillary dimension to freeze at either normal freezing or slightly less than normal freezing temperatures (— 1° — 4° C).[3]
(b) The ability of water particles contained in soil pores of capillary dimension to resist freezing at abnormally low temperatures (as low as — 70° C) [3,4,5]

(c) The ability of water particles of freezable size, during the process of freezing to draw to themselves from adjacent fine capillaries the small particles of water which individually do not freeze at ordinary freezing temperatures.[3,4,5] When drawn to the existing ice crystal, however, these small water particles freeze and increase the size of the original ice crystal. Continuation of this process causes the original ice crystals to increase in size as long as they are being furnished small water particles drawn up through the fine capillaries from the ground water supply.

Figure 5. Early Cracking in Concrete Pavement Eliminated by Placing Tar Paper on Subgrade. (Photograph furnished by R. W. Crum.)

In sands no important frost heave occurs[2] because practically all of the contained water freezes at normal freezing temperatures[5] and small unfrozen water particles do not exist in amount sufficient to cause the frozen particles to suffer appreciable growth.

Permeable silts which are capable of raising water rapidly and through distances of considerable amount are apt to suffer very important frost heave. These silts may be capable of raising by capillarity at the rate of approximately 0.9 pound of water per square foot of soil per day when the ground water elevation is 4 feet below the surface of the ground.[6] At this rate a layer of water approximately 5½ feet in depth would be raised during one year.

The capillary raise may be as high in cohesive clays as in silts. The speed with which water rises in clays, however, is much less than in silts Consequently, in dense clay soils with low ground water level and absence of lateral seepage, only limited amounts of water are available for ice segregation Under these conditions the soil adjacent to the growing ice crystals is apt to dry out and shrink due to the loss of moisture[7] The ground water elevation in clays, therefore, must be comparatively high in order that important frost heave may occur. Or the clay must be wet due to water absorption, with manipulation on top of the subgrade

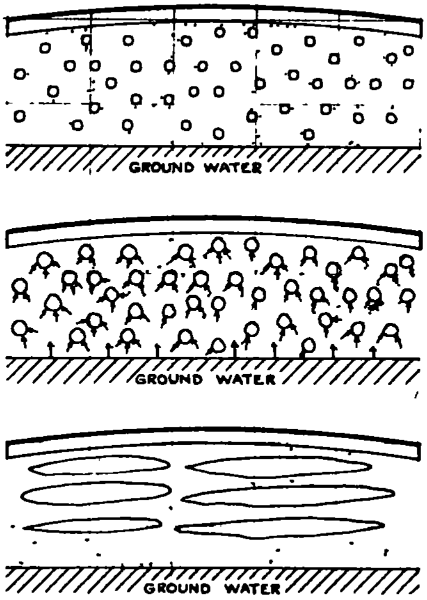


Figure 6. Diagrammatic Sketch of Frost Heave

Upper. Circles represent water particles of size freezable at normal freezing temperatures. Dots represent water particles which fail to freeze at normal freezing temperatures.

Middle: Shows frozen water particles (circles) growing by drawing to themselves the small unfrozen particles (dots) and the flow of capillary moisture from the ground water to fill the soil pores vacated by the small unfrozen water particles

Lower· Resulting layers of ice which cause the road surface to heave

Additive to the detrimental effects of heaving is the softening of the subgrade during thaws due to the liberation of excessive amounts of water trapped by both frozen under-soil and frozen shoulders.

Due to a variety of causes frost depth under roadways is apt to be greater than under shoulders Also thawing is apt to occur first under the roadway, therefore, water liberated in this manner cannot penetrate the frozen soil along the edge of the roadway and reach the drain located there Thus the drains must be placed at the location of maximum frost depth which is likely to coincide with the location of initial thawing In this respect the center drain according to L L Allen, Minnesota State Highway Department, serves (a) to lower the moisture content of the soil before freezing and (b) to provide for the disposal of water liberated by thaws

