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BUREAU OF PUBLIC ROADS

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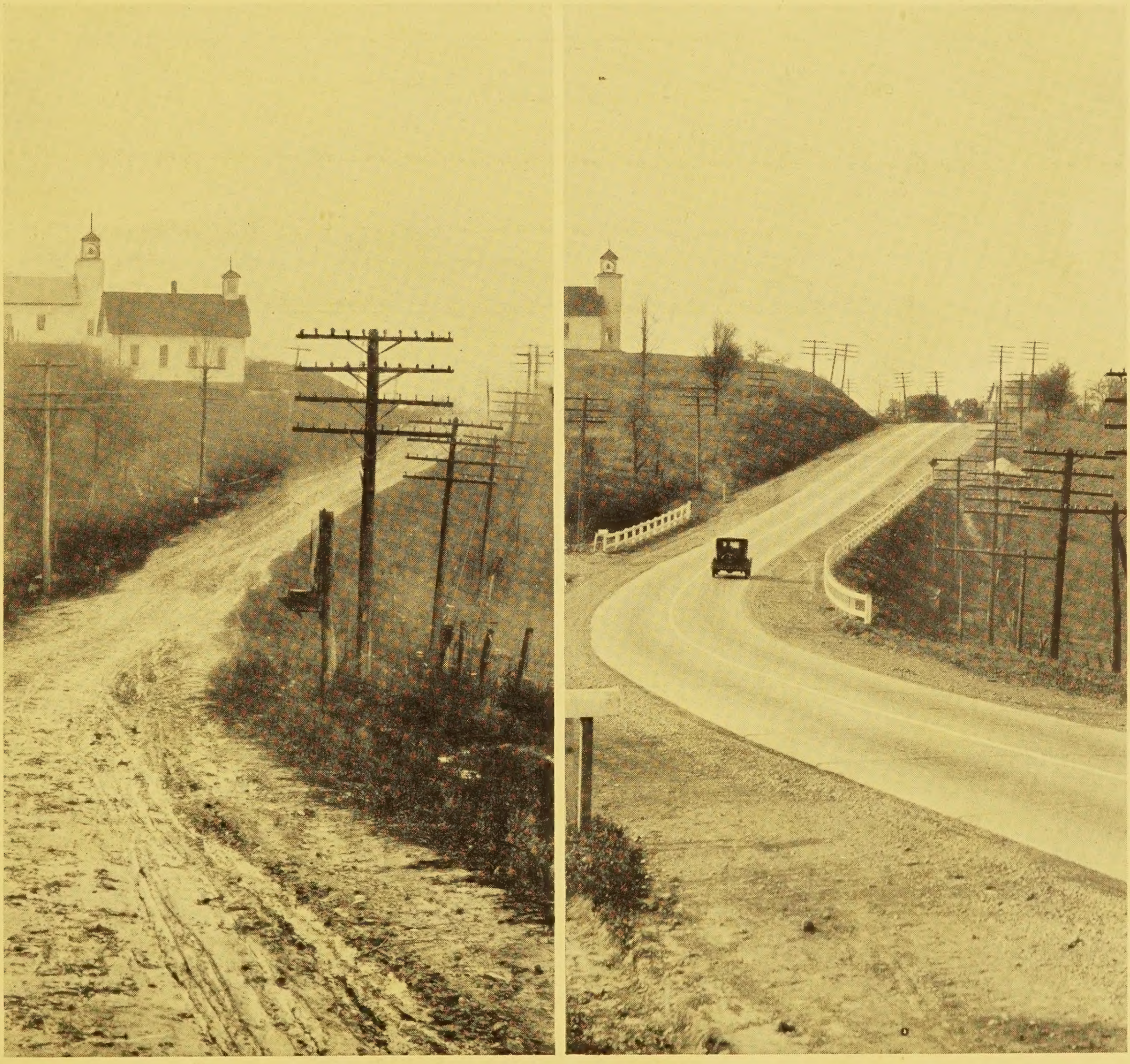

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PRESENT STATUS OF SUBGRADE SOIL TESTING

BY THE DIVISION OF TESTS, UNITED STATES BUREAU OF PUBLIC ROADS

Reported by C. A. HOGENTOGLER, Highway Engineer; Dr. CHARLES TERZAGHI, Research Consultant; and A. M. WINTERMYER, Senior Engineering Aide

FROM time to time the Bureau of Public Roads has felt compelled to change its subgrade testing procedure for the purpose of increasing the value of the results obtained from its laboratory work. To prevent any misunderstanding arising from changes in test or test procedure, it seems desirable to review the present status of soil testing and to explain the reasons which have led to modifications of tests.

There were several reasons for these changes. First, there seemed to be an overlapping since certain tests disclosed properties which were shown by other tests in different terms. Results of certain tests were complex in meaning and difficult to interpret. Other tests were influenced by the personal equation of the operator or were undesirable because of the length of time required to make them.

Second, the conception of the purpose of soil testing has changed. Originally the purpose in making soil tests was to obtain direct information on the behavior of subgrade soils in the field. Certain tests (capillary moisture, water capacity, moisture equivalent, field moisture equivalent) were intended to show how much water a subgrade soil would take up or retain when subjected to certain conditions. Other tests (volumetric change, lineal shrinkage) were intended to determine the shrinkage which occurred when the moisture content of the soil was reduced from one of the above values to zero.

Unfortunately, experience has disclosed the fact that the reaction of cracked and crumbled soils in the field can be different from that of soils specially prepared for laboratory tests. Information furnished by field surveys indicates that road failures are dependent upon surrounding conditions (location in cut or fill, drainage, climate, etc.) as well as the type of soil, and that failures may occur on what are considered good subgrade soils if certain conditions are present, and likewise failures can be prevented on the worst of subgrade soils by eliminating undesirable conditions. Thus soil tests alone can not show whether a road surface will or will not fail. They can only indicate the existence of the probability of failure and their function is limited to finding out whether, and to what degree, the raw materials of soils encountered in different localities are similar.

OBJECT OF REPORT TO GIVE ENGINEER CONDENSED REVIEW OF SOIL TESTS

At present laboratory soil tests are made solely to give information on the make-up of the soil as regards size of grain, shape of grain, uniformity, chemical composition, organic content, and colloidal content. Such tests are being used in conjunction with the subgrade and pavement surveys now being made by the United States Bureau of Public Roads with the assistance of the United States Bureau of Soils. In this work the field identification of soils is made in accordance with the classification of the latter organization and is based primarily on structure of soil in the field and grain size. It is hoped that, for engineering purposes, the results of the laboratory tests will make possible the grouping of the thousands of soil types which were necessary for agricultural purposes into a comparatively small number of classes with numerical limits.

The research on which to base this grouping of soils for engineering purposes consists of two parts, as follows:

1. An analysis and correlation of results of tests on natural soil samples from all parts of the United States, supplemented by only a few results of tests on synthetic soil samples.
2. A supplementary investigation now in progress to throw additional light on some of the indications found under the first head. This second part of the work involves a large number of tests of synthetic samples obtained by adulterating a small number of representative soils with various percentages of organic matter, colloids, mica grains, and sand grains having different sizes and shapes.

This report concerns only the first part of the work, and its purpose is to supply the highway engineer with a complete list of the soil constants furnished by the various tests of the bureau, and to give him a condensed review of the properties expressed by these constants according to the present state of our knowledge and to illustrate the statements with numerical data.

The report concerns:

I. Soil constants furnished by the early subgrade tests of the Bureau of Public Roads.
II. Data furnished by the Rose tests.
III. Data furnished by the Atterberg tests.
IV. Data furnished by the Terzaghi tests.
V. Significance of the various tests.
VI. Interrelationship of results of the different tests.
VII. Selection of simplified tests for laboratory procedure.
VIII. Conclusions.

The soil tests originally used by the bureau were known as mechanical analysis, capillary moisture, moisture equivalent, volumetric change, dye adsorption, and slaking value tests. At a later date the Rose tests were adopted for field investigations in several of the Western States. Then the Atterberg consistency tests came under consideration and finally the Terzaghi tests were introduced as a means for a more thorough physical interpretation of the results of current or of prospective routine tests. These tests have all been described in previous publications.[1] The following paragraphs merely represent a brief review of what has already been published about these different tests.

EARLY SUBGRADE TESTS REVIEWED

1. The *mechanical analysis* originally served for dividing the soil into three fractions, viz, clay with particles smaller than 0.013 millimeters, silt with

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[1] Procedure for Testing Subgrade Soils, by J. R. Boyd; PUBLIC ROADS, vol. 6, No. 2, April, 1925.

Practical Field Tests for Subgrade Soils, by A. C. Rose, PUBLIC ROADS, vol. 5, No. 6, August, 1924.

Adaptation of Atterberg Plasticity Tests for Subgrade Soils, by A. M. Wintermyer PUBLIC ROADS, vol. 7, No. 6, August, 1926.

Simplified Soil Tests for Subgrade Soils and Their Physical Significance, by Dr. Charles Terzaghi, PUBLIC ROADS, vol. 7, No. 8, October, 1926.

Principles of Final Soil Classification, by Dr. Charles Terzaghi, PUBLIC ROADS, vol. 8, No. 3, May, 1927.

The Slaking Value Test, by Prof. F. H. Eno, Proceedings Highway Research Board, 1926.

particles 0.013 to 0.074 millimeters, and sand, 0.074 to 1.651 millimeters. The limits of the fractions were selected arbitrarily and were independent of any precedent. Later the sizes for these fractions were changed to conform with the more satisfactory practice of the United States Bureau of Soils in which the clay particles are less than 0.005 millimeter, silt ranges from 0.005 to 0.05 millimeter, and the sand particles are larger than 0.05 millimeter.

2. The *moisture equivalent*[2] represents the percentage of water (based on the dry soil weight) retained by a saturated soil specimen (5 grams dry weight) after having been subjected to a centrifugal force of one thousand times gravity. This procedure differs from that used by the Bureau of Soils inasmuch as the Bureau of Soils uses a 25-gram sample. Owing, however, to difference in the size of containers used, the initial thickness of the soil layer (1 centimeter) is the same for both the 5 and the 25 gram samples. In special determinations, the Bureau of Soils has used a centrifugal force considerably in excess of one thousand times gravity.

3. The *capillary moisture* is the percentage of water (based on the dry weight of the soil) which a specimen of dry soil, 10 centimeters high, in a glass tube 25 millimeters in diameter, takes up when the bottom of the soil is immersed in water.

4. The *volumetric change*[3] is the percentage of volume change which occurs when the moisture content of the specimen is reduced, by evaporation, from a standard moisture content to zero. The standard moisture content was made equal to either the capillary moisture or the moisture equivalent percentage. Originally, the volume change percentage was based on the wet volume of the soil and later, on the dry volume of the soil.

5. The *dye adsorption number* indicates the amount of analine dye (methyl violet) which is adsorbed by the soil specimen.

6. The *slaking value* indicates the rapidity with which a dry soil cylinder disintegrates when immersed in water.

DATA FURNISHED BY THE ROSE TEST

7. The *field moisture equivalent value* is the minimum percentage of water at which the soil refuses to absorb a drop of water placed on the smoothed surface of the sample.

8. The *lineal shrinkage value*[4] is the percentage of reduction in the length of a soil bar (based on the wet length) when the moisture content is reduced from the field moisture equivalent percentage to zero.

DATA FURNISHED BY THE ATTERBERG TESTS

The Atterberg tests were introduced some 15 years ago by A. Atterberg, of Kolmar, Sweden, for the purpose of comparing the degree of plasticity of different soils. They consist in determining the moisture content (in per cent of weight of the dry soil) at which a liquid soil passes successively into the plastic, the semisolid, and the solid state.

9. The *lower liquid limit* is the minimum water content of the soil (in percentage of the weight of the dry material) at which a definite number of repeated shocks exerted with a standard intensity will just cause the lower rims of a divided soil cake to flow together.

10. The *lower plastic limit* is the minimum moisture content at which the soil can still be rolled out into threads with a diameter of $\frac{3}{16}$ inch without the threads breaking into pieces.

11. The *plasticity index* is the difference between the lower liquid and the lower plastic limits.

12. The *shrinkage limit* is the minimum moisture content at which the voids of a drying soil are still completely filled with water, or (according to Atterberg) the maximum water content at which a further loss of moisture by evaporation is not associated with a corresponding decrease of the volume of the sample. The water contents, which correspond to these two definitions, are practically identical.

13. The *shrinkage ratio* is the percentage of volume change divided by the percentage of moisture change above the shrinkage limit.

DATA FURNISHED BY THE TERZAGHI TESTS

These tests have been developed by Dr. Charles Terzaghi for determining the purely mechanical properties of the soil which have a direct bearing on the behavior of the subgrade under load (compressibility, expansion, permeability, and elasticity).

14. *Compressibility* is measured by the compression produced by loading a laterally confined, wet soil specimen resting on a porous stone, through which the excess water can freely drain away.

15. The *elastic expansion* (elasticity) of a soil is measured by the swelling of a laterally confined specimen of wet soil, associated with removing a load which previously has acted on the specimen. During the test the water is allowed to soak into the specimen while swelling proceeds.

16. The *permeability* of a soil is computed from the speed with which the excess water drains out of the soil, through a porous stone, under the influence of a constant load.

SIGNIFICANCE OF THE VARIOUS TESTS DISCUSSED

Mechanical analysis.—The results of this test furnish information as to the grain size and uniformity of the material. By changing only one of these two properties of a soil, for instance, the average grain size (by grinding the soil in a ball mill), all of the properties disclosed by other soil tests change. This is particularly conspicuous when the grain size drops below about 0.005 millimeter. The mechanical analysis, if it is carried far enough, and includes separation of the fraction smaller than 0.005 millimeter, discloses important soil properties. Unfortunately such an analysis costs so much in time and labor that it can not be used as a routine test. Besides this, it does not furnish any information on another important soil property, the shape of the grains. At equal grain size and equal uniformity, two soils may

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[2] The Moisture Equivalent of Soils, by Lyman J. Briggs and John W. McLane, U. S. Bureau of Soils Bulletin No. 45, 1907.

The Wilting Coefficient for Different Plants and Its Indirect Determination, by Lyman J. Briggs and H. L. Shantz, U. S. Bureau of Plant Industry Bulletin No. 230, 1912.

Use of Moisture Equivalent for the Indirect Determination of the Hygroscopic Coefficient, by Frederic J. Alway and Jouette C. Russel, Jour. Agr. Research, vol. 6, No. 22, 1916.

Relation of the Mechanical Analysis to the Moisture Equivalent of Soils, by Alfred Smith, Soil Science, vol. 4, 1917.

The Moisture Equivalent in Relation to the Mechanical Analysis of Soils, by Howard E. Middleton, Soil Science, vol. 9, No. 2, 1920.

[3] *Volumetric change* is the name of a definite test result (the volume change resulting from reducing the moisture content from either the capillary or moisture equivalent value to zero) and should not be confused with the term "volume change" used in various parts of the discussion and which refers to no specific moisture content.

[4] *Lineal shrinkage* is the name of a definite test value (the shrinkage resulting from reducing the moisture content from moisture equivalent or field moisture equivalent value to zero) and should not be confused with the term "shrinkage" which concerns no specific moisture content.

be very different, according to the shape of the soil grains.

In the regular laboratory tests of the Bureau of Public Roads, the mechanical analysis merely serves to free the soils from the coarser sand.

Moisture equivalent.—The significance of the moisture equivalent is rather obscure, and the results obtained by the test depend to a considerable extent on the test conditions.

With high silt contents, the moisture equivalent value has been found to depend on the centrifugal force employed. For high clay contents, the test results can be erratic because of puddling of water on the surface of the specimen.

For heavy clays Joseph and Martin [5] found that the moisture equivalent of a normal soil becomes smaller as the weight of the soil taken for the determination increases. With some soils, however, the reverse is true, due to waterlogging. Also, a soil may have a high moisture equivalent without showing waterlogging.

Finally, it has been observed with respect to medium and heavy clays that the moisture equivalent decreases with increasing time of centrifuging at equal centrifugal force and equal sample size.

The effects of the quantity of silt, the speed of centrifuging and the time of centrifuging on the moisture equivalent value have been discussed in detail by several investigators.[6]

Considering these facts, it seems that the moisture equivalent represents a rather complex combination of compression and permeability.

Capillary moisture.—The capillary moisture is merely a measure of the volume of voids of a soil sample prepared under certain arbitrary standard conditions, minus the void space which permanently remains filled with air. Because of the personal equation which enters into preparing the sample, the necessity of repeatedly weighing the sample, and the time required for making the test, the test is not considered a very desirable one.

Volumetric change and shrinkage ratio.—The volumetric change is the change in volume associated with the drying to constant weight of a specimen whose original water content was equal to the capillary moisture or the moisture equivalent. Therefore the *volumetric change at capillary moisture* depends in part on the same factors as the capillary moisture and the *volumetric change at moisture equivalent* depends in part on the same factors as the moisture equivalent. The influence of the other factor (the shrinkage limit) on the volumetric change determinations will be discussed later.

The shrinkage ratio was originally believed to represent a specific property of the soil, independent of other soil constants. It has since been learned that the shrinkage ratio can easily be computed from the volume and the weight of the dry sample only. This will be shown in connection with the discussion of the shrinkage limit.

Dye adsorption.—The result of the dye adsorption test is a measure of the quantity of dye which is adsorbed on the surface of the individual soil particles. Hence the dye adsorption number is a rather complex function of the specific surface of the material, its chemical character and the nature and quantity of electrolytes present in the soil. Since the greatest part of the specific surface of the soil is made up of the surfaces of the finest soil constituents (called the colloidal fraction), the dye adsorption number can be said to depend on the quantity, the chemical character, and the degree of adsorptive saturation of the soil colloids. At present it is not possible to evaluate the relative importance of each of these different factors. For certain highly plastic soils, the time required in making the tests may be several weeks, thus making the testing of such soils prohibitive.

Slaking value.—The slaking value depends on the amount of expansion of the soil sample when brought into contact with water, on the speed with which the water penetrates the interior of the soil, and on the character of the cracking produced by unequal expansion of the sample. The test is not fully satisfactory in its present form, because soils may have equal slaking values and yet slake in different manners. Efforts are being made to remedy this shortcoming of the test. Because of the influence of temperature it should be performed at a constant temperature and a value of 70° F. has been selected.

Field moisture equivalent and lineal shrinkage.—The Rose test (field moisture equivalent) measures the minimum quantity of water at which the soil can still be considered to be completely saturated. The state of saturation is indicated by incapacity of the soil to absorb a drop of water deposited on the smoothed surface of the sample. In comparing this definition with the definition of moisture equivalent it is evident that the two tests, insofar as method is concerned, have practically nothing in common. The test combines the advantage of simplicity with the fact that the results depend but very little on the personal equation.

In practice the Rose test is usually performed in connection with the determination of the lineal shrinkage. The two tests combined furnish an approximate conception of the volume change associated with subsequent wetting and drying.

