

The Science of Soil Stabilization

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This paper defines the science of soil stabilization and views soil systems from many different angles in order to lay the proper foundation for an understanding of the different soils encountered by the engineer, of the desirable and undesirable properties of these soils, and of the possible supplementation of these properties in order to change the soils into construction materials. This introductory paper is limited to the pointing out of important fundamentals and also to the presentation of certain approaches and data that are not normally found in soil-stabilization literature.

● THE science of soil stabilization is that body of principles that explains and guides the practice of soil stabilization. Soil stabilization, in its widest meaning, comprises every physical, physico-chemical, and chemical method employed to make a soil serve better its intended engineering purpose. In its specific meaning, as commonly understood in highway and airport engineering, soil stabilization is the name given to those methods of construction in which soils are treated to provide base courses, and occasionally surface courses, which can carry the applied traffic loads under all normal conditions of moisture and traffic for an economic service life of the paved area. The paved areas may be roads, airport aprons and runways, parking and loading places, feeding courts or other surface structures of comparable stability and durability requirements.

The major established uses of soil stabilization are: (1) lifting a country or region out of the mud or out of the sand for better economic development, now especially important for under-developed areas; (2) providing bases and surfaces for secondary and farm-to-market roads, where good primary roads are already in existence; (3) providing bases for high-type pavements where high-type rock and crushed gravel normally employed for such bases are not economically available; (4) for city and suburban streets where the noise-absorbing and elastic properties of certain stabilized soil systems possess definite advantages over other construction materials; and (5) for military and other emergencies where an area must be made trafficable within a short period of time.

Soil stabilization involves: (1) diagnosis of the resistance properties of a given soil and required supplementation of these properties for the intended use in physical,

physico-chemical, or chemical terms; (2) translation of the supplementary requirements into available materials and processes, and decision on use of specific method (or choice of method) on the basis of economy, practical feasibility, or special (military or other emergency) considerations; (3) construction, consisting normally of comminution, mixing with stabilizing material, and densification; and (4) economic considerations relating to the total cost composed of cost of materials, construction, and maintenance for the service life of the structure.

There exists a tendency on the part of laboratory workers to overlook the importance of Items (3) and (4). This may lead to a dangerous self-deception and may even impede the proper development of the science of soil stabilization. This science is not a pure but an applied one, and the actual processes of application must not only be considered but must be analyzed scientifically in order that the most rational and most effective, i. e., the most economical, method of construction be used in each particular case. In many cases, the use of a chemical construction aid may increase only slightly the cost of stabilizing materials but decrease greatly the cost of construction by facilitating the mixing and compaction process.

SOILS AND THEIR PROPERTIES

The term "soil" covers a large variety of materials existing under widely differing conditions. For a thorough understanding of soils and their properties it is well to look at them from different angles. A first step is to list definitions of the term soil as employed by different disciplines that deal intensively with the material covered by this term.

DEFINITIONS OF THE TERM "SOIL"

Highway Engineering

Soil consists of disintegrated rock and organic matter found on the surface of the earth, the particles of which may range in diameter from less than 0.0001 inch to a few inches and in which the fines are a product of natural, weathering forces. Soil may or may not contain organic matter. Engineering soils include bank gravel, bank sand, blow and dune sand, agricultural soils ranging from those of predominately sandy texture to colloidal clays, and mixtures and combinations of these (1).

The different size fractions of the mineral portions of soils are named and defined in Table 1.

Textural classification of soil is based on gradation. The scheme of classification and naming is shown by Figure 1.

Geology

Soil is the superficial unconsolidated mantle of disintegrated and decomposed rock material, which when acted upon by organic agencies, and mixed with varying amounts of organic matter, may furnish conditions necessary for the growth of plants. In its broadest sense the term "soil" has been used to include all the mantle of rock decay (2).

Pedology

Soil is the climatically conditioned petrologic and biogenic transformation product of the outermost layer of the solid earth crust (3); it is a natural body, differentiated into horizons varying in type and amounts of mineral and organic constituents, usually unconsolidated and of varying depths (4); soil is a unique creation that differs from the parent material below in morphology, physical properties and biologic characteristics; and the soil mantle of the earth may be termed "the pedosphere" alongside the atmosphere, the lithosphere, and the hydrosphere (5). The pedologic soil is a dynamic system subject to temperature, moisture, and biologic cycles and developing in a certain genetic direction under the influence of climate. The rate of this development is influenced by parent material, vegetation, and human activity (6).

With respect to scientific content and general usefulness, the pedologic soil concept is the most important. It has resulted in a natural system of soil classification and soil mapping which, though originally qualitative, can be easily supplemented with semi-quantitative and quantitative engineering information. General pedological soil maps exist for practically every part of the world. For many localities, soil maps are available on a scale as low

TABLE 1
Size Fractions of Mineral Portions of Soils

Name	In Inches		In Millimeters		By Sieve Number		
Gravel	3.0	to	0.08	76.2	to	2.0	3-in. to No. 10
Sand	0.08	to	0.002	3.0	to	0.05	No. 10 to No. 270
Silt	0.002	to	0.0002	0.05	to	0.005	
Clay			<0.0002			<0.005	
Colloids			<0.00004			<0.001	

as one inch to the mile.

Pedological soil types can be recognized easily from air photographs (7) and certain conclusions with respect to soil stabilization can be drawn solely from recognition of the pedological soil type of a certain area. The principal soil areas of the world are shown in Figure 2. The climatic and vegetational soil types of the United States are shown in Figure 3. The general and specific application of pedology to engineering is treated in detail by Woolton in the third paper of this symposium.

SOIL AS A POLYDISPERSE SYSTEM

Soil is a polydisperse system composed of (1) solid inorganic and organic particles, (2) an aqueous phase carrying matter in solution (and sometimes in dispersion), and (3) a gaseous phase of varying composition. The gaseous phase is functionally related to biologic activity. The aqueous and the gaseous phases are usually considered together as pore space or porosity. The porosity varies in amount and in dimensional and form characteristics from soil to soil, from layer to layer, and in the surface layers from season to season.

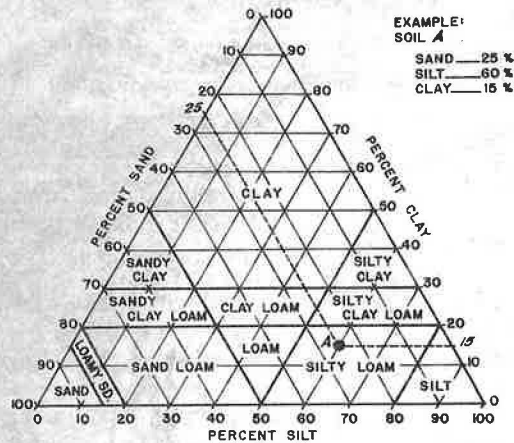
Characteristics of the Solid Phase

Soils as polydisperse systems may contain particles ranging from atomic size (10^{-8} cm) to gravel and stone size. Since the soil information of greatest interest is found mostly in the international pedologic

literature it is indicated to use the accepted international terms and definitions in presenting granulometric compositions.

Designation	Diameter in mm
Stones	>20
Gravel	20 - 2
Coarse sand	2 - 0.2
Fine sand	0.2 - 0.002
Silt	0.02 - 0.002
Clay	<0.002

Materials larger than 0.02 mm. are usually called granular; those smaller than 0.02 are called silt-clay materials. Soils containing more than 65 percent of coarse material are called granular soils; those containing more than 35 percent of silt and clay are called silt-clay materials.



SOIL CLASSIFICATION CHART

Figure 1

In a compacted state, granular soils contain a granular skeleton giving them good volume stability and friction properties, while the silt-clay materials show volume changes with changing moisture content and possess low angles of internal friction.

Soils are given textural names in ac-

TABLE 2
Mechanical Composition of the Principal Soil Classes

Soil Class	Limits in the proportions of the Soil Separates		
	sand %	silt %	clay %
Sand	80 - 100	0 - 20	0 - 20
Sandy loam	50 - 80	0 - 50	0 - 20
Loam	30 - 50	30 - 50	0 - 20
Silty loam	0 - 50	50 - 100	0 - 20
Sandy clay loam	50 - 80	0 - 30	20 - 30
Clay loam	30 - 50	20 - 50	20 - 30
Silty clay loam	0 - 30	50 - 80	20 - 30
Sandy clay	55 - 70	0 - 15	30 - 45
Silty clay	0 - 15	55 - 70	30 - 45
Clay	0 - 55	0 - 55	30 - 100

cordance with the identification chart in Table 2; this was taken from Reference 8, and also represents international pedologic usage:









Combining the silt and clay fractions as silt-clay materials, we may establish three major physical groups of mineral soils.

