

PHYSICAL-CHEMICAL PROPERTIES AND ENGINEERING PERFORMANCE OF CLAYS

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ABSTRACT

Fabric (texture and structure) and mineralogic composition determine the response of clays and shales to events occurring during construction and operation of engineering works. A new system of classification of the fabric of earth materials is proposed. Characteristic mineralogic composition of clays and shales, especially in the western United States, is described. Fabric and composition are correlated with soil mechanics properties and engineering performance. Needed research on clays and shales as a basis for design, construction, and maintenance of engineering structures is emphasized.

INTRODUCTION

Clays are important to the designer and the construction engineer because their structures frequently rest upon clayey formations, excavations commonly must be made into clayey materials, vast quantities of earth materials containing clays are used in embankments and linings, and clays occur commonly as constituents of engineering materials such as aggregate, pozzolan, and grout. Moreover, clays present many unique problems to the engineer primarily because their physical and chemical instability renders masses of earth susceptible to ready and repeated change of form and volume in response to loading or unloading, vibration, and changing moisture content. As though these qualities were not sufficiently annoying, the degree to which clays respond to these actions commonly changes with adsorption of ions or molecules from solution, precipitation interstitially of granular substances, and alteration of internal texture and structure.

Through recognition of these characteristics of clays, the engineer can minimize unanticipated difficulties in construction and operation of engineering works. Also, intriguingly enough, the susceptibility of clays to change in response to their physical and chemical environment leads at once to methods by which undesirable properties can be improved.

With increasing size and complexity and hence cost of structures, success of the works must be more assured in spite of the fact that available sites commonly are less desirable from the standpoint of stability.

Only the first chapters in the tale are yet told, but advance is being made in this field of soil mechanics under the leadership of engineers and scientists in many countries. Of particular note are the contributions of H. F. Winterkorn, A. Casagrande, E. F. Preece, B. K. Hough, T. W. Lambe, E. A. Hauser, D. T. Davidson, and their associates in the United States; K. Endell, E. H. Ackermann, E. Schmid, H. G. F. Winkler, and their associates in Germany; L. F. Cooling, L. Casagrande, A. W. Skempton, K. E. Clare, P. C. T. Jones, and their associates in England; J. E. Jennings and his associates in South Africa; and others in Russia, Holland, France, Switzerland, Sweden, and elsewhere.

Engineers also are concerned with clays in areas other than soil mechanics. Work is in progress in study of clays as they affect both natural and manufactured aggregate, as they can be used in grouting or drilling fluids, and as they contribute to activity of pozzolanic

admixtures for concrete. These investigations are being conducted in governmental, university, and industrial laboratories in the United States, England, France, Germany, Russia, Italy, Mexico, Japan, India, Brazil, and other countries.

Development of physical-chemical concepts in engineering has drawn heavily from knowledge in related fields, particularly agriculture, mineralogy, geology, ceramics, and chemistry. Workers in Germany, United States, England, France, Russia, Australia, and Japan have been especially fruitful.

This paper describes the properties of clays in relation to their mineralogy and fabric and their performance during construction and operation of engineering works. Particular emphasis is given areas of ignorance with a view to stimulating research directed to their exploration.

SOIL MECHANICS AND THE PHYSICAL-CHEMICAL APPROACH TO ENGINEERING INVESTIGATION OF CLAYS

Developing hand in hand with the applied science of soil mechanics, principally during the past 25 years, has been an increasing awareness of the need for a better understanding of the physical-chemical processes affecting the response of earth materials to engineering activities, such as loading or unloading of foundations, changing of the ground-water regime, introduction of new substances, and excavation and recompaction.

Soil mechanics is based upon physical, mechanical, and hydraulic laws. In engineering application, properties of earth materials are obtained from field and laboratory tests which are carefully designed to be quick and comparatively low in cost. These tests are the basis for most design and construction practice for structures resting upon or composed of earth materials. To be classed among the common procedures are the more or less standardized tests for particle-size distribution, consolidation, shear resistance, penetration resistance, permeability, and many others. Consistent with the point of view permeating all engineering, these tests are applied to measure the performance of materials under conditions simulating those on the job. Most remarkable of the empirical procedures is the so-called airfield classification (AC) system, developed by Arthur Casagrande (1948; Abdun-Nur, 1950) which is based primarily upon visual inspection and observation of the response of earth materials to simple manual tests without equipment. This system with some modification is now used widely in engineering practice. The general success of the method demonstrates that its empirical concepts take root in fundamentals of performance of earth materials in engineering.

Physical-chemical investigation of clays is based upon analyses of fabric, mineralogic constitution, and the chemical composition, and the response of the materials to chemical or physical-chemical treatment. Although physical-chemical research on soil mechanics problems was begun more than 15 years ago, progress has been slow. Knowledge of physical-chemical properties of soils

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developed in the fields of mineralogy, geology, agronomy, ceramics, and chemistry has been adapted to study of engineering problems and especially devised investigations have been conducted in several laboratories, most notably by H. F. Winterkorn, T. W. Lambe and their associates. These methods have been applied successfully in several large engineering organizations to aid in planning of soil investigations, as supplements to standard soil mechanics tests, to elucidate anomalous behavior, to forewarn of possible difficulties, to aid in selection of design and construction methods, and to develop remedial measures to correct failures in operation. They do not replace the physical and mechanical tests.

Nevertheless, examples of the successful application of physical-chemical knowledge of soils to the solution of significant engineering problems are few. Lee's control of the permeability in the lining of the lagoon on Treasure Island in San Francisco Bay (1941), and the investigation of soil stabilization by Winterkorn (1940; 1946; 1953; and Eckert, 1940; and Choudbury, 1949), Casagrande (1937; 1939; 1947; 1949), Endell (1935), Davidson (1949; and Glab 1949), Preece (1947), Lambe (1954) and others are good examples of the application of fundamental knowledge of mineralogy, fabric, and physical-chemical characteristics of soil. They portend an enlarging future.

The paucity of application of fundamental information to the solution of engineering problems is explained by difficulties inherent in the solutions and by the inability of most of those capable of effectively analyzing the physical-chemical conditions controlling earth materials to specify practical remedial measures which will overcome the engineering difficulties. In turn, this lack of ability is in part the result of the limited opportunity afforded individuals skilled in the physical-chemistry of earth materials to follow continuously the development of engineering projects from the earliest stages of investigation and preliminary design. Indeed, only in the past decade has the geologist gained acceptance in this regard. The opportunity for the earth materials scientist still is to come.

In general and with rare exception, the physical-chemical conditions controlling earth materials at engineering sites are elucidated, if at all, only by special investigations conducted after difficulties are encountered and only after the time is past for successful application of methods based upon physical chemistry. The imminent destruction of costly structures or the need for reconstruction of damaged facilities usually demand direct means, such as excavation of the offending unstable materials, driving of piles, or others, including, all too commonly, the restoration of the condition which originally resulted in failure.

Scientific investigation of problems of soil engineering cannot replace empirical mechanical tests, for these supply entirely adequate data for most projects. Rather physical chemistry, petrography, and geology permit critical evaluation of data developed by the empirical tests at individual projects, because inquiry along these lines reveals the precise cause of given performance, the continuity and extent of materials with given properties, and structural relations within soil masses, such as attitude of strata, faults, and lithologic discontinuities. Moreover, they form the basis for improvement of exist-

ing tests and define the need for additional new standard tests. Most important, however, the scientific study of soils for engineering purposes will (1) forewarn of dangers inherent in specific engineering situations, (2) make possible the development of superior means of stabilization and selection of the most appropriate method for use on individual projects, and (3) dictate means by which the danger of failure of soil masses in service can be minimized, as for example, through appropriate design of drains, vents, or moisture barriers where control of water is essential.

To be of maximum service to the designer and the construction engineer, the soil scientist engaged in engineering problems always must recognize that the ultimate objective of the effort is the constructing, rebuilding, or maintenance of a structure. His investigations and recommended procedure should be consistent with that end. The criterion of successful engineering is adequacy at minimum cost.

PHYSICAL-CHEMICAL PROPERTIES OF CLAYS

Physical-chemical properties of earth materials are those qualities and responses which arise in the mutual spacial relationships of the constituent molecules. Physical-chemical properties merge imperceptibly into chemical properties with rising significance of phenomena involving only individual molecules, atoms, and ions. On the opposite end of the dimensional scale, physical-chemical properties grade into physical properties as the primary phenomena come to involve to greater and greater degree the mutual relations and mechanical interaction of major units, such as rock particles, whole crystals, masses of earth material, or bodies of fluid. Clearly, all of the observable properties of materials arise by combination of physical, physical-chemical, and chemical properties, each to greater or lesser degree.

Physical-chemical properties of interest in soil mechanics of earth materials depend primarily upon electrostatic and gravitational forces existing at the surface of the solid phases, the area of surface per unit volume of material available to fluids permeating the mass, and the amount and kind of interstitial liquids and gases. Consequently, physical-chemical properties of earth materials arise in mineralogical or compound composition and fluids content. By control of cohesive and adhesive forces between solid and solid and between solid and fluid, the physical-chemical properties influence or control development of fabric of materials. The nature and magnitude of physical-chemical properties of the mass depend upon both mineralogical or compound composition and the fabric at all levels of dimension at and above the molecular.

FABRIC

The fabric of an earth material is the pattern established by the arrangement and mutual relationships of the constituent particles and amorphous masses and the discontinuities. Fabric constitutes a more or less continuous three-dimensional repetitive pattern in space, and includes such factors as packing, boundary relationships, discontinuities, grain size or granularity, the presence or absence of a matrix, shape and roundness of particles, and orientation. As used in petrofabrics, fabric also includes the symmetry of arrangement;

Table 1. A textural classification of earth materials (major subdivisions only).

Texture	Definitive character
Clastic.....	Granular, without interlocking of grain boundaries
Crystalline.....	Granular, with interlocking of grain boundaries
Amorphous.....	Glassy or gelatinous
Biofragmental.....	Particulate, with particles conchoidal, fibrous, radiate, acicular, spindle-shaped, reticulate, or spiral

further work may make possible the application of these principles to earth materials. In this paper, "fabric" will include large or small physical features of an earth material and so encompasses concepts of both "structure" and "texture," as commonly used by many soil scientists, petrographers, and geologists. The much-debated term "structure" is reserved here for the gross geologic features, such as bedding, depositional attitude, and the over-all form or shape of a geologic body. A discussion of these structural features is not included.

For the purpose of this paper, a grain is defined as a hard particle which acts as a unit under stress. An aggregation is defined as a coherent assemblage of grains or argillic particles so joined as to act as a unit under stress. In the nomenclature of petrofabrics, grains have been called elements or units, whereas aggregations have been called superindividuals (Fairbairn, 1949).

Based upon the mutual relationships of the constituent particles and amorphous masses, the fabric of earth materials can be classified as clastic, biofragmental, crystalline, and amorphous (table 1). Classification of materials according to this system does not depend upon a knowledge or an assumption of the origin of the material, although by observation of the fabric, the origin usually can be deduced.

The elastic materials are particulate and the boundaries of the particles do not interlock. This group includes the terrigenous sediments (including some limestones), pyroclastic materials, and breccias. The biofragmental materials are a variety of elastic materials, but are sufficiently distinctive in the shape of the particles to justify separation. Biofragmental earth materials are composed of grains which are spindle-shaped, spiral, fibrous, radiate, rod-like, conchoidal, or cylindrical. They usually consist of the hard parts of organisms, such as diatoms, radiolaria, sponges, mollusks, and corals.

The crystalline fabric is composed of particles whose boundaries interlock. Materials belonging to this group typically are those precipitated from solution, and include crystalline igneous rocks, hydrothermal vein deposits, metamorphic rocks, and chemically precipitated sediments, such as many limestones and saline deposits.

The amorphous fabric is not particulate, being essentially composed of noncrystalline masses. This fabric is exemplified by volcanic glass, opaline chert, and certain organic materials.

Clearly, gradations exist between the four types of fabric. Clastic and biofragmental materials commonly are admixed with crystalline or amorphous substances. Also, crystalline materials are combined with amorphous

substances in widely varying amounts. Clastic, biofragmental, amorphous, and crystalline rocks and soils are completely intergradational.

Clastic fabric may be interrupted by discontinuities, such as fractures, abrupt changes in grain size, holes produced by plant and animal life, changes in matrix, and natural openings produced by leaching.

Classifications of fabric may be based most definitively upon (1) the nature and frequency of discontinuities (table 2) and (2) the relationships of the particles and amorphous masses constituting the material (table 3). The writers wish to outline the principles of the system primarily to stimulate investigation and research in this neglected field of soil mechanics. No new nomenclature is introduced.

Also to be recognized is the point that the objective of the classification scheme is the systematic examination of fabric. Consequently, no attempt is made to correlate the various fabrics with specific petrographic types. Indeed, it is readily evident that with the common system of petrographic nomenclature now in use, earth materials of widely different fabrics might be given the same lithologic name, such as sand, silt, clay, loess, and so on. With a clear concept of fabric in mind, those interested in soil mechanics might ultimately develop a system of nomenclature which will designate a variety of fabric types. However, this is for the future.

A systematic study of the fabric of earth materials is important to the soil mechanics engineer because the properties and performance of earth materials depend upon the mutual arrangement of constituents and the discontinuities (A. Casagrande, 1932). Consequently, rational analysis of the properties and performance of materials in tests or service can be accomplished only if differences of fabric are recognized. By correlating fabric with results of tests and experience, the engineer can predict more reliably the properties to be anticipated in new ground, the need for specific tests will be recognized, and the data obtained from tests can be extrapolated more definitively over the area of interest.

Fabric Based on Discontinuities

When a fabric is interrupted by discontinuities, the resulting forms and patterns alter the over-all fabric of an earth material and change its properties. For example, two materials having similar composition and particle-size distribution in bulk, but differing in distribution of the coarse and fine particles in the fabric, as with stratification, will exhibit widely different physical and physical-chemical properties. Similarly, small fractures, plant root holes, or pores affect the mass properties of the earth material.

The forms produced by fracturation are quite diverse. Fracturation may be caused by unequal stresses, such as result from differential heating, heating and cooling, wetting and drying, freezing and thawing, swelling and shrinking, chemical dissolution, consolidation or shear failure, and the action of plants and animals. The distinctness of fracturation and stability of the forms are influenced markedly by the type and kind of clay minerals, organic matter, and other cementing materials.

In order to elucidate the diverse forms which an earth material can exhibit, a fabric classification of clastic earth materials based on discontinuities is proposed

Table 2. A classification of fabric of clastic earth materials based on discontinuities.

	Group	Type	Kind	Size of features	Aggregation
Fractures subordinate	Isotropic	Massive	Nonporous Porous Highly porous	Fine Medium Coarse	Absent Poorly defined Moderately defined Well defined
	Anisotropic	Planar	Foliated Laminated Lenticular Scaly	Fine Medium Coarse	Absent Poorly defined Moderately defined Well defined
Fractures prominent	Isotropic	Blocky	Spheroidal Cuboidal Irregular	Fine Medium Coarse	Absent Poorly defined Moderately defined Well defined
	Anisotropic	Columnar	Prismatic Cylindroidal	Fine Medium Coarse	Absent Poorly defined Moderately defined Well defined
		Planar	Foliated Laminated Lenticular Scaly	Fine Medium Coarse	Absent Poorly defined Moderately defined Well defined

Table 3. A classification of fabric of clastic earth materials based on particle relationships.

	Packing	Granularity	Coatings	Type of matrix	Orientation	Cementation	Particle form
Clastic	Grains in contact	Coarse Granular >4.76 mm	Grains coated Grains not coated	No matrix Clastic matrix Granular Argillic Crystalline Amorphous Biofragmental	Random Preferred	None Points of contact Intergranular filling	Rounding: Rounded Subrounded Subangular Angular Shape: Equant Tabular Rod-like Irregular
		Medium Granular <4.76 mm >0.074 mm					Rounding: Subangular Angular Shape: Equant Tabular Rod-like Irregular
		Micaceous					
		Fine Granular <0.074 mm					
		Micaceous					
	Grains not in contact or Argillic	Granular	Coarse Granular >4.76 mm	Grains coated Grains not coated	Intergranular braces Argillic Amorphous	Random Preferred	None Points of contact Intergranular filling
Medium Granular <4.76 mm >0.074 mm			Grains separated by matrix Argillic Amorphous Biofragmental		Rounding: Subangular Angular Shape: Equant Tabular Rod-like Irregular		
Fine Granular <0.074 mm							
Argillic		Medium Argillic <4.76 mm >0.074 mm	Grains absent Grains coated Grains not coated	Argillic Amorphous	Random Preferred	None Interparticle filling	Shape: Tabular Rod-like
		Fine Argillic <0.074 mm >0.005 mm					
		Very fine Argillic <0.005 mm					

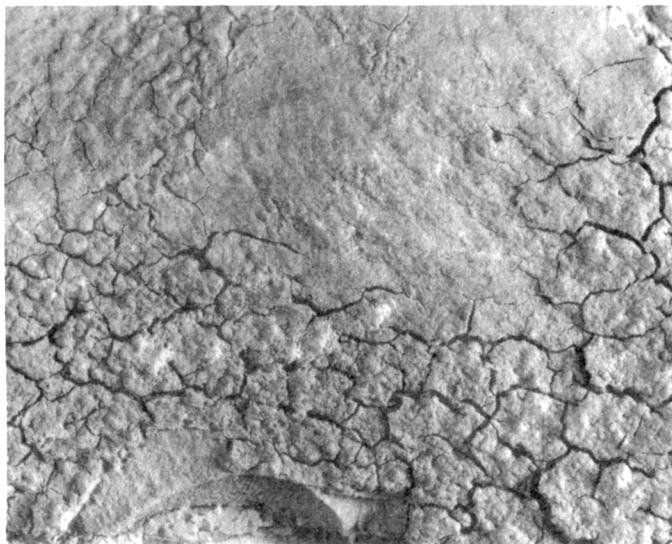


FIGURE 1. Claystone, Wellton-Mohawk Canal, Arizona, showing change from Ca-beidellite (massive) to Na-beidellite (cracked). Clay aggregations show within Na-beidellite fragments. Magnification 5x.