Atterberg tests.—The Atterberg tests determine the states of consistency through which a soil passes in succession if the water contained in its voids gradually evaporates. These successive states are graphically represented in Figure 1, which shows for a plastic soil that the volume change is directly proportional to the loss of water from the lower liquid to the shrinkage limit, after which no further shrinkage occurs. For friable soils the plastic range is approximately zero.

The liquid limit represents the minimum water content at which a standard number of shocks of standard intensity just begin to transform part of the sample (the lower rim of the two sections of the soil cake) into the liquid state.

The plastic limit represents the lowest moisture content at which the soil can still be molded without cracking. Preliminary investigations at the Arlington laboratory indicate that the plastic limit is approximately equal to the maximum moisture content at which the soil sample still exhibits an appreciable resistance to deformation.[7] This finding is significant

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[5] The Moisture Equivalent of Heavy Soils, by A. F. Joseph and F. J. Martin. The Journal of Agricultural Science, vol. 13, Pt. I, January, 1923.

[6] Simplified Soil Tests for Subgrade Soils and Their Physical Significance, by Dr. Charles Terzaghi, PUBLIC ROADS, vol. 7, No. 8, October, 1926.

The Moisture Equivalent of Soils, by M. D. Thomas and Karl Harris, Soil Science, vol. 21, 1926.

[7] Work by B. H. Levenson, referred to in "Simplified Tests for Subgrade Soils and Their Physical Significance," by Charles Terzaghi, PUBLIC ROADS, vol. 7, No. 8, October, 1926.

in that it demonstrates that the Atterberg method for determining the lower plastic limit is a practical means of differentiating between soils in the plastic and nonplastic states.

The plasticity index is assumed to measure the degree of plasticity of the soil. According to Atterberg the higher the plasticity index the greater is the quantity of sand which must be added to make the soil lose its plasticity.

The shrinkage limit represents the maximum moisture content which the soil can contain without a further loss of water causing a corresponding decrease in volume. It approximately coincides with the water content at which the air starts to penetrate the interior of a drying sample. At this moisture content the color of the sample changes from dark to light.

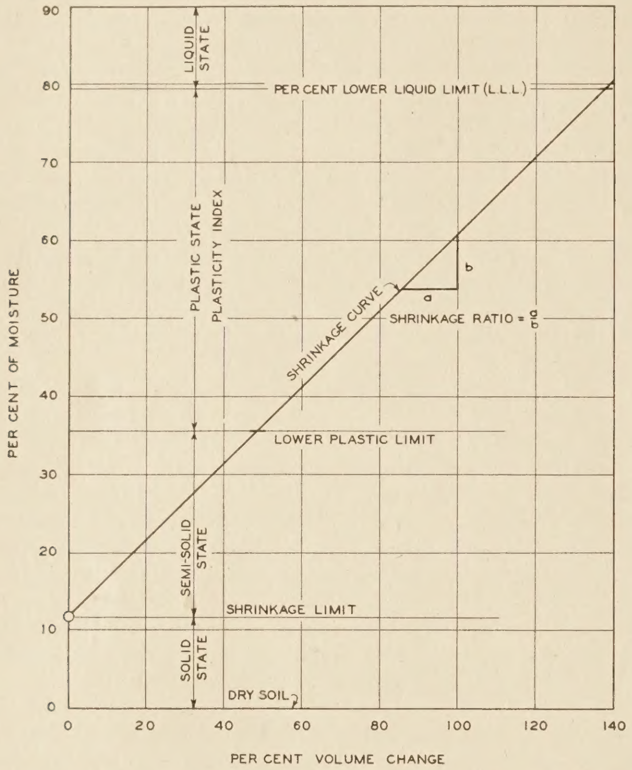

FIG. 1.—A TYPICAL SHRINKAGE CURVE FOR A PLASTIC SOIL

Atterberg determined the shrinkage limit by repeated weighing combined with accurate measurements of the distance between two points on the sample. It has been suggested that these rather tiresome operations can be omitted because the shrinkage limit can be computed from the volume of the original sample and the volumes of the dry sample.[8] Thus, let

V = volume of wet soil sample in cubic centimeters.

V_o = volume of the dry sample in cubic centimeters. This is also the volume at the shrinkage limit.

w = water content of the wet sample expressed as a fraction of the dry weight.

S = water content of the sample at the shrinkage limit, expressed as a fraction of the dry weight.

W = weight of the wet sample in grams.

W_o = weight of the dry sample in grams.

Since the change in volume above the shrinkage limit is due entirely to the loss of water—

$V - V_o$ = the volume of water evaporated in cubic centimeters.

The weight of the water at V equals wW_o and at the shrinkage limit is SW_o; therefore $wW_o - SW_o$ = the weight of water evaporated in grams.

Since the specific gravity of water is 1, the volume in cubic centimeters equals the weight in grams; thus

$$wW_o - SW_o = V - V_o \text{ and}$$

$$S = w - \frac{V - V_o}{W_o} \qquad (1)$$

The shrinkage ratio R or the slope of the shrinkage curve, Figure 1, can be computed from the same data. The slope of this curve is merely the total volume change of the sample expressed as a fraction of the dry volume, divided by the moisture change between w and S. Therefore

$$R = \frac{\dfrac{V - V_0}{V_0}}{w - S}$$

which becomes, by substitution from equation 1,

$$R = \frac{\dfrac{V - V_0}{V_0}}{\dfrac{V - V_0}{W_0}} = \frac{W_0}{V_0} \qquad (2)$$

In like manner, the specific gravity (the weight of the dry soil in grams divided by its true volume in cubic centimeters) can be computed. The true volume of the dry soil equals the apparent volume, V_0 minus the water content at the shrinkage limit, SW_0; therefore

$$\text{Specific gravity} = \frac{W_0}{V_0 - SW_0} = \frac{1}{\dfrac{V_0}{W_0} - S} = \frac{1}{\dfrac{1}{R} - S} \qquad (3)$$

Finally the volume change can be computed for any variation in moisture content w_1 to w_2.

When both w_1 and w_2 are above the shrinkage limit

$$\text{Volume change} = (w_1 - w_2)R$$

When only w_1 is above the shrinkage limit

$$\text{Volume change} = (w_1 - S)R$$

When both w_1 and w_2 are below the shrinkage limit

$$\text{Volume change} = 0$$

The Atterberg tests have the advantage of furnishing at a small expense of time and labor, three constants, each one expressing a different group of soil properties. The lower liquid limit essentially depends on grain size and grain shape. For similarly shaped materials, it increases with decrease of grain size. For materials of equal grain size, the lower liquid limit increases with the increase of scalelike particles.

The lower plastic limit and the plasticity index also depend on the shape and size of the grains. The shrinkage limit depends upon the size of the grains, the shape of the particles, and also upon the uniformity of the soil.

It has been suggested that the plasticity of a soil is related to the silicon, iron and aluminum ratio. Investigators of the Bureau of Soils state that the shrinkage

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[8] Simplified Tests for Subgrade Soils and Their Physical Significance, by Charles Terzaghi, PUBLIC ROADS, vol. 7, No. 8, October, 1926.

of a soil is closely related to both the colloidal content and to the chemical composition of the soil. Hence, the plasticity and shrinkage limits seem to reflect the influence of the size of grain, the shape of grain, the uniformity of the soil, the chemical make-up and the colloidal content by three independent figures.

The tests which have previously been described may be called "simplified tests." Except for the mechanical analysis and dye adsorption these tests merely inform us about the water content of the soil under more or less arbitrary conditions, artificially produced in the laboratory. If the results of these tests have any relationship to the mechanical properties of the subgrade, this relationship is not known and can be learned only from indirect evidence.

Compressibility, elastic expansion and permeability tests.—To facilitate the interpretation of the simplified test results, it seemed advisable to work out some standard test the results of which would furnish direct information as to the mechanical properties of the soil. The Terzaghi tests were introduced for this purpose. Because of the time and labor required for performing these tests, there is no intention of considering them as prospective routine tests. They should be considered merely as a means for obtaining positive information about the relation which exists between the results of the different simplified tests and the purely mechanical properties of the subgrade. When this purpose is accomplished the Terzaghi tests will become unnecessary.

INTERRELATIONSHIP OF THE RESULTS OF DIFFERENT TESTS

There has been presented in the preceding section descriptions of a number of different simplified tests, furnishing not less than 13 different soil constants. To determine whether any relationship exists between these constants, two correlations have been made. The first concerned the interrelationship of the various simplified tests, and the second was intended to determine the influence of the clay, silt, and sand fractions on the various simplified tests.

The interrelationship of the results obtained from a number of tests is shown in Figures 2, 3, and 4. According to these figures, no strictly exact relation exists between the results of any two simplified tests as far as the results of tests performed on individual soils are concerned. Yet for certain sets of tests—for instance, moisture equivalent and lower liquid limit (fig. 3), or field and centrifuge moisture equivalent (fig. 4)—some broad relationships seem to exist. For other pairs, as for instance, slaking value and lower liquid limit, even such a broad relationship is conspicuously absent. These broad relationships could be called "statistical laws." In Figure 2, these statistical laws are represented by curves passing close to those points which represent the averages of the individual tests. The individual test results are omitted and the variation of the data for the individual soils is represented by the length of the heavy horizontal lines. These diagrams show that a statistical relation exists between the moisture equivalent, the capillary moisture, the volumetric change at capillary moisture, and the dye adsorption tests.

Figures 3 and 4 show the results of individual tests of both friable and plastic soils from all parts of the United States. These diagrams show the following:

1. For both plastic and nonplastic soils, statistical relations exist between the moisture equivalent and the lower liquid limit (fig. 3–A), the centrifuge and field moisture equivalents (fig. 4–A), and between the lower liquid limit and the field moisture equivalent (fig. 4–C).

2. For plastic soils statistical relations exist between the moisture equivalent and the plasticity index (fig. 3–B), the moisture equivalent and the lower plastic limit (fig. 3–C), the moisture equivalent and the volumetric change at moisture equivalent (fig. 3–E), the lower liquid limit and the plasticity index (fig. 3–F), the lower liquid limit and the lower plastic limit (fig. 3–G), the field moisture equivalent and the lower plastic limit (fig. 4–D), and the field moisture equivalent and the plasticity index (fig. 4–F).

From the discussion of the factors which influence the shrinkage of a soil from any arbitrary moisture content to zero, it becomes evident that the relations between capillary moisture and volumetric change at capillary moisture, and between field moisture equivalent and lineal shrinkage at field moisture equivalent, are similar in character to those existing between the moisture equivalent and volumetric change at moisture equivalent. Figure 3–E shows that some nonplastic soils follow the relation between moisture equivalent and volumetric change at moisture equivalent which is general for plastic soils, but the great majority do not follow it, having but little volumetric change. Out of 100 nonplastic soils tested, 98 had a volumetric change (at moisture equivalent) of 16 or less. Of this number 57 were zero. From this it may be concluded that, in general, the relation between certain arbitrary moisture contents and volumetric changes at those moisture contents which applies to plastic soils does not necessarily apply to nonplastic soils, and the fact that the volumetric change of all nonplastic soils is so nearly the same makes this test, by itself, of no practical significance with respect to soils of that class.

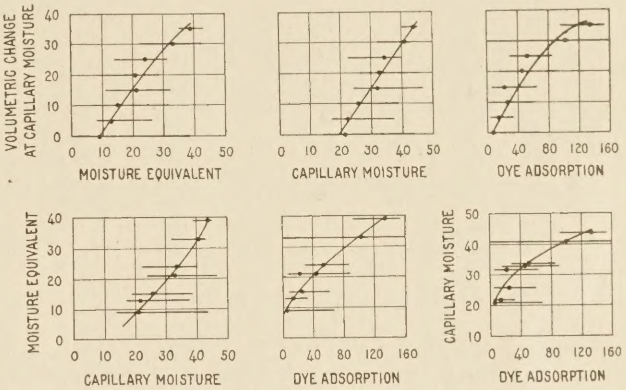

Fig. 2.—Diagram Showing Interrelation Between Various Tests. Each Point Plotted is the Average of Several Tests Results, the Range of Such Results Being Shown by the Horizontal Line Through the Point

3. For both plastic and nonplastic soils no statistical relation exists between the slaking value and the lower liquid limit (fig. 3–I), the plasticity index (fig. 3–J), the lower plastic limit (fig. 3–K), and the shrinkage limit (fig. 3–L). Also the average shrinkage limit values change but little with variation in average values for moisture equivalent (fig. 3–D), lower liquid limit (fig. 3–H), plasticity index (fig. 3–N), volumetric change at moisture equivalent (fig. 3–M), and field moisture equivalent (fig. 4–E).

4. For values less than 30 the field moisture equivalent is a rough approximation of the centrifuge mois-

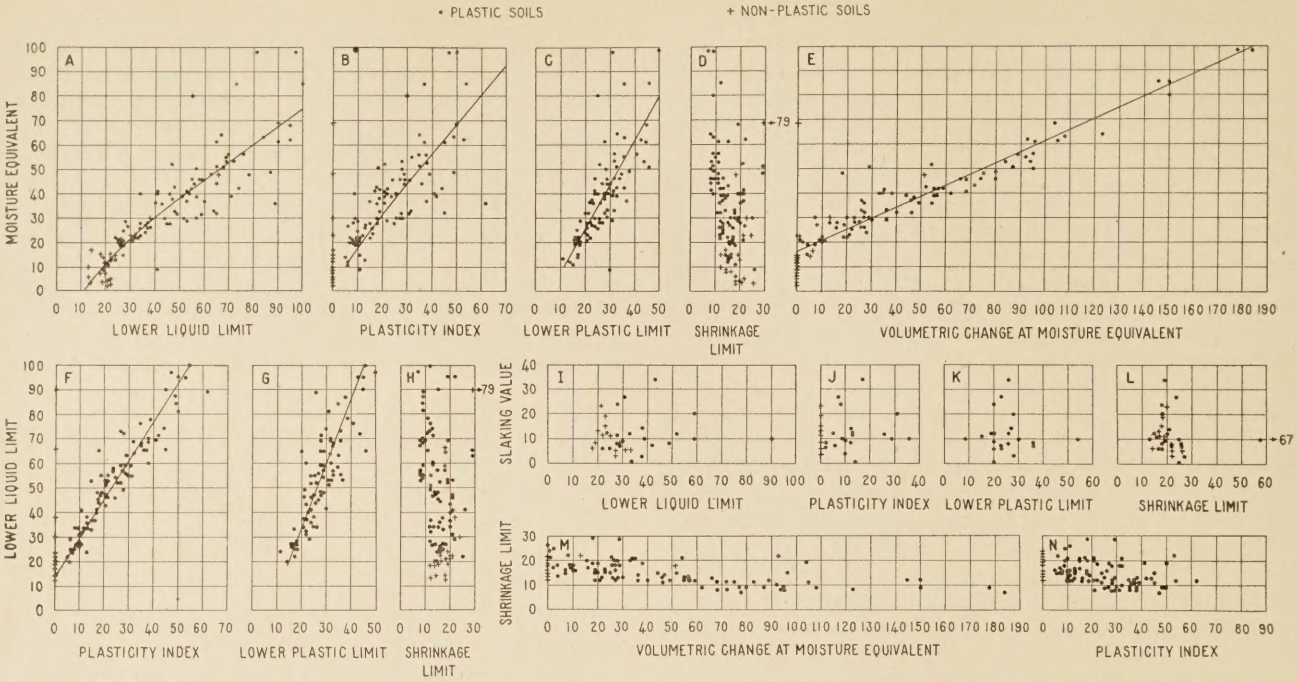

FIG. 3.—DIAGRAMS SHOWING INTERRELATION OR ABSENCE OF INTERRELATION BETWEEN VARIOUS TESTS

ture equivalent (fig. 4–A) and for values below 70 the values obtained from centrifuging a 5-gram sample are in substantial agreement with those obtained by centrifuging a 30-gram sample (fig. 4–B). Beyond this point little reliance can be placed on the results. For this reason the points representing moisture equivalent values higher than 70 were discarded when the average value curves were drawn in Figures 3 and 4.

Based on the foregoing, the simplified soil tests may be arranged in three groups as follows:

Group I.—Tests related for both plastic and non-plastic soils.

- Lower liquid limit.
- Moisture equivalent.
- Field moisture equivalent.
- Capillary moisture.
- Dye adsorption.

Group II.—Tests related to those of Group I for plastic soils primarily.

- Lower plastic limit.
- Plasticity index.
- Volumetric change at moisture equivalent.
- Volumetric change at capillary moisture.
- Lineal shrinkage at field moisture equivalent.

Group III.—Tests related neither to those of the foregoing groups nor to each other.

- Shrinkage limit.
- Slaking value.

In spite of the general relationship which exists between the different members of Groups I and II, the individual variations throughout are large enough to make it impossible to express the corresponding properties with a sufficient degree of accuracy by a single constant. This is even more evident from the results of the second set of tests (synthetic mixtures) given in Table I. It can be seen that no definite relation exists between either the shrinkage limit or the lower plastic limit and the clay, silt, or sand fractions. In general, however, the moisture equivalent, the volumetric change at moisture equivalent, the lower liquid limit and the plasticity index values all increase with increase of clay content. Further information on these relations is given in Figure 5, which shows graphically the results of Table I.

A comparison of the upper and lower rows of diagrams in this figure shows that the relation between both the moisture equivalent and the volumetric change values and the sand fraction is less variable than the relation between these two values and the clay fraction. The relation between the lower liquid limit and the clay fraction seems to be slightly less variable than the relation between this value and the sand fraction and the plasticity index (for plastic soils) seems to be definitely related to the clay content.