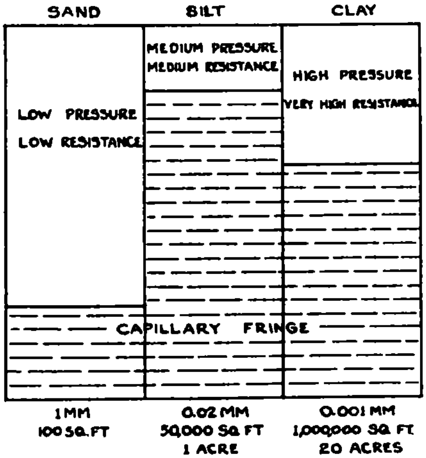


Figure 7

Sketch showing why drains must be placed very deep in order to prevent frost heave in silts The capillary rise which feeds the growing frost crystal depends upon (a) the capillary pressure which forces water up into the soil pores, and (b) the frictional resistance offered by the soil pores to the flow of water The capillary pressure increases with decreasing soil particle size. The frictional resistance to flow increases with increase in surface area of soil particle Silts with grain size of about 0 02 mm. seem to possess the proper combination of both capillary pressure and frictional resistance productive of high capillary rise. In silts and mucks (see Figure 13) drains must be placed at a comparatively great depth The areas shown at the bottom of the sketch represent the total surface area of soil particles contained in one cubic foot of soil mass.

Also according to both A C White[8] and J T Henton[9] drains backfilled with gravel and placed longitudinally under the center of gravel road surfaces are effective for curing frost boils in both Minnesota and Wisconsin.

Especially important with respect to frost heave (according to W. I Watkins, U S Bureau of Chemistry and Soils, E A. Willis, U. S Bureau of Public Roads, and John Morton, New Hampshire State Highway Department) are soils consisting of sand to a depth of as much as 12 or 18 inches underlain with silt zones which sag and permit water to accumulate

Practically this information suggests that:

1. Any admixture which serves to reduce the moisture content possessed by the subgrade soil is apt to reduce the extent of frost heave.
2 Any treatment which serves to prevent water entering the subgrade from above may serve at the same time to prevent increase in the moisture content of the subgrade to depths depending upon the permeability of the subgrade soil. Consequently a treatment of this character may serve to reduce the extent of frost heave suffered by the subgrade due to water absorption from above.

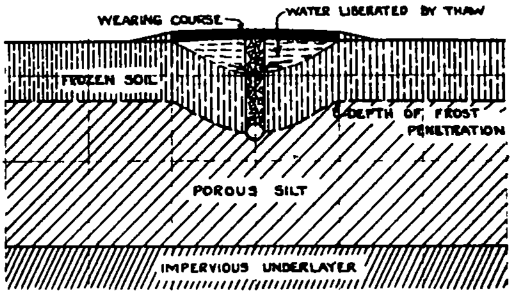


Figure 8 Sketch Showing How the Center Trench Serves to Dispose of the Water Liberated by Thaws

3 Any admixture which serves to furnish cohesion in silts is apt to reduce also the extent of frost heave suffered by subgrades consisting of silt.
4 Drains backfilled with porous material placed longitudinally under the center of gravel road surfaces, and in depth slightly greater than the depth of frost penetration should serve to (a) reduce the extent of frost heave in silts by reducing the moisture content possessed by the soil before freezing and (b) prevent loss of stability in silts by disposing of water liberated during thaws.

THE FUNCTION OF BITUMINOUS SUBGRADE TREATMENTS WITH RESPECT TO THE CONSTRUCTION OF MACADAM PAVEMENTS ILLUSTRATES BENEFITS APT TO BE FURNISHED BY SUBGRADE TREATMENTS

Primarily the failure of macadams on other than elastic subgrades is due to the subgrade soil penetrating the interstices of the macadams In order that this may occur, (a) the subgrade soil must

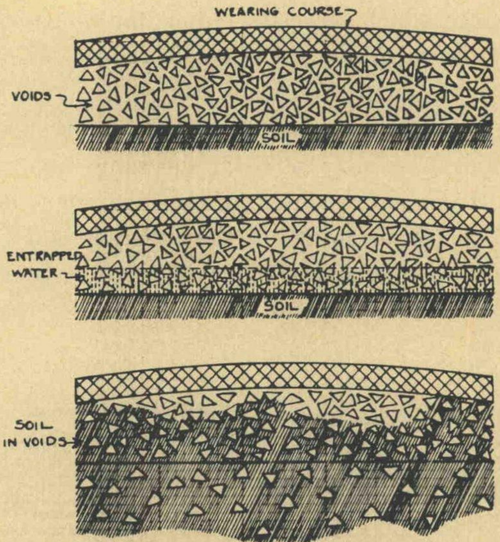


Figure 9. Sketch Illustrating the Failure of Macadam and Porous Base Courses

Upper: New roads with pores in base course.
Middle: Water trapped in pores of base course.
Lower: Penetration of subgrade soil into pores of base course.