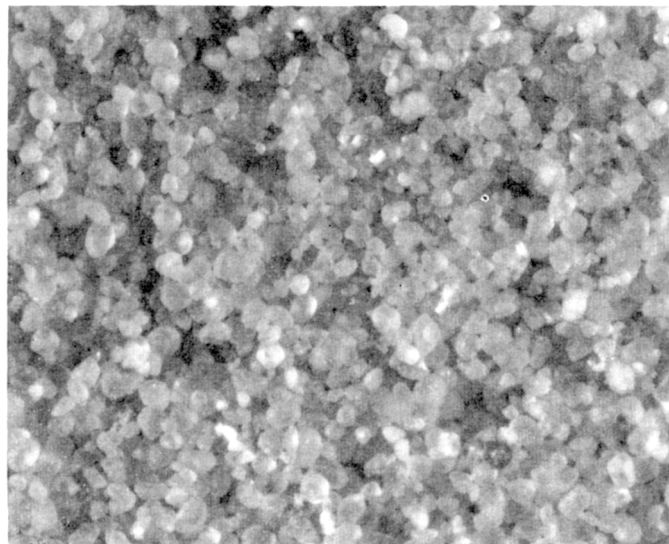


FIGURE 2. Massive, highly porous fabric (grains in contact). Navajo sandstone, Glen Canyon Dam site, Arizona. Magnification 10x.

(table 2). This classification is somewhat similar to that proposed by the National Committee on Soil Structure (Russell et al., 1929) but differs in that this classification is not limited to soils. It encompasses fabrics of both loose and indurated soils, sediments, and rocks of all origins.

The first broad division of earth materials depends upon the prominent or subordinate character of the fractures. Fractures interrupt the continuity of the fabric; hence, two earth materials having similar grain relationships, but differing fracturation, will differ in physical properties. For example, a claystone near Yuma, Arizona, is in the process of changing from a Ca-beidellite to a Na-beidellite. Both materials have similar internal grain relationships, but differ in fabric discontinuities as the result of excessive shrinkage of the Na-beidellite (fig. 1).

Each of the two broad divisions of the classification is subdivided into isotropic and anisotropic groups. Materials classified as isotropic exhibit three almost equal axes or are uniform in all directions; whereas, anisotropic materials possess distinctly different dimensions in different directions. The isotropic fabric can be massive or blocky. Massive types are devoid of any perceivable form; whereas, the blocky type is characterized by forms resembling a rough cube or other equidimensional forms. The anisotropic fabric can be columnar or planar, depending upon whether the vertical axis is longer than the horizontal axes (columnar) or is shorter (planar).

The massive type of fabric can be nonporous, porous, or highly porous (fig. 2). The pores may be larger or smaller than the grains or aggregations. The blocky type exhibits three kinds of form; namely, spheroidal, cuboidal, and irregular. The columnar type is characterized by prismatic or cylindroidal kinds of form. The prismatic form can be further differentiated into those which are hexagonal, square, or trigonal in cross section and into long or short forms.

The planar type exhibits discontinuities which represent either differences in particle size between layers, cleavage in one direction, or other two-dimensional fabric changes. This type is differentiated into four kinds of form. A foliated planar fabric consists of very fine discontinuous layers, which can be almost parallel or gently undulating and can be easily split into flakes. A laminated planar fabric includes more or less continuous layers of varying thickness (figs. 3 and 4). A lenticular planar fabric is composed of aggregates which are shaped like a double convex lens and are discontinuous (fig. 5). A scaly planar fabric is composed of aggregates shaped like a concavo-convex lens.

Three size grades are recognized for each of the various kinds of form, being designated as fine, medium, and coarse. The fine grade includes forms less than 2 mm in diameter. For platy, blocky, and massive types, the medium grade is 2 to 10 mm, and coarse grade is greater than 10 mm in size. Being usually larger features, the columnar types range from less than 1 cm for the fine grade, 2 to 10 cm for medium grade, and over 10 cm for the coarse grade.

The degree of aggregation of each of the kinds of form is designated as absent, poorly defined, moderately defined, and well defined to denote the distinctness with which the various aggregations manifest themselves. Aggregation is absent in the Navajo sandstone (fig. 2). Aggregations may or may not be water stable. Aggregations commonly are water stable when coated or impregnated by lignaceous or proteinaceous substances or iron oxides. The void spaces between aggregations might be empty or filled by amorphous or crystalline material. The Porterville claystone in the vicinity of Lindsay, Exeter, and Porterville, California, shows well-developed aggregated fabric, the aggregations being composed mainly of beidellite and coated with iron oxides (fig. 6). The aggregations resist slaking in water unless worked mechanically.

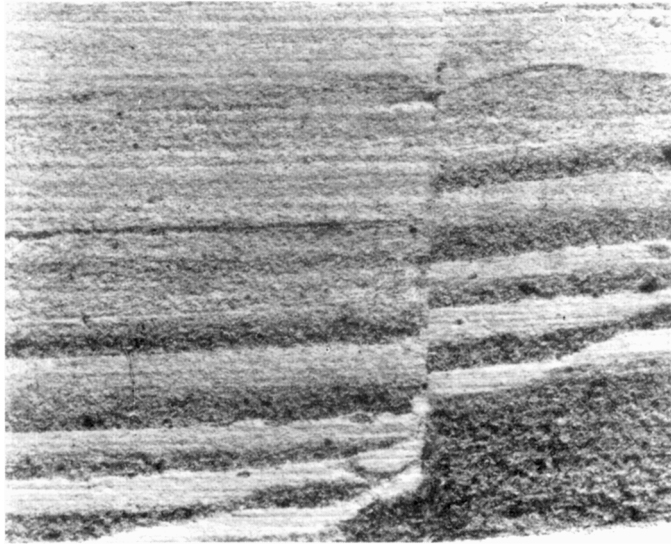


FIGURE 3. Planar, laminated fabric with fractures subordinate. Nespelem formation, near Coulee City, Washington. Magnification 6x.

Fabric Based on Grain Relationships

Packing. Packing is the spacing and mutual arrangement of particles constituting a fabric. The response of particulate earth materials to stress depends primarily upon the packing of the particles, and secondarily upon the boundary relationships, particle shape, properties of the particles, and amount and properties of the matrix. Consequently, a classification of fabric based upon particle relationships should indicate at once the mutual spacial relations of the primary components of the fabric. Accordingly, in table 3, elastic materials are subdivided into those in which (1) grains are in contact and (2) grains are not in contact, or the material is argillic.

In materials in which the grains are in contact, there are theoretically six different ways spherical particles can be arranged. (Graton and Frazer, 1935) Inasmuch

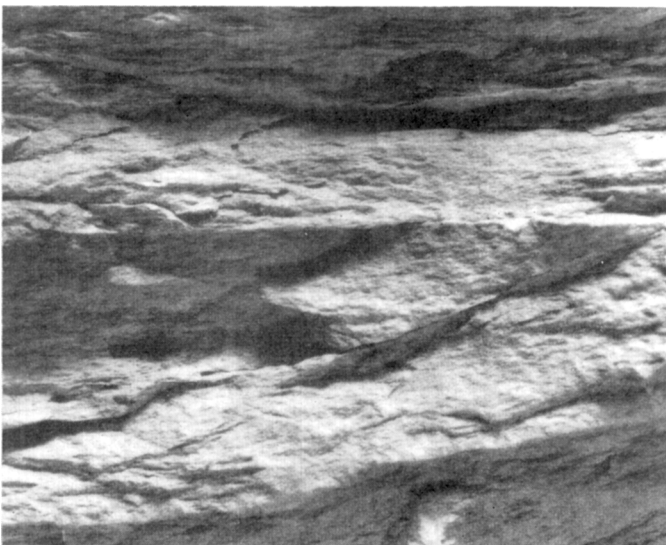


FIGURE 4. Laminated fabric with fractures prominent. Illitic shale, Yangtze Gorge, China. See fig. 10 for microscopical details. Magnification 6x.

as soil particles are not spheres, only two of the six possible types will be considered; namely, cubic and rhombohedral. These two types of packing represent the least efficient and most efficient modes of arrangement. When grains are cubically packed, a moderate amount of consolidation with reorientation of the particles will result if no matrix is present. If a matrix is present, consolidation with reorientation may or may not take place depending upon the nature of the matrix. When grains are efficiently packed, consolidation will be small even without a matrix.

Earth materials in which grains are not in contact are the materials which are of the most concern to engineers. The stability of these materials is for the most part controlled by the type and amount of matrix, and the stability of water films. When particles are not in contact they are separated by intergranular braces, a matrix in excess of the volume necessary to fill the intergranular spaces, or water films. The volume of the matrix material in some instances may constitute only 25 to 30 percent of the whole, yet the grains may not be in contact

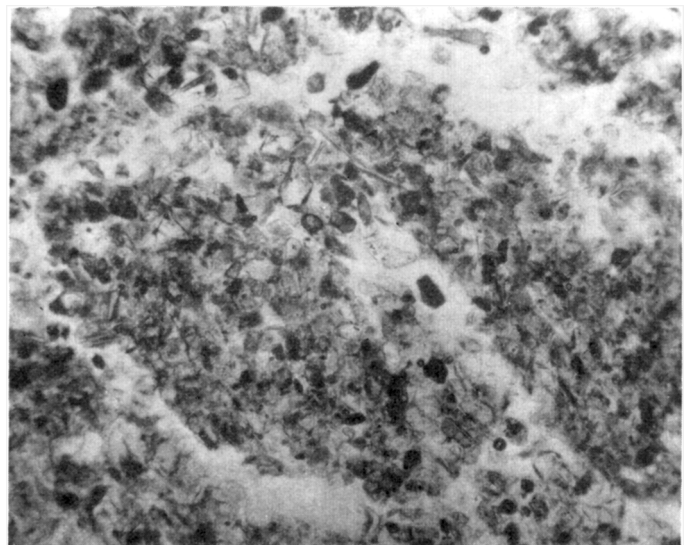


FIGURE 5. Aggregations composed of silt-sized grains which are cemented together by a montmorillonite-type mineral. Loess, Ashton Dam site, Nebraska. Magnification 70x.

because of the packing of the grains and the distribution of matrix material.

Materials classified as argillic may be composed of the clay minerals, clay-like minerals (such as sericite, chlorite, and vermiculite), boehmite, gibbsite, or crystalline iron oxides. These materials may or may not be aggregated. Occasionally, clastic argillic fragments result from erosion of original clay formations; in the materials so formed, the clastic argillic particles may be intermixed with any proportion of gravel, sand, silt, or dispersed clay (fig. 7).

Granularity. Many different methods of classifying the components or units of earth materials into groups have been and are in use. The components are divided into gravel, sand, silt, and clay sizes, depending upon the mean diameter of the components. Naturally, different amounts of each size group are obtained in an analysis of a given material, according to the limits placed on each group and the method used. In practice, particle

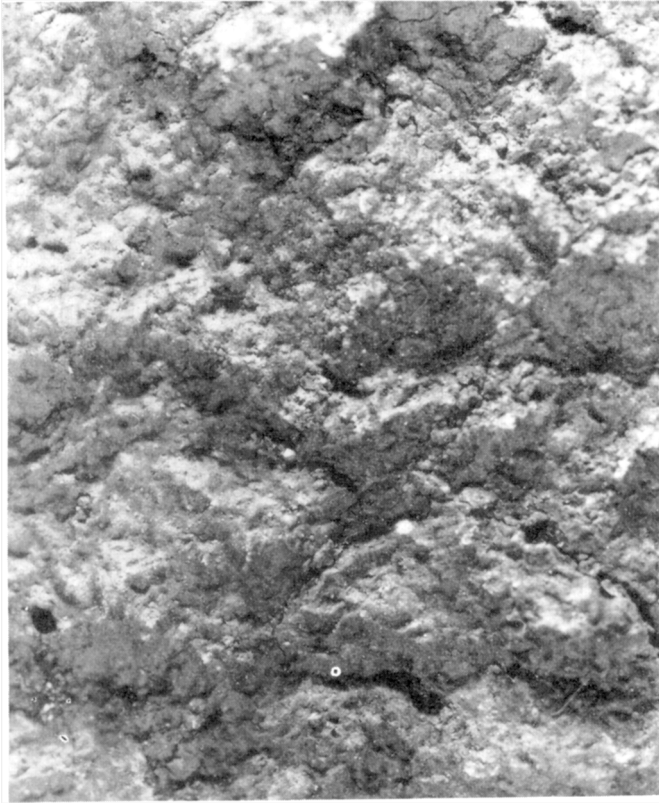


FIGURE 6. Lenticular fragments and small argillic aggregations. Beidellite claystone. Porterville clay, near Lindsay, California. See fig. 11 for microscopical details. Magnification 6x.

size is expressed in terms of volume, settling velocity, weight, surface area, cross-sectional area, and the traverse intercept.

Most laboratories use a combination of settling rate and sieving to classify earth materials on the basis of size. Particles larger than 0.074 mm in diameter are classified by a series of screens; particles less than 0.074

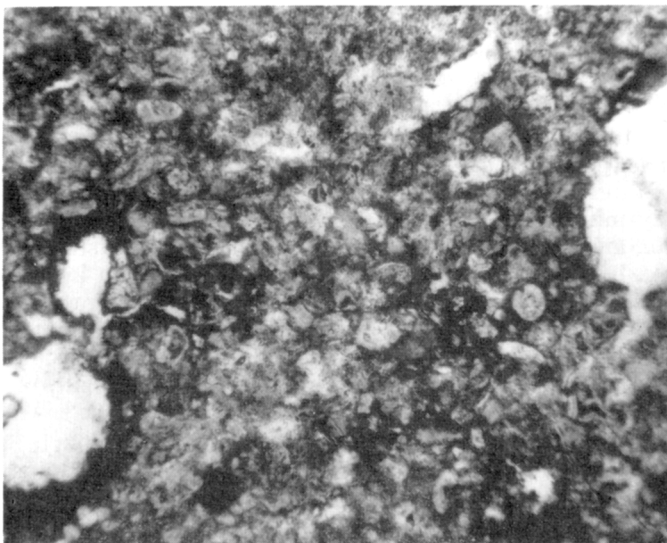


FIGURE 7. Medium- to fine-argillic fabric. Claystone containing halloysite and montmorillonite aggregations. Fena River Dam, Guam. Irregularly shaped white areas are root holes. Magnification 100x.

mm in diameter are commonly classified by the hydrometer method, which is based on the settling velocity of the particles. The Bureau of Reclamation (Adbun-Nur, 1950) and many other engineering organizations set the upper limit of silt at 0.074 mm, inasmuch as particles at and below this size cannot be resolved by the unaided eye. As many of the important engineering properties of soils depend on the content of fine-grained granular components and clay minerals, it is important that the amounts of these components be determined as accurately as possible.

Grain Coatings. The granular element of an earth material may be coated with a variety of materials such as clay minerals, iron oxides, or any of the substances listed as cementing materials. The coatings may bind the grains together or they may merely coat the grains leaving the material loose.

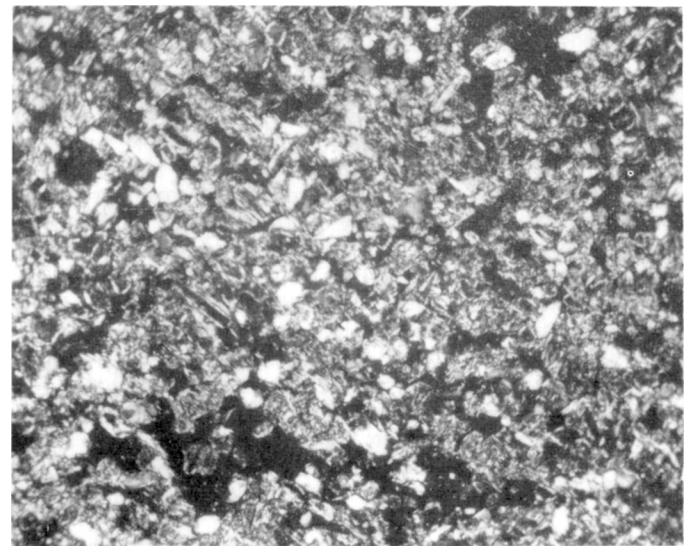


FIGURE 8. Loess, Ashton Dam site, Nebraska, showing grains supported by intergranular braces. Nicols crossed. Magnification 70x.

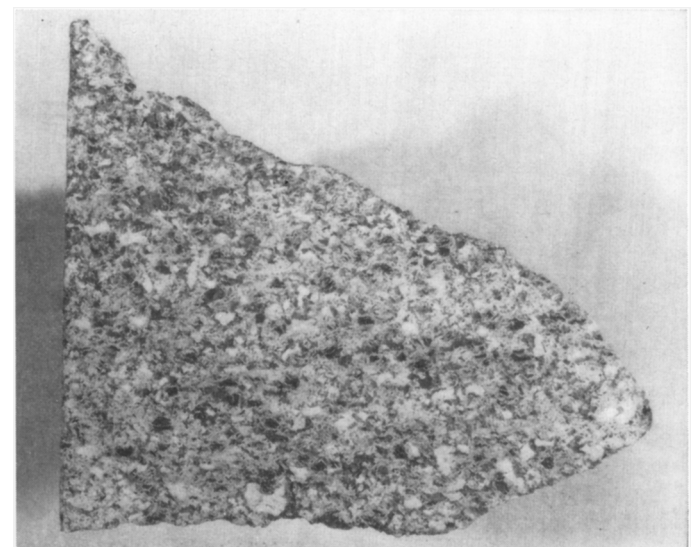


FIGURE 9. Claystone, Ione formation, near Friant, California, showing sand-sized argillic aggregations, composed of kaolin (white) cemented by very fine-grained kaolin. Magnification 2/3x.

For example, many loesses in Kansas and Nebraska are composed largely of fine sand- and silt-size grains, each one of which is enclosed by a thin hull of montmorillonite. These clay hulls are attached very firmly to the granular components so that even long agitation by an electric mixer and moderate treatment with acid fail to dislodge them. The bonding action of the clay coatings in loess explains the relatively high dry strength of loess in spite of its open fabric.