Figure 6 shows how both the silt and clay fractions affect the test values. Each curve shows the results of tests in which the clay content was kept practically constant and the silt content varied. The distance between the curves is a measure of the effect of the increase in clay content and the angle which the lines

TABLE I.—*Influence of clay, silt, and sand fractions on simplified test values*

Clay	Silt	Sand	Moisture equivalent	Volumetric change	Lower liquid limit	Lower plastic limit	Plasticity index	Shrinkage limit
Per cent	*Per cent*	*Per cent*	*Per cent*	*Per cent*	*Per cent*	*Per cent*	*Per cent*	*Per cent*
0	20	80	9	0	18	18	0	15
0	50	50	18	0	23	23	0	19
7	7	86	9	0	18	18	0	15
10	25	65	15	2	19	19	0	13
9	71	20	26	14	28	28	0	18
14	43	43	28	23	24	19	5	16
20	0	80	13	0	23	23	0	16
20	30	50	23	15	27	17	10	14
20	50	30	26	17	30	20	10	17
20	80	0	37	28	37	23	14	20
24	12	64	18	3	26	17	9	15
26	37	37	29	24	33	20	13	16
24	52	24	29	21	33	21	12	17
24	64	12	39	40	38	25	13	17
35	5	60	21	10	32	19	13	16
37	26	37	30	24	38	22	16	16
35	60	5	41	39	42	26	16	19
50	0	50	28	20	42	22	20	17
52	24	24	35	30	45	26	19	18

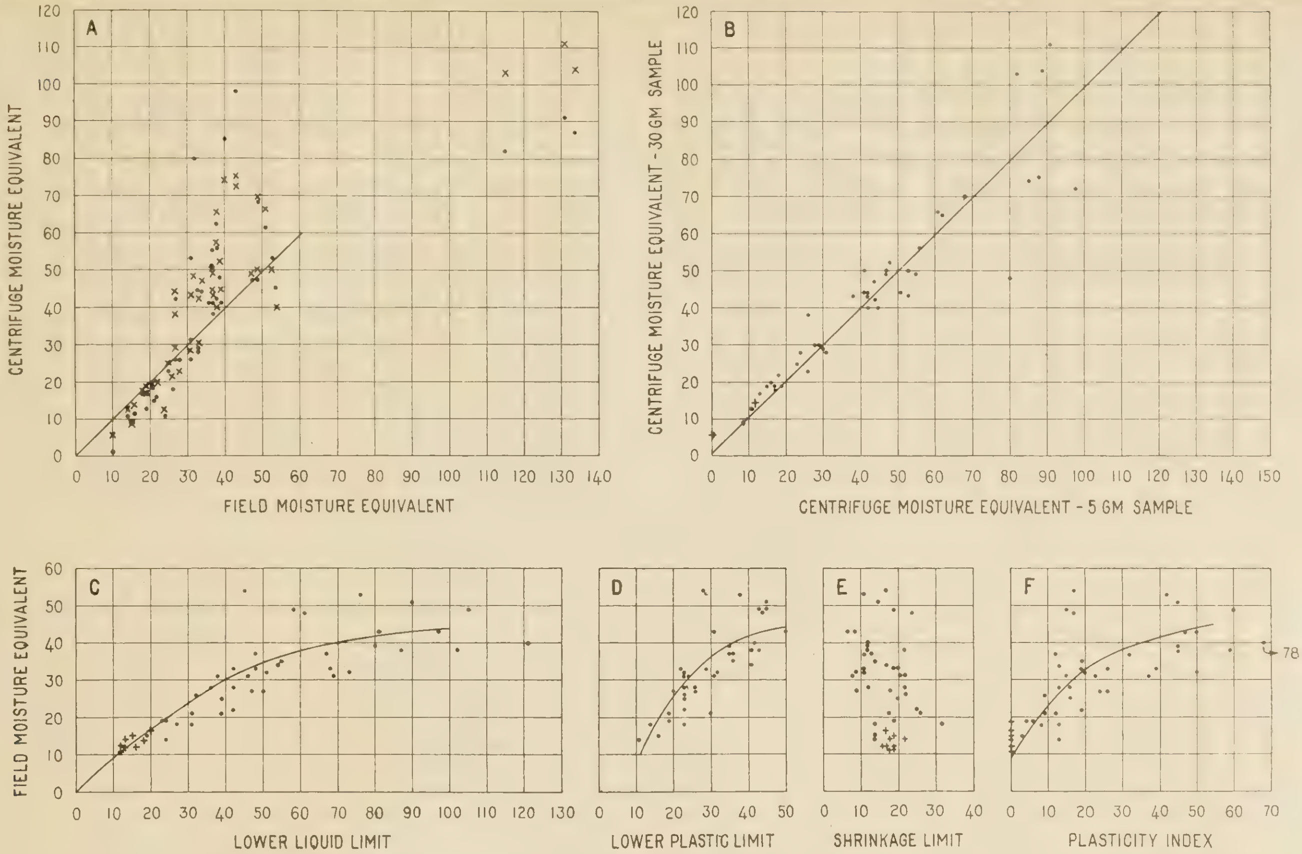

Fig. 4.—Diagrams Showing Interrelation or Absence of Interrelation Between Various Tests

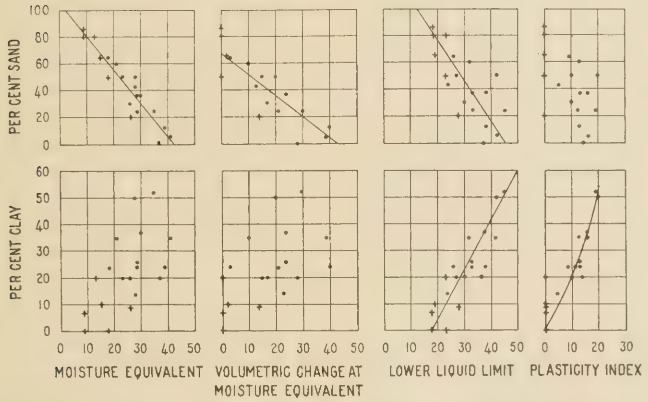

Fig. 5.—Graphical Representation of Interrelation of Test Data Shown in Table 1

make with the vertical is a measure of the silt influence. If this angle is zero the silt has no influence; if it is 45°, the test values (clay content constant) increase 1 per cent with each increase in silt of 1 per cent. This figure shows that the moisture equivalent and the volumetric change at moisture equivalent values are influenced by both the clay and silt contents (grains less than 0.05 millimeter); the lower liquid limit is influenced to some extent by silt (grains 0.05 to 0.005 millimeter), but primarily by clay (grains less than 0.005 millimeter); the lower plastic limit (for plastic soils) is influenced by silt to about the same extent as the lower liquid limit, but the influence of clay is somewhat less than for the lower liquid limit; the plasticity index is influenced primarily by clay; and the shrinkage limit is not appreciably influenced by either the clay or the silt fractions.

Thus it seems that the moisture equivalent, the volumetric change at moisture equivalent, the lower liquid limit and the plasticity index reflect the influence of grain size and uniformity as disclosed by the mechanical analysis determination. It is possible that the lower plastic and shrinkage limits are influenced by very small particles not separated in the mechanical analysis determination or that they may be influenced primarily by grain shape.

SIMPLIFIED TESTS FOR LABORATORY PROCEDURE SELECTED

In practice, the tests to be made on a soil sample must be limited to a reasonable number. The problem is to select from the different possible soil tests those which furnish a maximum amount of information at a minimum of time and labor. To secure a maximum amount of information, every test should be independent of any other test, that is, each test should determine a different soil property. It is desirable that the tests should not be influenced by the personal equation, should be simply and quickly performed, and should not be limited in scope to any particular types of soils.

In the foregoing discussion it has been shown that the tests can be arranged in three groups, depending on their interrelationship with each other. Following the criterion laid down above, it seems logical that the simplified test procedure should include at least one test from each of the related groups and all of the tests of the nonrelated group.

In Group I the capillary-moisture test is undesirable because of the time required to make the test; it is not practical for certain heavy clays, and is influenced to some extent by the personal equation. There is no evidence that it adds to the information derived from tests not having these disadvantages. The dye-adsorption test is impractical for heavy soils and the moisture equivalent test is complex in meaning and is erratic for heavy soils. The field-moisture equivalent test is simple to perform and within the range originally proposed for this test is satisfactory. However, except for a few particular soils, the results from this test fail to increase proportionately with those of related tests when test values are greater than about 30. The one remaining test of this group is the lower liquid limit. It can be performed quickly and easily and is practical for all types of soils. Consequently this test was selected from Group I.

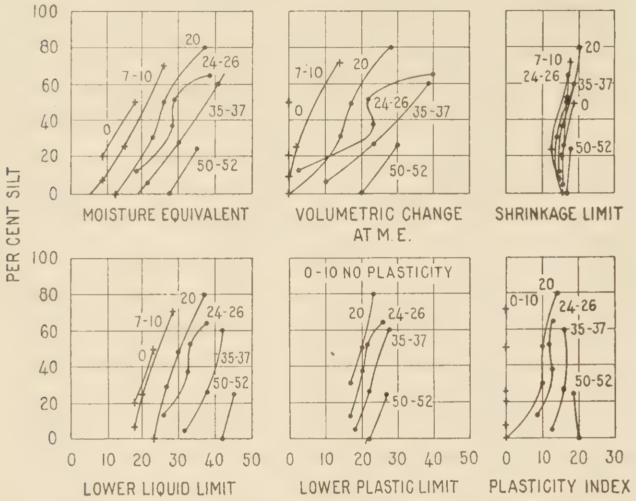

FIG. 6.—EACH CURVE SHOWS THE RESULTS OF TESTS IN WHICH THE CLAY CONTENT WAS APPROXIMATELY CONSTANT (AMOUNT SHOWN ON EACH CURVE) AND THE SILT CONTENT VARIED

It will be noted that excluding the dye adsorption test, the tests in Group II can be paired off with corresponding tests of Group I as follows:

(*a*) Lower liquid limit and lower plastic limit (including the plasticity index).

(*b*) Capillary moisture and volumetric change at capillary moisture.

(*c*) Moisture equivalent and volumetric change at moisture equivalent.

(*d*) Field moisture equivalent and lineal shrinkage at field moisture equivalent.

Considering the tests of Group II it is logical to make a selection corresponding to the selection from Group I. Consequently the lower plastic limit and the plasticity index were chosen from Group II. The lower plastic limit is quickly and easily determined and is practical for all plastic soils. The plasticity index is obtained by a simple computation from the liquid limit and plastic limit values.

The volumetric change from capillary moisture and moisture equivalent and the lineal shrinkage from moisture equivalent are undesirable for several reasons. In the first place, the volume change from any moisture content can be quickly computed from the shrinkage limit and shrinkage ratio values. This applies also to the lineal shrinkage because this value bears a simple arithmetical relation to the volume change in a soil. A zero volumetric change (at moisture equivalent) or a zero lineal shrinkage simply means that the moisture equivalent (or field moisture equivalent) is below the shrinkage limit. In the second place, the shrinkage from any arbitrary moisture content has significance only if this moisture content represents the maximum moisture content which occurs in the subgrade in the field and if the shrinkage of the prepared laboratory sample is the same as that of the undisturbed soil in the field. There is no evidence to warrant these assumptions.

In some instances a lineal shrinkage value of 5 has been used as the dividing line between good and bad subgrade soils. This value is equivalent to a volumetric change at moisture equivalent of about 18. It has previously been shown that with few exceptions all nonplastic soils lie below this value. Therefore it is possible that considerable work could be avoided if, first, the rolling method (lower plastic limit) were used to determine whether or not the soil is plastic and, second, only the plastic soils were tested for shrinkage.

Since all of the tests of the unrelated group (Group III) should be included, the shrinkage limit and slaking value tests are added to those selected from Groups I and II. The shrinkage ratio is determined by a simple computation and is therefore included. The reports on soil tests by the bureau therefore consist of a record of the following:

1. Mechanical analysis: Percentage of sample retained on the 2-millimeter sieve, percentage of sample passing the 2-millimeter and retained on the 0.5-millimeter sieve, and the percentage of the sample passing the 0.5-millimeter sieve.
2. Lower liquid limit.
3. Lower plastic limit.
4. Plasticity index.
5. Shrinkage limit.
6. Shrinkage ratio.
7. Slaking value (70° F.).

The dye adsorption test and the field moisture equivalent are being further investigated. The hydrometer method for determining the percentage of the smaller sized soil particles held in suspension is also being investigated.[9]

CONCLUSIONS

1. The tests which have been proposed for investigating the physical properties of raw material of the subgrade are the simplified and the final soil tests.

The simplified tests can be performed with very simple devices and within a very short time. They do not, however, disclose information as to the mechanical properties of soils.

The final soil tests furnish soil constants, having a simple and direct bearing on the mechanical properties of soils. Their disadvantage is that a great amount of time and labor is required in obtaining the desired results.

The advantages of both groups of tests can be utilized by performing the final tests on only a limited number of individual soils which are representative of various groups of soils which have been submitted to the simple tests.

2. Results of certain tests are found to be connected with each other by fairly well defined statistical laws or by laws applicable to the average results obtained by testing a great number of different soils. The results of other tests do not seem to be connected by any law.

Depending on the extent of the interrelationship of their results, the simplified soil tests may be arranged in three groups, as follows:

I. Tests statistically related for both friable and plastic soils.

II. Tests statistically related to those of Group I for plastic soils primarily.

III. Tests statistically related neither to members of the other groups nor to each other.

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[9] The Hydrometer Method as a New and Rapid Method for Determining the Colloidal Content of Soils, by G. J. Bouyoucos, Soil Science, vol. 23, No. 4, pp. 319–330.

(Continued on page 24)

POWER-SHOVEL OPERATION IN HIGHWAY GRADING

A REPORT OF OBSERVATIONS MADE ON GOING PROJECTS BY THE DIVISION OF MANAGEMENT, BUREAU OF PUBLIC ROADS

Reported by **T. WARREN ALLEN**, Chief, Division of Management, and **ANDREW P. ANDERSON**, Associate Highway Engineer

Part 2.—HAULING WITH TEAMS AND WAGONS

HIGHWAY construction organizations are generally composed of a number of interdependent units from which full production can be secured only when the capacity of each of the subordinate organization units is at least equal to the capacity of the primary producer and properly synchronized with it. A power-shovel grading outfit as commonly operated on highway work is such an organization. It is obvious that no matter what capacity the shovel may have, its output, except when casting, can never exceed the capacity of the hauling units which are moving the excavated material. To secure a high rate of production at the shovel it is imperative that the hauling equipment handle this production at an equally high rate. If the distance over which the material is hauled were constant, the number of hauling units of any given kind required to handle the output could be determined readily. After these had been supplied the problem would be narrowed down to the correct management of the equipment and the use of correct methods.

TEAMS AND WAGONS are to-day the cheapest means of transporting the output of the power shovel to the dump where the haul does not exceed 500 or 600 feet and there is room for efficient handling, but it would be a mistake to state that this will continue to be the case.

Motorized equipment is rapidly being developed to higher efficiency and it is believed that the time is not far distant when its performance in terms of volume, speed, and cost will give it precedence over teams and wagons. Development has already reached a point where this is true under some working conditions.

In practice no such fortunate conditions exist. The hauling distance frequently varies greatly from day to day and sometimes from hour to hour. It is seldom practical to supply the hauling equipment needed to maintain full production on all lengths of haul because of the capital and carrying charges involved.

TIME OF LOADING, DUMPING, ETC., STUDIED

There are a number of distinct types of hauling equipment—(*a*) horses or mules and wagons, (*b*) trucks, (*c*) crawler-type tractors with trailers, and (*d*) the industrial railway. Speaking in general terms, teams and wagons are still the type most widely used on highway grading work. Crawler tractors with large trailer wagons are relatively new in this field, but appear to have great possibilities. Trucks are widely used, and where the hauling surface is or can be maintained in uniformly good condition generally prove quite satisfactory. The industrial railway is not so common on highway work. It is efficient where the grades are light, the haul long and the quantities large—conditions often found in railroad work but not so often in highway work.

In power-shovel work the ideal balance between the shovel and the hauling equipment is had when the hauling equipment is of just such capacity and number that it can just keep the shovel in continuous operation at its proper rate of production. But, in practice, as the hauling distance changes, the amount of hauling equipment must also be changed if this balance is to be maintained.

The operations of the hauling equipment consist of getting into position to receive the load, receiving it, taking it to the dump, dumping, turning at the dump, and returning to the shovel for another load. The time consumed for each load moved, excepting the time of haul to the dump and the return for another load, is fairly uniform for a given type of equipment and set of operating conditions and is called the "time constant." Table 1 shows the time taken in these operations on a number of projects on which two-horse wagons of different capacities were used. The average time found on these jobs for the different operations varies considerably. This is to be expected. For example, the loading time will vary with the number of dippers required to the load, the kind of material handled, the skill of the shovel operator, and all the numerous factors which affect the time of the shovel cycle.

Too many contractors do not seem to realize the importance of saving seconds on these repetitive operations. For the first job shown in Table 1 the time constant—that is, the average sum of the repetitive operations—is 110.5 seconds, while for the next job it is only 77.5 seconds, a difference of 33 seconds, or more than one-half minute per load due to a difference in the efficiency of dump handling. With a shovel operating at 70 loads per hour this represents the equivalent of one team for more than six hours per 10-hour day. Incidentally, these tables indicate the advisability of using 1½-yard wagons instead of 1¼-yard, and also that 2-yard wagons are still better. Table 2 shows the manner in which the data were recorded in the field studies.

Table 1 shows quite clearly the time necessarily taken up in loading, dumping, turning around on the dump and getting under the shovel, and how the time may be extended by miscellaneous delays. On some poorly managed jobs these delays may reach as much as two or three minutes per load hauled. The extension of the time constant by two minutes is as effective in reducing output as a 240-foot extension in the average haul. Much of this delay can be eliminated by careful supervision of the operation of the wagons, by keeping the traveled way in good condition, and, particularly by giving attention to conditions at the shovel and on the

TABLE 1.—*Stop-watch readings on operation in hauling with two-horse bottom-dump wagons on different jobs*

1¼-YARD WAGONS

[Time constant—110.5 seconds]

Loading	Waits or delays at dump	Dumping load	Turning at dump	Turn and maneuver at shovel
Seconds	*Seconds*	*Seconds*	*Seconds*	*Seconds*
11	156	15	21	15
10	201	6	17	12
9	53	3	15	21
43	----------	4	14	19
29	----------	8	18	17
19	----------	5	15	21
17	122	24	15	17
118	17	11	18	16
51	84	9	17	16
39	30	9	12	22
43	31	8	32	9
80	----------	7	17	13
19	----------	6	20	8
18	39	6	19	15
37	188	5	15	13
46	271	18	17	10
13	12	5	11	13
7	----------	3	12	12
42	15	11	23	17
21	43	20	16	18
29	----------	2	13	15
12	----------	6	14	15
17	----------	7	10	18
13	----------	6	11	17
8	----------	4	11	10
10	22	3	13	11
34	42	5	9	10
14	21	5	19	8
18	----------	5	14	12
95	----------	7	11	15
36	----------	8	16	12
41	----------	6	15	10
58	----------	6	17	15
Av. 32.0	40.8	7.7	15.7	14.3

1½-YARD WAGONS—TWO DIPPERS TO THE LOAD

[Time constant—77.5 seconds]

27	----------	3	17	9
29	----------	5	12	11
32	17	8	12	10
42	----------	5	10	13
35	----------	4	17	17
50	----------	5	12	15
46	29	4	13	12
37	----------	8	9	30
36	----------	6	13	22
42	----------	8	8	17
30	----------	3	5	15
43	----------	4	8	28
34	----------	4	7	19
31	----------	5	10	21
36	----------	3	6	19
42	----------	3	5	16
42	----------	5	7	16
43	78	5	12	16
37	----------	4	15	19
54	----------	4	12	17
38	----------	7	24	20
Av. 38.4	5.9	4.9	11.1	17.2

1½-YARD WAGONS

[Time constant—78.1 seconds]

31	----------	5	14	----------
33	25	6	18	----------
47	----------	12	23	----------
42	25	15	39	----------
31	18	10	28	----------
33	17	4	8	13
26	15	10	14	10
25	----------	7	11	15
27	24	7	15	12
30	----------	6	10	9
34	10	7	14	12
27	----------	7	12	10
25	----------	6	13	13
42	----------	6	14	12
Av. 32.4	9.6	7.7	16.6	11.8

dump. "Bottle necks," a careless clean-up around the shovel, restricted working area on the dump, etc., all adversely affect the output of the hauling equipment.