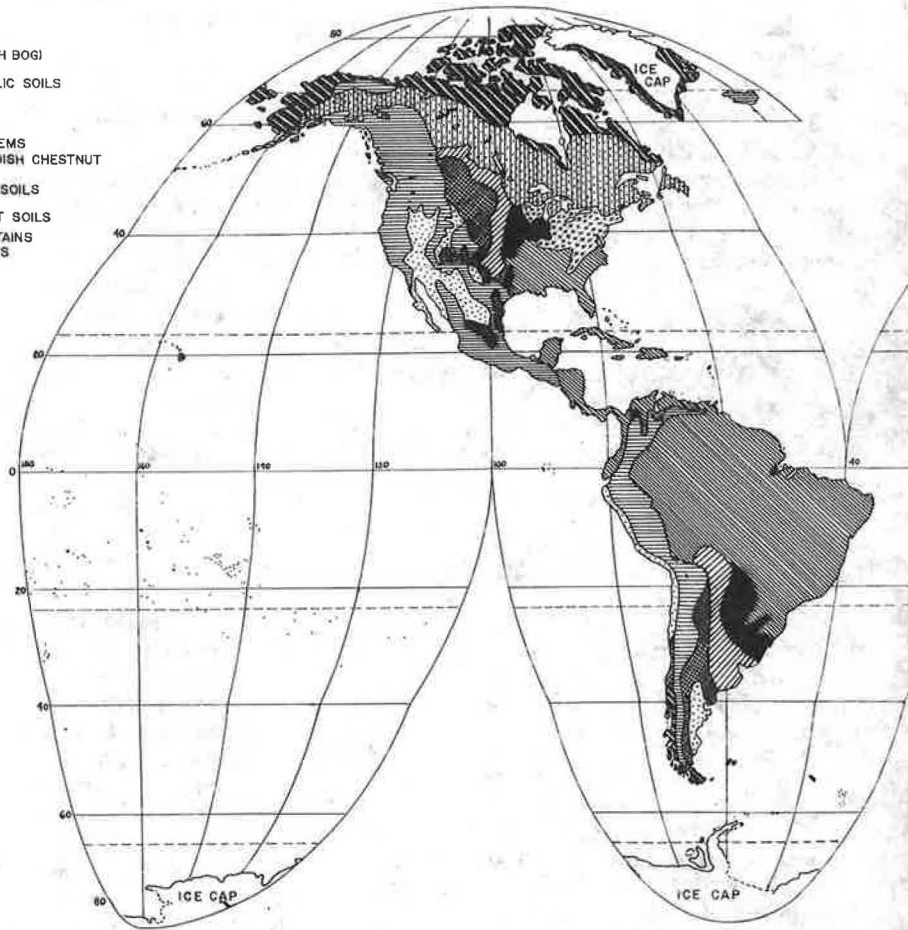
Designation	Percentage silt-clay
Granular soils	0 - 20
Cohesive-granular soils	20 - 35
Cohesive-nongranular soils	35 - 100

During the early days of agricultural chemistry it was quite common to make gross chemical analyses of soils and soil materials. However, the analytical data did not indicate the availability as plant food of the determined elements, nor were they of diagnostic significance with respect to other soil properties of practical agricultural value. This type of analysis was succeeded by determination of plant-food values, on one hand, and of the granulometry and mineralogy of the solid soil constituents on the other hand. The recent introduction of nuclear meters for determinations in situ of soil moisture and soil density, and the possibility of further development for other purposes of this type of methodology has given real scientific and practical value to the "obsolete" data on elementary soil composition. Most of the best data on elementary soil composition are found in the older rather than in the newer soil literature.

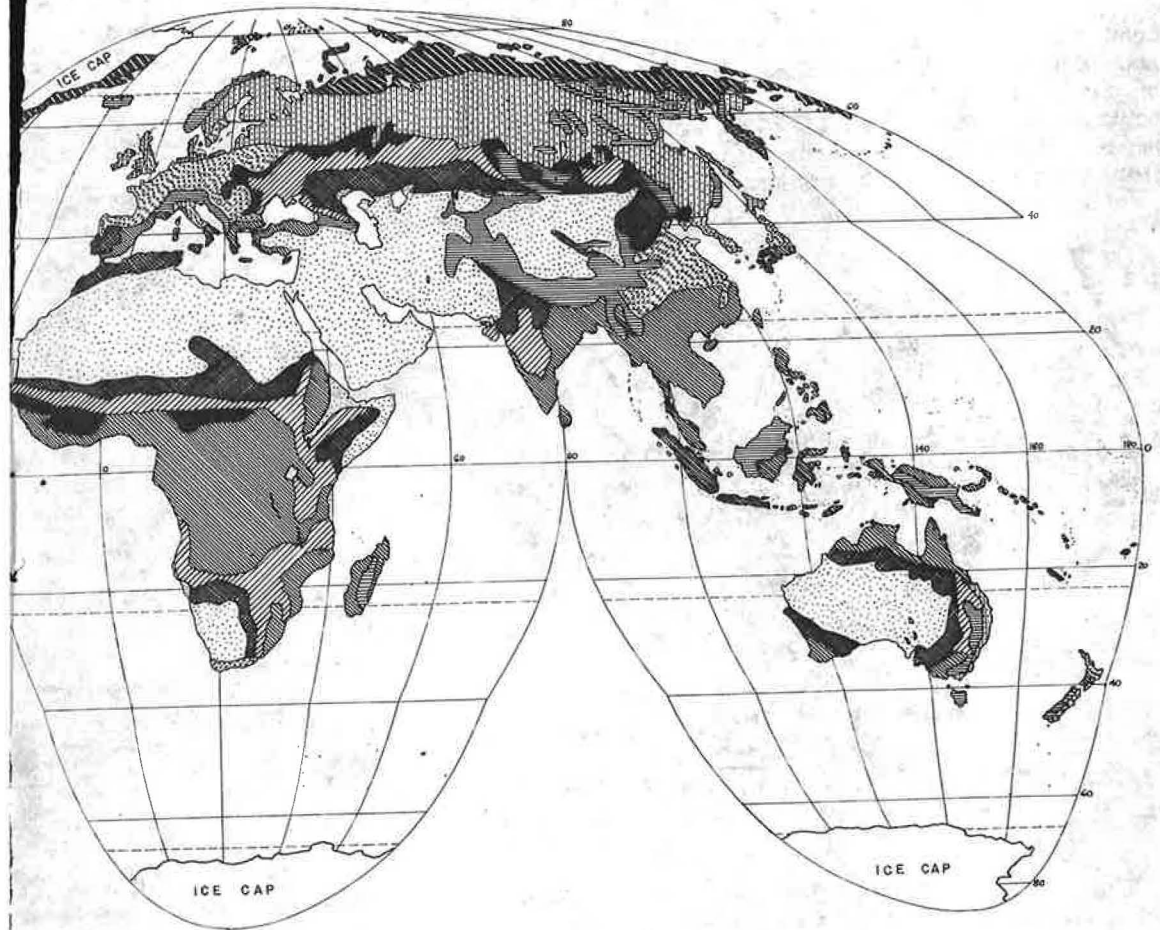
Considering the great variability of the chemical composition of the parent materials from which soils are formed, an equally great variability in soil composition may be expected. Fortunately, the active soil-genetic factors reduce this variability by something akin to an analytical separation on a gigantic scale. This separation brings about: (1) breakdown of complicated pyrochemical minerals into simpler hydrochemical compounds; (2) complete or partial removal of soluble reaction products or their concentration in specific layers of the soil profile; and (3) dislocation of colloidal and clay-sized particles and their concentration in specific layers of the soil profile.

The most general chemical soil classification was made by Marbut (9) by dividing soils into two general classes: (1) Pedalfers, soils of humid climates (pre-

-  TUNDRA
-  PODZOLS (WITH MUCH BOG)
-  GRAY-BROWN PODZOLIC SOILS
-  LATERITIC SOILS
-  PRAIRIE SOILS & DEGRADED CHERNOZEMS
-  CHERNOZEMS & REDDISH CHESTNUT SOILS
-  CHESTNUT & BROWN SOILS
-  SEROZEMS & DESERT SOILS
-  SOILS OF THE MOUNTAINS & MOUNTAIN VALLEYS



Figure



precipitation > evaporation, therefore, water percolation and elutriation) possessing a relative concentration of iron and aluminum compounds in one of the profile horizons and (2) Pedocals, soils of semi-arid and arid climates (precipitation \leq evaporation) possessing a CaCO_3 concentration zone within or on the surface of the soil profile.

The general shift from the chemical composition of parent rock to that of the A and B horizons of soils and the difference in chemical composition of the A and B horizons is shown in Table 3. This table presents analytical data reported by Clarke (10) as oxides but herein transposed into elementary composition.

for peat and bog soils. It is usually below 20 percent, but a heavy clay soil may contain over 10 percent of water and still may be dry and dusty to the eye and to the touch.

Soil organic matter is a mixture of many different compounds, the more important of which are carbohydrates, proteins, fats and resins, and waxes. The absolute amounts and relative proportions of these compounds vary with the climate and with macrobiologic and microbiologic activity in the soil. The organic matter is concentrated in the surface layers and decreases with increasing depth in the soil. It ranges from less than 1 percent in inorganic soils and sands to almost 100 percent of the solid matter in peat bogs.