Kubiens (1938) has developed a classification of soils in which the two main divisions are based upon the presence or absence of grain coatings. This grouping corresponds rather well to a genetic classification of soils. However, for soil mechanics properties, packing is found to be the most fundamental aspect of fabric, the nature of grain coatings being of considerably lesser significance.

Type of Matrix. The absence or presence of a matrix exerts a great influence on the physical properties of earth materials. A matrix just filling the voids between grains at maximum hydration tends to add stability to the materials under stress. This point is elucidated in subsequent sections of this paper.

Earth materials composed of gravel and sand may contain no matrix or any one of several matrices (table 3). Fine granular materials (silt size), however, can contain only argillic or amorphous matrices. Materials having a granular matrix are quite different from materials containing an argillic matrix. Similarly, a material with a crystalline matrix is quite different from material with a elastic or amorphous matrix. Materials containing a granular matrix may display properties similar to those of otherwise similar materials containing a bio-fragmental matrix. Also, argillic matrices may produce properties similar to those resulting from some types of amorphous matrices. However, materials containing a montmorillonite-type clay mineral in the matrix will behave quite differently from materials containing the other kinds of matrix. Variations in properties will occur in materials containing montmorillonite according to the kind of exchangeable cation present.

Any type of matrix may occur intermixed with one or more others. However, one type is usually present alone or strongly predominates over others.

In certain materials in which the grains or particles are not in contact, the fabric is supported by intergranular braces. This type of matrix is of considerable engineering importance. In some loess, granular components are widely separated by intergranular braces composed of very fine silt intermixed with beidellite or montmorillonite (fig. 8). This fabric is characteristic of one type of loess in which the strength is high when the material is dry, but with wetting the fabric collapses and a large consolidation takes place. Intergranular braces may also be composed of argillic or amorphous material.

The medium, fine, and very fine argillic materials may contain an argillic or an amorphous matrix. For example, in the Ione formation near Friant, California, sand-size argillic aggregations composed of kaolinite are bound together by a matrix of kaolinite (fig. 9). Study of argillic materials from many areas may reveal that elastic argillic aggregations cemented by argillic or

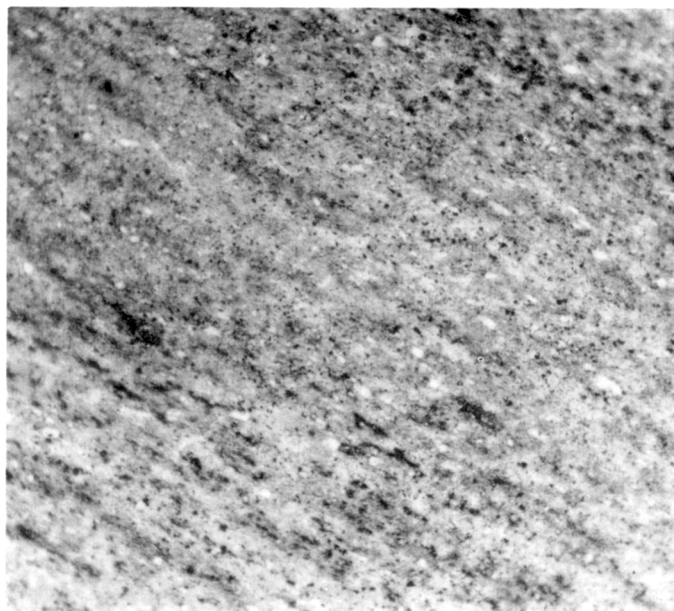


FIGURE 10. Very fine argillic fabric, with preferred orientation. Illite shale, Yangtze Gorge, China. Magnification 60x.

amorphous materials are widespread and that their manner of transportation and deposition and general fabric characteristics are somewhat similar to those of sand and silt.

Orientation. The orientation of the elements in a fabric of an earth material may be random or preferred. In petrofabrics, the symmetry of the fabric is also determined and further work may justify more definitive designation of orientation in elastic fabrics. By complete study of the orientation and symmetry of the fabric of earth materials and rock, better static and dynamic test procedures are being developed and a better understanding of the mass properties of the earth material inevitably will result.

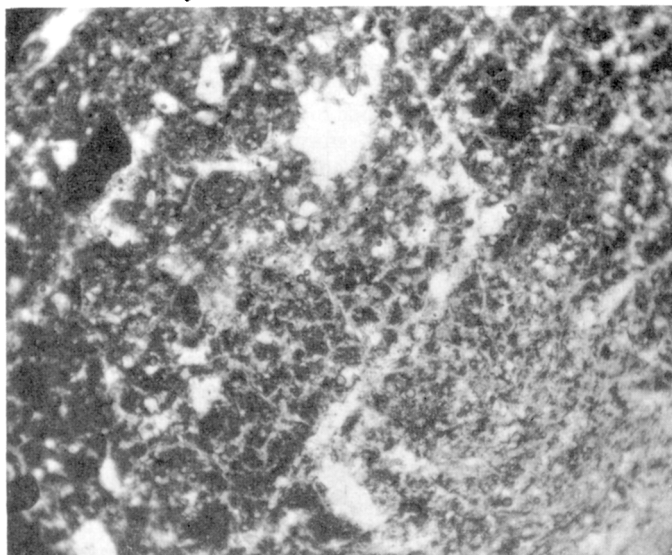


FIGURE 11. Medium and fine argillic fabric. Beidellite claystone, Porterville clay, near Lindsay, California. Dark areas and aggregations of beidellite cemented mainly by argillic matrix (thin, white, irregular streaks between dark aggregations). Magnification 50x.

When the elements of an earth material are arranged in such a manner that no repetitive pattern is observable, the fabric is said to possess a random orientation. When the elements are arranged in a repetitive pattern, the fabric possesses a preferred orientation. Random orientation is well illustrated by the Navajo sandstone, Glen Canyon Dam site, Arizona (fig. 2). A detailed study of the fabric of this rock probably would reveal some type of orientation. Preferred orientation, in which all of the elements are aligned with their longest axes parallel to each other, is observed in many shales. As viewed with polarized light, the whole fabric acts more or less as an anisotropic crystal. This type of orientation is illustrated by an illite shale from near the Yangtze River Gorge, China (fig. 10).

Materials with a preferred orientation are more likely to fail at lower shear values than are similar materials in which the orientation is random. Some degree of preferred orientation of the constituent particles may in turn orient the pore spaces in an earth material in such a manner that directional permeability and porosity result, as is typical of loess. The determination of directional permeability in sands is of importance in the primary and secondary recovery of oil.

Cementation. A great variety of mineral substances may occur as cements in clastic earth materials. Cementing substances can be classified into two general categories: (1) reversible, and (2) irreversible. A cement in an earth material is said to be reversible if the properties of the material changed by manipulation and dehydration are regained with wetting and remolding, and restoration of the original conditions of temperature and pressure. Otherwise the cement is said to be irreversible. Common cements found in earth materials are:

<i>Reversible</i>	<i>Irreversible</i>
Clay	Carbonates (calcite and dolomite)
Soluble salts	Iron oxides
Water	Aluminum oxides
Ice	Silica
	Organic matter

Any one of these cementing substances may occur as the main cement, but commonly both reversible and irreversible cements occur together in almost any combination. Thus, water and clay, calcite and clay, or water, calcite, and silica, may occur together. Loose, clean sands are essentially cohesionless when dry; conversely, when water is present, the sand can be molded to any desired shape, and the molded shape will be retained with drying. However, only a minute force is sufficient to destroy the molded form. When clay minerals (except halloysite, $4\text{H}_2\text{O}$) are added to the water-sand system, the material is easily molded, and when dry, the molded form possesses many times the cohesion of the water-sand mixture. Both these clay minerals and the water act essentially as reversible cements; the dry material can be rewetted, remolded, dried, and the materials will develop cohesion again.

When substances like gelatinous silica and hydrated iron and aluminum oxides are precipitated in the soil in amounts large enough to constitute the major cementing material, the soil may be molded to a desired shape if not dried. During drying the material retains its shape and is resistant to shearing stresses, but when broken the material resists remolding. The cohesion of

the mass may or may not be increased significantly by the addition or presence of these irreversible cements, depending upon the type of irreversible cementing material, degree of induration, and the amount of water present. Thus, dry heavy clays may be as strong as or stronger than some earth materials cemented with calcium carbonate or hydrated oxides.

Cementation may occur in various degrees. Grains may be cemented together at the points of contact (fig. 2), or the interstices may be partially or completely filled with cementing matrix. Clays can be cemented by various cementing materials, but in contrast to granular materials they possess a natural ability to cohere. Cohesion between particles of clay minerals may be high, even while adhesion between the clay mineral and granular constituents is relatively weak.

The cementing materials may be deposited with the grains or they may be introduced later by meteoric or hypogene water. The interested reader is referred to various articles on the origin and mineralogy of cementing materials (Waldschmidt, 1941; Johnson, 1920; Frye and Swineford, 1946).

Particle Form. The particle forms in an earth material are quite diverse and difficult to evaluate. The majority of the components of earth materials can be said to be irregular in shape, but some grains, such as zircon, hornblende, some quartz crystals, sillimanite, and diatoms, possess regular shapes. In order to describe particle shape, the form of the components of an earth material may be compared with regular geometrical forms as follows:

- Equant—Dimensions in all three mutually perpendicular directions are equal or the dimension in one direction is less than $1\frac{1}{2}$ times that of the other directions
- Tabular—The length and width of the particle are more than $1\frac{1}{2}$ times the thickness
- Rod-like—The length of the particle is more than $1\frac{1}{2}$ times the width or thickness
- Irregular—No geometrical form

More specific detailed geometrical forms can be used as a basis for description of particular shapes. Thus, equant could be subdivided into spherical, cubical, and octahedral shapes; tabular into disk-like or platy; and rod-like into prismatic, cylindrical, or bladed.

In order to express the shape of particles numerically, the concept of sphericity of particles is used in sedimentary petrography (Pettijohn, 1949) and can be introduced in more detailed investigations of earth materials. Sphericity is a measure of the degree to which a particle approaches a spherical form. Sphericity is expressed as the ratio of the diameters of the grains. If the grain diameters are a , b , and c (length, width, and thickness, respectively) four different shape classes; namely, disks, spheroids, blades, and rods can be distinguished.

Rounding, in contradistinction to sphericity, is a measure of the angularity of the edges and corners of particles. Roundness is expressed as the ratio of the summation of radii of the individual corners of the particle, divided by the number of corners, to the radius of the maximum inscribed circle. Depending upon the degree of rounding of the corners and edges, particles can be classified as rounded, subrounded, subangular, and angular.

The shape of the particles materially affects some of the physical properties of earth materials. Fraser (1935) has shown how porosity is affected by change of grain shape in sands whose gradation is the same. Permeability is also dependent to some degree upon the shape and degree of rounding of the particles, as well as other aspects of fabric, such as size, packing, sorting, and continuity of voids. Materials containing diatoms exhibit high compressibility because of their peculiar shape. Diatom tests are exceedingly thin, as compared to their length and width, and in a sense act as platy units, much like the micaceous minerals, except that their strength and elasticity are not so great as those of mica.

The degree of rounding of the granular components affects the stability of a loose sand. The greater the angularity, the more the components tend to interlock and thus to increase internal friction and the angle of repose of the material. However, because of irregular distribution of stress, angular grains tend to fracture and granulate more readily than do similar materials composed of rounded grains.

MINERALOGIC COMPOSITION

Granular Components

The grains (granular components) of earth materials are the hard particles of rocks, minerals, and organic structures which act as individual units under stress. Such components are best illustrated by quartz, feldspar, calcite, dolomite, the hard remains of diatoms, radiolaria, mollusks, and such rock types as granite, rhyolite, basalt, volcanic ash, limestone, sandstone, schist, and gneiss. These components, when predominant, form the fundamental framework or skeleton of earth materials. By means of this framework, pressure is transmitted from grain to grain throughout the mass. When they are the only components present, the material is a loose gravel, sand, or silt. Granular components are almost always present in argillie elastic materials.

Granular mineral and rock fragments are derived from igneous, sedimentary, and metamorphic rock by chemical and mechanical weathering. They commonly represent the rocks and minerals most resistant to chemical and mechanical weathering. Quartz is the dominant granular component of most soils; feldspars are widespread; rock particles almost always are present, and may dominate, as in areas underlain by fine-grained rocks. High content of feldspars commonly is found in residual soils where feldspar predominates over quartz in the original bedrock. In areas of dry or cold climate, feldspars remain abundant through long distances of transport by streams, as for example in the sands and gravels of the Great Plains states, which were derived from granitic rocks and gneisses of the Rocky Mountains.

The minerals commonly observed in soils as sand- and silt-size particles are (in order of decreasing abundance):

- | | |
|--------------------|-----------------|
| 1. Quartz | 11. Olivine |
| 2. K-feldspars | 12. Sillimanite |
| 3. Na-Ca-feldspars | 13. Zircon |
| 4. Calcite | 14. Rutile |
| 5. Dolomite | 15. Magnetite |
| 6. Muscovite | 16. Tourmaline |
| 7. Biotite | 17. Staurolite |
| 8. Chlorite | 18. Garnet |
| 9. Hornblende | 19. Sphene |
| 10. Aügite | 20. Apatite |

Calcite and dolomite are present in soils and in rocks as detrital grains more often than is generally recognized. In earth materials, calcite and dolomite may be present also as precipitated crystals which act as detrital grains, or calcite and dolomite may cement the grains together, forming concretions, caliche, or calcareous hardpan. For purposes of this classification, micaceous minerals, such as muscovite, biotite, and chlorite, are considered as granular components of earth materials when present in sand- or silt-size particles. However, when these minerals are present in clay-size particles, they should be classed as clay-like because their crystallographic structure usually is degraded. Hence, micaceous minerals may be regarded as intermediate between granular minerals and argillie materials.

Argillie Materials

Clay and Clay Minerals. The clay minerals are one of the most important constituents of earth materials and many of the properties of earth materials are influenced by the identity, amount, particle size, and chemical composition of the clay minerals. Three large classes of clay minerals are recognized, namely: the kaolinite, montmorillonite, and illite (hydrrous mica) groups.

In any discussion of the mechanical components of earth materials two conflicting conceptions arise concerning the word "clay," one referring to particle size and one to mineralogic composition. In general, "clay" is meant to comprise the components of earth materials which are very fine-grained (say, less than 5 microns in size) and plastic when moist. More definitively, however, unless mineralogically identified, these fine-grained components should be referred to as clay size. During the past two decades, largely as the result of analysis of soils by X-ray diffraction methods, it has been determined that clays almost universally contain one or more hydrrous aluminum and magnesium silicates which are crystalline.

Plasticity is usually associated with the definition of clay, but clay minerals vary greatly in their plastic properties. Kaolinite and halloysite may exhibit moderate or only slight plasticity, and halloysite commonly is nonplastic. On the other hand, montmorillonite is highly plastic. Illite is widely variable in plasticity. Moreover, the term "clay" cannot be restricted justifiably to minerals which possess plastic properties by short-time manipulative tests, since clay minerals can acquire plastic properties after a long period of time of hydration.

For purposes of this paper, clay will be defined as earth materials which are very fine-grained and plastic when wet, or which contain high proportions (25 percent or more by volume) of minerals of the montmorillonite, illite, or kaolinite groups.

Clay minerals may be absent from earth materials, such as certain gravels, sands, and silts (glacial rock flour), or they may be almost pure, as in some clay deposits. In most earth materials gravel, sand, silt, and clay minerals are mixed in various proportions. The clay minerals may occur as coatings on grains, cementing materials between grains, or as silt- and sand-size aggregations (fig. 11). Mineralogic composition in relation to engineering properties of many soils is reported by Lambe and Martin (1953).

Crystallography of Clay Minerals. The crystallographic structure and chemical composition of clay minerals have been extensively investigated (Pauling, 1930; Gruner, 1933; Hendricks, 1936; Hofmann et al., 1933), and are discussed in detail elsewhere in this volume. The definitive relationships of crystallography, chemical composition, and atomic substitution should be reviewed in order that the inter-relation of these properties and engineering performance of various clay minerals can be recognized.

Suffice it to say that clay minerals may be subdivided into three main categories: (1) the micaceous or platy clay minerals; (2) the fibrous clay minerals; and (3) the amorphous clay minerals. The clay mineral species may be arranged as follows:

1. Micaceous Clay Minerals

a. Kaolinite Group

<i>Dioctahedral</i> *	<i>Trioctahedral</i> **
Kaolinite	Antigorite
Halloysite, 2H ₂ O	Chrysotile
Hydrated halloysite, 4H ₂ O	Cronstedite
Nacrite	Chamosite
Dickite	Amesite

b. Montmorillonite Group

<i>Dioctahedral</i>	<i>Trioctahedral</i>
Montmorillonite	Saponite
Beidellite	Hectorite
Nontronite	Vermiculite (jefferisite)

c. Hydrous Mica Group

<i>Dioctahedral</i>	<i>Trioctahedral</i>
Illite	Hydrobiotite
Pinite	Mg-illidromica
Glauconite	
Celadonite	
Brammalite	

d. Mixed Layer Group

Anauxite
Bravaisite
Vermiculite-chlorite
Kaolinite-nontronite
Montmorillonite-illite

2. Fibrous Clay Minerals

a. Sepiolite Group

Sepiolite
Garnierite
Pilolite

b. Palygorskite Group

3. Amorphous Clay Minerals

a. Allophane

Because so little is known concerning fibrous clay minerals, a brief comment will be made on their mineralogy. Fibrous clay minerals include two subgroups. One subgroup comprises minerals with a sepiolite structure, the second those with a palygorskite structure. These two minerals, palygorskite and sepiolite, have been studied by DeLapparent (1935) and Longchambon (1937). Sepiolite is a hydrous magnesium silicate, whereas palygorskite is a hydrous magnesium aluminum silicate. The possibility that these two minerals belong to one isomorphous series is quite unlikely in view of their totally different crystallographic structure.