TABLE 1.—*Stop-watch readings on operation in hauling with two-horse bottom-dump wagons on different jobs*—Continued

1½-YARD WAGONS

[Time constant—85.0 seconds]

Loading	Waits or delays at dump	Dumping load	Turning at dump	Turn and maneuver at shovel
Seconds	*Seconds*	*Seconds*	*Seconds*	*Seconds*
43	----------	8	16	32
40	----------	7	10	19
36	----------	9	16	24
39	----------	7	18	40
48	----------	7	14	10
32	----------	7	18	11
43	----------	6	14	----------
42	----------	7	14	----------
41	----------	7	14	----------
50	----------	5	13	----------
38	----------	6	14	----------
45	----------	4	9	----------
46	----------	7	11	----------
Av. 41.8	----------	6.7	13.9	22.6

2-YARD WAGONS—THREE DIPPERS TO THE LOAD

[Time constant—86.0 seconds]

51	----------	9	5	([1])
66	----------	13	6	----------
85	----------	12	6	----------
73	----------	10	5	----------
48	----------	8	5	----------
58	----------	12	7	----------
71	----------	22	7	----------
60	7	13	8	----------
72	----------	19	7	----------
67	----------	15	8	----------
69	----------	7	6	----------
78	----------	11	6	----------
Av. 66.5	0.6	12.6	6.3	----------

[1] Turn at shovel included as part of time of return because of arrangement of return route.

TABLE 2.—*Form used in recording time of operations in hauling with teams*

[Date: March 19, 1926, a. m. Place: Milford, Pa. Weather: Clear, cool. Condition of road: Haul very muddy and rough; return good; through woods, dry. Shovel: —— Size: ¾-yard. Traction: Crawler tractor. Condition: Good. Kind and number of wagons: 7. Capacity: 1.5 cubic yards. Condition: Fair. Depth of cut: 6 feet. Material: Stiff clay]

Truck or wagon No.	Number of dippers	Loading	Going to dump	Waiting at dump	Dumping	Turning	Returning from dump	Turning	Waiting at shovel	Getting spotted	Round-trip time	Haul	Return
		Sec.	*Sec.*	*Sec.*	*Sec.*	*Sec.*	*Sec.*	*Sec.*	*Sec.*	*Sec.*	*Sec.*	*Ft.*	*Ft.*
3	2	30	88	----	3	5	149	15	104	17	411	325	650
1	2	43	103	----	4	8	157	28	97	11	451	325	650
2	2	34	93	----	4	7	170	19	87	13	427	325	650
4	2	31	89	----	5	10	177	19	125	11	467	350	650
5	2	36	102	----	3	6	192	21	42	17	419	350	650
6	2	42	99	----	3	5	196	16	188	15	564	350	650
7	2	42	102	----	5	7	180	16	-----	11	363	350	650
Average	2	37	97	----	4	7	174	19	92	14	443	350	650

PROFITS AFFECTED BY SIZE OF LOAD

Another matter deserving attention is the load hauled per wagon. While there is a good deal of variation in the average yardage taken out per dipper load by a ¾-yard shovel—this variation being in some measure caused by difference in operating skill, but to a much greater degree by the characteristics of the material—the ordinary net output per shovel appears to average about 0.50 cubic yard, or slightly less for ordinary common excavation as measured in place. Where two dipper loads are dumped in a wagon the average load will then be not far from 1 cubic yard. Under ordinary hauling conditions this is rather a light load for two good horses or mules, and especially so on short-haul work where the grades are light. On elevating grader work the two-horse wagon (1¼ cubic yards net size) is, as a matter of general practice, heaped full and when so loaded will carry about 1.3 cubic yards as measured in place. Loads as heavy as this require that more attention be given the roadway than ordinarily is the case, particularly in the East.

A comparison of the yardage moved per load where elevating graders are used and where shovels are used can not but leave the impression that the practice of putting two dipper loads onto each wagon without regard to whether the dipper is full or not is bad. Where there is a surplus of wagons at the shovel, not much harm is done providing wagons can be exchanged within the time required for filling the dipper. But when the haul is long and the wagon supply short, a very different condition prevails. The shovel is then idle a part of the time, so that a little extra effort spent in filling a wagon represents no loss. On the other hand, it takes as long to haul a half-loaded wagon to the dump as it does to haul one that is fully loaded. On long-haul work there is much to be gained by hauling full loads. The shovel runner should be charged with the responsibility of seeing that the wagons leave the shovel fully loaded, even if it is necessary to put on three or, in occasional instances, four dipper loads of material. The possibility of using the larger 1½ or 2 cubic-yard three-horse wagons deserves consideration.

Typical Operation with Team Hauling

In selecting hauling equipment care should be taken to see that the units can be so handled that no single operation such as turning, dumping or maneuvering will necessarily consume more time than is required for loading. Otherwise, this operation and not the shovel becomes the pacemaker. For ordinary highway grading work where fast shovel operation is so frequently possible, a hauling unit having a unit capacity of less than two dippers per load should never be considered. For ease in maintaining fast shovel operation, hauling units carrying three or more dippers per load are very desirable providing, of course, that they are otherwise adapted to the job.

SPEED OF TEAMS FOUND TO BE FAIRLY CONSTANT

Figures 1 and 2 show the average performance of teams and wagons on actual projects for both good and slow wagon operations. The rate at which a good team of horses or mules travels is about 240 feet per minute and is surprisingly constant from day to day and from job to job. Even difficult hauling conditions—that is, mud, rough roads, ordinary grades, etc.—although they may affect the rate of travel, do so less than might be supposed. It is true that some teams walk faster than the average and that a few tend to walk more slowly. Job conditions are such, however, that stock which tends to be fast gradually acquires the working pace of the average. Slow stock does not change its gait easily, and in bad cases ought to be sold and replaced by normally gaited animals. Table 3 shows the hauling speed actually attained on five different projects under

Light Loads and Increased Hauling Time Caused by Stumps and Soft Ground

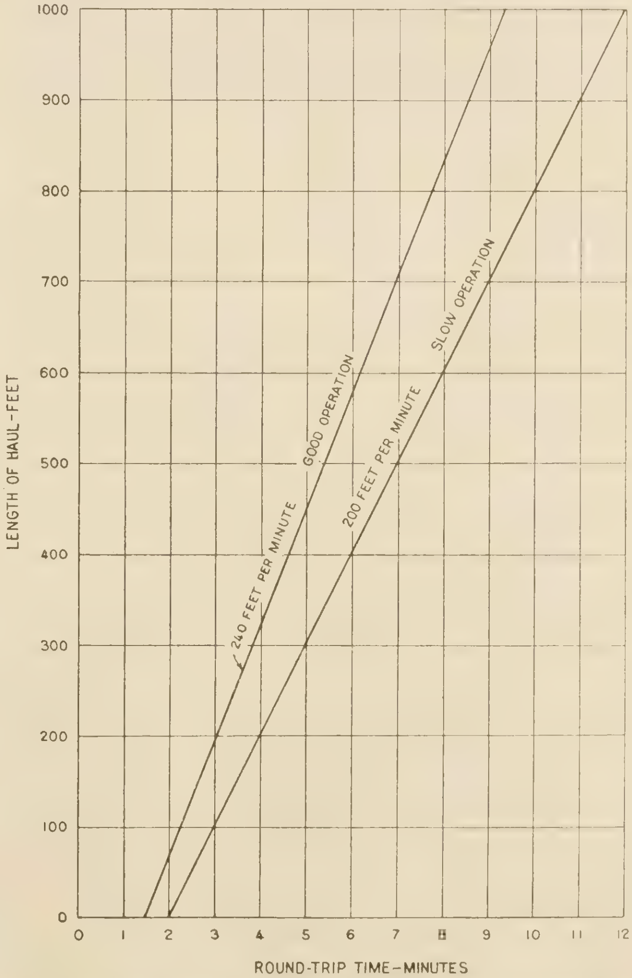

Fig. 1.—Round-Trip Time for Team Hauling with Good and Slow Operation. Time Constant Taken as One and One-Half Minutes with Good Operation and Two Minutes with Slow Operation

Table 3.—*Hauling time and speed of two-horse bottom-dump wagons exclusive of time of loading, dumping, turning, and delays. Data secured on five different jobs*

Length of haul	Hauling time		Round-trip travel time	Round-trip speed
	Loaded	Return		
Feet	*Seconds*	*Seconds*	*Seconds*	*Feet per minute*
		1½-YARD WAGONS		
550	140	138	278	237
600	149	143	292	246
500	124	126	250	240
350	87	81	168	250
350	77	75	152	274
350	82	82	164	256
500	111	105	216	277
200	58	45	103	232
300	77	71	148	243
300	70	64	134	268
200	55	50	105	228
500	130	132	262	229
500	124	132	256	234
5, 200	1, 284	1, 244	2, 528	Av. 247
		1¼-YARD WAGONS		
1, 590	363	353	716	266
1, 500	358	404	762	236
250	77	67	144	208
225	77	58	135	200
220	55	51	106	250
175	66	46	112	190
300	89	79	168	215
500	104	108	212	280
520	115	116	231	270
300	102	86	188	190
850	205	220	425	240
825	227	222	449	210
200	66	58	124	195
250	80	74	154	195
200	73	62	135	175
200	69	60	129	185
175	66	61	127	175
8, 455	2, 250	2, 185	4, 435	Av. 229
		1½-YARD WAGONS		
125	34	32	66	227
150	41	42	83	217
150	34	39	73	246
125	36	35	71	211
150	44	44	88	205
150	35	42	77	234
125	33	32	65	230
150	33	42	75	240
150	36	43	79	228
1, 275	326	351	677	Av. 227
		2-YARD WAGONS		
150	40	38	78	231
150	39	38	77	234
150	40	41	81	223
150	41	40	81	223
150	45	36	81	223
150	42	38	80	225
275	78	76	154	218
325	95	94	189	207
250	68	74	142	211
250	65	67	132	238
225	68	62	125	216
400	96	89	185	259
2, 625	712	693	1, 405	Av. 225
		1½-YARD WAGONS		
400	114	126	240	200
400	116	117	233	205
525	130	118	248	254
525	135	138	273	231
325	95	94	189	207
325	97	96	193	202
325	101	108	209	187
350	110	111	221	190
350	107	106	213	197
250	78	84	162	185
250	70	74	144	208
250	69	87	156	193
325	88	75	163	239
325	103	80	183	213
325	93	85	178	219
50	15	19	34	176
50	16	19	35	171
50	19	20	39	154
5, 340	1, 556	1, 557	3, 113	Av. 207

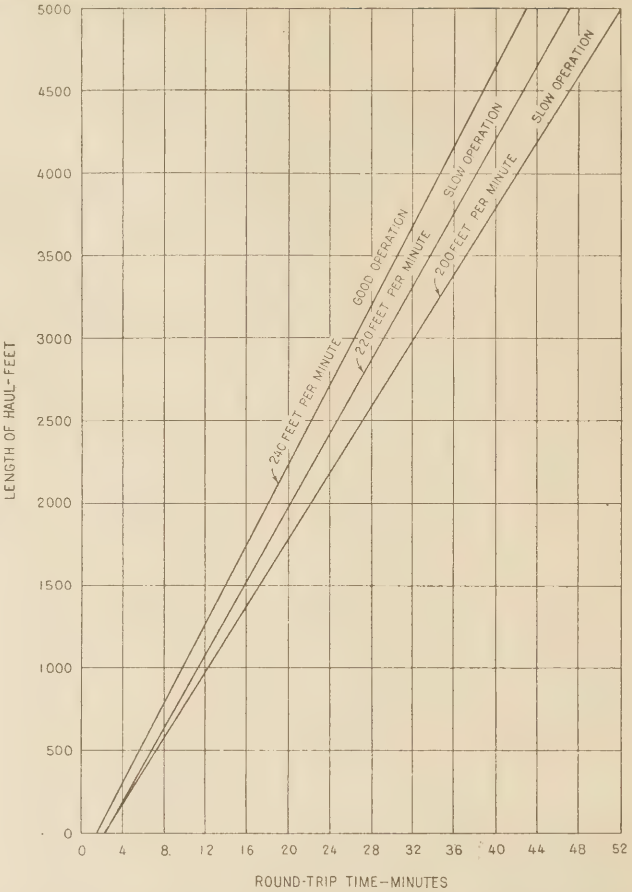

Fig. 2.—Round-Trip Time for Team Hauling with Good and Slow Operation. Time Constant Taken as One and One-Half Minutes with Good Operation and Two Minutes with Slow Operation

various operating conditions and grades of management. It will be noted that the average speed tends to be higher on the long hauls than on the short ones. The highest average speed on any job is 247 feet per minute, while the lowest is 207 feet per minute on a poorly managed job with a short haul over a bad surface.

The fact that good stock tends to maintain a uniform working speed is not a sufficient guarantee that a normal working speed is always maintained. Stock which has been handled by bad drivers and indifferently cared for or worked under lax job management, sometimes develops a working pace that is well below standard. Such stock should be placed in the hands of good drivers and speeded up to normal.

Driving at a speed above normal is sometimes found. If road conditions are good the stock usually will stand a pace that is a little above normal, particularly in returning light from the dump. There should not be much speeding up unless the country is fairly level. Increasing the pace up grades of any consequence is hard on stock, and even though the gain in output may exceed the loss in the value of the stock, gains obtained by damaging stock can not be recommended. Tables 4 and 5 show the results of determinations of hauling speed and time constants in field studies.

Table 4.—*Effect of road conditions and length of haul on average round-trip speed of teams—Studies made at Milford, Pa., in March and April, 1926*

[All studies were made on 2-horse teams and 1½-yard dump wagons. Each entry is the average of a 1-hour study]

Average dippers per load	Loading	Dumping	Turning at dump	Turning at shovel	Spotting	Round-trip speed	Waits and delays on each trip	Length of haul	Road conditions
	Sec.	*Sec.*	*Sec.*	*Sec.*	*Sec.*	*Ft. per min.*	*Sec.*	*Ft.*	
1	21.9	13.0	45.0	----	----	232	205.0	325	Good, smooth; no grades.
1¾	34.0	6.0	19.0	9.0	----	258	26.8	345	Very good.
2	36.0	13.2	10.3	10.0	----	244	48.0	460	Good; hard and dry.
1	13.4	6.0	14.0	10.6	----	261	99.0	460	Good gravel; hard and dry.
1	10.2	8.2	14.4	5.4	----	251	87.0	490	Good gravel; hard; no grades.
2.2	48.0	4.8	12.6	15.0	15.6	194	524.0	335	Very muddy, rough; bottle neck midway, 10 per cent down grade.
2	38.3	7.3	10.0	40.6	13.0	194	320.0	250	Very muddy, rough; bottle neck midway.
2	37.0	4.0	7.0	19.0	14.0	222	124.0	500	Load haul muddy and rough; return good, dry.
1.7	42.6	5.3	18.1	27.0	----	[1] 140	189.0	47	Very muddy and spongy; used snatch team.
2	55.0	12.7	14.3	13.7	----	[1] 140	351.0	50	Very muddy, 3 per cent down grade.
1.3	28.7	5.3	15.1	24.0	----	177	253.0	90	Muddy and sticky on fill; spongy at shovel.
1	12.0	6.6	19.0	10.4	----	[1] 158	110.0	90	Muddy but no deep ruts; weather cold
1	12.0	7.2	12.4	22.6	12.6	203	176.0	200	Very muddy and rutted.
1	12.0	5.7	17.8	10.2	4.0	230	80.0	688	Do.
1.5	28.7	7.5	16.3	15.5	4.2	224	185.2	309	

[1] Not included in average.

Table 5.—*Average value of time constant and hauling speed from representative studies where two-horse teams were used*

Capacity of wagons (cubic yards)	Loading.	Waits or delays at dump	Dumping	Turning at dump	Turning and manuevering at shovel	Total time constant	Length of haul	Hauling time		Round-trip travel time	Round-trip speed
								Loaded	Return		
	Sec.	*Sec.*	*Sec.*	*Sec.*	*Sec.*	*Sec.*	*Ft.*	*Sec.*	*Sec.*	*Sec.*	*Ft. per sec.*
1½	37.0	------	4.0	7.0	19.0	67.0	[1] 500	[1] 97.0	[1] 174.0	271.0	221
1¼	32.0	40.8	7.7	15.7	14.3	110.5	497	132.3	128.5	260.8	229
1½	38.4	5.9	4.9	11.1	17.2	77.5	400	98.8	95.7	194.5	247
1½	32.4	9.6	7.7	16.6	11.8	78.1	142	36.2	39.0	75.2	227
1½	41.8	------	6.7	13.9	22.6	85.0	297	86.5	86.5	173.0	207
2	66.5	0.6	12.6	6.3	------	86.0	219	59.3	57.8	117.1	225
1½	36.0	------	13.2	10.3	10.0	69.5	460	114.2	112.0	226.2	244
1½	34.0	------	6.0	19.0	9.0	68.0	345	80.4	80.1	160.5	258
Average	39.8	7.1	7.9	12.5	13.0	80.2	358	88.1	96.7	184.8	232

[1] Haul distance for loaded wagons 350 feet but return to avoid steep grade was 650 feet.

PROFITS OFTEN AFFECTED BY DUMPING PRACTICE AND METHODS OF FILL CONSTRUCTION

A conspicuous factor in increasing the cost of short-haul work is the common practice of working all of the wagons assigned to the shovel without regard to the number needed. When the haul is short, there is generally an over-supply of wagons and the teams must wait at the shovel before being loaded. This practice may be due, in part, to the variation in haul distance from hour to hour, but perhaps to a greater extent to the condition of the labor market. Men will not stay on the job unless they can have reasonably steady work. The result is that the operating expense is the same for all hauls up to the point where the output capacity of the shovel and the hauling capacity of the wagons are in balance.

In this connection it may be appropriately observed that much lost time would be saved if the dump were more scientifically handled. The present tendency is to confine the placement of material to a small area. This often has the advantage that it tends to keep the length of haul fairly uniform for all the hauling units. But, if the rate of production is high a small dump area is somewhat difficult to handle without more or less delays which are unimportant on short hauls with a surplus of teams, but which become exceedingly important on the longer hauls.