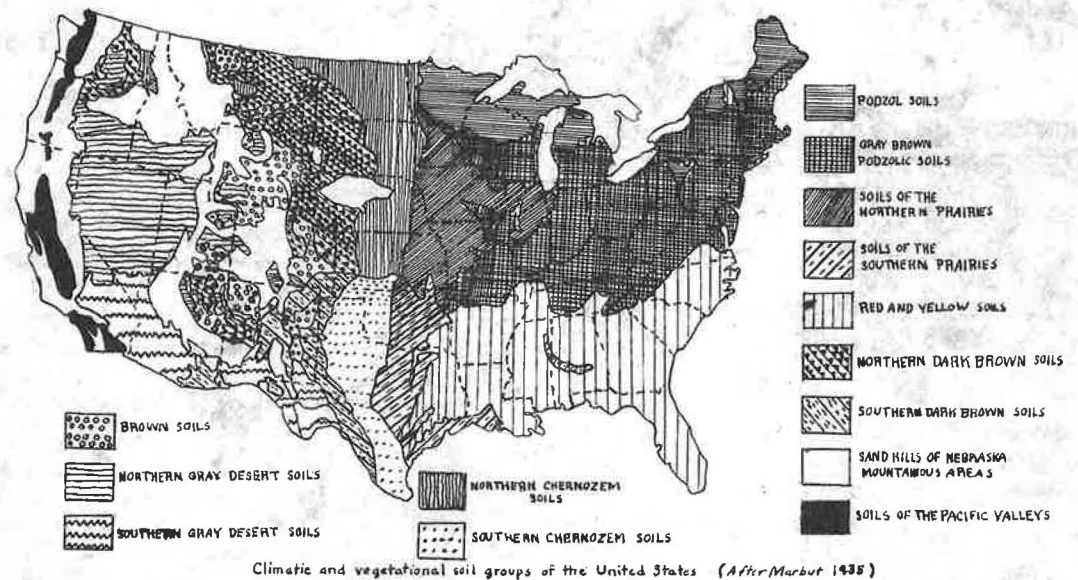


Figure 3

The elementary composition given in Table 3 refers only to the solid soil mineral matter and does not contain the contribution made by the variable soil moisture and the soil organic matter. Soil moisture provides additional O and H atoms, soil organic matter mainly C, N, O, H, S, and P atoms. Soil moisture is usually expressed as a weight percentage of the solid soil matter dried at 110 C. in accordance with the formula:

$$\text{Percentage moisture} = \frac{\text{wet weight} - \text{dry weight}}{\text{dry weight}} \times 100$$

Soil moisture may vary from less than 1 percent for dry sand to over 100 percent

In the semiarid Chernozem soils, the organic matter may run up to 10 percent of the weight of the dry soil. The average carbon content of humus is 56 percent. The average carbon-nitrogen ratio is 10 to 1. A value of 10 percent of organic matter, therefore, corresponds to 5.6 percent of carbon and 0.56 percent of nitrogen. Lateritic soils of the wet tropics, despite their often brilliant red and yellow inorganic appearance, have been found to contain up to 2 percent and more of organic matter.

The total amount of carbon in a soil is the sum of that contributed by the organic matter and that present in the profile as inorganic carbonates, especially those of

C_a and M_g . Horizons enriched in C_a and M_g are typical of Pedocal soils.

The words sand, silt, and clay have been introduced and defined earlier as designating certain size fractions of the ultimate particulate components of soils. It is of interest to see what conclusions with respect to soil chemical composition may be drawn from recognition or determination of the granulometry of a soil.

TABLE 3
Average Elementary Composition of the Earth Crust and of the A and B Horizons of Soils

Element	Earth crust (percent)	Soil	
		A Horizon (percent)	B Horizon (percent)
Al	7.13	5.30	6.24
Fe	4.38	2.35	4.05
Ca	3.52	.74	.71
Mg	2.35	.38	.51
K	2.54	1.43	1.71
Na	2.52	.81	.81
Mn	.08	.38	.09
Ti	.47	.54	.54
P	.13	.06	.06
S	.13	.05	.05
Si	28.00	35.10	35.70
O ^{a)}	48.18	52.78	49.73

a) Oxygen percentage does not include contribution from free water content.

Sand (2.0 - 0.02 mm.) is predominately quartzic and silicic in humid climates but may be any kind of mineral in dry climates. The white sands of New Mexico are gypsum sands; coral and shell beach sands may consist almost completely of calcium carbonate; the black sand of Yellowstone Park and some of the blue and purple beaches of the Pacific Islands are obsidianite sands as are some of the Alaskan and Aleutian beach sands (11).

TABLE 4
Elementary Composition of Silt Components

Minerals	Formula	Percentages Elementary Composition						
		O	Si	Al	K	Na	H	F
Feldspars:								
Orthoclase	$KAlSi_3O_8$	41.5	33.0	10.4	15.0	0	0	0
Albite	$NaAlSi_3O_8$	44.3	35.0	11.1	8	9.5	0	0
Muscovite:	$(OH)_2KAl_3(Si_3AlO_{10})$	44.0	21.0	20.2	9.8	0	0.24	4.7
Quartz:	SiO_2	53.2	48.6	0	0	0	0	0

Silt (0.02 to 0.002 mm.) particles resemble quite closely the composition of the parent rock with feldspar, muscovite, and quartz usually well represented. Representative formulas and compositional data are given in Table 4. We may conclude that in the silt fraction the silicon content ranges between 21 percent and 47 percent and the oxygen content between 42 percent and 53 percent.

The older soil literature contains many excellent data on chemical composition of the clay fraction (0.002 mm.) of different soils and soil categories. Many physical properties of clay systems could be related to ratio $SiO_2/Al_2O_3 + Fe_2O_3$ found in

chemical analysis of the clay, and it became a widespread practice to characterize natural clays by this ratio. In laterite soils this ratio falls below two; in other soils it is above two; it is two in the clay mineral kaolinite. Typical ratios (12) are given in Table 5.

During the last 25 years it has become possible to extract and recognize more or less pure crystallized minerals from the clay fraction. This development is treated in an excellent manner by Hauser in the fourth of this symposium. However, in view of the expected further development of nuclear meters that probe into atomic and nuclear compositions, it was considered worthwhile to present in Table 6 the elementary chemical composition of the principal clay minerals, as calculated from the oxide data given in (13).

The data on chemical composition of soil constituents are summarized in Table 7.

Characteristics of the liquid phase

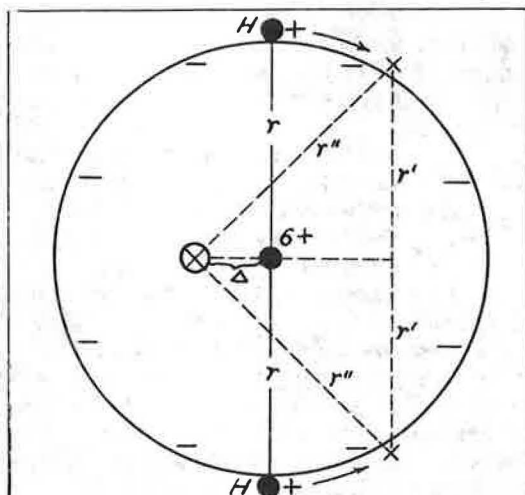
The chemical formula for water is H_2O , which represents a composition of 88.8 percent (by weight) of Oxygen and 11.2 percent Hydrogen. The H_2O molecules, however, because of their electric structure (Figure 4) are associated as well as dissociated as a function of temperature. Quantitative values are given below:

Temperature ($^{\circ}C$)	Concentration of H/and OH^- ions in pure water
0	2.8×10^{-8}
8	7.8×10^{-8}
25	1.0×10^{-7}
34	1.45×10^{-7}
50	2.3×10^{-7}

Association of Water Molecules as a Function of Temperature, From Raman spectra (14)

Temperature ($^{\circ}C$)	H_2O	$(H_2O)_2$	$(H_2O)_3$
Ice	0	41	59
Water at 0	19	58	23
Water at 38	29	50	21
Water at 98	36	51	13

Although the molecular size of a compound is indeterminate in the solid state



TRIANGULAR SHAPE OF THE H_2O -MOLECULE AS A RESULT OF THE POLARIZABILITY OF THE OXYGEN ION ¹⁾

1. Potential Energy when H-ions and oxygen nucleus fall on a straight line. Repulsion of positive parts:

$$\frac{+ 2 \times 6e_0^2}{r} + \frac{e_0^2}{2r}$$

e_0 = charge of one electron

Attraction between electron Shell and H-ions:

$$: \frac{- 2 \times 8e_0^2}{r}$$

$$= 4.77 \cdot 10^{-10} \text{ electrostatic units.}$$

2. Potential energy when H-ions are moved as indicated by arrows.

$$\text{Repulsion: } \frac{2 \times 6e^2}{r''} + \frac{e^2}{r'}$$

Attraction: Same as above.

At small dislocations r'' increases at greater rate than r' decreases. Equilibrium = lowest potential energy if H^+ positions are at an angle between 100° and 110° .

¹⁾ After Born, Heisenberg and Hund, Zsch. f. Physik 23, 388; 26, 196 (1924) 31, 81; 32, 1 (1925); Eucken, Arnold "Lerhbuch der Chemischen Physik," Leipzig, 929, (1930).

Figure 4

Tammann (15) and Bridgman have shown the existence of five different types of solid water that are functions of pressure and temperature conditions. Four of these types have corresponding liquid phases (see Figure 5).

The temperatures and pressures in the triple points of the one-component H_2O -system are given below:

Phases in Equilibrium	Temperature $^\circ C$	Pressure (kg/cm ²)
Water-Ice I-Ice III	-22	2050
Ice II-Ice-I-Ice III	-34.7	2170
Water-Ice V-Ice III	-17.0	3530
Water-Ice V-Ice VI	- 0.16	6380

The melting point of water decreases with increasing pressure to a minimum at $-22^\circ C.$ for 2,050 kg. per sq. cm; subsequently it increases, passing the $0^\circ C.$ mark around 6,300 kg. per sq. cm. and passing through $45^\circ C.$ at about 12,000 kg. per sq. cm.