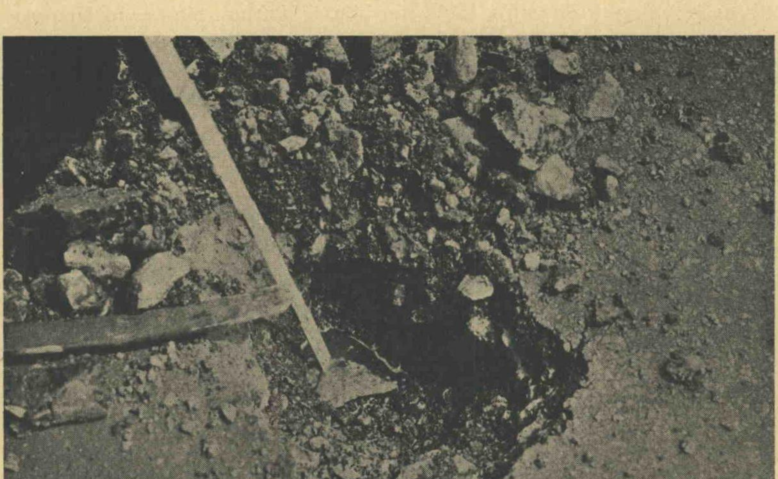


Figure 10. Entrapped Water Which Entered a Hole Dug in a Macadam Base in 3 Minutes. The Pavement Rested on a Fill 10 Feet High and the Hole Was Dug 7 Days After a Rain Storm

be wet and (b) voids in appreciable amount must exist in the under course of the macadam

Applying bituminous material on the subgrade and covering with a cushion of granular material before constructing the macadam, supplemented by drainage as specified for stage construction, is suggested to prevent failure of this character

Sands are not likely to work up into the interstices of macadams The object of treating them in this case therefore is to furnish the cohesion necessary for stabilizing cohesionless materials The increased stability furnished by treatments of bituminous materials which penetrate the sands to a depth of 1½ to 2 inches may serve to permit a reduction of appreciable amount in the thickness of the macadam wearing course

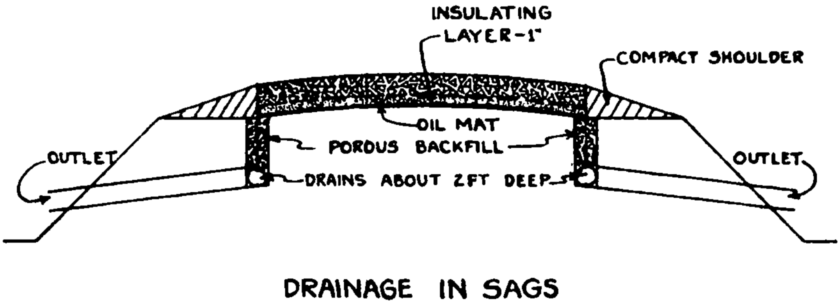


Figure 11. Preventive for Macadam Failures Treat Subgrades with Bituminous Material and Cover with Granular Material Drain All Sags in the Grade

The object of the treatment on clays is to furnish impermeable top coating Therefore in this case the depth of soil penetrated should be such as to furnish adequate bond between the bituminous coating and the dense subgrade soil It is possible that bituminous materials which penetrate the subgrade soil to a depth of 5/16 to ⅜ of an inch will furnish the bond in required amount

Why these skin treatments on clay subgrades may furnish benefit equal to that furnished by foundations of appreciable thickness is apparent Clay soil, until after it flows laterally, cannot penetrate the interstices of the macadam Clay soil cannot flow laterally until after it has attained very low cohesion due to water absorption Clay soil in the plastic state cannot absorb water when present unless the clay is manipulated Until the upper skin of clay in contact with the under stones of the macadam, is manipulated in the presence of water and softened, the soil located beneath this upper skin is not enabled to absorb water and soften. The water which is apt to cause this upper skin of an impervious clay soil to soften must of necessity be water resting on the surface of the subgrade and trapped in the interstices of the macadam. The bituminous treatment prevents this water from both coming in contact with and softening the upper skin of the subgrade soil. The cushion layer of granular material serves to fill the voids in the macadam.