An even more important cause of lost team time is the common practice of beginning fills at a point near the shovel and extending the fill and cut in opposite directions. As a result the haul generally varies from practically zero at the beginning to the full distance between balance points at the finish. Figure 3 shows a typical example of this kind. If both cut and fill are started at grade point B, the length of haul will increase until when the shovel reaches the point A, the dump will have reached C with a haul of 1,200 feet. Under ordinary operating conditions 3 two-horse wagons would be sufficient to maintain full-shovel production at the beginning, but 15 would be necessary

"Bottle Necks" Almost Always Increase the Average Trip Time of Hauling Units

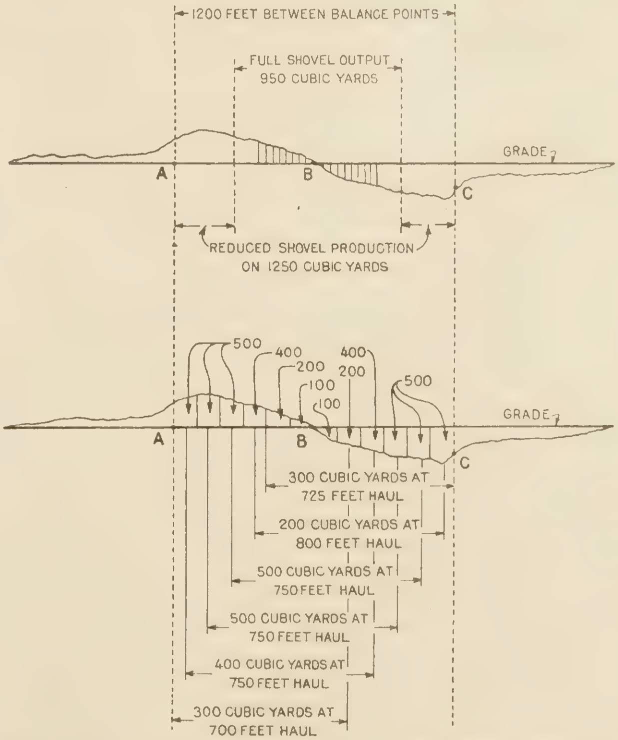

Fig. 3.—Diagram Showing Haul Distances Where End Dumping is Practiced and Where the Fill Begins at the Balance Point and is Carried in the Same Direction as the Cut. Based on Assumption that Full Shovel Production (¾-Yard Shovel) is Maintained Up to a 750-Foot Haul with Ten 2-Horse Teams

at the end. If enough teams are brought on the job to maintain full-shovel production when the longest haul is reached, then 12 will be idle during the first part of the work.

Better results can often be obtained by beginning the fill at the balance point B, and working it back toward the cut, i. e., by working the fill and the cut in the same direction. This tends to maintain a more nearly uniform haul distance and balance between shovel output and wagon supply. Assume that 10 teams are available on the job illustrated in Figure 3, and that they can just handle full-shovel production with a haul of 750 feet. If operation is conducted in the usual manner with the fill being extended away from the shovel—950 cubic yards will be handled within the haul distance at which the wagon supply can support full production at the shovel. Beyond that distance production decreases until when the end of the fill is reached the teams are able to haul only about two-thirds of full shovel production. The lower portion of Figure 3 shows that it is possible to complete the work without exceeding a haul of 800 feet and that for only 200 cubic yards. For the remaining 2,000 cubic yards the ten teams should be able to maintain full shovel production. At no time will more than one team be idle nor more than one additional team be needed. Production will amount to about 99 per cent of possible shovel output. If the job is handled by the other method then the shovel production for 1,250 cubic yards will be at an average rate of only about 78 per cent of full production and 86 per cent for the entire cut with correspondingly increased cost. This is a matter of no small consequence when margins of profit are narrow.

There are times when work can not reasonably be conducted in this way, as in rough and mountainous country where end dumping must be practiced. Sometimes boggy soil, rough or stump covered land, etc., make hauling over the original ground surface difficult. Other examples could be noted. Nevertheless there are a large number of projects where saving of some importance can be made by working the cut and the fill in the same direction.

FORMULAS DERIVED FOR DETERMINING HAULING COSTS

The total time required per trip for taking on the load, dumping it, turning around at the dump, getting into position at the shovel, and necessary miscellaneous delays has been termed the time constant and together with the time required to haul the load to the dump and to return from the dump to the shovel makes up the total time required to handle a load. This time constant plays a very important part in fixing the cost of all short-haul work for any given set of conditions. Its relation to the various factors other than management which influence the cost of hauling, is expressed as follows:

$$C=\frac{5}{3}\frac{A}{W}\left(\frac{2}{S}+\frac{T}{L}\right) \qquad (1)$$

$$K=\frac{A}{60W}\left(\frac{2L}{S}+T\right) \qquad (2)$$

Where

A = the rental or cost of the vehicle in cents an hour of working time (team, wagon, and driver).

W = average load of vehicle in cubic yards.

S = average round-trip operating speed of vehicle, exclusive of all standing time, in feet a minute.

T = time constant—that is, sum of time in minutes required per trip for loading, dumping, turning, and all regular waits and delays.

L = length of haul in feet.

C = cost of hauling material in cents per cubic yard station.

K = cost in cents per cubic yard of hauling the material the entire distance L.

These formulas can be used to find not only the probable cost of the hauling under any given set of conditions, but also to indicate what type of equipment should prove most advantageous. For fixed values of S, T, and L, the hauling cost varies directly as $\frac{A}{W}$. But, for the kind of equipment suitable for use with the power shovel in ordinary grading work, the variation of $\frac{A}{W}$ is over a comparatively limited range. For team hauling the cost of a two-horse team, wagon, and driver, or A, is generally found to be between 75 cents and $1 per hour and the average load, or W, carried by the wagons from 1 to 1½ cubic yards. The extreme range of the fraction is thus 100 per cent, but for any given region the limit is usually fixed within 10 to 20 per cent. For three-horse teams with wagon and driver the cost is usually found to be between $1 and $1.25 an hour and the average load is between 1½ and 2 cubic yards. The extreme range of the fraction $\frac{A}{W}$ is then about 67 per cent, but for any given locality it is seldom greater than one-fourth of this. Variations in the value of $\frac{A}{W}$ are not large and are usually favorable to the larger units.

The length of haul, L, is of course dependent on the job, but the speed, S, and the time constant, T, vary with both the equipment used and the conditions under which it is operated. The speed at which a team will travel under fair conditions and good management should be close to 240 feet a minute and seldom less than 220 feet, even under adverse conditions.

The time constant, T, varies with a number of conditions, the more important being the kind, size, and type of the hauling equipment, the efficiency of the management, the character and condition of the material, and the width of the roadway. For two-horse team haul, T might under very favorable conditions be as low as one minute and should not exceed two minutes even under unfavorable conditions. For three-horse teams, T usually varies between one and one-half and two minutes under normal field conditions. Under adverse conditions or poor management, these figures may readily be doubled.

Returning to the equation (1) we note that under prevailing prices and conditions, the factor $\frac{5A}{3W}$ is not likely to be much different whether we use two or three horse teams. The term $\frac{2}{S}$ for teams will generally be between 0.01 and 0.008 and under good management and fair conditions may be expected to be about 0.0083.

The term, $\frac{T}{L}$, however, varies inversely with the length of the haul. As the haul may be anything from a few feet to several thousand feet, it is clear that this term will vary between wide limits. It is also clear that on short hauls—that is, where L is small—the speed, S, can never under actual field conditions be high enough to materially affect the cost of hauling per cubic yard station. In order to illustrate this more fully Table 6 has been prepared, based on a value of T of one and one-half minutes for two-horse teams and two minutes for three-horse teams.

Particular attention is called to the fact that the time constant, T, as used in this discussion has reference only to actual working conditions. Extraordinary delays or shut-downs when both the shovel and the hauling equipment are idle are not included. The effect which the type of hauling equipment has on the cost of carrying the job during such periods of idleness is to be discussed later.

The hauling cost never forms more than a part of the total operating cost in power-shovel work. Consequently, this formula should not be used to forecast the actual unit production cost unless it is reasonably certain that the number of hauling units with the shovel will be in proper balance with the rate at which the shovel can handle the particular material in question, or allowance made for any deficiency in hauling units. Estimates of probable unit production cost or probable job costs should therefore, in general, follow the method illustrated in the latter portion of this article.

Table 6 brings out the following pertinent facts:

For any given speed and time constant the cost of hauling for any distance decreases as the load increases. The advantage, therefore, lies with the larger wagons providing road and operating conditions will permit their use.

For any given size of load and time constant any attainable increase in the round-trip speed produces only a relatively small decrease in the cost of hauling on short-haul work. It is only on long-haul work that speed becomes of major importance, but even then it can not attain the importance of an equal percentage increase in the size of the load.

When using teams on short hauls speed is of relatively minor importance in comparison with the size of the time constant. Table 7 brings out the preponderant effect of the time constant on short hauls and its relatively minor importance on long hauls. The table shows the number of loads which can be hauled per hour for various distances when the average round-trip speed is constant at 240 feet per minute, with time constants of from 1 to 4 minutes per round trip. Decreasing the time constant from 4 to 1 minute per trip for a 100-foot haul increases the number of loads per hour by almost 164 per cent. When the haul is 3,000 feet and all conditions as to speed, etc., remain the same, a like decrease in the time constant increases the number of loads by only a little over 12 per cent. In other words, the important elements for the management to watch in connection with the hauling equipment are: (1) The speed and size of the load, but especially the size of the load, on all long-haul work; and (2) the size of both the time constant and the load, but especially the size of the time constant, on all short-haul work.

DIAGRAMS DEVELOPED FOR PRELIMINARY CALCULATIONS

For rapid preliminary calculations formulas 1 and 2 may be solved by use of the diagrams shown in Figures 4 and 5. The following examples will illustrate the method of using these graphs:

1. What will be the cost per cubic yard-station when the haul is 575 feet, the time constant 4 minutes per load, the average round trip speed 300 feet per minute, the average load 2½ cubic yards, and the cost of the vehicle $1.75 per hour?

Enter the left margin of Figure 4 at 575 feet and proceed horizontally to the intersection with the time-constant curve having a value of 4 minutes, then vertically to the intersection with the diagonal line for a speed of 300 feet per minute, thence horizontally to the intersection with the diagonal sloping downward toward the left and marked "60 = Base," thence proceed vertically to intersection with diagonal marked 70, since $\frac{A}{W}$ in this case is equal to 70. The number on

Table 6.—*Cost of hauling common excavation with teams and wagons*

[Cost of two-horse team, wagon, and driver taken at $0.75 per hour; cost of three-horse team, wagon, and driver taken at $1 per hour]

TWO-HORSE TEAMS

Haul in feet	Average round-trip speed, feet per minute							
	220				240			
	Size of average load				Size of average load			
	1 cubic yard		1¼ cubic yards		1 cubic yard		1¼ cubic yards	
	K	C	K	C	K	C	K	C
100	3.011	3.011	2.409	2.409	2.917	2.917	2.333	2.333
200	4.148	2.073	3.318	1.659	3.958	1.979	3.167	1.583
300	5.284	1.761	4.227	1.409	5.000	1.667	4.000	1.333
400	6.420	1.605	5.136	1.284	6.042	1.511	4.833	1.208
500	7.557	1.511	6.045	1.209	7.083	1.417	5.667	1.133
600	8.693	1.449	6.955	1.159	8.125	1.354	6.500	1.083
700	9.830	1.404	7.864	1.123	9.167	1.310	7.333	1.047
800	10.966	1.371	8.773	1.097	10.208	1.276	8.167	1.021
900	12.102	1.345	9.684	1.076	11.250	1.250	9.000	1.000
1,000	13.239	1.324	10.591	1.059	12.292	1.229	9.833	0.983
1,500	18.920	1.261	15.136	1.009	17.500	1.167	14.000	0.933
2,000	24.602	1.230	19.682	0.984	22.708	1.135	18.167	0.908
3,000	35.966	1.199	28.773	0.959	33.125	1.104	26.500	0.883

THREE-HORSE TEAMS

Haul in feet	Average round-trip speed, feet per minute							
	220				240			
	Size of average load				Size of average load			
	1½ cubic yards		2 cubic yards		1½ cubic yards		2 cubic yards	
	K	C	K	C	K	C	K	C
100	3.232	3.232	2.424	2.424	3.148	3.148	2.361	2.361
200	4.242	2.121	3.182	1.591	4.074	2.037	3.056	1.528
300	5.253	1.751	3.940	1.313	5.000	1.667	3.750	1.250
400	6.263	1.566	4.697	1.174	5.926	1.481	4.444	1.111
500	7.273	1.455	5.455	1.091	6.852	1.370	5.139	1.028
600	8.283	1.380	6.212	1.035	7.778	1.296	5.833	0.972
700	9.293	1.328	6.970	0.996	8.704	1.243	6.528	0.933
800	10.303	1.288	7.727	0.966	9.630	1.204	7.222	0.903
900	11.313	1.257	8.485	0.943	10.556	1.173	7.917	0.880
1,000	12.323	1.232	9.242	0.924	11.481	1.158	8.611	0.861
1,500	17.374	1.158	13.030	0.869	16.111	1.074	12.083	0.801
2,000	22.424	1.121	16.818	0.841	20.741	1.037	15.555	0.778
3,000	32.525	1.084	24.394	0.813	30.000	1.000	22.500	0.750

K = Total cost in cents of hauling each cubic yard the given distances.
C = Average cost in cents per cubic yard station for the given distances.

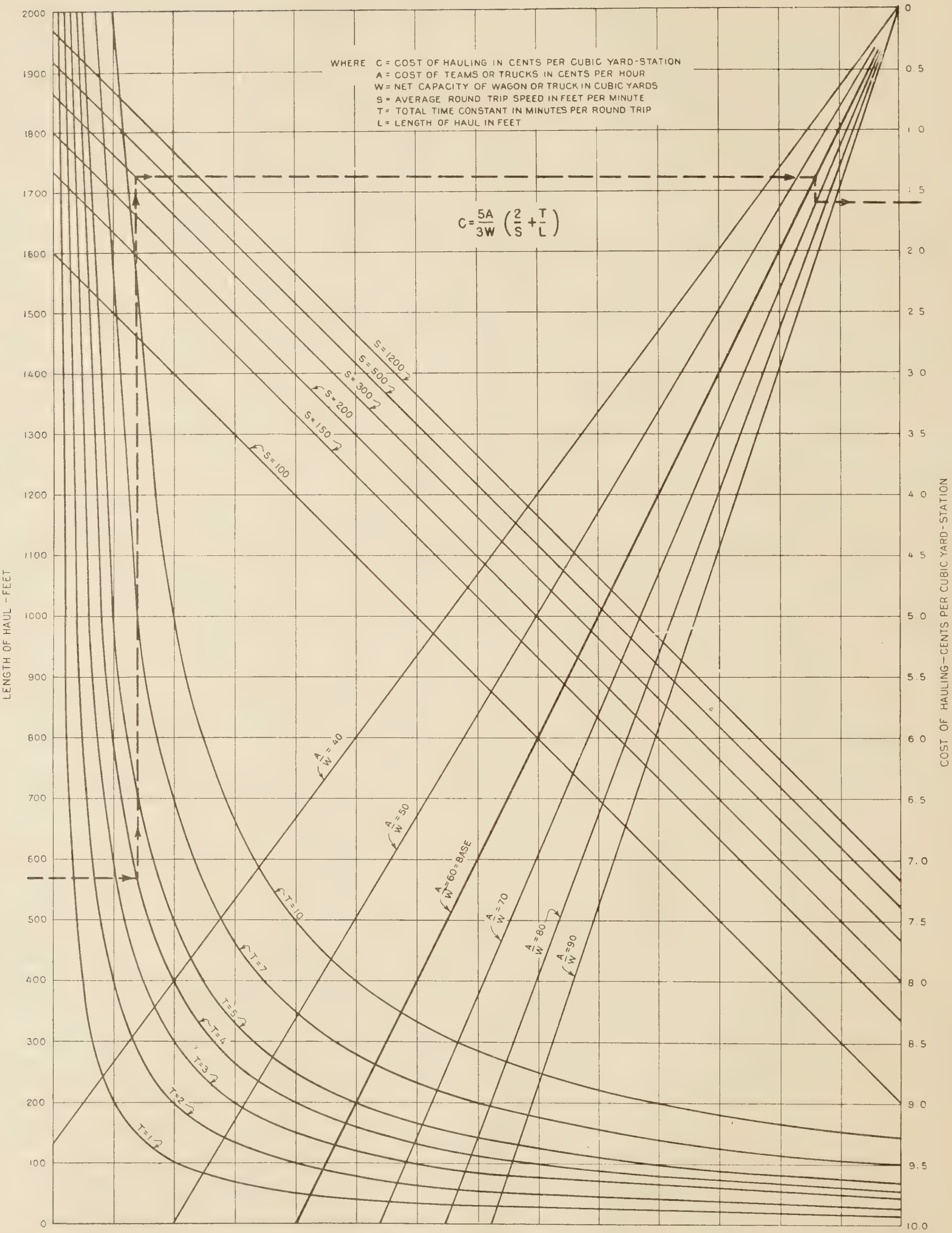

Fig. 4.—Diagram for Use in Solving Formula for Determining Cost of Hauling Per Cubic Yard Station

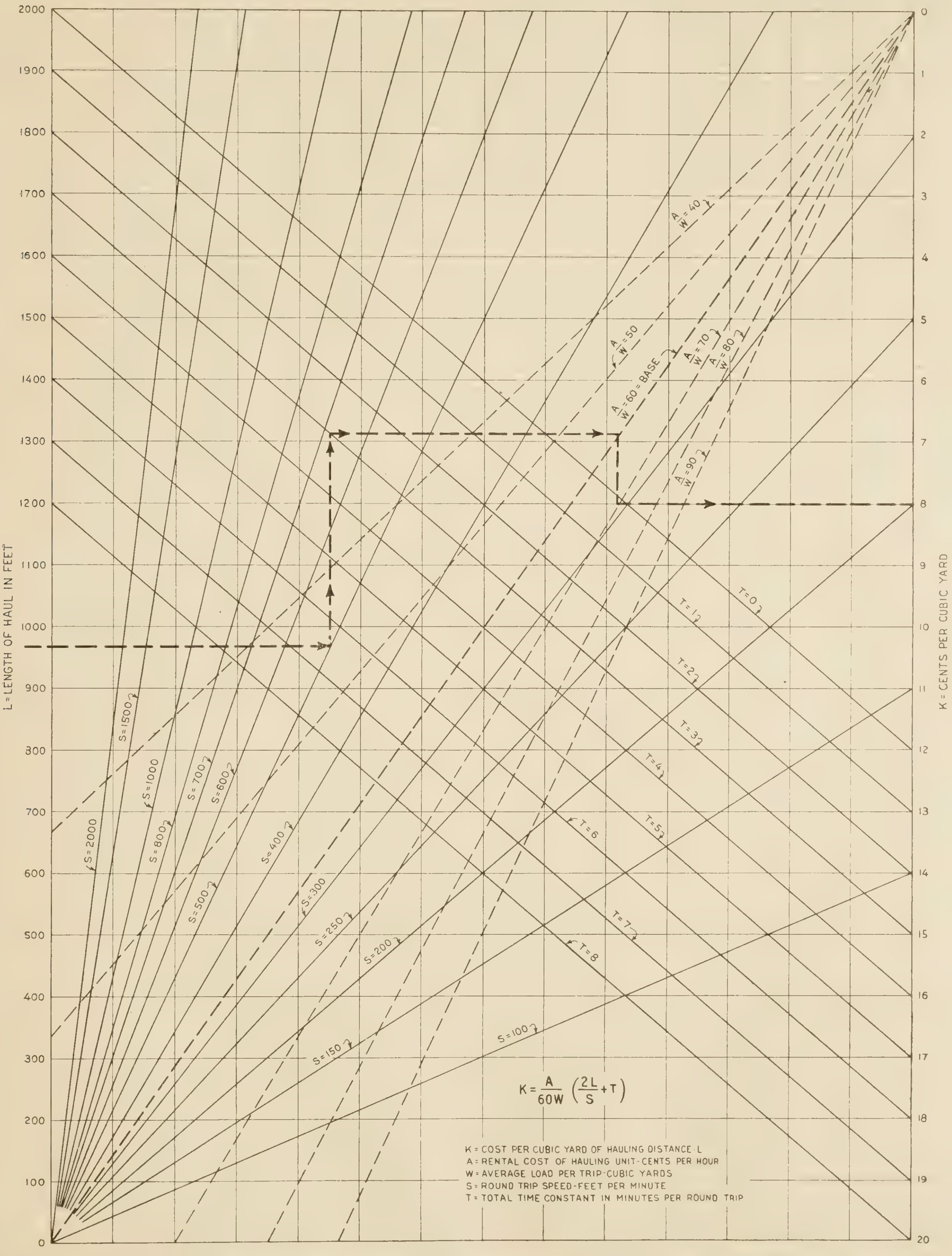

FIG. 5.—DIAGRAM FOR USE IN SOLVING FORMULA FOR DETERMINING COST OF HAULING 1 CUBIC YARD A DISTANCE *L*

TABLE 7.—*Loads hauled per hour at average round-trip speed of 240 feet per minute for various time constants, T, and given distances*

[Loads per hour $= \frac{60S}{2L+ST}$]

Haul in feet	Total time constant, *T*, in minutes							
	1	1¼	1½	1¾	2	2½	3	4
100	32.75	28.83	25.73	23.25	21.20	18.00	15.67	12.41
200	22.50	20.60	18.96	17.57	16.38	14.40	12.85	10.60
300	17.15	16.00	15.00	14.11	13.35	12.00	10.90	9.24
400	13.84	13.11	12.42	11.81	11.25	10.29	9.48	8.18
500	11.60	11.09	10.60	10.15	9.75	9.00	8.38	7.35
600	10.00	9.60	9.25	8.90	8.58	8.00	7.52	6.67
750	8.28	8.00	7.75	7.50	7.28	6.86	6.48	5.86
1,000	6.43	6.27	6.11	5.96	5.81	5.54	5.30	4.87
1,500	4.44	4.37	4.29	4.21	4.14	4.00	3.87	3.64
2,000	3.40	3.35	3.30	3.26	3.21	3.17	3.10	2.90
3,000	2.32	2.29	2.26	2.24	2.22	2.17	2.14	2.07

the right margin opposite this intersection, or 1.6 cents, is the approximate cost per cubic yard station of hauling material.