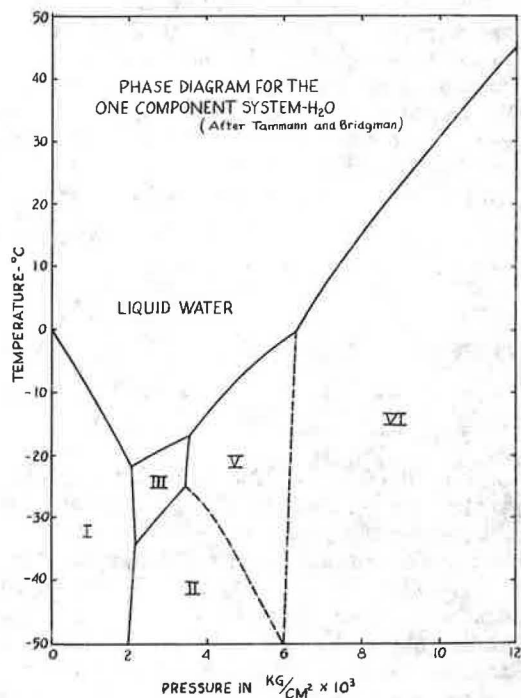


Figure 5

These data have been presented because: (1) The peculiar behavior of water is due to the polarity of its molecule; that is, its electric and geometric properties. (2) The large adsorption forces exerted on water molecules by the surfaces of

TABLE 5

Relationship Between Silica-Sesquioxide Ratio and Base Exchange Capacity

Clay	Base Exchange capacity ME/100 gm	Source	Ratio SiO ₂ /R ₂ O ₃
Cecil	13	An Alabama clay loam	1.3
Susquehanna	47	Well-oxidized Alabama soil	2.3
Putnam	65	Heavy Missouri silt-loam	3.2
Wabash	78	Missouri alluvial clay	3.2
Lufkin	82	Black Belt soil from Alabama	3.8
Montmorillonite	95	From Wyoming Bentonite	5.0

Note: The base exchange capacity represents the milliequivalents of cations adsorbed on the surface of 100 grams of colloid and exchangeable for other cations that may be introduced into the system.

solid soil particles act similar to externally applied pressures; that is, they may liquify solid water or solidify liquid water. (3) Adsorption forces of the order of magnitude that solidify water at 45 C. (12,000 kg. per sq. cm.) are not at all uncommon

such as exist on the surfaces of the particulate matter in soils.

Water in soil is never pure but holds materials in solution and dispersion. Dissolved materials are mainly salts and acids. In saline soils the solutions may

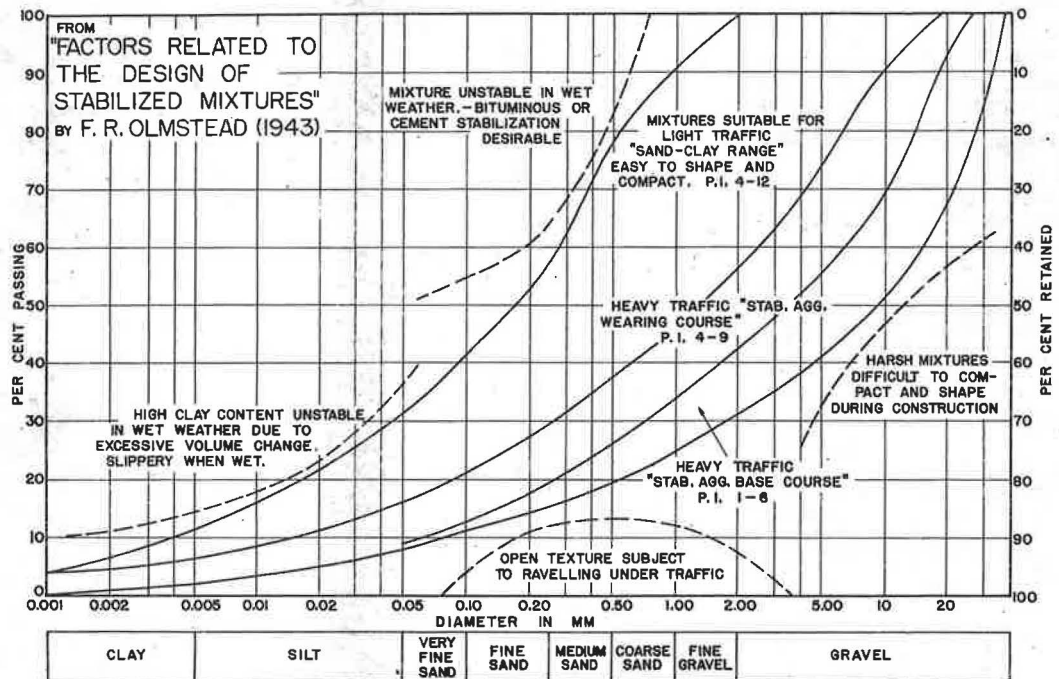


Figure 6

on the surfaces of soil particles. (4) All physical properties (mechanical, electrical, optical, acoustical) of cohesive soils are functionally connected with the behavior of the water substance in strong pressure, electrical and magnetic fields

actually be saturated with different salts. In humid climates the solute concentration is relatively low. The water layers next to the solid particles are under high adsorption pressures, which may be larger than 25,000 kg. per sq. cm. The water

may be in a solid condition at temperatures above 50 C. The adsorption forces decrease exponentially to about 50 kg. per sq. cm. at the so-called hygroscopic moisture content, and hence more slowly to zero for the water content at which the soil-water system behaves essentially as a liquid (liquid limit). The course from hygroscopic moisture content to the liquid limit is illustrated by the following data (13).

Condition	Adsorption pressure in kg. per sq. cm.
Hygroscopicity	50
Permanent wilting point	12.5
Wilting point (dead water)	6.25
Vacuum moisture equivalent	0.55

The hygroscopicity of a soil increases with increasing clay content and with increasing $\text{SiO}_2/\text{R}_2\text{O}_3$ ratio of the clay. At the interphase between the surface of the solid soil components and the water film an electric potential is established, which gives rise to electrokinetic phenomena in soils. The magnitude of this potential and the thickness of the interphase or electric double layer is a function of the surface-

condition is called the plastic limit (17); that at which the soil passes into a liquid condition is called the liquid limit. These limits, like the hygroscopic water content, increase with increasing clay content and with increasing $\text{SiO}_2/\text{R}_2\text{O}_3$ ratio of the clay and are, in addition, functions of the type and amount of exchange ions on the clay and of the ions in the aqueous phase.

The mechanical resistance of cohesive soils increases with decreasing water content. Physical properties that increase with increasing water content are: permeability to water, dielectric constant, heat conductivity, and sound velocity. Properties that rise to a maximum and subsequently fall with increasing water content are: electric conductivity, electro-osmotic water transmission (16), thermo-osmotic water transmission (18, 19), and ease of compaction or density achieved with a certain compactive effort.

Properties of soil-air

The portion of the soil porosity not filled with water represents the soil-air. Soil-air is in constant exchange with the atmosphere and its composition reflects that of the atmosphere except for the concentration of those components that are

TABLE 6
Percentage of Elements in Common Clay Minerals

Mineral Element	Mica-like Minerals					
	Kaolinite	Halloysite	Montmorillonite	Beidellite	Nontronite	Mica-like Minerals
Si	20.6-25.3	18.9-21.7	22.6-24.2	21.4-22.3	14.7-22.5	23.7-24.5
Al	15.9-21.3	17.9-20.8	10.6-14.4	6.4-14.7	0.21-12	11.5-17.4
Fe	0.22-1.46	0-0.29	0.15-1.02	0.58-13.5	11.0-29.8	0-4.6
Mg	0-0.6	0-18	1.26-3.96	0.12-1.8	0.06-2.4	1.2-2.7
Ca	0.021-1.1	0.06-0.57	0.6-2.6	0.35-2.0	0.43-3.2	0-0.42
K	0-1.25	0.25	0.17-0.5	0.08	0.08-0.32	5.1-5.7
Na	0-0.89	0.074-1.48	0.22-0.59	0.07-0.74	0-0.15	0.07-0.37
Ti	0-0.86	-	-	0.48	0-0.06	0.3
H ^a	1.2-1.6	1.5-2.6	1.9-2.63	1.9-2.5	0.56-1.44	0.71-0.78
O ^a av.	53.79	56.62	57.18	56.06	50.45	50.22
H ₂ O contents included in H and O above	11.0-14.3	13.4-23.7	17.1-23.7	17.3-22.6	5.1-13.0	6.4-7.0

Note: ^a This includes the contribution from hydration and other strongly absorbed water which does not make the clay wet.

chemical composition of the solid, of the amount of water present, and the type and amount of ions carried in solution (16).

The water content at which a soil passes from an essentially solid to a plastic con-

dition is called the plastic limit (17); that at which the soil passes into a liquid condition is called the liquid limit. These limits, like the hygroscopic water content, increase with increasing clay content and with increasing $\text{SiO}_2/\text{R}_2\text{O}_3$ ratio of the clay and are, in addition, functions of the type and amount of exchange ions on the clay and of the ions in the aqueous phase.

used up or produced by microbiological activity in the soil. Such substances are mainly oxygen, which is used up, and carbon dioxide, which is produced. Atmospheric air contains 20.939 ± 0.004 volume

TABLE 7
Average Elementary Composition of the Different
Size Fractions of Soils

Dominant Elements	Percentage of dominant elements		
	in Clay	in Silt	in Sand ^a (average comp. humid climate)
O	50 - 57	41 - 53	41 - 53
Si	15 - 25	21 - 47	21 - 47
Al	02 - 21	0 - 20	0 - 20
Fe	0 - 30	0 - 5	0 - 5

Note: ^a For special sands (desert, coral, shell, and other beach sands) the chemical composition must be individually ascertained.

percent of oxygen and 0.031 ± 0.0016 volume percent of CO₂. According to Ebermeyer (20) the proportion of CO₂ in the soil atmosphere is a function of all the physical and chemical factors that condition soil activity and productivity. Typical data found by him for the CO₂ content at 70 cm. depth in volume percent of the soil atmosphere are given below:

Humus-free, fine granular quartz sand	0.340
Humus-free, coarse granular quartz sand	0.340
Humus-free, fine granular lime sand	0.548
Humus-free, heavy, clayey loam	0.726
Humus-free, loess loam	0.745
Humus-and lime-containing loam	1.314
Humus-containing sandy loam	

garden soil	1.638
Humus-rich, fertilized, loamy sand soil	1.876
Moor soil	6.649
Garden soil, very rich in humus and lime	6.880
Fertilized with stable manure	7.020

The oxygen content of soil-air decreases as a function of the increase of the CO₂ content, since the CO₂ is derived from the Oxygen. More detailed data on soil-air can be found in the pertinent chapters of References 13 and 13a.