The name "attapulgitite" was proposed by DeLapparent (1935). Later work by Bradley (1940) showed

that the structure of "attapulgitite" is analogous to that of the amphiboles. Palygorskite with a very similar, if not identical, chemical composition and X-ray diffraction pattern was named by Fersman (1908) in 1908. Consequently, the name "palygorskite" should take precedence over "attapulgitite." As shown by X-ray diffraction analysis, the main mineral in deposits of so-called "attapulgitite" in Florida and Georgia is palygorskite. Varying amounts of a montmorillonite-type mineral also are present. In some occurrences, palygorskite is described as mountain cork and mountain paper. The mineralogy and paragenetic relationships of palygorskite are described by Macksoud (1939).

Sepiolite, often referred to as meerschaum, is of limited occurrence but is apparently widespread. Garnierite is a nickeliferous member of the sepiolite group. Since the ionic radius of nickel is close to that of magnesium, nickel can substitute for magnesium in the lattice quite easily. X-ray diffraction patterns of garnierite from New Caledonia, one of the type localities, are almost identical with the X-ray diffraction patterns for sepiolite. Pilolite or hydrous magnesium aluminum silicate from Euboea, Greece, as shown by A.S.T.M. X-ray Diffraction Data Card No. II-41, also yields an X-ray diffraction pattern very similar to that of sepiolite. Other minerals probably belong to these two groups, forming a sequence analogous to the montmorillonite group.

Occurrence of Clay Minerals. The formation of clay minerals is discussed in detail by Ross and Hendricks (1945), Grim (1942), and Hoskings (1940). Clay minerals form in response to physical-chemical conditions, the determining factors being acidity or alkalinity of solutions, drainage, oxidation or reducing conditions, and the availability of chemical elements. The available elements, as determined by the original rock, dominate the early stages of alteration. For example, a tuffaceous material at Fena River Dam, Guam, contains montmorillonite and halloysite; the halloysite forms the matrix, whereas the montmorillonite constitutes the bulk of the embedded tuff fragments. At Pierce damsite near Singapore, Malaya, granite is weathered to depths in excess of 60 feet; the feldspar crystals being converted in place to fine kaolinite and the biotite to vermiculite, the quartz remaining intact. With progress of alteration and differential leaching of original elements of the parent material, the physical-chemical conditions come to dominate and similar clay mineral suites may be developed from divergent rock types (Hoskings 1940).

Kaolinite in earth materials is much more common in the eastern and southern parts of the United States than in western United States. Many of the occurrences of kaolinite in western United States are of hydrothermal origin. Kaolinite clays of high purity of sedimentary origin occur in parts of the Dakota and Lakota formations near Mesa Alta, New Mexico. Kaolinite is widespread as a minor constituent of many clays and shales, as in the Tongue River formation near Barnes, South Dakota, in which it constitutes 25 percent; shale of the Benton formation, Golden, Colorado (10 percent); shale of the Mowry formation, Tiber Dam site, Montana (15 percent). Kaolinite clays and sandstones containing intermixed anauxite are abundant in the Ione formation of California. Vermicular kaolinite and flakes of anaux-

* Dioctahedral (Brindley, 1951) clay minerals are those in which approximately two of three positions in the octohedral layer of the half unit cell are occupied by cations.

** Trioctahedral (Brindley, 1951) clay minerals are those in which approximately three of three positions in the octohedral layer of the half unit cell are occupied by cations.

ite constitute 5 to 35 percent of altered pumicites of the Bozeman formation near Kalispell, Montana. Other occurrences of kaolinite and related minerals are discussed by Kerr and Kulp (1949).

Information on the occurrence and engineering properties of halloysite and hydrated halloysite in earth materials is meager, but with developing techniques of mineralogic analysis it is becoming more apparent that halloysite is quite widely distributed. Halloysite has been observed in earth materials from Nairobi, Kenya; in tuffs at Howard Prairie Dam site, Oregon; in paleosols on terraces of the Trinity River, California; in tuffs at Fena River Dam, Guam; and in very small amounts at other localities admixed with other clay minerals. The halloysite soil from Nairobi is of especial interest because the typical tubular structures are visible with the petrographic microscope. Engineering properties are discussed in a later section.

Montmorillonite-type clay minerals, which are present in small to moderate amounts in the earth materials of the eastern United States, are the most widespread clay minerals in earth materials of the western United States. Montmorillonite-type clay minerals are common in the Graneros formation near Osage, Wyoming (85 percent); the Bear Paw formation near Fort Peck, Montana (50 percent); the Porterville clay of central California (35 to 65 percent); the Pierre shale formation near Jamestown, North Dakota (80 to 85 percent); the Wasatch formation near Ivie, Utah (80 percent); the Creede formation near Wagon Wheel Gap, Colorado (60 percent); the Mowry shale formation near Laramie, Wyoming (50 percent); the Eagle Ford formation near Dallas, Texas (50 percent); and elsewhere. Montmorillonite-type clay minerals also occur in small proportions in many formations, as in the Valley Springs formation, Valley Springs, California (3 percent); the Monterey formation, California (5 to 25 percent); the Brule, Arikaree, and Frontier formations in Wyoming (25 to 45 percent); and the Ringold formation, near White Bluffs, Washington (15 to 35 percent). Nontronite is widespread in altered basalts, where it develops from palagonite, ferromagnesian minerals, and plagioclase.

Space does not permit the listing of additional occurrences of montmorillonite-type clay minerals encountered in the western United States. Other occurrences of montmorillonite are cited by Ross and Hendricks (1945) and by Kerr and Kulp (1949).

Illite-type clay minerals are fairly common in earth materials of the western United States. The estimation of their amounts in earth materials is difficult as they often occur intermixed or interlayered with montmorillonite, vermiculite, chlorite, and other micaceous minerals. Illite has been observed in the Pierre formation, Boulder, Colorado (40 to 50 percent); the Lower Dakota formation, Carter Lake, Colorado (50 to 60 percent); the Morrison formation near Tenderfoot Mesa, Colorado (40 to 50 percent); the Carlisle formation near Cedar Bluffs, Nebraska (50 to 60 percent); the Benton formation near Golden, Colorado (40 percent); the Nespelem formation near Grand Coulee Dam, Washington (10 to 40 percent); the Flathead formation near Trident, Montana (30 percent); and in recent glacial deposits at Eklutna, Alaska (40 to 50 percent). Illite is also observed in small amounts in the Green River

formation near Rifle, Colorado (15 percent); the Eagle Ford formation, near Dallas, Texas (20 percent); and the Chadron formation, Weld County, Colorado. The occurrence of illite in many other earth materials is described by Grim (1942).

Certain earth materials contain crystallographically interlayered minerals, such as montmorillonite and illite (Bradley, 1946); vermiculite and hydrobiotite (Gruner, 1934); and vermiculite and chlorite (Brindley, 1951; Bradley, 1946). Other combinations are probable. Interlayered vermiculite and chlorite are an important constituent of the glacial lake deposits of the northwestern United States, especially in the Nespelem formation of Washington (fig. 3). These combinations also occur in physical mixtures. It is often difficult to determine whether a given clay is a physical mixture or is composed of interstratified clay minerals. Walker (1949) has devised a method to differentiate various clay minerals, and the differential thermal method is useful in identifying interlayered minerals.

Crystalline Hydrated Oxides. Most of the earth materials contain small amounts of crystalline hydrated iron oxides (goethite) or simple oxides (hematite) and possibly hydrated aluminum oxides (boehmite and gibbsite). In soils occurring in subtropical and tropical regions, the iron and aluminum oxides quite commonly occur together, as in laterite, or aluminum oxides may predominate as in bauxite. These compounds occur mixed in various proportions, with or without clay and detrital minerals, depending upon the climate, degree of weathering, type of parent rock, and transportation agent.

The hydrated oxides of aluminum and iron represent the end products of rock and mineral decomposition; that is, they are the compounds which remain after the more-soluble constituents have been leached out.

In general, these oxides act as cementing agents for other constituents of earth materials.

Organic Matter

Organic matter found in sedimentary rocks, water, and recent soils, usually is very complex chemically and physically, inasmuch as many factors, processes, and types of organisms have contributed to its formation. Natural carbonaceous organic matter can be classified into five main groups, namely: (1) carbohydrates; (2) proteins; (3) fats, resins, and waxes; (4) hydrocarbons, such as coal, asphalt, petroleum; and (5) carbon. Benzoic acid, vanillin, and hydrobenzoic acid were found by Shorey (1914) in an organic hardpan in the Leon soil of Florida. In addition to the above constituents, earth materials contain living organisms and newly formed products of their metabolism. Carbohydrates, such as cellulose, hemicellulose, and lignin are the most abundant organic compounds in earth materials. These compounds are derived by decay of plant structures.

Earth materials vary greatly in content of organic compounds. Desert soils contain the least amount of organic matter. Soils of humid, temperate, or cold regions commonly contain abundant organic matter, peat being an extreme example. Laterites contain only small amounts of organic matter. In prairie soils, organic matter is usually confined to the upper 3 feet and ranges from 5 to 10 percent. Organic matter found in marine

shales may consist of petroleum, hydrocarbon, carbon, and "kerogen." According to Trask (1939) only a few marine sediments contain more than 10-percent organic matter and only a few contain less than 0.5 percent. Organic matter is most common in the finest fractions of sediments. On the average, clayey materials contain four times as much organic matter as do sands and twice as much as silty materials.

Much of the organic colloids or "humus" in soils are derived mainly from plant lignins. The organic colloids vary greatly in their properties according to the parent material, climatic conditions, and state of decomposition. Lignin-humus, as these organic colloids are often designated, possess outstanding cation-exchange capacity, whereas cellulose and hemicellulose possess small exchange capacity.

Soluble Compounds

Soluble compounds, such as inorganic salts, are present in many of the soils of the arid and semiarid regions of the world. In recent unconsolidated sediments, inorganic salts accumulate in arid and semiarid regions wherever inland or poor subsurface drainage exists or where irrigation is practiced. Soluble salts also accumulate on low alluvial flats along seacoasts in humid areas.

Soluble salts in soils are of interest because their presence affects the value of land, its potential use, the feasibility of irrigation projects, the durability of concrete in engineering structures, the permeability of earth or bentonite linings of canals and reservoirs and soil stabilization practice. Saline and alkali soils occupy considerable portions of certain areas and according to Zakharov (1927), alkali soils underlie 24 percent of the area of the Union of Soviet Socialist Republics. They are widespread in the Dakotas and parts of Colorado, Wyoming, and eastern Montana, and in the southwestern part of the United States.

Soluble constituents of earth materials originate by decomposition of other minerals or by precipitation from hypogene, connate, or saline surface waters.

Through mechanical disintegration and chemical processes, such as hydration, carbonation, oxidation, reduction, and dissolution, the elements composing rock-forming minerals are made soluble and are carried to the ocean or to inland basins by surface or ground water. Some geologic formations yield soluble salts directly by leaching of soluble compounds.

Many different salt compounds are present in saline and alkali soils. The most common compounds are the chlorides, carbonates, and sulfates of sodium and the sulfates and chlorides of calcium and magnesium. Calcium and magnesium carbonates are not significantly soluble in pure water, but they become soluble when acted upon by weak acids. In general, potassium chloride and carbonate are not common, although in certain occurrences they may be the dominant salts. Borates and nitrates, although concentrated as crusts on soils in various regions, are not common in most areas. In some soils, double and triple salts form by wetting and drying. Glacial soils from northern Montana and southern Alberta, when saturated with water and allowed to air dry, yield a triple salt, tentatively identified as Chile loeweite. The original soils contain gypsum ($\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$) which partially dissolves with wetting. Cation exchange then takes place, Na^+ , Mg^{++} , and K^+ being re-

placed in part by Ca^{++} . The released Na^+ , Mg^{++} , and K^+ then combine with the sulfate radical to form the triple salt upon drying. Similarly, gypsum occurring naturally in sodium bentonite will effect partial cation exchange upon wetting of the material, and impedes swelling.

For purposes of classification, soils containing salts are designated in the United States as: (1) saline, (2) saline-alkali, and (3) nonsaline-alkali (Anon., 1947).

Saline earth materials contain abundant but widely variable amounts of chlorides and sulfates of calcium and magnesium and, less commonly, nitrates of sodium. Sodium in exchangeable form is subordinate. Calcite and magnesite may also be present. These saline earth materials may be developed from normal earth materials under poor drainage conditions. The excess of soluble salts maintains the clay minerals in flocculated condition and the fabric of the soil is open and permeable.

The saline-alkali soils contain both soluble salts and exchangeable sodium. These saline-alkali soils are formed by both salinization and alkalization. The fabric of these soils is similar to that of saline soils so long as excess salts are present. However, when leached, the clays disperse and the fabric becomes similar to that of nonsaline-alkali soils.

The nonsaline-alkali-earth materials contain sodium as the main exchangeable cation; small amounts of chlorides, sulfates, and carbonates of calcium and magnesium are present. These earth materials develop from the saline-alkali earth materials by leaching of soluble salts or by erosion, transportation, and redeposition of montmorillonite-rich fractions. Hydrolysis of these soils forms sodium hydroxide (and subsequently sodium carbonate by carbonization) and any organic matter becomes dispersed through the soil, producing a dark color. If large amounts of organic matter are present, the soils are referred to as "black alkali." These soils are dense and possess a massive fabric.

Amorphous Constituents

The amorphous compounds in earth materials are mainly hydrated oxides of iron, manganese, aluminum, and silicon; the hydrous aluminum silicate, allophane; volcanic glass; the altered basic glass, palagonite; and, as mentioned above, certain organic compounds. Amorphous phosphate compounds are rare.

The amorphous hydrated oxides are present in earth materials in small amounts. They generally occur intermixed with clay at seams, as coatings on grains, and in intergranular voids. Allophane also occurs in small amounts in earth materials, but, because it is difficult to identify, allophane is rarely reported.

Volcanic glass is present in many of the earth materials in the western United States, ranging from only a trace to virtually the entirety of the materials, as in pumicite. As these glasses are very susceptible to chemical alteration, montmorillonite is commonly present. Kaolinite is the less-common argillie alteration product in the western United States. Palagonite is an indefinite hydrous mineraloid containing MgO , FeO , Fe_2O_3 , Al_2O_3 , and SiO_2 , which alters readily to montmorillonite, nontronite, saponite, or kaolinite minerals, depending upon the environmental conditions. Basaltic glass and palagonite are widespread in certain areas such as the Pacific

Northwest; nontronite is ubiquitous in association with palagonite, saponite occurs sparsely. In the Hawaiian Islands palagonite typically alters to kaolinite (Dean, 1947).

SURFACE CHEMICAL PHENOMENA

Adsorption

Adsorption is the change in concentration occurring at the interface or phase boundary between solids and liquids, solids and gases, and liquids and gases, with or without chemical reaction. To be included are such interrelated phenomena as adsorption and exchange of molecules, cations, and anions. Inorganic and nonpolar or polar organic compounds, take part in the three adsorption processes. Adsorption may be the result of coulombic or gravitational (van der Waals') forces. The electrical unbalance (coulombic) causing adsorption arises in part through partial or complete substitution in a crystal of ions of differing valency, at broken electrostatic bonds, at areas of polarization, and by chemisorption upon accessible hydroxyl groups or other ions at the surface. In the clay minerals, adsorption may take place at the edges and side surfaces and between the clay packets, as in expanding lattice minerals like montmorillonite.

The clay minerals act as adsorbents for liquids, gases, and suspended solids in liquids. Only limited data are available on the adsorption of gases by clays, but Nelson and Hendricks (1943) have shown that inert gases are adsorbed only on external surfaces of clay crystals. Abundant data are available, however, on the adsorption of liquids by clays.

Molecular Adsorption. The adsorption of water molecules by clay minerals of the montmorillonite group results in an increase in the c-axis spacing without any appreciable change in dimensions of the a- or b-axis. This phenomenon was first studied crystallographically by Hofmann, Endell, and Wilm (1933) and by Hofmann and Bilke (1936) who measured the variation of the c-axis spacing with different vapor pressures. Bradley, Grim, and Clark (1937) postulated that H-montmorillonite forms definite hydrates which contain 6 to 24 H₂O molecules per unit cell. Hendricks and Jefferson (1938) suggested that different degrees of orderliness existed in the water held between the packets of the crystal and that the greatest degree of orderliness is attained in H-montmorillonite. The adsorbed water molecules are thought to assume a hexagonal arrangement, analogous to the crystallographic structure of ice, and to develop one, two, three, or four layers with increasing vapor pressure. The spacing along the c-axis increases stepwise with formation of each new water layer (Bradley, et al., 1937; Hendricks and Jefferson, 1938).

The exchangeable cation in a clay mineral of the expanding lattice type determines the amount of water vapor taken up under equilibrium conditions (table 4). In 1940, Hendricks, Nelson, and Alexander (1940) demonstrated that the water adsorbed at low relative humidity by Ca-, Mg-, and Li-montmorillonite hydrates the exchangeable cation which lies in the interpacket space on the (001) plane. Ca and Mg cations are hydrated by 6 molecules of water, whereas Li⁺ is hydrated by 3 molecules of water. Other cations, such as Na⁺, K⁺, and H⁺, apparently are not hydrated. Development of

Table 4. Effect of exchangeable cation on adsorption of water by Mississippi bentonite.^a

Exchangeable cation	Equilibrium water content (g/g dry clay) relative humidity of atmosphere (percent)		
	5	50	90
Na ⁺	0.025	0.120	0.28
K ⁺	.015	.100	.20
H ⁺	.045	.190	.36
Ca ⁺⁺	.070	.22	.36
Mg ⁺⁺	.085	.22	.34

^a From Hendricks, Nelson, and Alexander (1940).

the hexagonal water net is completed only after hydration of available Ca⁺⁺, Mg⁺⁺, and Li⁺ in exchange positions. At relative humidity in the range of 5 to 90 percent, Na- and K-montmorillonite adsorb less water from the vapor phase than do Ca- and Mg-montmorillonite. However, Na-montmorillonite adsorbs more water from the liquid state than do Ca- or Mg-montmorillonite. The significance of differing adsorptivity of clay minerals containing the common exchangeable cations is discussed in greater detail in the section dealing with consistency and the compressive strength of clays.