2. Find the total cost of hauling material 965 feet when the cost of the vehicle is $1.75 per hour, the time constant 3 minutes, the speed 500 feet per minute and the average load 2½ cubic yards.

Enter Figure 5 on the left-hand margin at 965 feet and proceed horizontally to intersection, with speed line for 500 feet per minute; then vertically to intersection, with time constant line for 3 minutes; thence horizontally to diagonal, sloping downward toward the left and marked "Base = 60;" thence, since $\frac{A}{W} = 70$, go down vertically to line marked 70, which is opposite 8.0 on right margin. This is the cost in cents per cubic yard of hauling material 965 feet under the above given conditions.

DETERMINATION OF NUMBER OF HAULING UNITS AN IMPORTANT PROBLEM

Failure to provide sufficient well-conditioned and properly operated hauling units to handle the full shovel capacity is more than any one thing responsible for low output and consequent loss of profits. But not all low production and high unit costs can be charged to the shortcomings of the contractor. Whenever the design is such that the length of haul fluctuates frequently and irregularly over wide limits, the cost is bound to be high under any plan of operation. It is doubtful if the designing engineer realizes the extra cost he imposes on projects by failing to give proper consideration to haul lengths. In fact, the cost of handling jobs of this kind may be so high as to preclude any possibility of a profit unless taken at a margin far above customary prevailing prices. On jobs with widely fluctuating hauls the problem of determining what hauling equipment should be sent to the job in order to obtain the lowest practical operating cost for the entire job is, therefore, a very important problem and one which will be considered in some detail. Whenever the customary practice is followed of sending to the job a definite number of hauling units which are retained until the work is completed, the following method can be used to determine the number required to complete the job at the lowest probable cost. The hauling formulas are as follows:

$$C = \frac{5A}{3W}\left(\frac{2}{S} + \frac{T}{L}\right) \qquad (1)$$

$$K = \frac{A}{60\,W}\left(\frac{2L}{S} + T\right) \qquad (2)$$

$$Q = \frac{60S}{2L+ST} \qquad (3)$$

$$N = \frac{2L}{St} + \frac{T}{t} \qquad (4)$$

$$Y = \frac{St}{2} \qquad (5)$$

Where

C = cost of hauling in cents per cubic yard station.

K = cost in cents per cubic yard of hauling the material a distance L.

Q = number of loads hauled per hour by one vehicle.

N = number of vehicles needed to just handle full shovel output for any haul L.

Y = increase in length of haul in feet at which another vehicle must be added if shovel is to maintain full production.

A = cost or rental of each vehicle in cents per hour.

W = average pay load in cubic yards carried by vehicle.

S = average round-trip speed in feet per minute exclusive of all stops.

L = length of haul in feet.

T = total time constant in minutes; that is, the sum of the average time required each round trip to take on the load, dump it, turn and maneuver both at the dump and shovel, and all stops or delays.

t = time in minutes required to take on load, or longest regular delay if this exceeds the loading time.

MASS DIAGRAM REQUIRED IN PLANNING WORK

When a job is to be analyzed for the purpose of determining the most economical equipment, the first step is to determine the haul distance (in stations) from the excavation and embankment quantities appearing on the project plans. The yardage for each of the various haul distances can be determined most readily by means of a mass diagram. The mass diagram is simply a curve showing the algebraic sum of the cumulative station quantities plotted consecutively station by station from left to right with reference to a horizontal base line, cuts being considered as plus and fills as minus quantities with the proper factor applied for swell or shrinkage. (See fig. 6.) Thus, a rising slope of the curve indicates cut and a falling slope indicates fill. At each balance point the curve crosses the base line. A horizontal portion indicates grade—that is, neither cut nor fill—while any line drawn parallel to the base will only cut the curve at points between which cuts and fills will balance. Areas above the base line indicate a forward haul, and areas below the base line represent a backward haul, while the area inclosed by the curve and the base line between balance points represents the total cubic yard stations of haul between such points.

The total cubic yard stations of haul involved in any project is fixed by the design. The contractor is limited to determining in what manner and with what equipment he can perform this work at the lowest possible cost. To do this he must know not only the total cubic yard stations of haul and the average haul for the job or balance sections but he must know how far he must haul the material each day he is on the job. If the fills are to be placed by end dumping or any other method of working the cuts and fills in opposite directions, the quantities for each length of haul between balance points can be taken almost directly from the mass diagram by simply noting the vertical distance between each of a series of lines drawn parallel to the base and so spaced that each line is 100 feet or any other desired unit shorter or longer than its neighbor. The vertical distance between any two of these lines represents the yardage which has a haul equal to the distance represented by the average of the two bounding horizontal lines.

Where a sag is encountered in the curve as the lines are ruled progressively from the base toward the apex, the first line cutting the curve should be moved up or down until just tangent to the curve at the point where the sag is nearest the base line. This secondary base line should then be considered as the base for the remaining areas of the curve or until another sag is encountered, in which case the same process is repeated. The quantities with the corresponding hauls can then be scaled or read from the diagram and entered in the tabulation prepared for each section between balance points.

The mass diagram can also be used to find the quantity for each haul distance when the dump and cut are both worked in the same direction since the total area within the curve of the mass diagram—that is, the total cubic yard stations of haul—is not altered by the order in which the individual quantities are moved nor where they are placed so long as no useless haul is performed. In this case it is convenient to space the parallel horizontal lines at some given unit, as, for example, 100 cubic yards apart, and also to draw vertical lines at each grade point—that is, at each summit. The distance which any quantity will be hauled is then measured by the mean distance of this quantity from the grade point—that is, the vertical line—plus the mean distance from this grade point to its place of disposal. Figure 6 shows the areas for which the haul distances are combined when using this method.

The method may be varied to correctly represent the placing of any particular excavation at any point in the embankment. The quantities with their corresponding haul distances are then entered in the table in the same manner as in the first case. Since all quantities in cut are represented by corresponding fill areas, this method is not likely to result in any large errors passing undetected. The first two columns of Table 8 show the summarized results of calculations of this kind. Such data should appear on all plans involving grading.

METHOD OF DETERMINING TEAM SUPPLY OUTLINED

It is then necessary to determine the probable rate of production at the shovel on the basis of past experience with material of the type involved, the cross-section to be used, etc. As an example, it will be

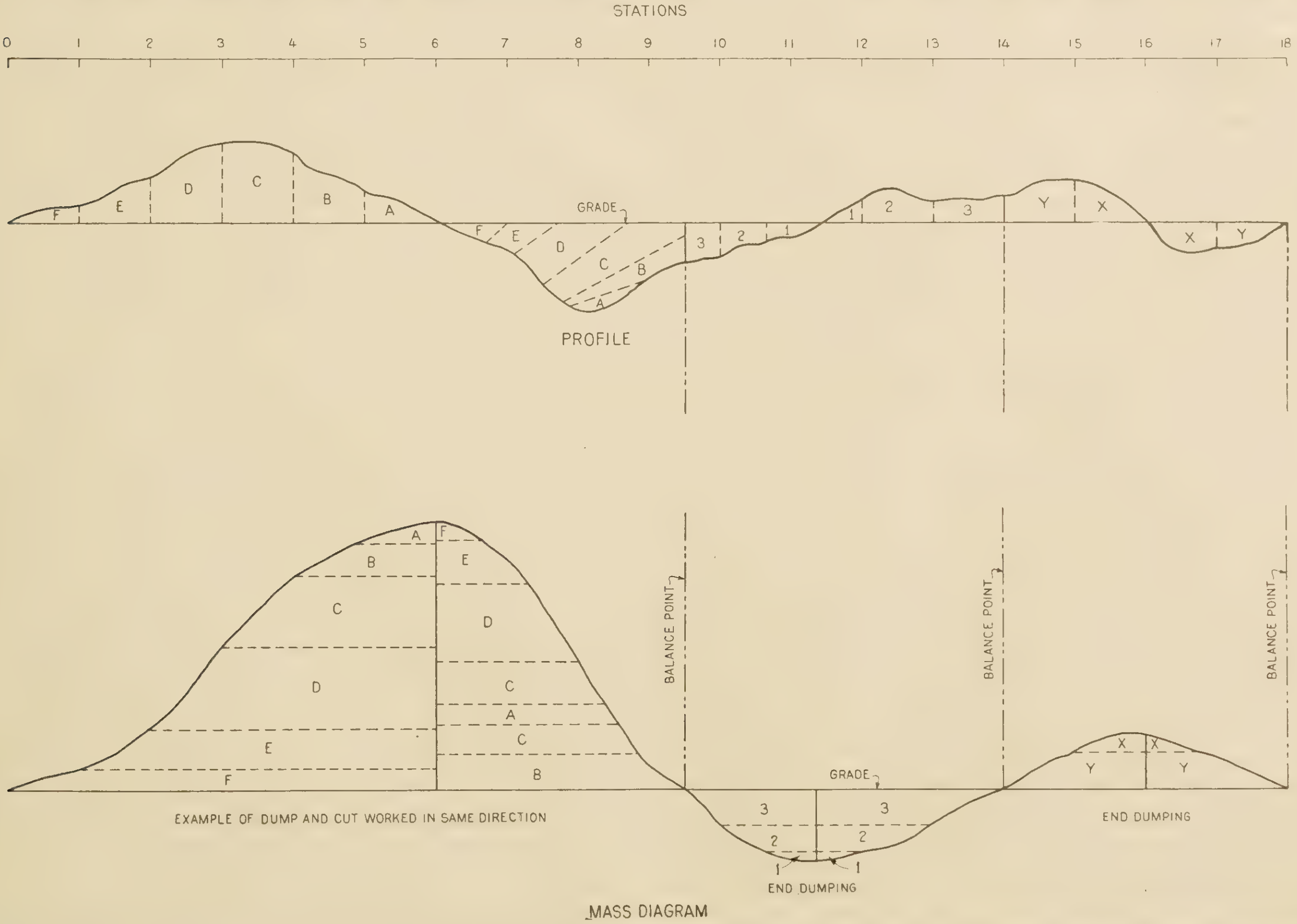

FIG. 6.—PROFILE AND MASS DIAGRAM SHOWING EXAMPLES WHERE THE DUMP AND CUT ARE CARRIED IN THE SAME DIRECTION AND WHERE END DUMPING IS PRACTICED

assumed that the conditions are such that the shovel can maintain a fairly constant rate of 72 cubic yards per hour or 720 cubic yards per 10-hour day, and that hauling will be done with wagons carrying two dipper loads averaging 0.45 cubic yard each, or 0.9 cubic yard per wagonload as measured in place. The shovel output will then amount to 80 wagonloads per hour.

The number of days' work involved if full shovel production were maintained throughout the job is next determined as indicated in column 3 of Table 8. If a team supply for the longest haul is sent out and we assume a team speed of 240 feet a minute and a time constant of 1½ minutes with three-fourths minute for loading time, we find from formula (4) that 53 teams would be required. But, to send out 53 teams is obviously not a practical procedure. The problem is to find the number of teams which, continued on the job, can complete it at the lowest total cost. Direct formulas for this purpose would be too complex and a solution by comparative elimination or a graphical solution is preferable. The remaining columns of Table 8 show such a trial for 15, 17, 18, 19, 20, 22, and 23 teams, the figures shown being woiked out through the formulas previously given.

In applying the formulas to this example it has been assumed that a team and wagon costs $7 a day, operating the shovel $50 a day, and handling the dump (no rolling) costs $15 a day. These costs, of course, vary on different jobs, but those given are thought to be fairly representative and will serve for purposes of illustration. The figures include operating cost and depreciation, but do not include overhead, weather losses, getting on and off the job, etc., since this study pertains only to direct operating costs. With these assumptions we find that the shovel and 15 wagons, with dump handling, cost $170 a day; with 18 wagons, $191 a day; with 20 wagons, $205 a day; with 22 wagons, $219 a day; and with 23 wagons, $226 a day.

If, for example, 15 wagons are provided and 80 loads are to be taken out every hour, each wagon must haul 5⅓ loads per hour if full production is to be maintained. This is one load every 11¼ minutes. At this rate full production can be maintained only up to about 1,200 feet. At one load every 15 minutes (20-team basis) full production can be maintained up to 1,650 feet. After these limits are reached, production will be in the proportion that the number of teams used bears to the number of teams required to support full production. Percentages of full production are given in columns 5, 7, 9, 11, 13, 15, and 17 of Table 8. Calculating the work which will actually be performed in a day is simply a matter of applying the percentage figure to the figure for full production. Knowing the daily production the number of days required for the particular haul distance is determined as shown in columns 6, 8, 10, 12, 14, 16, and 18. The summation of these columns gives the number of working-days required to complete the job, and these multiplied by the daily cost of operation give the total cost of moving the material.

In this case the most economical number of teams to send to the job is 18 and the cost of completing the job will be $43,472. The difference, however, between the cost of using 17, 18, or 19 teams is small, and 17 would no doubt be the preferable number to send out, especially if conditions are such that the time losses may be higher than normal.

DESIGN GIVING SMALLEST YARDAGE AND CLOSEST BALANCE NOT ALWAYS CHEAPEST TO CONSTRUCT

A number of interesting observations may be drawn from the data given in Table 8, which is, on the whole, typical of long-haul jobs. In order to maintain full production at the shovel even at the moderate rate assumed, 53 teams would be required on the longest hauls. The daily operating cost would then be $436, and the cost of the job would be more than $20,000 in excess of that determined as the lowest possible cost. Where the haul ranges frequently from short to very long, it is not practical to maintain high production at the shovel when the very long hauls are reached.

If conditions had been such that the team supply could have been regulated so as to always just maintain full shovel production regardless of the length of the

TABLE 8.—*Determination of number of teams for most economical operation on a job with considerable variation in length of haul—A constant team supply is assumed*

Quantity	Length of haul in stations	Production at 720 cubic yards per day[1]		15-team basis		17-team basis		18-team basis		19-team basis		20-team basis		22-team basis		23-team basis	
		Days to complete each haul	Number of teams required	Production	Days required	Production	Days required	Production	Days required	Production	Days required	Production	Days required	Production	Days required	Production	Days required
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
Cubic yds.				*Per cent*		*Per cent*		*Per cent*		*Per cent*		*Per cent*		*Per cent*		*Per cent*	
7, 200	5	10	7. 6	100. 0	10. 0	100. 0	10. 0	100. 0	10. 0	100. 0	10. 0	100. 0	10. 0	100. 0	10. 0	100. 0	10. 0
18, 720	6	26	8. 7	100. 0	26. 0	100. 0	26. 0	100. 0	26. 0	100. 0	26. 0	100. 0	26. 0	100. 0	26. 0	100. 0	26. 0
14, 400	9	20	12. 0	100. 0	20. 0	100. 0	20. 0	100. 0	20. 0	100. 0	20. 0	100. 0	20. 0	100. 0	20. 0	100. 0	20. 0
10, 800	12	15	15. 3	98. 0	15. 3	100. 0	15. 0	100. 0	15. 0	100. 0	15. 0	100. 0	15. 0	100. 0	15. 0	100. 0	15. 0
5, 760	15	8	18. 7	80. 3	10. 0	89. 4	8. 9	96. 3	8. 3	100. 0	8. 0	100. 0	8. 0	100. 0	8. 0	100. 0	8. 0
10, 080	18	14	22. 0	68. 2	20. 6	77. 1	18. 2	82. 0	17. 1	86. 5	16. 2	90. 9	15. 4	100. 0	14. 0	100. 0	14. 0
7, 200	24	10	28. 7	51. 3	19. 5	59. 2	16. 9	62. 8	15. 8	66. 3	15. 1	69. 7	14. 3	76. 7	13. 0	80. 3	12. 5
7, 200	30	10	35. 3	42. 5	23. 5	48. 1	20. 8	51. 0	19. 6	53. 9	18. 5	56. 7	17. 6	62. 4	16. 0	65. 3	15. 3
14, 400	40	20	46. 4	32. 3	62. 0	36. 7	54. 5	38. 8	51. 6	41. 0	48. 8	43. 1	46. 4	47. 6	42. 1	49. 7	40. 5
10, 800	46	15	53. 1	28. 2	53. 2	32. 0	46. 9	34. 0	44. 2	35. 7	42. 0	37. 4	39. 8	41. 5	36. 2	43. 4	34. 5
106, 560	---------	148	---------	---------	260. 1	---------	237. 2	---------	227. 6	---------	219. 6	---------	212. 5	---------	200. 3	---------	195. 8
Cost per day------		$436 (53 teams)		$170		$184		$191		$198		$205		$219		$226	
Cost to complete---		$64,528 (53 teams)		$44, 217		$43, 645		$43, 472		$43, 481		$43, 562		$43, 866		$44, 251	
Production factor (percentage of full shovel capacity)--		100 (53 teams)		57		62		67		67		70		74		76	

[1] Total cost to complete job if teams could be supplied as needed, $33,778.

haul, then the job could have been completed for $33,778, or almost $10,000 less than for the most economical choice of a constant team supply throughout the job. A shovel job which involves wide and irregular fluctuations in the length of haul is certain to prove unduly expensive because of the practical impossibility of maintaining a proper balance between the production capacity of the shovel and that of the hauling equipment. The design which gives the smallest yardage and the closest balance is therefore not always the cheapest to construct. This is a point which should be kept in mind in preparing plans for jobs where power shovels may be used.