It is often desirable to know the actual volume of solids in a given volume of natural soil. Representative values for different soils are given below:

Soil Type	Pore space %	Volume of solid particles %
Moor soil	84.0	16.0
Sand soil	39.4	60.6
Loess loam	45.1	54.9
Clay soil	52.7	47.3

Natural soils always possess air spaces even if allowed to take in all the water they can. Of course, after long-time flooding this air space may be rather small. The air capacity necessary for the normal growth of different plants is quoted in (13) (p. 281).

TABLE 8

COLLAMERITICS

The Science of Composition and Properties of Non-Metallic Construction Materials

based on		
Properties of the aggregates	Properties of Cementing Agents	Combination of Aggregates and Cementing Agents.
A Physical	A Inorganic	A Design of
I Granulometry Laws of Arrangement and Packing as a function of 1) Size and gradation 2) Shape factors a) spherical b) cubic c) plate-like d) needles and fibers	I Simple: Gypsum and lime Plasters. II Complex: Sorel and hydraulic cements.	I Mortars with inorganic or organic cements. II Concretes: Portland Cement-, bituminous-resinous-, clay-, etc.
II Mechanical 1) Strength and toughness 2) Abrasion resistance	B Organic I Bituminous: asphalts, pitches, tars. II Natural and synthetic Resins, elastomers and related substances.	III Plastics: Powder-, paper- and fiber-filled.
B Physico-Chemical and Chemical	III Gums and Glues	
I Reactivity and Bonding with cementing materials		
II Reactivity with deleterious substances		

Plant	Air Capacity %
Sweet grasses	6 - 10
Wheat	10 - 15
Oats	10 - 15
Barley	15 - 20
Sugar beets	15 - 20

THE SOIL IN SITU

Soils are creations of climatic forces and may be considered attuned to them. These forces derive from daily and seasonal temperature variations, from fluctuations in moisture content, from the annual swell and sink of the biologic potential, and from any other periodic phenomenon that affects the surface layer of the earth. As a result of these factors, soils in situ are not mixtures of their components but are natural organized systems, as was shown in the section on soil genesis.

These systems continue to be exposed to the forces that formed them and their properties are in a continuous state of flux. As a result of this situation, soils in situ share many essential properties with "living" systems and may almost be considered as living even if we disregard the large microflora and microfauna dispersed in soils that render soils actual living systems. Important consequences of this fact are discussed by Woollorton in his excellent and comprehensive contribution to this symposium (paper No. 3 on Engineering Pedology and Soil Stabilization).

Soil Aggregations

The primary particles of a soil are very rarely encountered as independent individual constituents but are cemented together into secondary aggregations and crumbs by means of inorganic or organic binders (21). The stronger secondary particles even persist in disturbed and molded specimens, which results in relatively large angles of friction of clay soils in the molded wet or in coherent air-dry condition. The aggregation increases the size of the soil pores which results in a greater permeability for water and air (in accordance with Poiseuille's law) than the soil would have in single-grain structure even at the same porosity value.

Soil Dynamics

The periodic daily and seasonal warming and cooling of the earth surface result in a temperature wave penetrating into the soil. The physical picture is as follows: (1) the normal daily and yearly temperature fluctuations on the surface of the earth can be expressed as sinusoidal waves; (2) because of the heat conductivity of the earth, these surface waves are transmitted into the interior; however, the amplitudes (differences in temperature) are dampened because of the heat capacity of the earth substance; and (3) because of the time necessary for heat transmission, the maximum of the dampened temperature waves become increasingly retarded with increasing depth of penetration until at the depth of one wave length, the retardation equals the time period. For the same reason, the time of highest temperature at the soil surface is the time of lowest temperature at a depth of one-half wave length.

These relationships can be expressed mathematically as follows: The speed of propagation of the temperature wave is:

where

$$V = \frac{\lambda}{T}$$

$$\text{Since } \lambda = 2 \sqrt{\frac{\pi k T}{\rho c}}$$

$$V = 2 \sqrt{\frac{\pi k}{c \rho T}}$$

The speed of progression of the temperature wave is therefore inversely proportional to the square root of the period, while the wave length is directly proportional to the square root of the period. In other words, a long period has a long wave with a small speed of propagation, while a short period has a short wave with a great speed of propagation.

Since the square root of 365 is about 19, the length of the daily temperature wave is only $\frac{1}{19}$ of that of the yearly wave.

The maximum amplitude θ_x at a distance x from the surface is the following function of the maximum amplitude θ on that surface.

$$\theta_x = \theta e^{-\frac{2\pi x}{\lambda}}$$

$$\text{If } x = \lambda, \text{ then } \theta_{\lambda} = \theta e^{-2\pi} = \theta \frac{1}{535}$$

$$\text{If } x = \frac{\lambda}{2}, \text{ then } \theta_{\lambda/2} = \theta e^{-\pi} = \theta \frac{1}{23}$$

The damping effect is usually expressed by the ratio of the amplitudes at a distance of one-half wavelength. The damping ratio is therefore 23, which means that an amplitude of 23 deg. on the surface is reduced to 1 deg. at a distance of one-half wavelength.

Employing average values in the cgs. system for physical soil constants, namely:

$$\begin{aligned} k &= 0.004 \\ \rho &= 1.6 \\ c &= 0.4 \end{aligned}$$

we obtain for the length of the yearly wave:
= 1,560 cm.

and for the length of the daily wave:
= 82.4 cm.

L. A. J. Quetelet (1796-1874) who made the first reliable soil-temperature determinations gave 17 m. as the length of the yearly wave and 1 m. as the length of the daily wave. He also noted that, because of heat convection, the actual amplitudes at the lower depths were somewhat greater than calculated. The magnitude of the amplitudes at the lower depths is illustrated by the following data by Quetelet:

Depth m.	Observed m.	Calculated m.
0.19	13.28	13.28
0.37	11.35	10.28
1.95	7.6	.9
3.9	4.5	-
7.8	1.4	.6

For actual soil conditions, heat produced by microbial decomposition of soil organic matter must be taken into account in addition to heat convection as modifying elements of the straight heat-conduction concept. The predominance of heat conduction in the soil-temperature picture is sufficiently obvious, however, to make its basic theory an important tool in the hands of the highway and airport engineer.

Moisture moves in and out of the soil profile and up or down in the profile as a result of meteorological and soil physical factors. As has been seen previously, the dominant direction and pattern of moisture

movement determines the climatic soil type encountered.

The following potentials (22) are available for water movement in soils: (1) gravity potential acting on the water mass; (2) potential due to hydration energy of the ions, related to the heat of wetting, which can be determined directly or calculated from vapor absorption experiments; (3) potential due to the osmotic energy of ions held in a sort of Donnan equilibrium at the internal surface of the system; (4) the so-called capillary potential due to the surface tension of water; (5) the thermo-osmotic potential due mainly to the change in water affinity of the internal soil surface with change in temperature (19); and (6) vapor-pressure differences causing diffusion in the vapor phase (This phenomenon is of little practical importance in temperate climates but appears to be important in arid and monsoon climates).

Although the order of magnitude of these potentials can be approximately calculated from theoretical considerations and with the help of experimental data, little is known concerning the resistance to flow under these potentials. Except perhaps for the pure capillary flow under a pure capillary potential, flow under the named potentials is primarily of a film and not of a capillary character. Since practically nothing is known concerning the structure and shear resistance of such films, much theoretical and experimental work needs to be done in this field (23).

MECHANICAL RESISTANCE OF SOIL SYSTEMS

Assemblies of atoms, ions, and simple molecules may be in the solid, liquid, or gaseous state depending upon the relative magnitude of the mutual attractive forces and the kinetic dispersive forces. The latter increase with increasing temperature. At low temperatures the attractive forces prevail and the material is in the solid state; at intermediate temperatures the attractive and dispersive forces are more or less balanced resulting in the liquid state, and at high temperatures the dispersive forces prevail bringing the system to the gaseous state.

Typical for pure compounds is their definite melting point; the only difference between the solid and the liquid at the

melting point is the lesser density or the larger volume per unit mass of the liquid. This means that in the melting process, the heat of fusion introduced into the system has performed the work of pushing apart the constituent atoms or molecules; in other words, holes have been introduced into the system.

The much lesser resistance to mechanical forces of the liquid as compared with that of the solid at the melting point must then be due essentially to the presence of these holes. This concept is strengthened by the fact that for most atoms and simple compounds the volumes of a certain mass of material under atmospheric pressure at the densest state (V_0), the melting point (V_m), and the boiling point (V_b) are related as follows:

$$V_0: V_m: V_b = 1: 1.21: 1.42$$

Also, within the liquid state, the internal friction (η) of non-associated liquids has been found by Batschinski (24) to obey the following equation:

$$\eta = \frac{c}{V - V_s}, \text{ in which}$$

c = constant

V = volume of the liquid

V_s = volume of the unexpanded solid.