Consequently, the subgrade treatment serves

1. To eliminate the voids into which the clay would enter.
2. To eliminate the voids in which water would collect on top of the subgrade.
3. To prevent water resting on top of the subgrade from both entering and softening the subgrade soil.

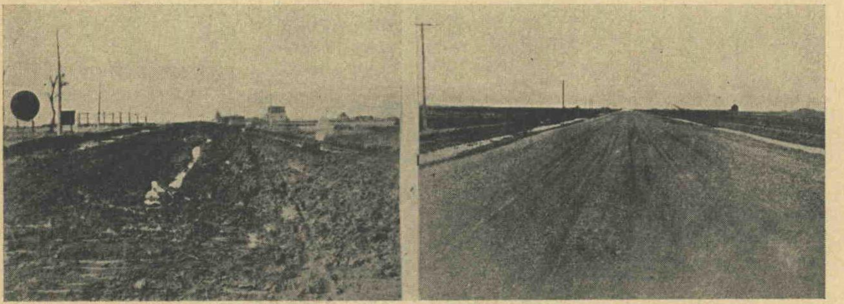


Figure 12. Effect of Bituminous Treatment Covered with Gravel Blotter Layer on Gumbo Soil

Left: Gravel road on gumbo after spring thaw.
Right: Thin gravel course on bituminous treated gumbo soil after spring thaw.
(Photographs furnished by F. C. Lang.)

SUBGRADES TENTATIVELY ARRANGED IN GROUPS

With respect to their performance the various subgrades may be tentatively arranged in groups[1] as follows:

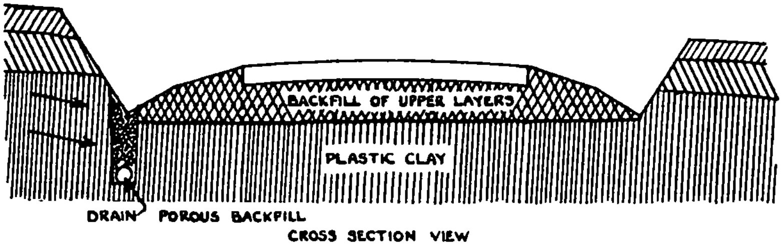
Uniform Subgrade

Group A-1. Well graded material, coarse and fine, excellent binder. Highly stable under wheel loads, irrespective of moisture conditions. Functions satisfactorily when surface treated or when used as a base for relatively thin wearing courses. Represented by the excellent top soils of Georgia.

Group A-2. Coarse and fine materials, inferior binder. Highly stable when fairly dry. Apt to soften at high water content caused either by rains or by capillary rise from saturated lower strata when an impervious cover prevents evaporation from the top layer. Represented by poorly graded top soils.

Group A-3. Coarse material only, no binder. Lacks stability under wheel loads but unaffected by moisture conditions. Furnishes excellent support for flexible pavements of moderate thickness and for relatively thin rigid pavements Represented by the Florida sands

Group A-4. Silt soils without coarse material, and with no appreciable amount of clay Apt to absorb water very readily in quantities sufficient to cause rapid loss of stability even when not manipulated When dry or damp, presents a firm riding surface which rebounds but very little upon the removal of load Apt to cause cracking in rigid pavements due to frost heaving and failure in flexible pavements due to low support Represented by New Hampshire silts.



SUBGRADE TREATMENT FOR PAVEMENT ON VERY DENSE PLASTIC CLAY WHICH HAS CAUSED CONSIDERABLE DISTORTION IN PAVEMENTS

Figure 13

Sketch showing how soils possessing shrinkage properties in high degree should be treated in cuts: Excavate to an appreciable depth below grade, (b) backfill with good top soil material; (c) use underdrains instead of ditches; (d) coarse materials such as gravel or rock should not be placed directly on soils of this character. Soils of this character are not apt to prove satisfactory when used in fills of appreciable height.

Group A-5 Similar to Group A-4, but furnishes highly elastic riding surfaces with appreciable rebound upon removal of load even when dry Elastic properties interfere with proper compaction of macadams during construction and with retention of good bond afterwards. Represented by highly micaceous soils of North Carolina

Group A-6. Clay soils without coarse material. In stiff or soft plastic state absorb additional water only if manipulated. May then change to liquid state and work up into the interstices of macadams.