The uptake of polar organic molecules and the formation of complexes by montmorillonite and halloysite have been investigated by Hofmann and associates (1934), Bradley (1945), and MacEwan (1944). Bradley (1945) has shown that glycols and glycol ethers produce two molecular layers between the montmorillonite micelles. Both Bradley and MacEwan (1944) have shown that hydrated halloysite forms complexes with polar organic compounds, such as the mono- and dihydric alcohols, glycol, and many others. Vermiculite (Walker, 1950) also forms complexes with glycol, the glycol forming single molecular layers between the packets. Dyal and Hendricks (1950) have devised a gravimetric method whereby the amount of minerals having the montmorillonite type of expanding lattice can be estimated by the amount of ethylene glycol retained.

Cationic Adsorption. Either organic or inorganic cations may be adsorbed by clay minerals. If the adsorptive process is reversible, that is, if an equivalent number of previously adsorbed cations are released into solution while the introduced cations are being adsorbed, the term cationic exchange is used. All clay minerals

Table 5. Cation exchange capacity of clays.^a

Mineral	Capacity (me. per 100 g)
Montmorillonite.....	60 to 160
Illite.....	20 to 40
Kaolinite.....	2 to 15
Halloysite.....	6 to 70
Attapulgite.....	25 to 30
Vermiculite.....	65 to 146

^a After Grim (1942), Barshad (1948), and Lewis (1950).

possess a cation exchange capacity, but the capacity varies greatly (table 5) due to differences in crystallographic structure, differing atomic substitution, particle-size distribution, and the location in the crystal lattice at which atomic substitution occurs, that is, in the octahedral in contrast to the tetrahedral portions of the lattice. As only limited substitution occurs in the crystal lattice of kaolinite and because kaolinite clay minerals are comparatively coarse, cation exchange capacity is low. Spiel (1940) has shown that the cationic exchange capacity of kaolinite increases with fine grinding. This increase most likely arises in the greater number of broken bonds and possibly in partial destruction of the clay lattice. The exchange positions for kaolinite are located mainly on the external surfaces.

Atomic substitution in the lattice is much greater in montmorillonite than in kaolinite minerals. This, together with characteristically very small particle size, produces high exchange capacity in montmorillonite. Fine grinding does not increase the cation exchange capacity. Illite is intermediate in exchange capacity. The over-all substitution in the lattice structure of illite is as in montmorillonite, but differs in that the atomic substitution is mainly in the tetrahedral position. The surface charge is compensated by potassium, which has such an ionic radius that it fits closely into the surface on the 001 plane of opposing packets and ties the packets together. Consequently, potassium is more or less fixed in illite, as in the micas. Beidellite appears to be intermediate between illite and montmorillonite. Vermiculite is reported by Barshad (1948) also to possess a high cation exchange capacity (table 5).

Investigations by Jenny and associates (1932; 1936) of release of exchangeable cations from beidellite following treatment of monovalent homoionic modifications with an ammonium salt and of divalent homoionic modifications with a potassium salt, indicate the relative ease of release of exchangeable cations to be $\text{Li}^+ > \text{Na}^+ > \text{NH}_4^+ > \text{K}^+ > \text{Mg}^{++} > \text{Ca}^{++} > \text{H}^+$. Thus, the cations to the right of the series such as Ca^{++} and H^+ , are more strongly held by the clay mineral and have a greater replacing power than do the cations to the left in the series. The relative replacing power of various cations then is seen to be $\text{H}^+ > \text{Ca}^{++} > \text{Mg}^{++} > \text{K}^+ > \text{NH}_4^+ > \text{Na}^+ > \text{Li}^+$. If a clay mineral is suspended in a solution containing equivalent concentrations of sodium and potassium ions, the potassium ions will be adsorbed in the greater amounts.

Based upon treatment of an NH_4 -montmorillonite, Schachtschabel (1940) concluded that the relative ease of replacement or release of NH_4^+ from NH_4 -montmorillonite at various concentrations of replacing cations is:

$\frac{\text{me/100 ml}}{\text{of water}}$	
10	$\text{Li}^+ < \text{Na}^+ < \text{H}^+ < \text{K}^+ < \text{Mg}^{++} < \text{Ca}^{++}$
100	$\text{Li}^+ < \text{Na}^+ < \text{Ca}^{++} < \text{Mg}^{++} < \text{H}^+ < \text{K}^+$

If Schachtschabel's series at a concentration of 10 me/100 ml of water is merely written in reverse, it is seen that this series is similar to the replacing power series derived from the work of Jenny and associates, except that H^+ is now in an intermediate position, and NH_4^+ is not included. At a concentration of 100 me/100 ml of water, the relative replacing power of cations is only generally similar to the replacing power of cations

listed above, that is, Ca^{++} and Mg^{++} are reversed and H^+ and K^+ are reversed. This experiment demonstrates that the relative replacing power of the various cations varies with the concentration of the solution. Other significant factors are probably responsible for the various reversals of replacing power of ions on clay minerals, such as the previous history of the clay minerals, the type of clay mineral, the original exchangeable cations, size of the replacing cation, the valence of the replacing cation, hydration of the cations, and possibly the type of anions participating.

Some organic compounds, such as the aliphatic and aromatic amines, have been found to act like inorganic cations in exchange phenomena. Gieseking (1939) found that organic cations of the types NH_3R^+ , NH_2R_2^+ , and NHR_3^+ are adsorbed in exchange positions by montmorillonite and that water adsorption and swelling properties were reduced. By X-ray diffraction studies, Hendricks (1941) demonstrated that aromatic amines penetrated the intermicellar spaces of montmorillonite and produced characteristic spacings. These treated clays adsorbed less water than the corresponding Ca- and Na-montmorillonite. Mielenz and King (1951) showed that if an aqueous solution of benzidine is added to Ca-montmorillonite in slight excess that the d(001) spacing differs only slightly from that of the untreated mineral (13.0 Å against 13.1 Å).

Consequently, under these conditions of treatment, adsorption of the organic molecule is largely on broken prism edges of the clay mineral lattice. Moreover, after removal of the adsorbed water by heating at 190° C, the spacings are the same and the original differences are thus recognized as due to adsorbed water. However, if montmorillonite is treated with considerable excess of benzidine solution near the boiling point, the benzidine is found to be introduced along the d(001) interlayer space. H-montmorillonite treated with solid benzidine at 150° C also develops two molecular layers in the interlayer space, the d(001) spacing being 15.7 Å. The observations demonstrate that the method of treatment of the sample with the amine determines whether exchange takes place on the 001 surface or externally. It is interesting to note that if benzidine is adsorbed externally, a yellow form develops upon drying; however, if the benzidine is adsorbed between the clay packets, the blue form remains after drying.

Grim, Allaway, and Cuthbert (1947) observed that amines and other organic cations were completely adsorbed by illite, kaolinite, and montmorillonite when added in amounts less than the exchange capacity. When added in excess, large organic cations were adsorbed in amounts greater than the exchange capacity, probably under the influence of van der Waals' forces. Water adsorption of these clays was reduced by treatment with the organic compounds.

The amount of adsorption of dyes by the clay minerals has been determined only by a few investigations. Bosazza (1944) shows that 1 gram of each of three kaolinites adsorbed 0.0074 to 0.0082 gram of malachite-green and 0.0083 gram of methyl violet; whereas 1 gram of Wyoming bentonite adsorbed 0.036 to 0.047 gram of these dyes. Mielenz and King (1951) found that kaolinite adsorbed 0.0188 gram of malachite-green; whereas halloysite adsorbed 0.039 gram, illite 0.0343

gram, montmorillonite 0.065 to 0.0925 gram, and nontronite 0.0502 gram. Weil-Malherbe and Weiss (1948) have determined that acid-treated bentonite adsorbs 0.04 to 0.06 gram of benzidine per gram from an aqueous solution of benzidine and from 0.092 to 0.168 gram of benzidine per gram of sample from an aqueous solution heated to boiling and shaken 30 minutes. Study of molecular and cationic adsorption and exchange of dyes and amines, which produce colored compounds by acid-base or oxidation-reduction reactions, probably will reveal much about the surface chemistry and details of crystallographic structure of clay minerals.

Like the clays, the organic colloids are capable of cation exchange. The organic colloids are negatively charged and according to Baver (1940) the viscosity and hydration properties of humus are altered by the adsorbed cation. Humus varies in its cation exchange capacity from at least 119 to 400 me/100 g.

Anion Adsorption. Stout (1939) has shown that the clay minerals are capable of anion exchange and, in particular, that kaolinite and halloysite can adsorb phosphate ions. Later work by Dean and Rubin (1947) indicates that adsorption of the phosphate anion is due to the replacement of hydroxyl groups on the surface of the clay. The adsorbed phosphate ions on kaolinite could be replaced by arsenate ions. It was found that the anion exchange capacity is equal to the cation exchange capacity. Both the phosphate and arsenate ions are tetrahedral in form like silica, and evidently can attach themselves to the broken edge of the silica sheet and act as an electrically unbalanced silica tetrahedron. According to Mattson (1929) a negative anion adsorption is developed for chloride, sulfate, and ferrocyanide in montmorillonite minerals; the concentration of the anion is greater in the surrounding solution than in the adsorbed solution.

Formate ions also are adsorbed by H-montmorillonite. This phenomenon was observed after preparation of H-montmorillonite from Na-montmorillonite by treatment of the clay with formic acid, washing, and drying. The adsorption of the formate anion increased the particle size and reduced the plastic index and liquid limit, but the cation exchange capacity of the clay minerals was lowered only 0.5 me/100 g.

Electrokinetic Properties

The electrokinetic properties of a substance arise by virtue of the release of ions from the surface of a solid particle into a liquid; the adsorption of ions from the liquid; substitution of atoms of differing valence in the lattice; and by the adsorption of polar molecules on the surface of the particles. The factors controlling adsorption and release of ions and polar molecules were discussed previously. If a force, either mechanical or electrical, causes a relative motion of the solid or liquid, electrokinetic phenomena arise.

Particles suspended in a liquid containing an electrolyte, tend to adsorb ions to satisfy broken electrostatic bonds partially and to produce a liquid-solid interface of the smallest free energy. In clay-water systems OH-ions are adsorbed most abundantly at edges and corners of the broken lattice. The other adsorbed ions form a diffuse cloud at a finite and variable distance from the solid interface. These ions in the outer layer participate in exchange reactions and may be called

counter or contra ions. In natural clay-water systems, the counter or exchangeable ions are usually cations of (in decreasing order of abundance for soils of humid regions) calcium, magnesium, potassium, and sodium. H⁺ is the dominant exchangeable cation in acid clays. Sodium is abundant as an exchangeable cation in soils of arid regions. Fe⁺⁺⁺ may be present as a counterion in some poorly drained and acid soils. Fe⁺⁺⁺ and Al⁺⁺⁺ usually are not present as exchangeable cations.

The adsorbed or fixed layer on the solid surface and the outer layer are known as the electric double layer. Helmholtz visualized this electric double layer as being rather rigid in form and of limited dimensions, but later work by Freundlich and Gouy has shown that the counterions exist as a diffuse cloud grading imperceptibly into the surrounding dispersed liquid phase. Concepts of the electric double layer are discussed in detail in many places (Hauser and Le Beau, 1946; Marshall, 1949; Glasstone, 1946).

If polar compounds are present and the surface is negatively charged, the dipoles orient themselves with the positive charge of the dipole toward the negative surface. At a distance from the particle surface, the electric field strength diminishes and the degree of orientation of the molecules becomes progressively less until the molecules are oriented randomly.

Electrokinetic properties of clay minerals are discussed at greater length elsewhere in this volume.

Electroendosmosis. The electrokinetic phenomenon of electroendosmosis was first discovered by Reuss in 1808 and was later developed mathematically by Helmholtz in 1879. Helmholtz visualized the existence of layers of ions surrounding particles and correlated this electrostatic structure mathematically with the plates of an electric condenser separated by a dielectric. This rigid concept as developed by Helmholtz is no longer regarded as valid, inasmuch as evidence indicates the ions occur in diffuse clouds rather than in distinct layers.

If an electromotive force is applied along a capillary tube filled with water, the water moves because of the charge developed on the wall of the capillary tube and an oppositely charged layer developed in the water at a finite distance from the wall of the capillary. Similarly, if an electromotive force is applied across a mass of wet clay, water moves as a result of the electric field acting on originally charged particles or ions. In a natural soil-water system, most of the particles, particularly the clay minerals, are charged negatively. When an electromotive force is applied to the system, the diffuse cations shear away from the immobile layer and move, together with associated water, toward the cathode.

Regardless of deficiencies in details of the Helmholtz theory, the conditions of electroendosmotic flow are approximated in the following terms (Glasstone, 1946):

$$V = \frac{\zeta DI}{4\pi\eta K}$$

V = volume of electroendosmotic flow

ζ = zeta potential

D = dielectric constant of the liquid

I = applied current

η = viscosity coefficient

K = specific conductivity of liquid

According to Winterkorn (1953) the Helmholtz theory is tenable for materials containing coarse pores but cannot be accepted for materials containing fine pores of the order of 0.05 mm and less.

At the present time, much research is being conducted on electroendosmosis. No doubt present theories will be modified as data accumulate. Additional discussion of electroendosmotic phenomena is included in discussion of shear resistance.

Electrophoresis. When an electrical potential is applied across a suspension, charged particles move through the liquid to the anode or cathode, depending upon the negative or positive charge of the particle. This phenomenon is electrophoresis. In the applied electric field, the diffuse counterions constituting the outer part of the electric double layer are sheared away from the particle, and the particle and counterions then move toward opposite electrodes. Electrophoresis occurs in gases as well as in liquids. In sols of gold, ferric hydroxide, and arsenious trioxide, colloidal particles carry an electric charge and migrate in an electric field with a nearly constant migration velocity. It was observed by Freundlich (1930) that the migration velocity of certain lyophobic sols was fairly constant and that the migration velocity is not dependent upon the size or composition of the particles. The presence of electrolytes and the kind of suspending medium strongly influence the electrokinetic activity.

In experiments on lyophilic bentonite sols, Hauser and LeBeau (1941) demonstrated that migration velocity increases with decreasing particle size. With a given particle size, migration velocity decreases with increasing concentration of the suspended particles, except that in extremely dilute suspensions (up to 0.5 percent) the migration velocity remains constant for a given particle size. These characteristics of montmorillonite suspensions are explained by assuming that a change in concentration and particle size causes a change in the net charge and the thickness of the double layer on the edges, corners, side surfaces, and between the sheet-like particles of clay. Jenny and Reitemeyer (1934) measured the migration velocity of Putnam clay (beidellite) saturated with various cations and reported values ranging from 2.57 to 3.48 microns/second/volt/cm.

These phenomena are discussed further elsewhere in this volume.

Thermo-osmosis. When a temperature gradient exists between two portions of a soil mass, water moves from regions of high temperature to the region of low temperature. This phenomenon is designated as thermo-osmosis. An electromotive force also is associated with this phenomenon. Bouyoucos (1915) observed that at the optimum moisture content a maximum amount of water moves with a given temperature gradient. He also concluded that only a part of the water movement could be due to vapor transfer. Other workers, including Smith (1939), Trejo (1946), and MacLean and Gwatkin (1946), have concluded that the water transfer is due to mass transfer of vapor by convection.

From experiments with Putnam (beidellite) and Hagerstown (kaolinite) soils, Winterkorn (1947) concluded that thermo-osmotic flow of water takes place in water films and not by vapor convection transfer. The potential gradient developed during flow of water ap-

proximated 10 mv/cm/°C. The moisture transfer was attributed to the greater activity of the exchangeable cations at the cold side than at the warm side. Recalling that the exchangeable cations are bound to the negatively charged surface of particles so that they could not move to the warm side, the change in ionic activity produces a concentration potential at the cold side. This potential can be neutralized only by movement of water from the warm to the cold side.

Another possible explanation for this observed phenomenon involves thermoelectric forces. As compared with metals, soils are poor conductors; nevertheless, they do conduct electricity. If one portion of a moist soil is heated with respect to another portion, an emf will develop, as demonstrated by Winterkorn, and a weak current should flow from the hot to the cold area. As the current flows in the soil, water will migrate and collect in the cooler portions of the soil in a manner analogous to electroendosmosis. However, instead of being a special case of electroendosmosis, in which an external emf is supplied, this phenomenon is really a special case of streaming potential in which instead of a mechanical force, such as a hydrostatic pressure, producing a movement of liquid relative to the solid with a resulting emf, a temperature gradient causes relative movement of water, which then develops an emf.

SOIL MECHANICS PROPERTIES AND PERFORMANCE OF CLAYS

Soil mechanics properties of clays include both those qualities inherent in the material (static properties) and the response of the material (dynamic properties) to changing conditions, such as stress, wetting, drying, electrical potential, and many others. All of these properties arise in the fabric and mineralogic or compound composition (including fluids content). The properties of significance in performance of clays and shales in construction engineering are:

- I. Static properties of earth materials
 - A. Particle-size distribution
 - B. Unit weight
 - C. Void ratio
 - D. Specific gravity of the constituents
 - E. Fluids content
- II. Dynamic properties of earth materials
 - A. Consistency
 - B. Permeability
 - C. Thixotropy
 - D. Shear resistance
 - E. Compressive strength
 - F. Volume change
 1. Consolidation with loading
 2. Swelling with hydration
 3. Drying shrinkage
 4. Syneresis
 5. Frost heaving
 - G. Sensitivity to remolding
 - H. Slaking
 1. Electro-osmosis
 2. Thermo-osmosis

Performance of clays and shales is the response of materials in the geologic formation or in fill to the changing conditions during construction or operation of engineering works. The most significant aspects of performance of clays and shales can be classified as follows:

- I. Shear failure
 - A. Slope failure (landslides)
 - B. Foundation failure
- II. Settlement of structures
- III. Uplift of structures

- IV. Seepage
- V. Frost heaving
- VI. Slaking
- VII. Clays and shales in construction materials
 - A. Embankments and fill
 - B. Linings
 - C. Aggregates
 - D. Pozzolans
 - E. Grout

For brevity in discussion, properties and the related performance of clays and shales are discussed simultaneously.