It might also be well to include in the plans a tabulation of quantities by stations and also summarized information as shown in columns 1 and 2 of Tables 8 to 10. Such information would enable prospective bidders to note not only the lengths and quantities for the various hauls, but would also furnish them with the data so necessary for an intelligent planning of the most effective organization, as well as for deciding the sequence in which the various sections should be handled in order to maintain the highest rate of efficiency for the job as a whole.

The use of larger wagons carrying three full dipper loads would have reduced the number of vehicles necessary to maintain full shovel production on any length of haul by one-third, providing the larger load would not have necessitated any reduction in the average hauling speed. Three-horse 1½ to 2 yard wagons are frequently used with the elevating grader, and there seems to be no reason why they should not prove equally satisfactory on many power-shovel projects.

EFFECT OF HAUL DISTANCE ON COST DEMONSTRATED

Where the haul is kept within moderate limits two-horse team hauling is generally very satisfactory. Table 9 is illustrative of a job which permits a fair average rate of output with team hauling. The operation constants and costs are the same as those assumed for Table 8. With 8 teams, 10 loads must be hauled per team per hour, or 1 load every 6 minutes, if full shovel production is to be maintained. With 10 teams, 8 loads must be hauled an hour or 1 load every 7½ minutes. In the first case, full production can be maintained up to 570 feet; in the second up to 750 feet. The results of these calculations extended to 12 teams are shown in Table 9.

The cost of an 8-team outfit is $121 a day, of a 10-team outfit $135 a day, and of an 11-team outfit $142 a day. To maintain full production on a 1,200-foot haul, 15 teams are required. An outfit of this size would raise the cost to $170 a day. The total cost of operation with such an outfit would be $15,810. The cost with an 8-team outfit would be $15,440, or almost as high as for 15 teams. The cost with a 10-team outfit would be $14,607 and for an 11-team outfit $14,555. The lowest cost is had with 11 teams and the average rate of output can be maintained at about 91 per cent of full production. Naturally, the effect of moderate haul distances on cost is favorable, for aside from the fact that hauling itself is expensive, the increased output at the shovel materially reduces the unit cost of the work done by it.

Expressed in a little different way, with an 8-team outfit and conditions as assumed in this problem, it costs just twice as much to handle material with a 1,290-foot haul as it does with a 570-foot haul. (See column 5 of Table 9.) Balancing quantities beyond the 1,290-foot limit is therefore more expensive than borrowing and wasting anywhere within the limits at which the 8 teams can maintain full shovel production. Table 8 shows that if 15 teams are to be used on the job described, the point at which borrow and waste should be substituted for long haul is about 2,550 feet (see column 5), and with 20 teams it is in the neighborhood of 3,450 feet (see column 13).

The conditions imposed by these problems are typical. In designing projects on which power shovels are likely to be used, the limits beyond which the material should not be hauled deserve detailed study for each individual case. The methods used here are applicable to the solution of such problems but data as to costs, production, etc., based on local conditions must be substituted for that used in the illustrations above before definite decisions are reached in any individual case. The crux of the matter is, however, that long hauls are very expensive and their use in order simply

TABLE 9.—*Determination of number of teams for most economical operation on a job with only moderate variations in length of haul—A constant team supply is assumed*

Quantity	Haul in stations	Production at 720 cubic yards per day		8-team basis		10-team basis		11-team basis		12-team basis	
		Days to complete each haul	Number of teams required	Production	Days required	Production	Days required	Production	Days required	Production	Days required
1	2	3	4	5	6	7	8	9	10	11	12
Cubic yards				*Per cent*		*Per cent*		*Per cent*		*Per cent*	
14,400	Under 5	20	7.0	100.0	20.0	100.0	20.0	100.0	20.0	100.0	20.0
10,800	Under 6	15	8.7	92.0	16.3	100.0	15.0	100.0	15.0	100.0	15.0
7,200	Under 7	10	9.8	81.6	12.3	100.0	10.0	100.0	10.0	100.0	10.0
10,800	Under 8	15	10.9	73.3	20.5	91.7	16.4	100.0	15.0	100.0	15.0
5,760	Under 9	8	12.0	66.7	12.0	83.3	9.6	91.8	8.7	100.0	8.0
7,200	Under 11	10	14.2	56.2	17.8	70.4	14.2	77.0	13.0	84.6	11.8
10,800	Under 12	15	15.3	52.2	28.7	65.3	23.0	72.0	20.8	78.5	19.0
66,960		93			127.6		108.2		102.5		98.8
Cost per day		$170 (15 teams)		$121		$135		$142		$149	
Cost to complete job		$15,810 (15 teams)		$15,440		$14,607		$14,555		$14,721	
Production factor (percentage of full shovel capacity)		100 (15 teams)		73		86		91		94	

to balance quantities should never be tolerated, unless it can be clearly shown that the desired results can not be secured more economically in some other way.

If by redesigning the project on which Table 8 is based the hauls could have been limited to a maximum of 600 feet, then 9 teams could have maintained full production and the daily operating cost would have been only $128 per day. With the same total yardage the project could have been completed for $19,000. In other words, the hauls over 600 feet in length increased the cost by more than $24,000 (18-team basis), or more than 125 per cent.

The project analyzed in Table 9 contains a much smaller amount of long-haul work. But even here the hauls over 600 feet in length increase the total cost more than $2,600, an item well worth giving careful attention.

OFTEN ADVANTAGEOUS TO USE SURPLUS TEAMS WITH FRESNOES AND WHEELERS

One of the serious objections to the use of teams where a large outfit must be employed to maintain a proper relation to the shovel output is the high cost of carrying the teams. The cost of team time, assumed as $7 a day, is made up as follows:

Feed and care of team	$2. 50
Depreciation and repairs (team, wagon, and harness)	1. 00
Drivers (board $1, wages $2.50)	3. 50
Total	7. 00

Whether the teams work or not, they must be fed and cared for. In the case of teamsters it is generally customary to allow board even if no work is done and no wages paid. In such cases the idle-time cost of teams is at least half of the working time cost. Because of this fact, the labor situation and variations in length of haul from hour to hour there is seldom any effort to save money by sending out only enough teams to handle the shovel output for the day. Still, some money could be saved on most wagon jobs by such practice. But even if this is done as far as is possible without danger of labor difficulties, the fact that every idle team still generates about half of the working cost, is a heavy handicap, particularly on jobs with fluctuating long and short hauls where a relatively large number of teams must be used.

Considerable relief is possible on projects large enough to warrant the use of two shovels by so governing the work that when one is on long-haul work the other will be on short-haul work. On some jobs, stock not needed on the wagons can be put on fresnoes or wheelers. Where three-horse teams are used these can readily be converted into a fresno outfit. The price at which materials can be moved with fresnoes or wheelers is frequently as low or even lower than can be secured by means of the power shovel and the team supply necessary for the job as a whole, on hauls up to three or four hundred feet, and occasionally even more.

A glance at Table 8 will show that there are only 7,200 yards on this job out of a total of over 106,000 yards which might be profitably handled by fresnoes. The contractor would therefore hardly be justified in attempting to salvage any considerable amount of otherwise idle time on this job with fresnoes. However, as 18,720 yards on this project require a haul of about 600 feet, and this combined with the 7,200 yards involve about 25 per cent of the material on the whole project, it would be reasonable to examine the possibility of using wheelers with the teams not needed at the shovel and also the advisability of sending out more than 18 teams, thereby increasing the shovel production on the long hauls, and at the same time avoiding idle-time losses on the short hauls.

If 22 teams were sent to the job, enough teams to form a wheeler outfit would be available on hauls (shovel outfit) of 1,200 feet or less but not at greater distances. Table 10, columns 13 and 14, shows how the otherwise idle teams could be utilized to move all the material having a haul of 500 feet and 6,300 cubic yards of the material having a 600-foot haul before the longer hauls absorbed so many teams that the wheeler outfit would have to be abandoned. Providing the length of haul does not change too frequently, this should permit the completion of the entire job at a cost of at least $4,000 less than could be accomplished with the use of a shovel outfit only with 22 teams and about $3,700 less than the cost with 18 teams.

Table 10 shows in some detail the results which could probably have been secured by this method in the case of the project given in Table 8 by using a hauling outfit of 18, 19, 20, 22, and 23 teams, respectively. It will be noted that there is no gain in using more than 22 teams, while the probable gain from using more than 20 or 21 is too small to warrant the added risk incurred should weather or other conditions prove unduly adverse. The results shown in this table may be considered representative of the results of good management where there is much both long and comparatively short haul work.

Short-haul projects, such as the one shown in Table 9, do not offer as good opportunities for salvaging lost team time as are offered on long-haul jobs. Still the opportunity often exists. Under the conditions given in Table 9 the yardage to be moved less than 500 feet is so large that it suggests the use of fresnoes. If 11 teams were taken to the job, only 3 of them would be idle on the 500-foot hauls; but three teams are not enough to form an economical fresno or wheeler outfit. In this case the contractor might be able to sublet the yardage to be hauled less than 500 feet to a fresno or wheeler outfit at an advantageous price.

It is not possible to lay down any hard and fast rules governing jobs as described above. Each project must be considered on the basis of the facts governing its execution. All that can be said is that there is generally more opportunity to reduce cost by intelligently salvaging lost team time than contractors are now using.

PROFITS CAN OFTEN BE INCREASED BY WORKING WHEN CONDITIONS ARE ADVERSE

The problem of lost time is a serious one on all construction work, but it is particularly so where any considerable amount of stock is used. Take as an illustration, a shovel job where 10 teams are used. The cost of operating such an outfit has been given as about $135 a day. Commonly, the shovel runner and night watchman are on full time at about $10 and $3.50 per day, respectively. If the shovel is a steam machine, fires may also be kept up and in this way some fuel consumed. On the hauling side, the teams must be fed and cared for and, by general custom, the teamsters also must be fed. These expenses account for about $3.50 per day per team, or perhaps $35 per day for an outfit of this size. Often there are other items of expense. A blacksmith is sometimes employed. The job foreman and the time keeper generally are full-time men. The team used on the dump

TABLE 10.—*Analysis of use of spare teams as a wheeler outfit, based on the job analyzed in Table 8*

Quantity	Haul	Production at 720 cubic yards per day		18-team basis		19-team basis		20-team basis		21-team basis		22-team basis		23-team basis	
		Days to complete each haul	Teams required	Number of teams not needed at shovel	Short-haul yardage moved with wheelers	Number of teams not needed at shovel	Short-haul yardage moved with wheelers	Number of teams not needed at shovel	Short-haul yardage moved with wheelers	Number of teams not needed at shovel	Short-haul yardage moved with wheelers	Number of teams not needed at shovel	Short-haul yardage moved with wheelers	Number of teams not needed at shovel	Short-haul yardage moved with wheelers
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
Cubic yards	*Feet*				*Cubic yards*		*Cubic yards*		*Cubic yards*		*Cubic yards*		*Cubic yards*		*Cubic yards*
10, 800	4, 600	15	53. 1												
14, 400	4, 000	20	46. 4												
7, 200	3, 000	10	35. 3												
7, 200	2, 400	10	28. 7												
10, 800	1, 800	14	22. 0												
5, 760	1, 500	8	18. 7									[1] 3		[1] 4	
10, 800	1, 200	15	15. 3	[1] 3		[1] 4		[1] 3		[1] 4		5	600	6	900
14, 400	900	20	12. 0	6	2, 400	7	3, 200	5	1, 200	6	1, 800	7	2, 400	8	3, 000
18, 720	600	26	8. 7	9	5, 700	10	6, 000	8	4, 000	9	4, 800	10	5, 500	11	5, 600
7, 200	500	10	7. 6					11	5, 200	12	5, 000	13	5, 000	14	4, 700
Total yardage moved by spare teams					8, 100		9, 200		10, 400		11, 600		13, 500		14, 200
Number days job shortened					11. 2		12. 8		14. 4		16. 1		18. 7		19. 7
Plan I: Total cost of job when no use is made of spare teams. (See Table 8.)				$43, 472		$43, 481		$43, 562		$43, 736		$43, 866		$44, 251	
Plan II: Total cost when spare teams utilized on short-haul wheeler work				$41, 333		$40, 947		$40, 610		$40, 323		$39, 771		$39, 799	
Total saving by using spare teams on wheelers				$2, 139		$2, 534		$2, 952		$3, 413		$4, 095		$4, 452	

[1] Spare teams not sufficient to organize a wheeler outfit.

must also be fed and cared for and the teamster must be fed. If a roller is used the operator is generally on full-time pay. Often these items create an idle-time cost more than half as large as the normal cost of operation. Extended losses of time due to bad weather, to breakdowns, or from any other causes are for this reason financially disastrous.

This raises the question as to when work should be undertaken under adverse conditions. The practice to follow must be worked out for the particular job on the basis of operating cost, idle-time cost, unit price on work done, etc. The decision should be based on a calculation following the general lines of the following example: Assume that the idle-time cost of a shovel outfit with 10 wagons amounts to approximately $75 a day. The operating cost when work is under way (operating the dump included) is about $135 a day. The daily cost is increased only about $60 a day by operating. Consequently, if the work done is worth 35 cents a yard it is obvious that operation is justified whenever it is probable that it will be possible to take out more than 171 cubic yards per day ($60÷0.35=171).

This solution covers those cases where the haul is such that a profitable output can be had when working conditions are normal. But on most jobs there are times when the haul is so long that even when working conditions are normal, the value of the output does not equal the cost of operation. Such a situation requires a slightly different analysis. Suppose that under normal working conditions the haul is so long that only 300 cubic yards a day can be taken out. The value of a normal day's output at 35 cents per cubic yard is only $105 against a daily operating cost of $135—a loss of $30 a day. If the cost of lying idle remains constant at about $75 per day, while normal operation can at best produce a value of only $105 per day, the margin between lying idle and working is reduced to $30. In such a case work should be undertaken if there is a probability that more than 85 cubic yards per day can be taken out.

The above analysis suggests that the final profit may be as much affected by a reduction of the time losses incident to weather, breakdowns, etc., as by efficient operation when work is going on. On practically every job there is some lost time. On many the amount of lost time is large. The contractor who will operate in spite of adverse conditions as often as there is any reasonable chance of earning more than the difference between the cost of remaining idle and the cost of working, will, over any ordinary season, find that the effect of such procedure on the amount of his profit is surprisingly large.

In closing the discussion of wagons as hauling equipment, it ought to be observed that the wagons themselves give little trouble and that with a spare wagon in camp, lost time due to breakdowns can be almost completely eliminated. On some jobs there is quite a little time lost by permitting drivers to grease the wagons during working hours. Wheel and axle construction on most wagons is of old-fashioned design, not much visible change in it having taken place for many years. Losses from this cause should be eliminated by requiring that wagons be greased in the camp at night and at noon, but the results obtained in this way have not been altogether satisfactory. A much more promising solution has been observed on a number of jobs where contractors have bored the wheel hubs and installed fittings so that grease can be injected with a grease gun without removing the wheels. The whole wagon can then be greased in less time than was formerly required in greasing one wheel. Even with this change many contractors feel that they have to continue the practice of permitting the drivers to grease their wagons during working hours.

Basically, the trouble appears to be that as less and less stock is being used on construction work, the grade of labor available as drivers is falling steadily. Many contractors assert that it is much easier to find good truck or tractor drivers than it is to find men who can handle stock well. It is true that truck or tractor drivers demand higher wages, but the larger output of the equipment they handle makes it possible to pay the higher wages. Factors of this sort are rather intangible but, nevertheless, have considerable bearing on the advisability of using stock on a construction operation.

EXPERIMENTAL BITUMINOUS-TREATED EARTH ROAD BUILT

An experimental road has been constructed in South Carolina during the past year which, it is hoped, will result in the development of a satisfactory method of bituminous treatment of the loosely bonded sand-clay roads characteristic of the southeast coastal section of the country. This experiment is being conducted by the United States Bureau of Public Roads in cooperation with the South Carolina State Highway Department. The test road extends from Conway to Galivants Ferry, a distance of 21 miles. It is on an arterial highway and carries relatively heavy traffic during the spring and summer months.

The sand-clay soil with which this road is surfaced possesses little natural binder and is composed for the most part of fine-grained sand particles. As a result, the surface breaks down and becomes exceedingly dusty in dry weather, and when wet it cuts up rapidly and becomes almost impassable. The unstable nature of the road surfaces in this region precluded the use of the ordinary type of bituminous surface treatment, and it was decided, therefore, to investigate various types of bituminous mixed-in-place treatments. Table 1 shows the character of the various sections.

Mixing the Surface

Construction by the mixed-in-place method consisted of scarifying, shaping, and pulverizing the road surface, after which the bituminous material was applied in several applications by pressure distributors. The surface was disked lightly after each application. This proved valuable in preventing loss of the lighter constituents of the bituminous material. Mixing was done with a blade grader, the procedure being to carry the treated material from one side of the road to the other until a uniform mixture was secured. Then the material was spread, shaped, and allowed to compact under traffic. For those sections built to receive machine maintenance this completed the construction. The sections which were to receive a surface treatment were allowed to set up and harden for a week or ten days, after which they were given a single or a double surface-treatment, as indicated in Table 1.

Detailed records will be kept regarding the maintenance costs and service of the different sections so that the comparative value of the various treatments may be determined.

Table 1.—*Treatments used on various sections*

Section No.	Mixed base		Bituminous surface treatment	Cover material
	Depth	Bituminous material		
	Inches			
1-A	2	Asphalt, 150-180 penetration, cut back with naphtha.	Primer, same as for base; binder, asphalt (hot), 150-200 penetration.	Stone.
1-B	2	Asphalt 85-100 penetration, cut back with naphtha.	Primer, same as for base; binder, asphalt (hot), 150-200 penetration.	Do.
2-A	2	do	No primer; binder, same as for base.	Do.
2-B	2	do	do	Pea gravel.
2-C	2	do	do	Sand.
2-D	2	Asphalt, 100-120 penetration, cut back with naphtha.	do	Do.
2-E	2	do	do	Pea gravel.
2-F	2	do	do	Stone.
2-G	2	Asphalt, 150-180 penetration, cut back with naphtha.	do	Do.
2-H	2	do	do	Pea gravel.
2-I	2	do	do	Sand.
3	2	No. 5 road oil [1]	Primer, same as for base (for machine maintenance).	
4-A	3	No. 5 road oil with pressure still tar.[1]	None (for machine maintenance).	
4-B	3	No. 6 road oil with pressure still tar.[1]	do	
4-C	3	Flux A cut back with pressure still tar.	do	
5-A	2	Asphalt, 85-100 penetration, cut back with naphtha.	Primer, No. 4 road oil, with pressure still tar.	Soil.
5-B	2	do	Primer, asphalt, 150-180 penetration cut back with naphtha.	Do.
5-C	3	do	do	Do.
5-D	3	do	Primer, No. 4 road oil with pressure still tar.	Do.
6-A	2	Tar, 18-25 specific visc	Same as for base	Do.
6-B	3	do	do	Do.
6-C	2	do	Primer, same as for base; binder, tar, 25-35 specific viscosity (cold).	Stone.
6-D	2	do	Primer, same as for base; binder tar, grade 2 (hot).	Do.
6-E	2	do	do	Do.
7-A	2	Asphalt, 85-100 penetration, cut back with naphtha.	Primer, same as for base; binder, asphalt (hot), 150-200 penetration.	Do.
7-B	2	do	do	Do.
7-C	2	do	No primer; binder same as for base.	Do.
8		Untreated sand-clay	Primer, tar, 8-13 specific viscosity; binder, asphalt (hot) 150-200 penetration.	Do.