Figure 14

Upper: Typical appearance of Group A-6 or A-7 soils possessing shrinking properties in high degree.

Lower: Fill settling through a Group A-8 subgrade. Mound to right of roadway shows muck displaced by fill material.

(Photograph furnished by J. D. Fauntleroy.)

Furnish firm support essential in properly compacting macadams only at stiff consistency Deformations occur slowly and removal of load causes very little rebound Shrinkage properties combined with alternate wetting and drying under field conditions are apt to cause cracking in rigid pavements Represented by the Mississippi gumbo.

Group A-7 Similar to Group A-6, but when moist, deforms quickly under load and rebounds appreciably upon removal of load Thus, lacks firmness in support, similar to subgrades of Group A-5 Alternate wetting and drying under field conditions leads to even more detrimental volume changes than in Group A-6 subgrades May cause concrete pavements to crack before setting Represented by Illinois bumbo and typical adobes

Group A-8 Very soft peat and muck incapable of supporting a road surface without being previously compacted or displaced by a fill. Represented by Minnesota peat bogs

Non-Uniform Subgrades

Soils of this group cause concrete pavements to crack or fault excessively and flexible type surfaces to fail or develop rough riding surfaces

Group B-1 Non-uniform natural ground due to abrupt variation in soil characteristics, or soil profile, or to frequent change in field conditions

Group B-2 Non-uniform subgrade due to non-uniform composition of fill

Group B-3 Non-uniform subgrade consisting in part of natural ground and part of fill materials

SUBGRADE SOIL CONSTANTS INDENTIFY IMPORTANT SUBGRADE CHARACTERISTICS

The mechanical analysis which furnishes information only with respect to soil particle size within rather wide limits, is inadequate to furnish complete identification of subgrade characteristics That fraction indicated as sand for instance by the mechanical analysis may be either a round grain sand which flows under low moisture content (mere lubrication of grain surface) or an angular grained sand which flows only due to hydrostatic uplift Likewise, that fraction indicated as silt by the mechanical analysis may be compressible inert material or a micaceous material possessing elasticity in detrimental amounts Also those fractions designated as clay may differ

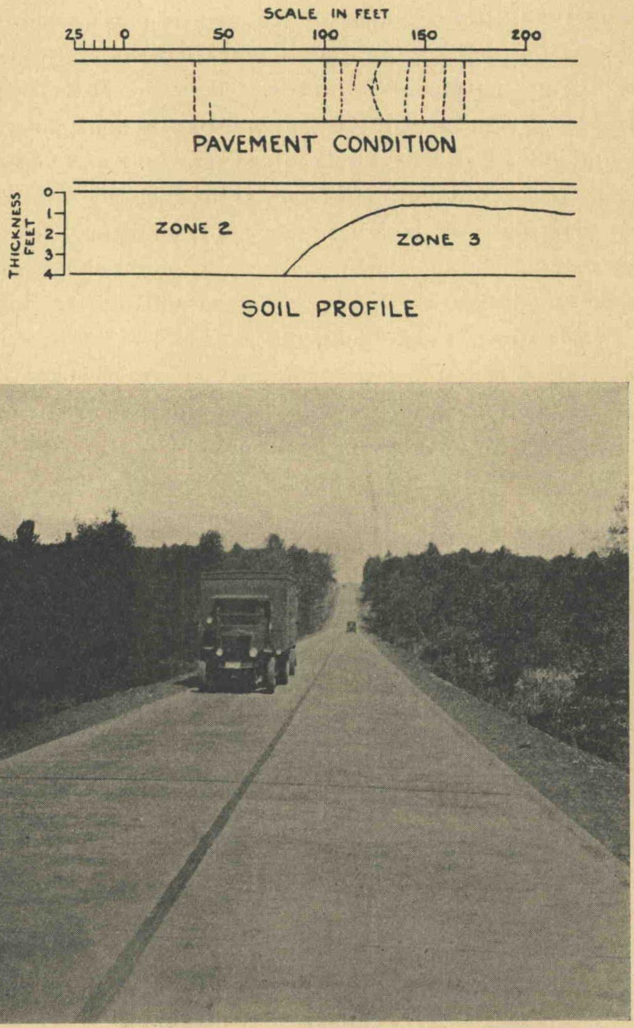


Figure 15

Upper: Cracking in concrete pavement due to non-uniform B-1 subgrade. Zone 3 is an impervious compact soil. Similar cracking would be apt to occur if Zone 3 had been rock or ledge.