STATIC PROPERTIES OF EARTH MATERIALS

Particle-size Distribution

Clays are composed predominantly of particles less than 20 microns in diameter, but sand, silt, gravel, and fragments of organic remains in varied proportions always are present. In soil mechanics analyses for engineering purposes, various limiting sizes for gravel, sand, silt, and clay are used by recognized engineering organizations (Burmister, 1949; Terzaghi and Peck, 1948). This leads to some variation in nomenclature of earth materials.

Particles classified by mechanical analysis involving sieving and differential settling include individual mineral grains, organic matter, rock fragments and pebbles, concretions, coagulated clusters of grains, and fragments of cementitious materials released by disaggregation of the sample. The fractions including particles larger than 5 microns are composed mainly of: (1) rock fragments; (2) terrigenous and secondary granular minerals, such as quartz, carbonates, feldspars, pyroxenes, and amphiboles; (3) micas and micaceous minerals; (4) organic remains, including plant fibers and humus; (5) concretions; and (6) aggregations of grains and argillie materials.

The fractions containing particles less than 5 microns in size are composed of: (1) clay minerals; (2) coagulated clusters of grains; (3) organic matter; and (4) very finely divided particles of rock and minerals, including fragments of cementitious substances. Clay minerals occur primarily as particles less than 2 microns in size and they can occur in particles as small as 0.1 millimicron, approaching the dimensions of the unit cell (Grim, 1942). However, crystals of clay minerals commonly occur in sizes larger than 5 microns and at least as large as 100 microns in undisturbed materials. Organic materials constitute particles down to 0.1 micron in size. Silica is common as quartz and cristobalite in particles at least as small as 0.1 micron (Grim, 1942; Soveri, 1950). Feldspars are abundant in sizes coarser than 2.0 microns, although they are found in sizes smaller than 0.2 micron. Hydrated oxides of iron and aluminum can be detected in particles as small as 1 micron. Calcite is commonly abundant in fractions as small as 2 microns.

The particle-size distribution of clay is susceptible to considerable change, depending upon the physical-chemical properties of the clay minerals (table 6), the mechanical processes involved in preparation of the sample for analysis (Anon., 1941), agitation of the suspension during differential settling procedures (Wintermyer, 1948), and the kind and amount of dispersing agent used. Particle-size distribution indicated by most procedures of size analysis demonstrates the response of the

Table 6. Mineralogic composition of size fractions of clays.*

Particle size, microns	Minerals in order of quantity		
	Predominating constituents	Common constituents	Rare constituents
<0.1	Montmorillonite Beidellite	Mica intermediates	Illite (traces)
0.1-0.2	Mica intermediates	Kaolinite Montmorillonite	Illite Quartz (traces)
0.2-2.0	Kaolinite	Illite Mica intermediates Micas Halloysite	Quartz Montmorillonite Feldspars
2.0-11.0	Micas Illites Feldspars	Quartz Kaolinite	Halloysite (traces) Montmorillonite (traces)

* After Soveri (1950).

material to a mechanical and a chemical process, rather than the particle-size distribution of the original material.

Clay minerals of montmorillonite type, especially with sodium as the exchangeable cation, are particularly prone to cleave and disintegrate along cleavage surfaces during agitation in water. Consequently, particle-size analysis made by differential settling, almost always indicates smaller sizes than actually are present in the natural clay. Montmorillonite minerals segregate into fractions less than 0.08 micron during fractionation of clays and shales (Pennington and Jackson, 1947). Calcium, magnesium, potassium, and hydrogen montmorillonites are not so dispersible, especially after drying, as are sodium montmorillonites so that apparent particle size will be greater if cations other than sodium predominate (Winterkorn and Moorman, 1941). Also, adsorption of organic molecules may inhibit dispersion of clay particles.

Because of their variable nature as the result of both chemical composition and exchangeable ions, illites vary in tendency to disperse. Some illites readily disperse to particles less than 0.1 micron, but illite commonly remains as particles greater than 0.2 micron and is abundant only in sizes greater than 2 microns. Mica is common in the range 0.2 to 2.0 microns; the degraded micas transitional to clay minerals are common even in sizes less than 0.1 micron.

Kaolinite tends to concentrate in the size range 0.2 to 2.0 microns. Many kaolins are difficult to disperse to particles as small as 1 micron. Yet individual kaolins release kaolinite into fractions as small as 0.08 micron. In a detailed engineering investigation of soils of the southeastern portion of the United States, Havens, Young, and Baker (1948) have demonstrated that, in soils containing both kaolinite and illite, illite typically becomes the more concentrated in the finest fractions. Dehydrated halloysite and allophane resist disaggregation and dispersion more than do the other clay minerals.

The primary cause of differing contribution of the several clay minerals to soil mechanics properties lies in the facility with which they are dispersed to particles less than 0.05 micron. The proportion of the fraction less

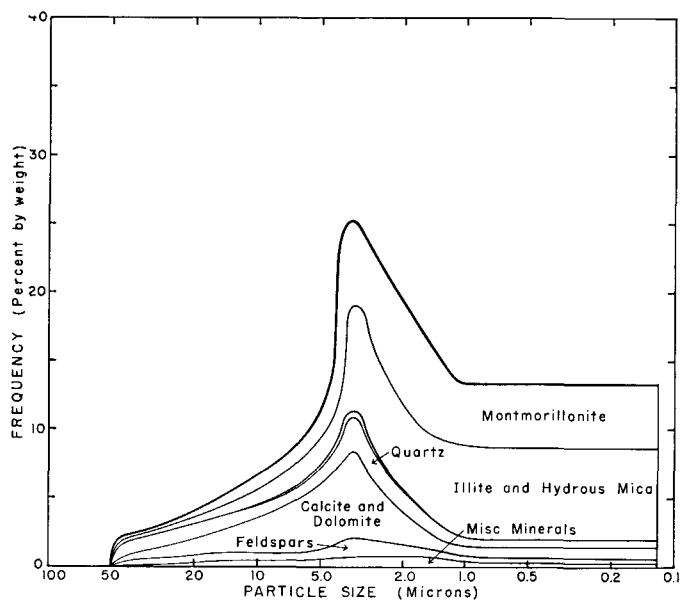


FIGURE 12. Particle size distribution and mineralogic composition of sodium montmorillonite clay, near Yuma, Arizona.

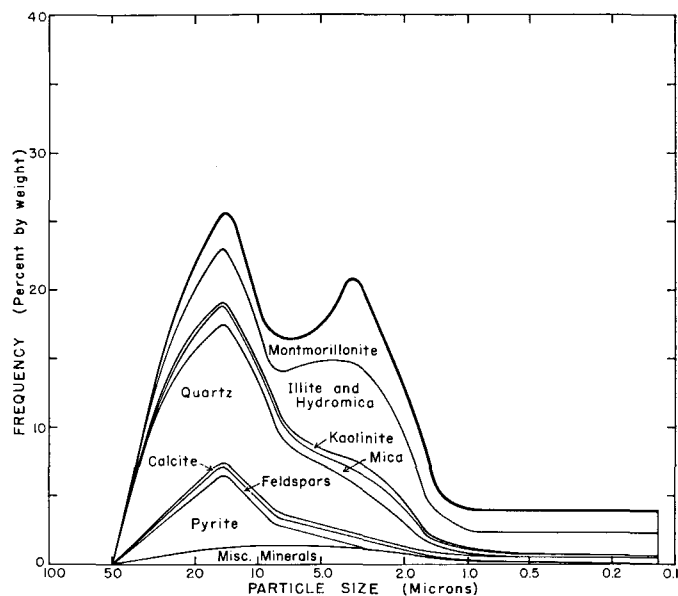


FIGURE 14. Particle size distribution and mineralogic composition of the Eagle Ford shale, near Dallas, Texas.

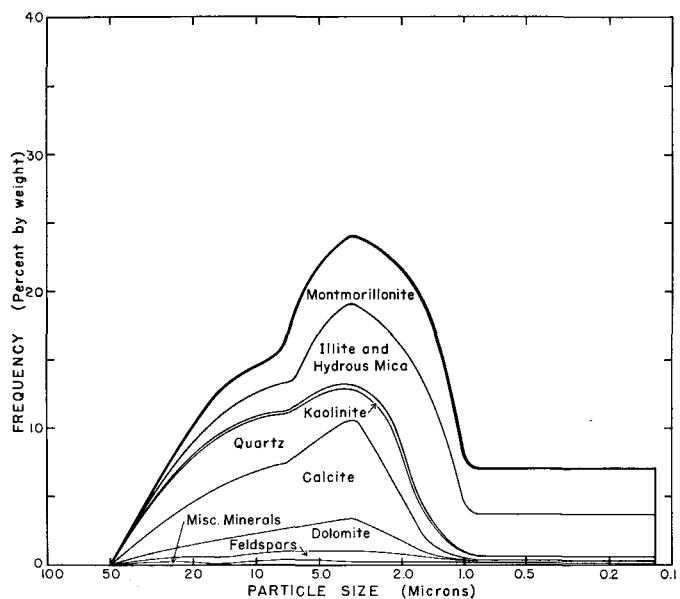


FIGURE 13. Particle size distribution and mineralogic composition of calcium montmorillonite clay, near Yuma, Arizona.

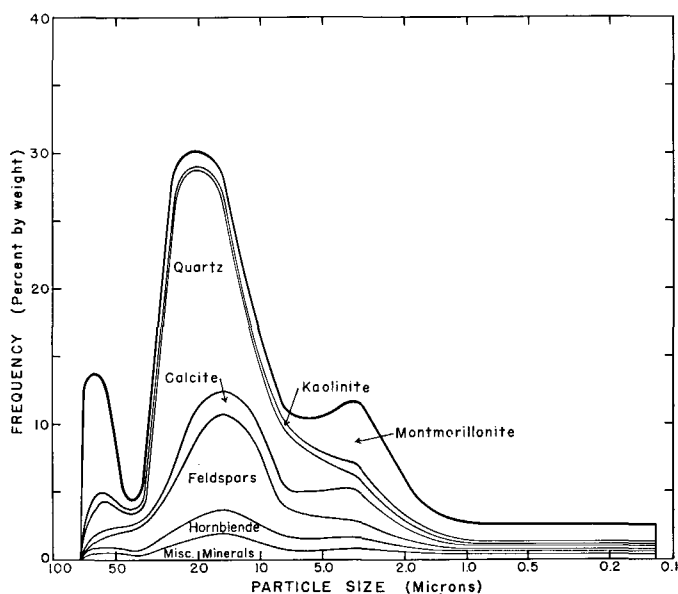


FIGURE 15. Particle size distribution and mineralogic composition of the Porterville clay, near Lindsay, California.

than 0.05 micron decreases from montmorillonite to illite to halloysite to kaolinite (Marshall, 1949). Of all these minerals, the particle-size distribution of montmorillonite clays is controlled most strongly by the exchangeable cation.

The relation of mineralogic composition to particle-size distribution is indicated by X-ray diffraction and microscopical analysis of separated fractions in accordance with procedures used by Grim (1949) and by Winkler (1938; 1949) using a minimum of agitation (figs. 12, 13, 14, 15, 16, and 17). No separation was attempted on size fractions below 1 micron. The cut-off point at 0.12 micron is arbitrary. The proportion of material in any size fraction can be determined as a ratio of the area between vertical lines drawn at the upper

and lower limit of the fraction to the total area beneath the uppermost curve. Two clays from near Yuma, Arizona, are of interest (figs. 12 and 13) because they illustrate the relative effects of exchangeable sodium and calcium in facilitating dispersion into the finest fractions. Granular components, including quartz, calcite, dolomite, and feldspars, are abundant only above 1 micron. With the sodium clay, illite becomes relatively more abundant in the less than 1 micron fraction.

The Eagle Ford shale (fig. 14) illustrates a complex clay mineral composition, including montmorillonite, illite or hydrous mica, and kaolinite. The bulk of the clay minerals is concentrated in the size range from 20 to 2.0 microns, the kaolinite disappearing and the montmorillonite and illite-hydrous mica clays increasing

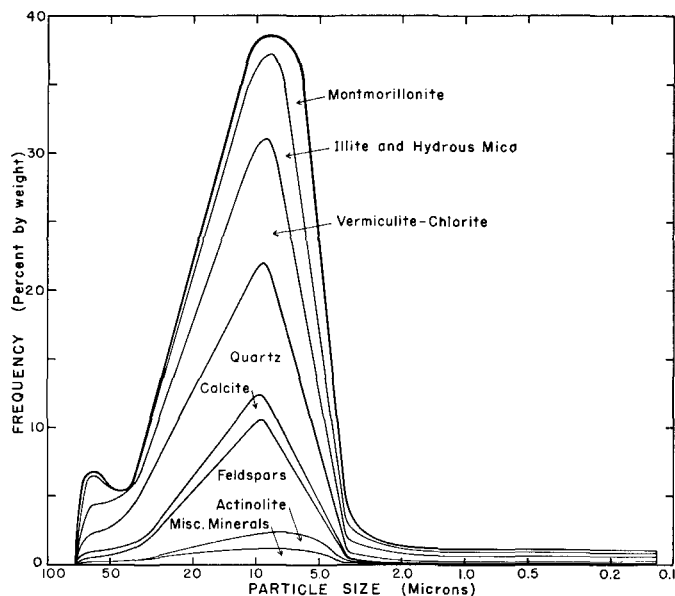


FIGURE 16. Particle size distribution and mineralogic composition of varved clay and silt, Nespelem formation, near Coulee City, Washington.

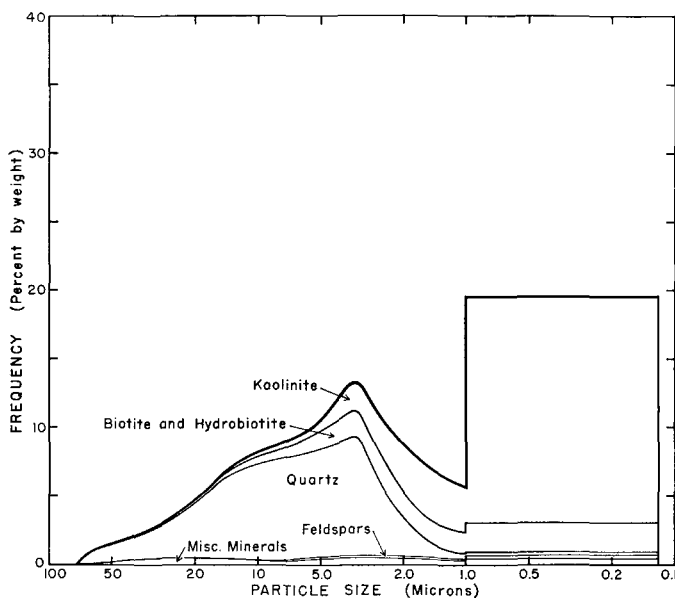


FIGURE 17. Particle size distribution and mineralogic composition of kaolin, Ione formation, Valley Springs, California.

in proportion in the less than 1 micron fraction. Such a gradation produces a dense fabric capable of excessive pressure development if expansive clays are present.

The analysis of the Porterville clay (fig. 15) demonstrates the presence of the well-developed, aggregated, argillie fabric which is evident petrographically (fig. 6 and 11). The montmorillonite-type mineral (beidellite) is concentrated in the coarse fraction (44 to 74 microns) and in the less than 7 micron size fraction. The coarsest fractions represent water-stable argillie aggregations which break down progressively with agitation and disappear entirely with usual methods of mechanical or hydrometer analysis. For example, in repeated hydrometer analyses on the sample, effecting mechanical disper-

sion merely by soaking and inversion of the hydrometer tube, the analysis of the coarse fractions is seen to vary as follows:

Particle size (microns)	Amount (percent by weight)			
	Trial 1	Trial 2	Trial 3	Trial 4
74 to 50	13.8	10.2	8.4	1.6
50 to 37	4.4	5.2	5.4	4.4
37 to 19	22.2	18.8	18.0	17.4

Consequently, the form of the gradation curve for this material varies remarkably with manipulation of the sample. The fraction less than 1 micron is composed almost completely of beidellite. Kaolinite occurs in very small proportions in all size fractions.

The Nespelem varved clay and silt (fig. 16) is composed of intermixed montmorillonite, illite, and hydrous mica and a micaceous clay-like mineral intermediate between vermiculite and chlorite. Minor aggregation is indicated in the fraction greater than 44 microns; very small amounts of material occur in fractions less than 3.5 microns. Calcium and magnesium are the main exchangeable cations. Analyses of samples of Nespelem silt are reported by Grim (1949).

The Valley Springs clay, a member of the Ione formation of Eocene age, widely exploited in the foothills of the Sierra Nevada is a ceramic clay composed predominantly of kaolinite (fig. 17). The kaolinite was derived by weathering and erosion of the Sierran granodiorite and was redeposited together with fine sand and silt in small lakes. The kaolinite is concentrated in the less than 5 micron fraction and most is less than 1 micron in size. Biotite and hydrobiotite show a similar distribution. The relative amount of hydrobiotite increases with decrease in particle size.

Additional analyses of this type for clays containing halloysite and allophane are published by Grim (1949).

In experiments with a beidellite clay (Putnam clay) involving replacement of the natural cations by hydrogen, sodium, potassium, magnesium, calcium, and aluminum, Winterkorn and Moorman (1941) found variations in apparent size fractions as follows:

Size fraction	H	Na	K	Mg	Ca	Al
Silt (0.05-0.005mm)	46.0	33.0	48.0	45.0	47.0	49.0
Clay (<0.005mm)	48.0	61.0	44.0	49.0	45.0	44.0
Colloids (<0.001mm)	26.0	48.0	21.0	25.0	22.0	23.0

The apparently greater content of particles of colloidal dimensions in the sodium-treated soil is outstanding. The relationship is an indication of both greater dispersion and greater adsorption of water by the particles. Adsorption of water by the particles effectively reduces the specific gravity and increases the dimensions of each particle.