There exists an intrinsic similarity between assemblies of particles of atomic and molecular size, on one hand, and of macroparticles of gravel and sand sizes on the other hand (25), which, of course, also holds for intermediate sizes. The main lesson to be learned from this similarity is the great importance of volume relationships with respect to mechanical resistance properties, of granular assemblies.

Previously, soils have been subdivided into the following three groups:

Designation	Percentage	
	Silt	Clay
1. granular	0 - 20	
2. cohesive granular	20 - 35	
3. cohesive	35 - 100	

Granular Materials

The mechanical resistance of soil sys-

tems is normally expressed as shear resistance S . For granular soils the shear resistance is usually expressed by the equation:

$$S = \sigma_n \tan \phi, \text{ in which}$$

σ_n = normal stress on the shear plane

$\tan \phi$ = coefficient of friction

The coefficient of friction is not a constant for a certain material but is a function of the voids ratio and also of σ_n . As a matter of fact, the shear phenomenon itself is a function of the voids ratio. At low voids ratios the shear forces must: (1) provide spaces into which the particles can move, i. e., the system must be expanded, and (2) move particles into these spaces.

At high voids ratios, there are sufficient spaces into which the particles may move; as a matter of fact, some of the excess spaces may even collapse, leading to a lower voids ratio and a greater resistance of the system.

At an intermediate (critical) voids ratio, the number of voids present is sufficient to accommodate the moved granules, the system suffering neither expansion nor densification.

In analogy with atomic and molecular solids we can consider a granular system as being essentially in the solid state as long as its voids ratio is below the critical and provided that it is confined within a certain volume. At the critical voids ratio the system passes, as through a melting point, from an essentially solid to a potentially liquid state.

In the solid as well as in the liquid state, the mechanical resistance is a function of the voids ratio as well as of form factors. For a particular material, the coefficient of friction can be expected to obey a relationship of the following type:

$$\tan \phi = \frac{k}{V - V_s}, \text{ in which}$$

k = constant

V = bulk volume of the particle assembly

V_s = effective volume of the solid particles.

The most-striking example of the influence of density or packing on resistance properties is the difference between the hardness of diamond and graphite.

The direct analogy between atomic and molecular assemblies, on one hand, and macromeritic assemblies on the other, holds not only for uniformly sized particulate components such as chemical elements and compounds and corresponding uniformly sized glass beads, beach sands, or similar materials, but also for mixtures of materials of different sizes, and thus for the graded materials so important in road construction.

The principles of granulometry and the extent to which they can be economically applied to construction materials have been studied most thoroughly for portland-cement concrete, (26, 27, 28). From these studies much can be learned for analogous soil systems which so far have been treated more or less on an empirical basis (29). A most important new application of granulometric principles is described in the paper by Pimentel dos Santos, which is the fifth paper of this symposium.

For particles of nonuniform and nonspherical size the densest packing is determined experimentally. In these experiments samples of the material are densified in a container of known volume either by rodding or by vibration. From the weight of the material required to fill the container and from its specific gravity, the absolute volume of the solid materials is calculated. Its subtraction from the total volume of the container gives the volume of voids.

In mixtures of materials of two size ranges such as gravel and sand the smaller size components will interfere with the close packing of those of larger size. Consequently, the absolute volume of the coarse aggregate contained in a unit volume of a mixture of coarse and fine aggregate is always smaller than the absolute volume of the coarse aggregate that can be packed by itself into a certain space. If the latter is called b_0 and if b is the volume of the coarse aggregate in the densified mixture of coarse and fine aggregate then the fraction $\frac{b}{b_0}$ is always smaller than

one. Its actual magnitude is a function of the size range of the coarse aggregate and of the fineness modulus of the sand (30). This means that the coarse aggregate is

bedded in the finer material. This bedding makes the mixture more workable and allows a modification of the properties of the entire system by modifying the bedding material. The latter may be done by introducing air bubbles or particles possessing special elastomeric, plastic, or other desired properties.

Since the resistance properties of granular materials are dependent solely on friction and since the frictional resistance is directly proportional to the normal pressure on the shearing plane, the resistance properties are very low in the surface layers of granular masses where the normal pressure on the shear plane is small. Therefore, such systems require cementation for their stabilization. The particles can be cemented together by any one of the large number of inorganic and organic cements or by combinations of inorganic cements with organic cements or with waterproofing agents. If the granular system contains both coarse and fine aggregates the cemented system is called a concrete. If the largest granules are of sand size, then the cemented system will be akin to a mortar. Such systems have been called collameritic systems, (colla = glue; and meros = particle) and include portland cement concrete, bituminous concrete, clay concrete (granular stabilized soil), water-proofed clay concrete and sand-clay as well as water-proofed sand clay (see Table 8). Since the cementing substance is the most active and often also the most expensive component, it is advisable to use as small a proportion of it as possible. This means, that the cementing substance should be used primarily for cementing and not for filling purposes. More economical fillers are usually available.

The type of cementing substance which can be used for the purpose of glueing coarse aggregate and sand particles together depends primarily on the prevailing climate. While under American conditions, mainly portland cement, flyash-lime combinations, and bituminous materials have been employed, in drier climates, gypsum plasters (31) sored-, and other water susceptible cements can be used successfully. With proper waterproofing the latter cements are suitable for soil stabilization even in moist climates (32).

So far we have dealt with systems com-

posed mainly of granular soils having less than 20 percent of silt-clay material. In the range of granular cohesive materials which contain up to 35 percent of silt and clay, we may have, at the higher silt and clay contents, well-graded material that corresponds to the established requirements of granular stabilization. With lesser contents in silts and clay, there is a lack of natural binder which must be made good by addition of binder soil or of cementing and waterproofing substances.

It is of considerable interest that binders composed of both silt-clay materials and of organic or inorganic cements have definite, and not only economical, advantages over using the pure cementing material. The work of Silbergh (33) had indicated the existence of an optimum clay content (depending on the activity of the clay) in the stabilization of sandy soil by various inorganic and organic stabilizers.

35 percent keep the granular particles from close contact and interlocking, with marked lowering of the friction of the system and with the loss of the skeleton effect. Such systems often possess great cohesive strength in dry condition but lose the strength in the presence of moisture which they absorb avidly under swelling.

There is, therefore, a dividing line between non-swelling and swelling soils which occurs at silt-clay contents of about 35 percent. In the non-swelling soils, even at the highest moisture content, the volume of the swelling constituents does not exceed the pore space left by the mutually contacting larger grains. In the swelling soils the coarse particles are isolated in a matrix of finer particles. The actual limiting proportion of swelling components depends upon the granulometry of the system and on the water affinity of the silt-clay material.

TABLE 9
MECHANICAL RESISTANCE PROPERTIES OF TWO SOILS AND EIGHT OF THEIR IONIC MODIFICATIONS AS DERIVED FROM TENSILE AND COMPRESSION TESTS ON AIR-DRY SPECIMENS AND FROM CONSISTENCY MEASUREMENTS IN THE MOIST STATE

Soil	Exchange cations	Strength *		Internal Pressure (psi)	Angle ϕ (deg)	Plasticity Index	Angle ψ (from P. I.) (deg)
		Tensile (psi)	Compress. (psi)				
Cecil	H	61	73	369	5.17	34	20.7
	Na	52	86	132	14.23	30	21.8
	K	63	110	148	15.72	38	19.7
	Mg	70	102	76	10.72	34	20.7
	Ca	51	125	86	24.83	34	20.7
	Ba	75	121	198	13.53	36	20.2
	Al	72	147	141	20.20	31	21.5
	Fe	60	142	103	24.00	36	20.2
	Natural	65	124	137	18.18	37	20.0
Hagers-town	H	105	445	133	38.17	21	24.0
	Na	135	342	233	25.79	40	19.2
	K	88	341	119	36.15	25	23.0
	Mg	110	575	136	42.65	27	20.5
	Ca	182	357	381	18.97	23	23.5
	Ba	153	341	278	22.33	21	24.0
	Al	93	368	124	36.65	16	25.4
	Fe	98	302	145	30.67	16	25.4
	Natural	160	312	349	18.78	26	22.8
Condition	Air dried			Moist to wet			

The paper by Reinhold in this bulletin shows for stabilization of a sandy soil with portland cement an optimum clay content of about 25 percent, an excellent construction material being obtained with 25 percent of clay and 10 percent of portland cement.

Silt-Clay Materials

Silt-clay constituents in excess of about

THE MECHANICAL RESISTANCE PROPERTIES OF SILT-CLAY MATERIALS

The shear resistance of cohesive soils is usually expressed by the equation:

$$S = \sigma \tan \phi + C$$

where S = shear resistance,

σ = normal stress on the shear plane,

$\tan \phi$ = coefficient of internal friction and

C = Cohesion

Actually, friction and cohesion in such systems are not independent of each other but are both functions of the density, the moisture content, and of the manner in which the particular moisture content has been attained. The friction portion of the shear resistance may be expected to follow the same type of volume law that has been previously described for the internal friction of liquids and of granular materials. The first step in understanding soil cohesion is to consider it as a result of the attraction forces acting from the mineral surfaces through the water films and of geometric factors that have the functions and therefore the properties of an angle of friction. Accordingly, one may write:

Cohesion = internal pressure \times $\tan \phi$.