Lower: Concrete pavement divided by means of crack control into slabs 10 feet wide by 20 feet long. Crack control of this type is apt to prevent detrimental effects of cracking due to non-uniform subgrade support.

widely with respect to performance Therefore, in order to identify the characteristics of subgrade soils, one must employ constants which disclose the degree to which soils possess particular physical properties. The constants suggested for accomplishing this purpose are the lower liquid limit, the lower plastic limit, the plasticity index, the shrinkage limit, the centrifuge moisture equivalent, the field moisture equivalent, the shrinkage ratio, the volumetric change, the lineal shrinkage and the slaking value

These constants may be briefly defined as follows:

Lower Liquid Limit Minimum moisture content of the soil in percentage of the weight of the dry soil at which a standard number of shocks of standard intensity just begins to transform the lower limit of two sections of the soil cake into the liquid state

Lower Plastic Limit The minimum moisture content in percentage of weight of the dry soil, at which the soil can still be rolled out into threads 3/16 inch in diameter without the threads breaking into pieces.

Plasticity Index. The difference between the lower liquid and the lower plastic limits

Shrinkage Limit * Mathematical computation according to the formula

$$S = w - \frac{V - V_0}{W_0} \text{ in which}$$

S = shrinkage limit, moisture content in percentage of weight of dry soil.

w = moisture content of the thoroughly wet soil cake in percentage of weight of dry soil.

V = volume of the wet soil in cubic centimeters when moisture content equals w

V_0 = volume of the thoroughly dried soil cake in cubic centimeters.

W_0 = weight of the thoroughly dried soil cake in grams

Centrifuge Moisture Equivalent. Moisture content in percentage of weight of the dry soil retained by a soil sample when subjected to a centrifugal force of 1000 times gravity after being allowed in the dry state to soak in water under zero pressure for a period of six hours.

Waterlogging in the centrifuge moisture equivalent consists of free water being retained on top of the soil cake after centrifuging.

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* See author's discussion of Professor Krynine's report, these proceedings

Field Moisture Equivalent Moisture content in percentage of weight of the dry soil at which a drop of water is not absorbed by the smoothed surface of the sample when its moisture content is being gradually increased by slowly adding water to the sample beginning with soil in the air-dried state

*Shrinkage Ratio.** The weight of the thoroughly dried soil cake in grams (W_o) divided by the volume of the thoroughly dried soil cake in cubic centimeters (V_o)

Volumetric Change Decrease in volume in percentage of the dried soil cake suffered by a soil sample when due to evaporation its moisture content is reduced to zero from an amount equal to some arbitrary moisture content †

Lineal Shrinkage Decrease in length in per cent of length of the wet soil cake suffered by a soil sample when due to evaporation its moisture content is reduced to zero from an amount equal to the field moisture equivalent

Slaking Value. Time in minutes required foi a soil sample after being wetted, molded into a cake, compressed and air dried to disintegrate when immersed in water

The laboratory tests which furnish the subgrade soil constants are the centrifuge moisture equivalent, the shrinkage limit, the lower liquid limit, the lower plastic limit, the slaking value and the field moisture equivalent

A combined sieve and Bouyoucos hydrometer method is used for determining the mechanical analysis

Both the testing of subgrade soils and the interpretation of soil test results requires the services of one specially trained in these matters and will not be discussed in this résumé.