In independent work on the Putnam clay, Marshall (1949) found that the quantity of material in the size range below 50 millimicrons was distinctly greater for the clay treated with lithium, sodium, and potassium, than for the clay treated with magnesium, calcium, barium, or hydrogen. Wyoming bentonite showed only slight variation in this regard after similar treatment. This difference in behavior of beidellite and montmorillonite seemingly relates to the site of the electrostatic deficiency leading to the adsorption of the external cations. Differences in apparent particle size probably will be found also upon detailed investigation of the effects of replacements of anions. For example, adsorption of

Table 7. Average size composition of clay samples.^a

Mineral	No. of samples	Grade limits (mm)—composition (percent)				
		>1/256	1/256–1/512	1/512–1/1024	1/1024–1/2048	<1/2048
Kaolinite.....	20	27.0	10.8	13.4	12.3	36.5
Halloysite.....	4	49.7	8.2	6.3	4.5	31.3
Dickite.....	4	84.9	9.0	2.2 ^b	1.1 ^b	2.8 ^b
Montmorillonite (Ca).....	5	39.7	14.6	14.1	7.0	24.6
Nontronite.....	1	21.6	14.6	15.8	11.2	36.8
Illite.....	2	31.3	20.0	17.1	5.4	26.2
Attapulgit.....	2	25.8	4.9	18.8	5.2	45.3

^a From California Research Corporation (1950).

^b Average of three samples.

the formic anion by montmorillonite markedly decreases dispersion and increases particle size through aggregation.

Studies of particle-size distribution by the pipette method of samples of the important clay minerals from many localities (table 7) were correlated by the California Research Corporation (1950) with electron microscope observations. The particle size typically was indicated to be smaller by the electron microscope than was indicated by settling velocities, probably because of aggregation of grains in the suspension.

Badly needed is a method of particle-size analyses which will reveal the size of the grains or masses which act as structural units of the fabric during volume change or strain. A similar need already has been recognized in agriculture (Yoder, 1936). This is a property of concern to the engineer because he wishes to know the manner in which the material will respond to stress, to entrance or drainage of water, or to other actions. Unlike the geologists or pedologist, he is not concerned with the process by which the material has formed; hence, in an analysis of earth materials as a basis for engineering interpretation of the probable performance of the soils in place or in fill, determination of particle-size distribution by rigorous mechanical and chemical treatment and excesses of water will produce misleading results.

Unit Weight and Void Ratio. Unit weight of earth materials is determined by the specific gravity of the solids and fluids composing the material, and their relative abundance. The ratio of the volume of fluids (typically water and air) to the total volume is the porosity. A more common factor in soil mechanics is the void ratio, representing the ratio of the volume of the void to the volume of the solid constituents in the soil.

Porosity and void ratio, and to a lesser extent unit weight, are expressions of the fabric of the material. Porosity and void ratio are greater (1) with departure from a well-graded condition, either through irregularities in gradation or because of concentration of exceptionally uniform sizes, and (2) with the introduction of fractures as the result of shrinkage or jointing. Porosity and void ratio are less if the soil has been impregnated with secondary deposits of mineral matter, either by infiltration of colloidal material or precipita-

tion of substances from solution. Except for infiltration or precipitation, porosity and void ratio arise in the grain-to-grain relationships established as the material accumulated in past geologic time or during construction of fill and modified by consolidation or shear.

As has been indicated previously, clay minerals are of prime significance in the development of the fabric of soils primarily because of their adhesive, cohesive, and plastic quality and their capacity for volume change with changing moisture content. For example, the highly porous structure of loess would be completely unstable and incapable of preservation if rims of montmorillonite or illite with intermediate moisture content were not present upon grains of silt and fine sand to act as intergranular binding at time of deposition. Reworked halloysite soils typically are very low in unit weight and high in void ratio possibly because of the tubular form of the ultimate particles of halloysite (Bates et al., 1950). For example, a halloysite soil proposed for use as fill in an earth dam being constructed by the city of Nairobi, Kenya, East Africa, possesses a natural unit weight of 50 pounds per cubic foot and optimum dry density of only 73 pounds per cubic foot with corresponding void ratio of 1.8 and 1.3, respectively. Similar values were obtained on halloysite soil used in construction of Fena River Dam, Island of Guam.

Investigations by Johnson and Davidson (1947) demonstrate the influence of exchangeable ion and clay mineral type upon moisture-density curves of kaolinite and montmorillonite soils. The density of the sodium-kaolinite soil is higher than that of the calcium-kaolinite soil, probably because the greater dispersion of the former permits development of a denser fabric at given compactive effort. Sodium-montmorillonite soil achieves a somewhat lower density at slightly higher moisture content than does kaolinite soil, presumably because adsorption of water by the montmorillonite reduces plasticity of the soil and swells the clay fractions.

As will be subsequently discussed, porosity and voids ratio of earth materials are changed with loading and consolidation of the material. This is true at high moisture content particularly. The degree of change effected by loading depends upon the gradation of the soil components, the swelling or shrinking properties of the clay mineral component, the amount and rate of loading, and

the degree of water resistance of the individual particles or argillic aggregations constituting the soil. If the unit load is maintained constant, the rate of change in porosity, voids ratio, and unit weight depends primarily upon the permeability of the soil.

Specific Gravity. Specific gravity of earth materials is important to engineering considerations primarily because it is used in calculation of other important factors, such as void ratio and degree of saturation. In standard tests for specific gravity of soils, as for example A.S.T.M. Designation: D 854 (1949), the basic assumption is made that the solid particles of the sample possess the same volume in air as in water and that no chemical or physical-chemical reaction takes place with the liquid used in the pycnometer.

As is manifest from the discussion of adsorption, clay minerals which are partially or completely dehydrated will adsorb water added to the pycnometer during the determination of specific gravity.

With adsorption of the water and its consequent increase in specific gravity, additional water must be added to fill the pycnometer. The calculated volume of the solids consequently is lessened and the determined specific gravity is increased. This error can be corrected by use of a nonpolar liquid instead of water. Comparative values for two samples of Colorado shale from Tiber Dam site containing high proportions of sodium-montmorillonite are as follows:

Sample No.	Specific gravity (using tetrahydro naphthalene)	Specific gravity (using water)
11F-263	2.683	2.72
11F-264	2.702	2.75

The difference found in specific gravity using polar in contrast to nonpolar liquids will vary with the kind and amount of clay mineral, the exchangeable cation, the ratio of liquid to solid used, and the particle size of the clay minerals. The effect should be significant only for montmorillonite group and illite clays.

Comparatively small changes in specific gravity produce significant differences in the calculated value of void ratio and degree of saturation of earth materials. Using the data for Sample No. 11F-263, above, the void ratio is calculated to be 0.36 if the specific gravity is taken as 2.72; whereas, the void ratio is 0.35 if the specific gravity is taken as 2.683. With a moisture content of 19.8 percent (the observed natural moisture content), the first result would indicate the sample to be 97.1-percent saturated, whereas the second indicates complete saturation.

Actually, however, because of the great adsorptivity of sodium-montmorillonite, virtually all of the water in Sample No. 11F-263 was adsorbed by the clay mineral constituent. Under these conditions, specific gravity of the solid constituents should have been indicated as 2.103, assuming a void ratio of zero. Conclusions regarding void ratio, degree of saturation, and the relative amounts of free and adsorbed water are significant with regard to shear resistance and possible volume change with loading or change in moisture content.

Depending upon the moisture content of the clay crystal, the specific gravity of montmorillonite can vary within wide limits. Calculations for hydrogen montmorillonite based upon adsorptive phenomena described

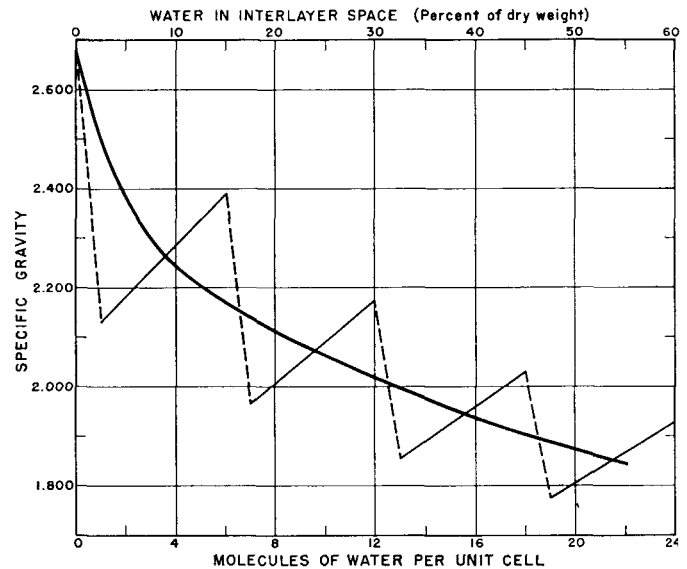


FIGURE 18. Theoretical variation of specific gravity of H-montmorillonite with adsorption of water along the 001 interlayer space.

by Bradley and associates (1937) are summarized in figure 18. They indicate a range from 1.775 to 2.683.

Fluids Content. Water and air are the fluids always present in naturally occurring earth materials. Water occurs in varying degrees of fluidity ranging from the free water existing in large voids to the water subjected to significant capillary tension to the adsorbed water held by forces of varying intensity upon external and internal surfaces with or without intimate association with exchangeable cations. The water in these various occurrences possesses differing properties, such as resistance to shear and vapor pressure. Loss of the several

Table 8. Free swell tests of Wyoming bentonite in various liquids.

Liquid	Temperature of liquid (°C)	Dielectric constant*	Free swell (percent)
Carbon tetrachloride	25	2.2	8
Benzene	25	2.3	8
Diethyl ether	21	4.3	35
Chloroform	25	4.5	5
Acetic acid	26	6.1	20
Aniline	27	6.8	20
Acetone	26	20.6	145
Absolute ethyl alcohol	26	24.2	80
Absolute methyl alcohol	27	33.4	165
Nitrobenzene	27	35.6	22
Glycerine	25	42.5	115
Succinonitrile	58	56.5	40
Water	23	78.5	1240
Formamide	20	109	770

* From Maryott and Smith (1951).

kinds of water at differing temperatures demonstrates the need for close control of temperature during drying of soils in preparation for physical and chemical tests.

Air is an important constituent of earth materials, particularly when application of heat or penetration by capillary water develops internal pressure in excess of the atmospheric. Air is the source of oxygen, which contributes to many alteration processes, and of CO₂, a compound participating in reactions which contribute greatly to changes in properties of earth materials.

As will be indicated at appropriate places in the following discussion, the physical-chemical properties of earth materials vary markedly with variation of dielectric constant, viscosity, and electrical conductivity of interstitial water, and with changes of concentration of dissolved solids. Moreover, these and other properties of aqueous solutions affect the hydration and surface-chemical properties of soil particles.

In studies of clayey loess, Denisov (1951) found consolidation with given load to be a function of the wetting fluid as follows:

Liquid	Dielectric constant	Additional settlement with wetting under load of 0.5 kg/sq cm (percent)	
		Undisturbed	Disturbed
Water	81.07	11.0	13.6
Acetone	26.60	5.2	8.5
Benzene	2.29	0.02	0.87

Electrolytic aqueous solutions decrease consolidation in the sequence: water > NaCl solution > AlCl₃ solution > FeCl₃ solution. Also, the angle of stable slope for un-

disturbed loess varied as follows for several wetting liquids:

Liquid	Dielectric constant	Angle of stable slope
Water	81.07	26°
Ethyl alcohol	24.1	29°
Benzene	2.29	35°

In slaking tests of Nebraska loess in which the binding agent is a montmorillonite clay, Karpoff and Gibbs (see Denisov, 1946) observed immediate and complete slaking in water, partial slaking in acetone, and little disturbance of the fabric in benzene.

All of the above observations demonstrate the effect of dispersion and swelling of the clay binder in the loess in decreasing friction at points of contact of the grains. Swelling of Wyoming bentonite was indicated previously in relation to dielectric constant and molecular structure of various organic liquids (table 8), the degree of swell tending to increase with increase of dielectric constant for compounds of similar molecular structure. Similarly, closeness of packing during sedimentation of finely divided solids, such as fuller's earth, alumina, iron oxide, silica, chalk, and talc, has been found to increase with increase in dielectric constant of the liquid (Fischer and Gans, 1946). Dielectric constant of the liquid is effective in these regards because the magnitude of attraction or repulsion by electrostatic charges between the solid particles is inversely proportional to the dielectric constant of the separating medium.

Dynamic Properties of Earth Materials

Plastic and Liquid Consistency Limits

The plastic limit is the minimum moisture content at which the soil is plastic.* The liquid limit is considered to be the minimum moisture content at which a soil is liquid.† In routine soil testing, the plastic and liquid conditions are established according to arbitrary criteria in empirical tests. The plasticity index is the difference between the plastic and liquid limits and thus defines the range of moisture content in which the soil is plastic. Stated differently, the plasticity index is the weight of water necessary to carry 100 grams of originally dry soil from a plastic to a liquid condition.

The magnitude of the plasticity limits depends primarily upon the content of particles less than 1 micron in diameter and the nature of the clay mineral. Havens, Young, and Drake (1949) demonstrated the influence of size range by comparison of the plasticity limits of numerous soils in both the natural condition and following separation of the fraction less than 1 micron. The data reveal that the types of clay minerals which exist in particles smaller than 1 micron or are susceptible of ready dispersion to this range, raise the plasticity limits significantly, particularly the liquid limit and plasticity index (table 9).

Sodium bentonites, such as are widespread in South Dakota and Wyoming, are characterized by liquid limit of 400 to 700 and plastic limit ranging from 50 to 100. Widely divergent limits reported for sodium bentonite

Table 9. Atterberg limits of earth materials in relation to the clay mineral.^a

	Plastic limit	Liquid limit	Plastic index
Illite			
Grundy County, Illinois	35.7	61.2	25.5
LaSalle County, Illinois	24.8	35.9	11.1
Vermilion County, Illinois	23.9	29.1	5.2
Jackson County, Ohio	28.8	54.0	25.2
Pretoria, South Africa	25.4	45.2	19.8
London, England ^b	26.3	74.0	47.7
Kaolinite			
Union County, Illinois	36.3	58.4	22.1
Twiggs County, Georgia	29.9	35.0	5.1
Near Bath, North Carolina	25.0	52.0	27.0
Cornwall, England	41.6	86.7	45.1
Dry Branch, Georgia	26.3	43.8	17.5
Na-Montmorillonite			
Belle Fourche, South Dakota	97.0	625-700	528-603
Clay Spur, Wyoming	55.0	501.0	466.0
Rock River, Wyoming	63.8	537.0	473.2
Near Shelby, Montana	48.0	227.0	179.0
Ca-Montmorillonite			
Pontotoc, Mississippi	81.4	117.5	36.1
Near Granby, Colorado	40.0	86.0	46.0
Attapulgite			
Quincy, Florida	116.6	177.8	61.2
Halloysite			
Eureka, Utah		Not plastic	
(hydrated) Lawrence County, Indiana		Not plastic	
Allophane			
Lawrence County, Indiana		Not plastic	

^a After White (1949), with additions.
^b Contains 5 percent of montmorillonite.

* The plastic limit is the lowest moisture content (percent by weight of oven-dry soil) at which the soil can be rolled into threads one-eighth inch in diameter without breaking into pieces (Allen, 1942).

† The liquid limit is the moisture content (percent by weight of oven-dry soil) at which the soil will just begin to flow when jarred slightly (Allen, 1942).

relate at least in part to thixotropic strength developed with rest. E. J. Kilcawley* found the liquid limit of a Wyoming bentonite to be 450 percent immediately after mixing, but about 700 percent if the sample was allowed to set for a week and tested by decreasing the water content through drying. The very high plasticity index of sodium montmorillonite, ranging from 450 to 600, demonstrates the enormous surface area to be satisfied before the adsorbed water films are sufficiently thick to permit their outermost zones to approach the characteristics of a liquid. At the liquid limit, water films on particles of Na-montmorillonite are calculated to be 100 to 200 Å thick. For calcium bentonite, the liquid limit ranges from 115 to about 140, and the plasticity index ranges from about 35 to 90 percent. Sodium bentonite should show little influence of particle size upon Atterberg constants because of the easy dispersion effected in the particles of clay mineral regardless of the natural size gradation. Calcium bentonite should show a greater variation of plasticity with fineness because of difficult dispersion, particularly after laboratory drying of the sample.

Illite is widely variable in properties, depending upon its particle-size distribution and its position in the montmorillonite-beidellite-hydromica-muscovite series. White (1949) has demonstrated the marked increase in Atterberg limits of illite soils with increasing fineness, a characteristic consistent with the difficulty of thorough dispersion of the mineral. Kaolinite contributes to only modest degrees of plasticity which increase but slightly with decrease in particle-size distribution.

Halloysite, hydrated halloysite, and allophane are reported by White to be nonplastic. However, Grim (1949) reports very high plastic properties for materials containing halloysite, in transition state between the hydrated ($4H_2O$) and partially hydrated ($2H_2O$) forms.

The plastic properties of granular earth materials or those containing illite, kaolinite, or halloysite as the predominant clay mineral, are changed markedly by additions of even very small proportions of montmorillonite (table 10). Of course, the effect is greatest if sodium is the main exchangeable cation of the montmorillonite, due to its influence on dispersion.

Winterkorn and Moorman (1941) have proved the influence of exchangeable ion on the plasticity range of a beidellite soil. With introduction of sodium, calcium, aluminum, magnesium, hydrogen, and potassium in portions of the soil, values ranged as follows:

Liquid limit	52.8 to 88 percent
Plastic limit	24.8 to 27.7 percent
Plasticity index	25.1 to 62.6

The following relative values of limits were found:

Liquid limit :	sodium > calcium > aluminum > magnesium = hydrogen > potassium
Plastic limit :	potassium > calcium > aluminum > magnesium = sodium > hydrogen
Plasticity index :	sodium > calcium > aluminum > hydrogen > magnesium > potassium

By comparison of these values with results of water intake measured on similar or identical materials by Bayer and Winterkorn (1935), a close relation between water affinity and plasticity index is indicated, the higher intake correlating with higher liquid limit and

* Personal communication.

plastic index values. The observation indicates that, with increased affinity of the beidellite for water, a greater proportion of water is required to produce adsorbed films whose outer periphery reacts to shear as a liquid.