For soils at very low moisture content this internal pressure is theoretically of the order of magnitude of 10^6 pounds per square inch. It falls logarithmically to zero at a moisture content at which the soil flows under its own weight, i. e., at which the soil behaves as a liquid (liquid limit). Because of secondary aggregation and nonideal arrangements of the cohesion-giving water films, the actual strength of cohesive soils is much smaller than the theoretical. It has been found (34) that even monocrystals of pure minerals such as sodium chloride give tensile strength values that are two to three orders of magnitude smaller than those calculated from theory. It is, therefore, not surprising that experimentally determined strength values for carefully dried clay soil specimens and the related internal pressures are systematically lower than 1,000 psi. and usually lie between 100 and 400 psi.

In Table 9 actual data are presented for compressive and tensile strength of specimens of nine ionic modifications of two different clay soils. The specimens were molded in the plastic range and carefully air dried (35). From the experimental data, angles of internal pressures were derived using the Mohr circle method. The Table also contains angles of friction derived for the same soils from the plasticity index according to Kögler and Scheidig (36). It is of interest that the angles of friction derived for the different ionic modifications of the same soil vary less for the plastic state for which Kögler's

formula was assumed to hold, than they do for the solid state for which the values had been obtained from compressive and tension data by use of the Mohr circle method.

Soils can be considered as (1) solids if their moisture content is below the shrinkage limit and if they have been dried to this point from higher moisture contents; as (2) being in the plastic state if their moisture content falls between the plastic and liquid limit; and (3) as liquids if their moisture content is above the liquid limit.

The location of these limits depends on the clay and colloid content of the soils, on the type and the activity of the clay fraction, and on the granulometry of the entire soil including its clay fraction. The greater the tendency to structure formation inherent in the clay the higher is its shrinkage limit. Also, the presence of ions furthering structure formation increases the shrinkage limit, while the presence of dispersing ions decreases the shrinkage limit.

The plastic state may be considered to begin as soon as the active surfaces in the soil system are covered with films of water that are sufficiently thick to be continuous and to have lubricating properties. Therefore, other factors being equal, the larger the amount of internal surface, i. e., the larger the clay content the higher the plastic limit.

However, dispersed clays may require thinner moisture film for lubrication than aggregated clay particles. For this reason the plastic limit sometimes falls with increasing dispersion of the clay fraction. The liquid limit represents theoretically a moisture volume which permits the independently acting primary or secondary soil particles to rotate freely. In fact, the possibility of free rotation of the constituent particles is considered as the most important index of liquidity. Therefore, the larger the proportion of plate-shaped particles and the larger the ratio of the volume of the rotation ellipsoids to the actual volume of the particles, the higher will be the liquid limits.

An increase in the dispersion of a clay may, on one hand, decrease the plastic limit and, on the other hand, increase the liquid limit. The presence of silt and sand fractions may modify these conclusions because of their interference and interaction with the clay particles. It has been found

quite often that increasing amounts of clay were inactivated in part by increasing amounts of silt particles on the surface of which they were strongly adsorbed (37).

Finally, there is a great influence of the granulometry. The latter is treated by Pimentel dos Santos. The scientific study of the resistance properties of silt-clay-water systems falls within the realm of the science of rheology, and there exists a great need for more fundamental studies following the concepts of Eyring (38), Mack (39), Ruiz (40), Nijboer (41), and others (42).

Stabilization of Silt-Clay Materials

The crucial difficulty involved in the stabilization of cohesive soils that do not contain granular skeletons is the fact that the seat of the resistance providing cohesion is also the seat of the water affinity. The cohesion increases with decrease in water content. Theoretically, the simplest method of stabilizing such materials is to (1) deprive the component particles of their water affinity and (2) to cement these particles together.

This exactly is achieved by the oldest method of soil stabilization, namely the burning of clay soils for the making of pathways, which has been used extensively by the Australian aborigines (43). However, the practical difficulties involved in this method are obvious; despite much recent experimentation with large road burners the most-promising use of this method is the manufacture of coarse ceramic aggregate and its subsequent use in granular soil stabilization.

The economics of this problem have been well explored in Argentina where the process was concluded to be feasible under certain conditions of absence of natural granular materials. The relationship between pedologic soil type and effectiveness of thermal stabilization has been studied especially in Russia (44).

Another use of this principle is to replace the water attractive inorganic exchangeable cations by means of water repellent organic cations and to cement the soil constituents, that have now lost their water affinity, together by means of an organic cement. This can be done using aniline-furfural and similar resins (45).

Another method is to create strongly water resistant secondary soil aggregates

which are then cemented together by means of inorganic binders such as Portland cement, flyash-lime combinations, gypsum plasters, soral cements, etc.

A less-positive but still effective method, if properly used, is to stabilize the moisture content of a soil system by preventing the intake of excess water. This water-proofing may be achieved by various materials such as asphaltic and pyrogenous bitumens, natural and artificial resins, fats, waxes, etc.

The scientific factors involved in water-proofing of cohesive soils have been studied in considerable detail (46, 47). Since it is usually desirable that the stabilized system contain a certain minimum volume of stabilizer, combinations of highly active materials with less active ones are often indicated as well as combinations of inorganic and organic stabilizers.

Finally, systems may be synthesized by low-temperature polymerization in which the actual soil constituents are held as particulate inclusions in a fibrous network or felt. The fibers may or may not be attached to the clay particles by ionic, resonance or other forces. However, this method requires a rather large amount of water which brings the system to the sticky point and often makes mixing extremely difficult. Also the excess water is likely to soften the subgrade and rob it of its supporting power. In addition, a rather large amount of expensive stabilizer (usually above 10 percent by weight) is required. Nevertheless, this is an interesting development and has certain uses in fields other than road construction.

The scientific principles involved in the stabilization of cohesive soils, including the microbial problems, have been treated quite thoroughly in the literature (48) and need not be discussed here in greater detail. In all these methods, except perhaps the thermal one, it is important that, at the time of treatment, the soil has sufficient moisture to satisfy its hydration requirements and that the particles are surrounded by continuous moisture films without excess or free water, since the latter may lead to undesirable stickiness of the system. Table 10 shows the relationship between soil stabilization and its supporting sciences. Figure 6 is a reproduction of a chart published in 1943 by Olmstead (49) in a paper entitled "Factors Related to the Design of Stabilized Mixtures." The

chart exposes most clearly the connection between soil texture and stabilization requirements.

SCIENTIFIC FACTORS INVOLVED IN THE CONSTRUCTION OF STABILIZED COURSES

The science of soil stabilization covers not only compositional, structural and resistance properties of stabilized systems but also the problems involved in their manufacture in the field. Construction-wise, soil stabilization involves the three unit processes: (1) comminution, (2) mixing, and (3) compaction.

shortened or even avoided by the use of "shortening agents." Among the latter aniline-furfural combinations have proved themselves as most versatile and most effective. While some of our modern comminution machinery has been developed with sufficient power to breakup even dry, hard-caked soils to sizes sufficient for subsequent stabilizing treatment, it is better science and better practice to bring the soil first to that degree of moistness at which it is most easily comminuted to particles of the proper size.

Energy of Comminution

At the present time, the energy of com-

TABLE 10

The Science of Soil Stabilization
rests on the three pillars of

<u>Pedology</u>	<u>Physical and Chemical Sciences</u>	<u>Body of Knowledge on Traditional Construction Materials</u>
<p>The science of physical and chemical soil characteristics as functions of:</p> <ol style="list-style-type: none"> 1) parent material 2) climate 3) topography 4) organisms 5) time 	<p>These allow judgement of soil deficiencies and indicate supplementation in physical and chemical terms that are translated into economically available materials, such as</p> <ol style="list-style-type: none"> 1) inorganic cements 2) organic cements 3) waterproofing agents with or without improvement of granulometry of the soil. 	<p>A stabilized soil, being a construction material, must resemble traditional construction materials in its essential resistance properties and structure. Especially important are granulometric considerations. Most non-metallic construction materials and most stabilized soil systems fall in the category of collameritic systems.</p>

In the case of purely granular soils the comminution factor is, of course, absent. The farmer who has a similar problem of comminution when he prepares the proper seed bed for his crop has learned that (1) for cohesive soils the plow is a most effective instrument and that (2) there exists a moisture range in which comminution to the desired particle size is most easy to achieve. The latter is within the plastic range but below the point where the water is already sufficiently free to stick to the plow metal (sticky point).

In regions where it is normally dry during the construction season it is easy to reach the most advantageous moisture content by addition of water. A real problem exists when soils have natural moisture contents above the sticky point; this may result in very costly delays of weeks and even months. These delays can often be

minution cannot be calculated exactly from theory alone; however, knowledge, even if only approximate, of this energy is of great economic as well as scientific importance. For this reason, an approach to the scientific solution of this problem is given in the following. The amount of energy required for comminution depends, among other factors, upon the ultimate particle size required and upon the extent to which granules of this size are already preformed in the natural soil. Accordingly, it should require relatively little energy to comminute soils to granules of gravel and sand sizes but very considerably more to break a clay soil down to the ultimate clay particle units.

There exist three general approaches for the calculation of comminution energy. In each approach certain assumptions must be made because of lack of pertinent sci-

entific data. (1) The work performed in creating two unit surfaces equals one half of the product of tensile strength and the distance over which the tensile force must be moved. (2) The work of comminution equals the maximum strain energy that can be stored by the body under consideration under the condition of strain application. Comminution is into "natural" structural units. (3) The work of comminution equals the surface energy of the new surfaces created.