CONCLUSIONS PRESENTED

Based upon the results furnished by the subgrade investigations carried on by the U. S Bureau of Public Roads and cooperating agencies the following conclusions have been presented:[1]

Subgrade Support

1 The support furnished by different subgrade soils varies widely with regard to intensity of support (high or low), character

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*Unit volume reduction per unit moisture content reduction for moisture contents above the shrinkage limit

† A moisture content equal to the field moisture equivalent is used when the lineal shrinkage is to be estimated from the volumetric change

of support (firm or elastic), and uniformity of support (constant or variable intensity of support), and thus permits a differential of considerable amount in pavement requirements

2 The character of support afforded by subgrade soils is dependent upon soil constituents such as sand, clay, silt, mica, organic matter and diatoms, and upon the structure of the soil and the field conditions under which it exists

3 The intensity of support in uniform subgrades depends upon the cohesion and internal friction in the soil, the area of load distribution, and the weight of superimposed pavement

4 High subgrade support requires either high cohesion or high internal friction, preferably both combined High cohesion is characteristic of clays with stiff consistency, high internal friction, of well graded sands, and a combination of both internal friction and cohesion of well-graded sands with a binder

5 The greater the internal friction the more will the support of the subgrade be improved by distributing the load over a larger area or by increasing the dead weight of the pavement

6 Increasing the intensity of subgrade support permits a reduction in the thickness of nonrigid foundations and increases the factor of safety against "breakage"* but not necessarily against longitudinal and transverse cracking in rigid pavements

7 Eliminating the clastic rebound in subgrades permits the construction of nonrigid pavement types otherwise not suitable

8 Increasing the uniformity of subgrade support reduces the extent of transverse and longitudinal cracking in rigid pavements and may provide against failure in nonrigid types

Drainage

9 Side ditches or deep trenches may intercept water furnished by porous strata and may serve to lower the ground-water level. Thus they may be effective for preventing failure in side-hill fills, for increasing the subgrade support, and for reducing the extent of frost heave.

10 Tile laid in trenches filled with porous material and placed under the edges of pavements serve to intercept water entering from the sides and to prevent the accumulation on top of the subgrade Thus, they may serve the same purposes as deep

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* Cracking of the pavement into small pieces due to load and uniform support

side trenches and, in addition, reduce the extent of softening of the subgrade due to saturation from the top Also they provide against the separation of cracked rigid slabs, due to successive freezing of water trapped by impervious shoulders

Subgrade Surface Treatments

11. Subgrade surface treatments consisting of oiling and blanket courses serve to prevent the infiltration of soft subgrades into superimposed pavements and thus they may very appreciably increase the service value of nonrigid pavements laid on fine silt or clay subgrades.

Subgrade Treatments

12. Subgrade treatments serve primarily to increase the intensity of subgrade support, although, depending upon conditions, they may also increase the uniformity of subgrade support. Thus, they are beneficial primarily only with respect to the construction of nonrigid pavements.
13. Intensity of subgrade support is increased by adding cohesive materials to sands, granular materials to clays, and both cohesive and granular materials to silts Adding moisture capacity reducers to retain high cohesion, and granular materials to supply internal friction, to clays may increase the benefits furnished by the addition of granular materials alone
14. Subgrade treatments should be planned on the basis of the information furnished by laboratory tests concerning the soil properties.

Base Courses

15. Compacted base courses serve primarily to furnish load distribution in nonrigid pavements.
16. Except when porus base courses extend from the bottom of the pavement to the top of a rock subgrade, compacted base courses may be the more efficient.
17. The penetration of the underlying clay into the voids of porous base courses may furnish conditions of support which, due to their lack of uniformity, may be extremely undesirable.
18. Base courses may reduce the extent of longitudinal cracking which would otherwise occur in rigid pavements This ceases to be a benefit in pavements which contain a center joint or groove.

19 Except when lack of uniformity in subgrade support is caused by conditions which exist in close proximity to the pavement, the efficiency of base courses for decreasing the extent of primary and secondary transverse cracking in rigid pavements is questionable

Pavement Design

20 "Beam" strength is desirable in pavements laid on soils whose low support is due to a lack of internal friction

21 "Beam" strength is not a necessity in pavements laid on soil whose low support is due to the absence of cohesion

22 "Beam" strength is not an essential requirement for wearing courses on Group A-1 subgrades

23 Increasing the thickness of rigid pavement furnishes an increase in the factor of safety against the occurrence of "breakage" but not to an appreciable extent against the occurrence of transverse cracking due to lack of uniformity in support

24 Crack control and steel reinforcement serve to eliminate the undesirable effects caused by such cracking as cannot be prevented in rigid pavements Their use permits a predetermination of the ultimate size of slabs, free from additional visible cracks, and also prevents faulting and separation of the slabs.