[1] Road oils Nos. 4, 5, and 6, conform to specifications OA4, OA5, and OA6, respectively, of Department Bulletin 691, Typical Specifications for Bituminous Road Materials.

(Continued from page 8)

3. Statistical laws which govern the relation between the results of the mechanical analysis and the results of the different simplified tests indicate that certain tests of Groups I and II reflect the influence of grain size as indicated by the clay, silt, and sand fractions. This is not true for the lower plastic limit, nor is it true for the shrinkage limit.

4. Statistical laws indicate that results of the moisture equivalent test are influenced primarily by the sand fraction, those of the lower liquid limit by both the sand and clay fractions, and the plasticity index is influenced by the clay fraction.

5. Considering the absence of any direct relation between the soil properties disclosed by the various simplified tests and those properties on which the quality of the subgrade actually depends, the measure of the practical value of any routine tests essentially depends on the speed and the facility with which the results can be obtained and the range of information furnished by the test results.

6. It is indicated that the plasticity and shrinkage determinations supplemented by the slaking test disclose more information on soil properties in proportion to effort expended than can be obtained from any other combination of simplified soil tests.

ROAD PUBLICATIONS OF BUREAU OF PUBLIC ROADS

Applicants are urgently requested to ask only for those publications in which they are particularly interested. The Department can not undertake to supply complete sets nor to send free more than one copy of any publication to any one person. The editions of some of the publications are necessarily limited, and when the Department's free supply is exhausted and no funds are available for procuring additional copies, applicants are referred to the Superintendent of Documents, Government Printing Office, this city, who has them for sale at a nominal price, under the law of January 12, 1895. Those publications in this list, the Department supply of which is exhausted, can only be secured by purchase from the Superintendent of Documents, who is not authorized to furnish publications free.

ANNUAL REPORTS

Report of the Chief of the Bureau of Public Roads, 1924.
Report of the Chief of the Bureau of Public Roads, 1925.
Report of the Chief of the Bureau of Public Roads, 1927.

DEPARTMENT BULLETINS

No. 105D. Progress Report of Experiments in Dust Prevention and Road Preservation, 1913.
*136D. Highway Bonds. 20c.
220D. Road Models.
257D. Progress Report of Experiments in Dust Prevention and Road Preservation, 1914.
*314D. Methods for the Examination of Bituminous Road Materials. 10c.
*347D. Methods for the Determination of the Physical Properties of Road-Building Rock. 10c.
*370D. The Results of Physical Tests of Road-Building Rock. 15c.
386D. Public Road Mileage and Revenues in the Middle Atlantic States, 1914.
387D. Public Road Mileage and Revenues in the Southern States, 1914.
388D. Public Road Mileage and Revenues in the New England States, 1914.
390D. Public Road Mileage and Revenues in the United States, 1914. A Summary.
407D. Progress Reports of Experiments in Dust Prevention and Road Preservation, 1915.
463D. Earth, sand-clay and gravel.
*532D. The Expansion and Contraction of Concrete and Concrete Roads. 10c.
*537D. The Results of Physical Tests of Road-Building Rock in 1916, Including all Compression Tests. 5c.
*583D. Reports on Experimental Convict Road Camp, Fulton County, Ga. 25c.
*660D. Highway Cost Keeping. 10c.
*670D. The Results of Physical Tests of Road-Building Rock in 1916 and 1917. 5c.
*691D. Typical Specifications for Bituminous Road Materials. 10c.
*724D. Drainage Methods and Foundations for County Roads. 20c.
*1077D. Portland Cement Concrete Roads. 15c.

DEPARTMENT BULLETINS—Continued

No. *1132D. The Results of Physical Tests of Road-Building Rock from 1916 to 1921, Inclusive. 10c.
1259D. Standard Specifications for Steel Highway Bridges, adopted by the American Association of State Highway Officials and approved by the Secretary of Agriculture for use in connection with Federal-aid road work.
1279D. Rural Highway Mileage, Income, and Expenditures, 1921 and 1922.
1486D. Highway Bridge Location.

DEPARTMENT CIRCULARS

No. 94C. T. N. T. as a Blasting Explosive.
331C. Standard Specifications for Corrugated Metal Pipe Culverts.

MISCELLANEOUS CIRCULARS

No. 62M. Standards Governing Plans, Specifications, Contract Forms, and Estimates for Federal Aid Highway Projects.
93M. Direct Production Costs of Broken Stone.
*105M. Federal Legislation Providing for Federal Aid in Highway Construction and the Construction of National Forest Roads and Trails. 5c.

FARMERS' BULLETINS

No. *338F. Macadam Roads. 5c.
*505F. Benefits of Improved Roads. 5c.

SEPARATE REPRINTS FROM THE YEARBOOK

No. *739Y. Federal Aid to Highways, 1917. 5c.
*849Y. Roads. 5c.
914Y. Highways and Highway Transportation.
937Y. Miscellaneous Agricultural Statistics.

REPRINTS FROM THE JOURNAL OF AGRICULTURAL RESEARCH

Vol. 5, No. 17, D– 2. Effect of Controllable Variables upon the Penetration Test for Asphalts and Asphalt Cements.
Vol. 5, No. 19, D– 3. Relation Between Properties of Hardness and Toughness of Road-Building Rock.
Vol. 5, No. 24, D– 6. A New Penetration Needle for Use in Testing Bituminous Materials.
Vol. 6, No. 6, D– 8. Tests of Three Large-Sized Reinforced-Concrete Slabs Under Concentrated Loading.
Vol. 11, No. 10, D–15. Tests of a Large-Sized Reinforced-Concrete Slab Subjected to Eccentric Concentrated Loads.

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* Department supply exhausted.

UNITED STATES DEPARTMENT OF AGRICULTURE

BUREAU OF PUBLIC ROADS

STATUS OF FEDERAL AID HIGHWAY CONSTRUCTION

AS OF

FEBRUARY 29,1928

GOVERNMENT PRINTING OFFICE

STATES	FISCAL YEARS 1917-1927			FISCAL YEAR 1928									BALANCE OF FEDERAL AID FUND AVAILABLE FOR NEW PROJECTS	STATES
	PROJECTS COMPLETED PRIOR TO JULY 1, 1927			PROJECTS COMPLETED SINCE JUNE 30, 1927			*PROJECTS UNDER CONSTRUCTION			PROJECTS APPROVED FOR CONSTRUCTION				
	TOTAL COST	FEDERAL AID	MILES	TOTAL COST	FEDERAL AID	MILES	ESTIMATED COST	FEDERAL AID ALLOTTED	MILES	ESTIMATED COST	FEDERAL AID ALLOTTED	MILES		
Alabama	$ 20,061,371.68	$ 9,615,099.94	1,400.2	$ 1,236,736.78	$ 595,970.35	79.1	$ 9,100,492.75	$ 4,426,605.45	498.8	$ 364,822.11	$ 182,411.03	36.3	$ 2,624,071.23	Alabama
Arizona	11,809,950.70	6,447,169.27	800.8	624,598.32	451,055.92	15.7	1,087,792.63	827,674.26	66.1	91,051.43	58,152.95	0.5	3,949,271.70	Arizona
Arkansas	22,337,014.63	9,525,192.75	1,560.6	152,842.19	72,184.34	13.4	4,631,806.95	2,060,254.76	227.7	681,701.85	340,850.92	14.2	2,167,002.23	Arkansas
California	35,128,269.04	16,967,026.82	1,306.3	4,314,968.39	1,974,069.47	101.1	7,151,646.44	3,227,432.68	142.8	278,091.63	158,949.52	9.5	4,715,188.51	California
Colorado	15,497,121.91	7,934,298.91	829.0	123,961.82	62,147.72	1.7	7,027,922.27	3,445,538.91	284.3	137,558.13	74,993.55	7.0	3,568,753.91	Colorado
Connecticut	6,397,392.29	2,444,000.54	137.3	1,352,857.40	367,626.33	17.7	5,712,748.89	1,597,373.38	69.6	1,139,177.58	191,246.72	12.0	680,332.03	Connecticut
Delaware	6,237,026.55	2,345,572.42	159.5	486,740.02	232,041.85	29.4	934,367.77	262,068.47	16.3				365,625.26	Delaware
Florida	7,476,856.31	3,627,912.60	245.1	4,232,517.04	2,026,119.95	83.1	5,890,343.66	2,456,558.94	136.3	1,065,050.69	413,332.63	27.8	1,361,791.88	Florida
Georgia	31,951,436.50	15,101,232.40	2,173.6	6,689,570.38	3,177,362.16	227.2	4,273,694.78	2,125,292.33	187.9	576,928.73	285,372.71	34.8	1,701,917.40	Georgia
Idaho	13,225,515.45	7,075,527.16	835.5	1,514,248.94	949,584.29	111.0	2,176,023.28	1,316,509.55	142.3	372,000.00	218,500.00	21.8	867,661.00	Idaho
Illinois	48,538,982.16	22,781,516.60	1,530.8	1,569,472.47	750,218.26	55.5	15,311,852.87	7,196,617.81	500.2	3,606,204.62	1,800,102.31	124.4	3,593,397.02	Illinois
Indiana	23,372,717.74	11,238,568.20	732.5	1,349,169.26	656,170.38	48.5	16,444,351.19	7,875,318.94	497.2	2,652,324.76	1,244,594.77	92.3	1.037,937.71	Indiana
Iowa	34,306,138.86	14,395,603.75	2,484.4	5,461,954.45	2,558,101.78	334.0	10,537,012.24	4,643,249.80	283.1	3,161,301.37	1,344,054.66	17.2	624,843.01	Iowa
Kansas	37,442,061.61	14,730,829.48	1,495.2	4,969,248.34	2,175,332.01	297.0	11,320,764.76	4,434,160.43	594.7	160,479.77	62,000.00	6.5	2,192,817.08	Kansas
Kentucky	23,216,600.53	9,510,694.75	874.9	1,762,380.04	810,911.86	78.0	9,101,025.50	4,298,703.55	394.5	50,000.00	25,000.00	5.4	1,406,474.84	Kentucky
Louisiana	15,877,552.20	7,093,892.21	1,178.7	1,332,121.58	597,801.48	48.7	5,135,234.16	2,415,139.55	143.0	1,972,200.89	845,811.25	103.9	352,353.51	Louisiana
Maine	10,564,800.06	4,858,452.67	357.6	1,721,246.42	649,751.76	56.4	1,504,499.76	536,989.44	39.4	87,912.01	43,956.00	5.6	1,737,903.13	Maine
Maryland	11,790,203.93	5,524,938.27	477.8	1,123,091.03	517,120.53	54.9	1,094,698.02	532,862.17	49.6				620,161.03	Maryland
Massachusetts	20,670,246.02	7,425,928.16	410.4	773,728.83	158,264.74	9.6	6,742,463.44	1,865,290.01	115.4	670,017.91	253,911.69	17.1	2,583,239.41	Massachusetts
Michigan	31,977,248.37	14,328,484.99	1,084.2	5,055,105.39	2,236,263.54	163.8	11,535,664.61	5,115,105.81	302.1	3,228,964.10	1,296,587.00	79.1	1,790,210.66	Michigan
Minnesota	45,099,648.47	19,046,145.67	3,643.5	5,852,424.86	2,001,398.90	248.7	4,027,299.75	1,203,100.00	216.7	2,755,557.79	822,000.00	117.1	752,471.43	Minnesota
Mississippi	18,331,230.75	9,004,294.62	1,314.1	2,350,525.54	1,161,642.92	127.4	5,611,980.42	2,704,661.12	292.2	534,593.39	267,296.68	30.9	1,607,730.66	Mississippi
Missouri	42,389,290.41	19,681,026.48	1,944.8	4,604,974.32	2,017,748.37	150.1	6,219,139.12	2,733,635.37	210.0	770,591.73	382,344.58	46.6	2,781,203.20	Missouri
Montana	12,854,995.72	7,287,288.69	1,151.6	489,287.01	349,014.14	57.8	4,102,067.93	2,872,304.60	328.7	1,075,181.41	595,984.70	122.6	5,424,367.87	Montana
Nebraska	16,157,040.25	7,739,386.39	2,246.6	4,868,348.71	2,350,493.10	491.3	11,133,051.68	5,488,936.73	1,088.0	652,054.90	323,638.77	63.3	1,902,899.01	Nebraska
Nevada	10,421,349.31	7,589,168.68	853.6	646,706.06	553,479.11	78.2	1,737,201.97	1,519,620.31	195.7	70,751.55	62,063.22	8.7	977,388.68	Nevada
New Hampshire	5,868,897.76	2,778,928.05	264.8	770,061.36	343,845.47	26.0	860,953.93	381,165.64	23.8	60,872.73	23,295.00	1.5	373,507.84	New Hampshire
New Jersey	22,228,240.08	7,495,364.48	316.3	4,104,873.30	1,092,705.00	72.8	3,609,234.53	736,624.17	47.9	341,175.49	117,102.35	8.2	895,357.00	New Jersey
New Mexico	13,336,250.94	7,937,598.06	1,505.2	1,201,108.18	780,538.63	92.4	2,775,504.98	2,193,025.93	182.8				2,437,347.38	New Mexico
New York	54,183,085.44	21,693,955.65	1,439.3	4,902,972.97	1,608,949.62	106.5	42,658,336.00	10,382,746.45	646.2	5,657,600.00	1,111,402.50	71.7	6,513,236.78	New York
North Carolina	35,295,849.21	14,518,903.16	1,460.1	2,995,878.13	1,394,904.59	109.2	1,925,134.96	910,448.18	46.8	405,969.75	202,259.87	6.7	2,119,956.20	North Carolina
North Dakota	15,881,558.55	7,746,293.68	2,715.6	3,577,440.70	1,978,919.27	459.4	3,664,691.54	1,810,554.43	581.1	803,054.61	363,598.66	156.9	1,237,683.96	North Dakota
Ohio	52,621,391.49	19,331,376.76	1,515.0	5,431,992.31	2,360,605.95	189.3	9,262,535.95	3,495,477.53	224.9	3,910,807.20	1,518,751.26	91.8	4,545,757.50	Ohio
Oklahoma	30,381,957.08	14,117,589.21	1,268.1	789,742.25	379,754.99	9.6	6,385,598.78	2,875,610.49	396.6	1,040,589.08	499,203.30	67.3	1,688,586.01	Oklahoma
Oregon	19,583,584.76	10,041,452.94	1,055.0	251,199.81	137,760.88	11.2	2,711,328.63	1,426,367.68	75.6	121,356.95	58,963.27	0.9	1,586,711.23	Oregon
Pennsylvania	77,726,174.22	26,317,620.32	1,534.3	5,222,540.90	1,648,904.59	114.3	17,090,664.30	5,136,174.58	315.3	2,859,445.23	914,454.30	57.4	3,991,148.21	Pennsylvania
Rhode Island	5,233,413.38	1,998,479.06	116.0	700,482.52	227,205.00	15.1	1,446,803.79	389,422.41	24.2	357,495.46	99,990.00	6.6	683,722.53	Rhode Island
South Carolina	17,002,039.93	7,526,988.80	1,568.4	2,124,613.95	1,013,264.39	69.0	8,633,545.44	2,525,564.55	230.7	2,340,146.60	390,000.00	44.7	460,227.26	South Carolina
South Dakota	19,262,063.24	9,507,525.54	2,502.9	817,654.40	440,893.32	156.0	4,578,599.88	2,424,376.33	672.9	516,180.98	262,051.18	95.6	975,988.63	South Dakota
Tennessee	24,283,035.03	11,551,457.55	868.7	2,840,769.08	1,280,556.31	71.2	7,790,805.93	3,249,298.59	209.8	1,644,421.58	788,610.33	62.2	1,637,446.22	Tennessee
Texas	78,190,246.37	31,566,960.45	5,466.4	8,039,061.10	3,680,171.03	282.4	15,464,959.64	6,599,069.38	494.3	3,434,733.01	1,392,610.64	100.3	6,367,467.50	Texas
Utah	9,154,377.33	5,767,079.95	628.9	1,046,447.43	766,587.30	94.5	2,565,950.26	1,900,190.36	156.0	366,406.99	162,890.09	21.6	917,030.30	Utah
Vermont	5,037,118.23	2,348,856.01	152.7	1,442,701.40	571,822.67	27.9	1,939,714.80	683,331.78	43.6	15,739.51	1,000.00	0.6	394,746.54	Vermont
Virginia	26,844,025.24	12,537,143.25	1,168.9	1,286,872.09	577,220.45	36.5	4,471,119.04	1,779,122.88	92.9	1,138,545.25	462,391.37	27.5	1,025,898.05	Virginia
Washington	18,184,505.97	8,246,551.95	711.1	1,359,328.87	586,736.32	32.3	4,293,090.35	1,884,600.00	113.5	1,053,266.08	325,000.00	13.9	1,377,645.73	Washington
West Virginia	10,424,847.32	4,573,748.01	419.4	3,116,200.38	1,202,718.18	85.3	5,176,565.25	2,251,111.80	194.9	129,443.32	64,721.66	6.7	847,643.35	West Virginia
Wisconsin	27,891,502.16	11,847,858.90	1,729.5	6,034,468.29	2,867,666.97	248.0	6,344,009.29	2,768,278.59	221.6				3,689,677.54	Wisconsin
Wyoming	12,650,712.15	7,139,267.05	1,315.9	1,503,999.96	962,836.11	83.6	2,169,196.59	1,382,696.58	224.1				955,390.26	Wyoming
Hawaii	343,364.15	97,440.00	6.5	866,148.12	275,109.33	14.1	915,459.37	276,727.46	15.6	301,973.75	60,383.43	3.2	1,121,742.78	Hawaii
TOTALS	1,154,740,601.48	510,007,691.24	60,957.6	125,085,383.09	55,631,551.63	5,385.9	326,278,950.07	134,642,990.16	12,257.7	52,653,741.92	20,111,834.77	1,849.9	97,230,932.20	TOTALS

* Includes projects reported completed (final vouchers not yet paid) totaling: Estimated cost $ 105,893,120.68 Federal aid $44,394,532.93 Miles 3,990.7