The required assumptions are for (1) the effective action radius of the cohesive forces, for (2) the modulus of elasticity, and for (3) the surface energy.

We shall employ Approach 2 and utilize Approach 3 to calculate the dimensions of easily produced natural soil units.

Using an average tensile strength value of 200 psi. for a dry clay soil (strongest state) and a probable modulus of elasticity value of 92,600 psi. (from German dynamic measurements), we may calculate a failure strain of:

$$\epsilon = \frac{200}{92,600} = 0.00216 \text{ inch per inch.}$$

Multiplying this strain by half of the failure stress, we obtain:

$$\begin{aligned} 0.00216 \times 100 &= 0.216 \text{ in. -lb. per cu. in.} \\ &= 0.018 \text{ ft. -lb. per cu. in.} \\ &= 0.018 \times 1.356 \times 10^7 \text{ ergs} \\ &\quad \text{per cu. in.} \\ &= 224 \times 10^3 \text{ ergs per cu. in.} \\ &= 39 \text{ joules per cu. ft.} \\ &= 1.45 \times 10^{-6} \text{ horsepower-} \\ &\quad \text{hours per cu. ft.} \end{aligned}$$

The last value represents the maximum strain energy that can be stored per cubic foot of the soil if employed as a bar in tension. If employed in pure bending, the value falls to a third of that given, and if used as a cantilever, to a ninth.

Similar calculations may be made for soils in the plastic range using data published by Professor Tschebotarioff (50). These data are given in the next table.

Soils	Plastic Limit %	Liquid Limit %	H ₂ O Content %	Tensile Strength Kg/cm ²	Strain at Failure %
Bentonite	53	540	101	0.21	3.4
Kaolinite	32	70	37.6	0.09	0.2
Illite	26	60	31.5	0.40	0.8
Clay "Pr"	23	30	19.8	0.08	0.8

From these data, the maximum strain energy that can be stored in pure tension can be calculated approximately as the product of half of the failure stress and the failure strain. Accordingly, we obtain:

Elastic Energy Stored per Unit Volume up to Failure						
Soil	cmkg/cm ²	mkg/cm ²	mkg/in ²	inkg/in ²	joule/ft ³	Hp-hr per ft ³
Bentonite	0.0057	35.7 x 10 ⁻³	56.5 x 10 ⁻⁵	101 x 10 ⁻³	9.9	3.69 x 10 ⁻⁵
Kaolinite	0.0009	0.9 x 10 ⁻³	1.47 x 10 ⁻⁵	2.54 x 10 ⁻³	0.25	0.093 x 10 ⁻⁵
Illite	0.0016	16.0 x 10 ⁻³	26.2 x 10 ⁻⁵	45.3 x 10 ⁻³	4.45	1.64 x 10 ⁻⁵
Clay "Pr"	0.0032	3.2 x 10 ⁻³	5.24 x 10 ⁻⁵	9.05 x 10 ⁻³	0.88	0.33 x 10 ⁻⁵

Size of natural breakage units

Assuming that the entire stored strain energy is used for the creation of new surfaces without actual breaking down of primary soil particles but having the new surface going through the film water between the particles, and assuming that adsorption forces on the surfaces of the solid particles raise the surface energy of water to about 150 ergs per sq. cm., we obtain a surface energy of 6.45 x 150 ergs = 968 ergs per sq. in. Dividing 39 x 10⁷ ergs per sq. cu. ft. by 968 ergs per sq. in. gives

$$4.03 \times 10^5 \text{ sq. in. per cu. ft.}$$

The surface in sq. in. per cu. ft. is 6 x 144 = 864 sq. in. for a cube of 1 foot side length and 6 x 1728 = 10,368 sq. in. if subdivided into cubes of 1 inch side length.

The general formula

$$\text{Surface in sq. in.} = \frac{10,368}{\text{side length in inches}}$$

For a surface of 4.03 x 10⁵ sq. ft. we obtain a side length of:

$$\begin{aligned} \frac{10,368}{4.03 \times 10^5} &= 0.026 \text{ inch.} \\ &= 0.066 \text{ cm.} \\ &= 0.66 \text{ mm.} \end{aligned}$$

This value indicates that the resulting particles are of the order of magnitude of a medium sand. This reasonable result indicates that the extrapolated assumptions made in its calculation are also reasonable. This fact is important not only for estimating power requirements in soil comminution but also with respect to soil response to dynamic loading by blasting and forced mechanical and sonic vibrations.

The calculations just presented are, of course, only a first approach. However, this approach should be followed up and should finally lead to a more rational de-

sign of comminution equipment than is possible at the present time.

Mixing Step

The problem of the energy and power requirements for adequate mixing of stabilizers with the soil material in its normal moist condition has as yet not been properly studied. While some extrapolation can be made from the experience in mixing problems of the chemical industry, the special properties of the soil mixtures involved in stabilization indicate the need for specific studies with such materials.

Densification Step

Because of the very intimate relationship between the density of a stabilized soil system and its resistance properties, compaction is probably the most important single feature in soil stabilization. In studies performed for the Civil Aeronautics Administration it has been shown that the difference between normal and modified Proctor compaction in certain stabilized soils was equivalent to the effect of approximately 2 percent of portland cement. This means that systems stabilized at the higher density with 2 percent less portland cement were equal in resistance to those stabilized at the more of Proctor density with 2 percent more of portland cement.

However, for this to be the case, the higher density had to be reached with a moisture content sufficient to satisfy the hydration needs of both the soil and the portland cement.

In view of the large amount of compaction tests that have been performed in soil laboratories under well standardized conditions, it would seem that enough knowledge is available for judging the work and power requirements in compaction. Actually the wall effect of the small molds that are used in the laboratory has never been definitely evaluated, and rational extrapolation from laboratory tests to field conditions has as yet not been accomplished.

In addition, the molding compaction actually used in the field differs often quite essentially from the compaction by means of the impact of the falling hammer employed in the laboratory test. These and other compaction problems should be

investigated on the basis of fundamental theoretical considerations.

Economic Considerations

Soil stabilization represents an engineering science and as such must include economics. Economic considerations are not restricted to the cost of materials which represents only a portion of the total cost but also must cover the costs of construction and of maintenance during the service life of the structure. It would be impossible to make here a complete analysis of all the important economic factors, but it can be pointed out that often a slight increase in cost of materials caused by the use of "construction aids" can be balanced by a lesser construction cost due to easier mixing and compaction of the treated soil. If such "construction aids" also improve the final quality of the system, so much the better.

The costs of traditional cementing and water proofing materials are relatively stable within certain regions, and it is not too difficult to decide which of several has economic preference in a particular location.

However, the relative costs vary for different areas. In one region portland cement may be more economical than bitumen as is the case in Portuguese East Africa, while in other regions, bitumen may be more economical than portland cement. The same holds true with respect to lime, flyashes, and other materials.

The economics are not as obvious in the case of chemicals that have not been used previously for soil stabilization purposes since the unit price of chemicals usually decreases with increasing industrial production. Therefore, it would be unreasonable to base economic conclusions solely on present prices of certain chemicals. However, it is very much to the purpose to point out certain fundamental economic facts.

It is obviously an economic waste to employ an expensive cementing material not only as a cement but also as a filler. As it is an economic waste to have one man build an entire automobile by himself, the same way it is uneconomical to have one chemical alone remedy all the various deficiencies of a soil. It is usually more economical to employ several

mono- or bi-functional substances instead of one alone that is polyfunctional.

Even in the case of beach sand stabilization for military purposes, where normal economics are out of the picture, it is certainly advisable not to use the more expensive resinous substance to do the entire job of cementing the sand grains together, but to dilute the synthetic resin by means of pitch, asphalt, or other organic or even inorganic cementing materials which can be easily employed in the process (11).

Also, if certain elastomeric properties are desired, these can be obtained by incorporation of elastomeric powders or dispersions. This possibility resides in the fact that the large bearing systems created in soil stabilization are quasi- or practically isotropic.

There is, of course, no such thing as a completely and truly isotropic system in nature since even the atoms and the nuclei are nonisotropic. Practical isotropicity depends upon the size of the largest component of the system with respect to the size of the area of stress application. If the latter is much larger than the coarsest components of the resisting material then we have practical isotropicity.

In portland-cement concrete we allow, for instance, sizes of the large aggregate up to a third of the smallest dimension of the structural system.

From the foregoing considerations it can be seen easily that it is a sound economical principle to employ several lower cost mono- or bi-functional components to achieve certain combined properties than to employ an expensive polymer in which several functions have been embodied.

CONCLUSIONS

It has been intended in this introductory paper to expose those soil properties that

are important for scientific soil stabilization, to indicate how these properties must be supplemented or modified in order to produce construction materials, and to point out material and economic facts of importance in actual construction.

If we accept Poincaré's definition that the essence of a science is to give the same name to different things, then it is evident that this condition is fulfilled in the case of scientific soil stabilization. The methods of stabilizing granular soils have been included in the collameritic system which embraces a large number of traditional construction materials as well as an important group of stabilized soils. At the same time it has been demonstrated how physico-chemical, chemical and physical principles are important in the proper stabilization of soils especially of those that do not possess a granular skeleton. Also, basic principles with reference to the economy of producing stabilized compositions have been pointed out.

This being an introductory paper, it was intended to indicate but not to anticipate the information which is presented in the subsequent papers on more specific subjects. This permitted concentration and emphasis on the principles involved. At the same time certain basic considerations and data relative to the complex system "Soil" could be presented which are not usually found in engineering literature.

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