25 A subgrade survey record, to be of practical use in the design of highways, should consist of a map showing the ground-water level and the soil profile together with a description of the physical properties (both laboratory and field) of the various soils which comprise the profile

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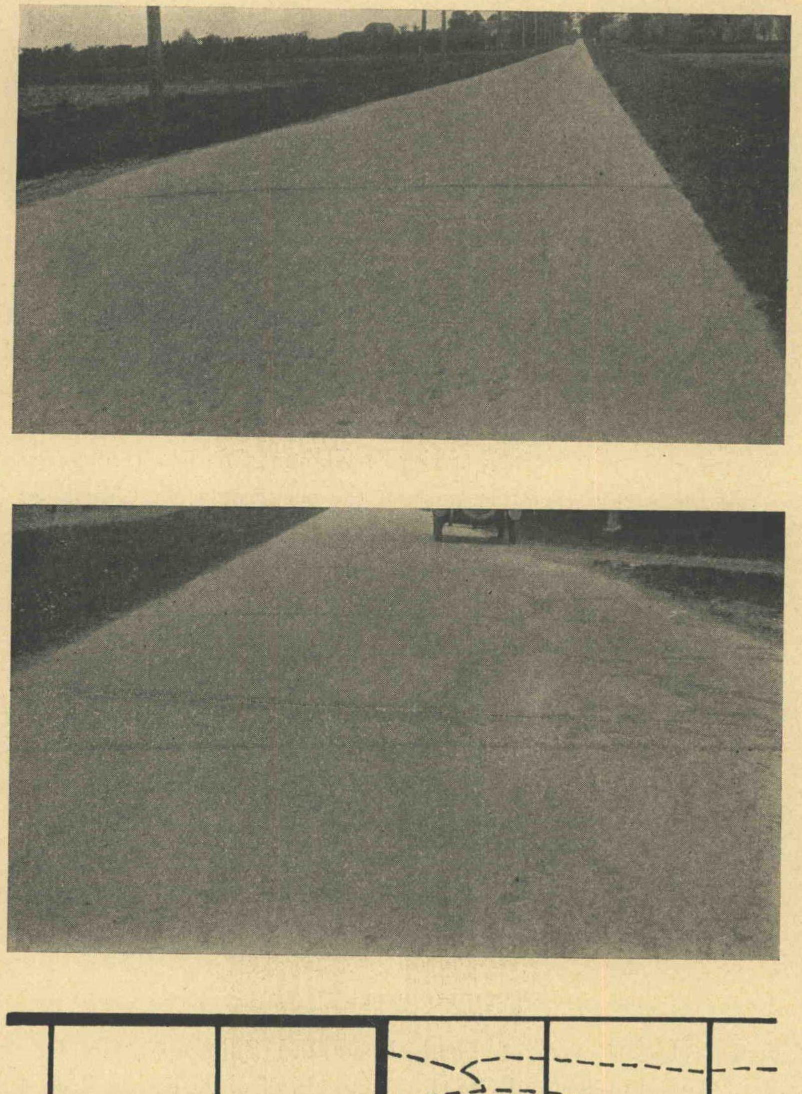

Figure 16. Effect of Light Weight Reinforcement for Reducing the Extent of Cracking in Pavements

Upper: Reinforced concrete slabs without cracks.

Lower: Badly cracked adjoining plain concrete slab.

Sketch at bottom: Map of pavement slabs. Those with heavy border are reinforced and contain no cracks. Broken lines show cracks in adjoining plain concrete slabs.

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DISCUSSION
ON
IMPORTANT DEVELOPMENTS WITH RESPECT TO SUBGRADES

MR J. A. SOURWINE, *U. S Bureau of Public Roads.* I want very briefly to pay tribute to Mr. Hogentogler and Mr. Terzaghi, who in their outline of new soil classifications, practically adapted for use in highway design, have achieved one of the boldest and one of the most basically valuable accomplishments which have come to highway research over a period of many years Their thoroughly practical soil groupings for use as a basis in highway design make possible further detailed study which under the old forms of soil grouping and classification, developed primarily for other than highway purposes, was not possible By their new practical groupings they make possible the application of much knowledge which we now possess, but which has previously been very difficult of practical application for highway use The possibilities of further cooperative, constructive research along the general lines as outlined by Mr Hogentogler, are tremendous His present study, in my judgment, marks an "epoch" in the development of soil research, as applied to public highway design and construction.