Data compiled from several sources (Winterkorn and Moorman, 1941; Samuels, 1950) demonstrate the marked reduction effected in liquid limit and plasticity index of montmorillonite (Wyoming bentonite) by replacement of naturally occurring sodium. The liquid limit and plasticity index decrease in the order: $Na^+ > H^+ > K^+ > Ca^{++} > Mg^{++} > Al^{+++} > Fe^{+++} = Th^{++++}$ (fig. 19). Change in liquid limit and plasticity index is far less marked for kaolinite, illite, and beidellite. For beidellite, the action of potassium in binding together adjacent packets of the crystal is evident in the low value of the liquid limit and plasticity index for the K-beidellite modification. Sodium influences properties of clays far beyond relative abundance in the exchange positions. According to Winterkorn (1953), if as little as 15 percent of the exchange capacity is occupied by sodium, montmorillonite exhibits the properties of homoionic Na-montmorillonite. Introduction of any of several cationic aliphatic amines to montmorillonite clay engenders hydrophobic qualities which radically decrease the liquid limit and plasticity index (fig. 20), and change significantly other physical and physical-chemical properties (Davidson, 1949; and Glab, 1949).

The physical-chemical properties controlling Atterberg limits relate to many fundamental soil mechanics properties. According to Winterkorn and Moorman (1941), Koegler has found an almost linear relationship between plastic index and the angle of friction of cohesive soils. Materials with a liquid limit up to 35 percent and values of plastic index in the range 0 to 15 will have high internal friction if well graded. With plastic index less than 5, cohesion is slight or absent. With higher plastic index, cohesion is high. Liquid limits in excess of 35 percent and plastic index greater than 15 correlate with increased content of clay minerals or organic matter, the necessary amount of clay to increase the magnitude of these properties into this range being least with the montmorillonite-type clays of sodium type. In this range dry weight is low (generally less than 100 pounds per cubic foot) and shrinkage, expansion, and capillarity are high. Burmister (1949) classifies plasticity according to plastic index as follows:

<u>Plasticity</u>	<u>Plasticity index</u>
Nonplastic	0
Slight	1 to 5
Low	5 to 10
Medium	10 to 20
High	20 to 40
Very high	40 and greater

Permeability

In their usual occurrence, clay minerals in earth materials are exceedingly fine and consequently tend to fill void spaces lying between grains of silt, sand, and gravel. Consequently, clay minerals characteristically decrease permeability of earth materials, especially of remolded clays in which structural features, such as shrinkage cracks, joints, stratification, or shear zones are absent. Permeability decreases with the regularity of particle-size distribution of the material, especially with the extension of the size range into

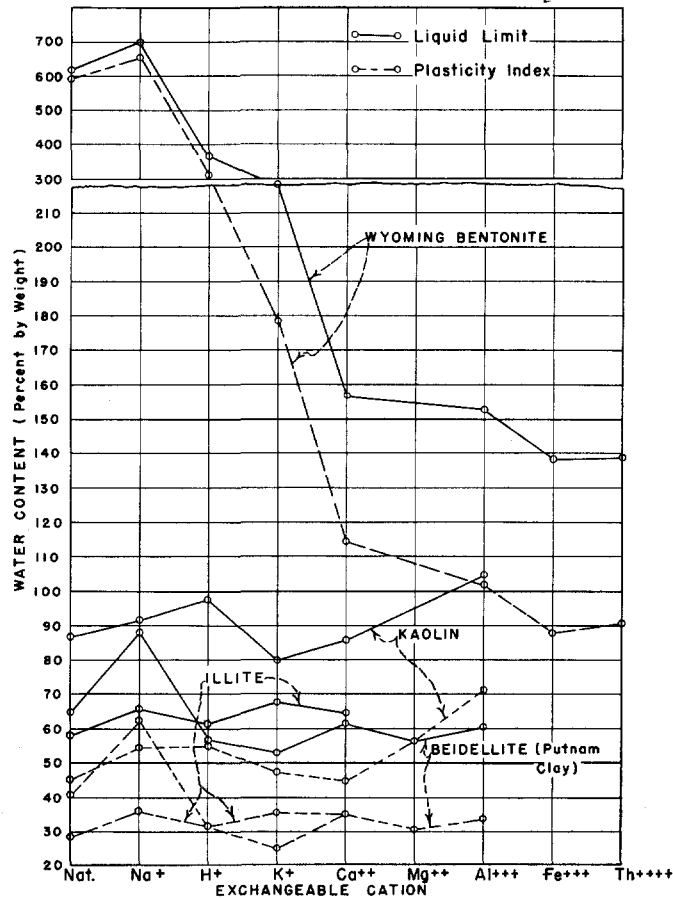


FIGURE 19. Effect of exchangeable cation on Atterberg consistency limits of clays (Winterkorn and Moorman, 1941; Samuels, 1950; Kilcawley, personal communications).

fractions below 1 micron. According to Lambe (1954b), the major factors influencing the permeability of fine-grained soils are: (1) soil composition, (2) characteristics of the fluid, (3) void ratio, (4) fabric, and (5) degree of saturation.

For remolded clays, under ordinary circumstances of saturation by relatively pure water, permeability of earth materials is least if montmorillonite-type clays are present and greatest if kaolinite is the clay mineral component. In tests upon beidellite clay, Winterkorn and Moorman (1941) found the permeability approximately equal for the hydrogen, calcium, and magnesium modifications, and distinctly less than that of the potassium modification at void ratio less than 1.3; but at void ratio greater than 1.3, the permeability of the magnesium modification rises rapidly and greatly exceeds that of the calcium soil. Although not reported directly, other tests of the sodium modification indicate that it possesses the lowest permeability of the several soil modifications investigated. In comparable tests of modifications of Wyoming bentonite, Samuels (1950) determined the permeability relation to be thorium > aluminum > calcium > sodium at loads less than 1 ton per square foot. At greater loads, the permeability of the calcium and sodium modifications is virtually nil (fig. 21). The permeability of the aluminum modification becomes negligible at loads of about 5 tons per square

foot. Permeability of treated kaolin is similarly affected by exchange of ions but the permeability is 4 to 20 times greater than for the bentonite modifications. For the kaolin the permeability decreases in the series aluminum > calcium > hydrogen > sodium, for given load.

The permeability of kaolin can be decreased greatly by decrease in particle size and increase in surface area (Harman and Fraulini, 1940). With increase of apparent surface area from about 30 square meters per gram to 240 square meters per gram the permeability of kaolin decreases by a factor of 3.5.

As has been implied, permeability of clay formations in place usually departs greatly from the permeability of the material when remolded. Structural features, such as shrinkage fractures developed by drying or syneresis, joints, bedding planes, and shear zones, lead to high permeability in many clays, claystones, and shale formations. Sealing of such fractures as the result of swelling of the clay mineral should not be depended upon in design of hydraulic works. In a study of coarse gravel containing abundant interstitial clay, Cary (1949) found a high degree of permeability apparently as the result of the intimate fracturing of the clay by shrinkage through syneresis. These fractures occurred both above and below the water table.

The foregoing discussion is based upon consideration of essentially pure water as the penetrating medium. Electrolytic solutions will greatly increase permeability of clay soils and formations by inhibition of swelling as the result of hydration. Newly introduced solutions can progressively effect ion exchange, in addition to the

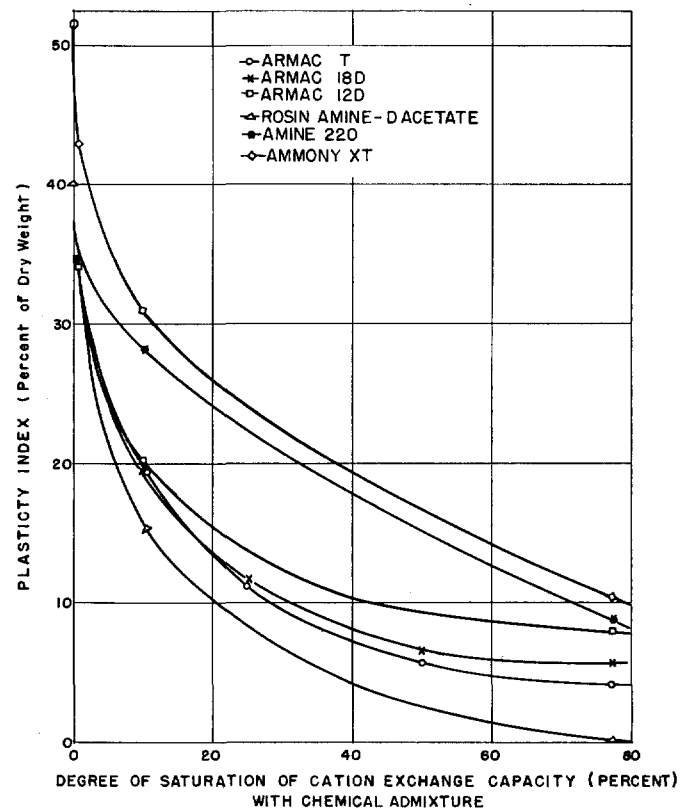


FIGURE 20. Effect of cationic surface active agents on plasticity index of a montmorillonite soil (Davidson, 1949).

flocculating or coagulating effect. Flushing of the electrolytic solution by water containing only small amounts of dissolved solids again will restore a reduced permeability, although semipermanent increases may be developed by the ion exchange process (Lee, 1941; Bodman, 1941).

In engineering practice, clays are used to control permeability of formations by linings of various types and by grouting. Linings include use of bentonite, loose earth blankets, and compacted earth. Loose earth and compacted earth linings may contain any species of clay mineral, the prime requisite for satisfactory installation being the low permeability of the lining in place. The permeability is a function of gradation, in-place density, the thickness of the lining, and the hydraulic conditions of operation.

Bentonite is used in various ways in linings: (1) as membrane $\frac{3}{4}$ to 2 inches thick, depending primarily upon the montmorillonite content, swelling properties, and fineness of the material; (2) mixed with soil and placed in a layer about 2 to 3 inches thick; and (3) mixed into soil in place by disking, harrowing, or rototilling. Several successful applications have been made by sowing of commercial bentonite over the surface. Elsewhere, canals and reservoir bottoms have been treated by silting action, the bentonite being first spread over or mixed in the water. Membrane linings require adequate cover for protection against drying and consequent cracking, curling, and erosion. Cracking as the result of syneresis might occur in membrane linings, even under water or moist cover material, but the conditions under which syneresis is significant remain to be determined. Admixture of bentonite with granular material increases the shrinkage limit and thus prevents formation of the penetrating cracks which are so typical of lean and fat clays.

Of critical significance in use of bentonite to develop impermeability, is the limiting expansion developed in sodium montmorillonite with adsorption of water. Although the osmotic adsorption of water by sodium montmorillonite is great, complete dispersion of the clay crystals is resisted by interlayer forces. This resistance to dispersion is easily demonstrated in simple free-swell tests in which particles of sodium bentonite expand to limiting bulk volumes up to 17 times their dry volume. However, with agitation, complete dispersion takes place readily.

Permeability of linings can be changed by ion exchange through continued contact with saline waters. As is evident from the review of laboratory tests previously described, exchange of sodium for calcium will increase permeability of linings owing their imperviousness to clay minerals. In practice this effect is developed particularly by saturation of bentonite linings from below by waters carrying dissolved gypsum ($\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$). The swelling of sodium bentonite is reduced greatly by contamination of the raw material with gypsum.

Apart from ion exchange, permeability is influenced by coagulation or dispersion of clays as the result of change of electrolyte content. Lee's (1941) treatment of the lagoon lining on Treasure Island in San Francisco Bay with sea water is an excellent and now classic

demonstration of effects of both ion exchange and the influence of electrolytes on soil structure and permeability. Upon flooding of the lining with sea water sufficient to permit seepage through the lining of a total of 40 inches of depth, the ratio of exchangeable sodium to calcium was changed from 1:1 in the original soil to an average of 2.2:1. Upon drainage of the excess salt water from the lagoon and introduction of fresh water, permeability of the lining was found to decrease as the result of collapse of the fabric of the clay and dispersion of the finest fractions with decrease of electrolyte content of contained water. The seepage rate at completion of the operation was found to be 0.10 inch per day in contrast to 0.90 inch per day prior to treatment.

Control of electrolyte concentration of clay-water mixture was put to advantageous use in the construction of Alexander Dam, Island of Kauai, Hawaiian Islands, (Cox, 1929; Anon., 1930; Anon., 1930a) when coagulation resulting in excessive permeability and low unit weight was prevented by a carefully controlled addition of soda ash to the slurry introduced to the core pool. The resulting dispersion decreased void ratio of the deposited material from 2.52 to 1.98 and the permeability decreased from 0.6×10^{-5} to 0.04×10^{-5} centimeter per minute.

Sodium bentonite is used as grouting material either with water alone, with liquid petroleum products, or as an admixture with portland cement. Bentonite-water grouting mixtures usually contain 4 to 15 percent by weight of the clay. In bentonite-portland-cement mixtures, bentonite constitutes 10 to 20 percent by weight of the total solids, the optimum proportion depending upon water-to-solids ratio and the nature of the formation to be grouted. Similarly, the ratio of bentonite to petroleum product depends upon the grouting conditions and the liquid used (Cordon, 1944). Bentonite or bentonite-cement grouts are ineffective in grouting sands containing fractions passing the No. 50 or No. 30 sieve, respectively (Burnett, 1936). They find best application in grouting of formations containing comparatively large and interconnected voids, channelways, and fractures.

Effectiveness of the bentonite water grout depends upon expansion of the clay in place within the openings to be sealed and upon thixotropic setting of the slurry. If hydraulic pressure is applied before setting occurs or if failure begins, permeability rises rapidly because of destruction of the established thixotropic gel structure. Best results are obtained if injections occur as coagulated matter so that swelling is completed after emplacement. Formations grouted with bentonite must be kept wet if the seal is not to be lost by drying shrinkage. Admixture of bentonite with portland cement, aids injection of the grout into the formation at given consistency, retards hardening of the cement, and improves the seal effected.

Thixotropy

As originally defined by Peterfi and by Freundlich (Freundlich, 1935; Green and Weltmann, 1946) thixotropy is an isothermal, reversible, sol-gel transformation. The phenomenon is well exemplified by marked increase in viscosity of sodium-bentonite sols with rest, and the subsequent decrease in viscosity with agitation. This sequence may be repeated indefinitely. Later

Table 10. Consistency and shrinkage limits of synthetic bentonite and kaolinite soils.

Composition (percent by weight)			Liquid limit (percent)	Plastic limit (percent)	Plasticity index (percent)	Shrinkage limit (percent)	Shrinkage ratio
Wyoming bentonite ^a	Kaolin ^b	Sand and Silt ^c					
100	-----	-----	501.0	35.0	466.0	8.1	1.78
50	-----	50	253.0	21.0	232.0	6.9	1.91
25	-----	75	128.0	15.0	113.0	24.9	1.47
10	-----	90	52.5	24.9	27.6	34.8	1.36
5	-----	95	30.7	25.8	4.9	29.3	1.48
-----	100	-----	52.2	25.3	26.9	25.3	1.43
-----	50	50	18.0	11.1	6.9	14.9	1.90
-----	25	75	16.3	15.1	1.2	15.1	1.88
-----	10	90	17.0	17.0	0.0	17.9	1.77
-----	5	95	-----	-----	-----	17.2	1.75
2.5	47.5	50.0	31.0	12.0	19.0	15.4	1.81
5.0	45.0	50.0	45.0	13.0	32.0	15.2	1.80
10.0	40.0	50.0	65.0	15.0	50.0	15.4	1.80
25	25	50	146.0	16.0	130.0	24.4	1.84
40	10	50	217.0	14.6	202.4	10.3	1.81
45	5	50	235.0	19.0	216.0	8.8	1.79
47.5	2.5	50	234.0	19.0	215.0	8.0	1.88

^a Natural bentonite, near Osage, Wyoming, containing about 85 percent of Na-montmorillonite.

^b Kaolin, near Bath, South Carolina, containing about 99 percent kaolinite.

^c Screened and washed from natural sand, Clear Creek, near Denver, Colorado, and containing equal parts by weight of No 50 to No 100 and No 100 to No 200 fractions.

Table 11. Atterberg consistency limits and stiffening limit for several clays and shales.

Geologic formation	Petrographic type	Predominant clay mineral	Consistency limits (percent of dry weight)			
			Liquid limit	Plastic limit	Plasticity index	Stiffening limit
Eagle Ford shale, near Dallas, Texas	Shale	Beidellite	49.0	25.0	24.0	132.0
Ione formation, Valley Springs, California	Claystone	Kaolinite	49.0	24.0	25.0	136.0
Graneros formation, near Osage, Wyoming	Claystone	Na-Montmorillonite	501.0	35.0	466.0	1560.0
Nespelem formation, near Coulee City, Washington	Varved clay and silt	Vermiculite-Chlorite-Illite, and Montmorillonoids	60.0	27.0	33.0	120.5
Alluvium, near Yuma, Arizona	Clay	Ca-Beidellite	80.0	28.0	52.0	123.0
Porterville clay, near Lindsay, California	Claystone	Ca-Beidellite	69.3	33.0	36.3	134.0

work questions the necessity for complete transformation of gel to sol as a prerequisite for thixotropy, the property being identified with a variation in viscosity with rate of shear (Green and Weltmann, 1946). The data strongly suggest that thixotropy results from development of a structure involving the suspended solids and the liquid phase. Thixotropy is a characteristic only of systems in which large volumes of liquid phase are adsorbed upon and held between particles. The upper limit of size of particles participating in the thixotropic structure are about 10,000 Å. After cessation of agitation, the particles supposedly are shifted about by Brownian movement, until a condition of balance of electrostatic and gravitational forces is attained (Larsen, 1946). Orientation of the solid particles and molecules of the liquid proceeds slowly, so that thixotropic strength develops progressively and is destroyed only through finite and measurable periods of time. Thixotropy in relation to shear resistance of earth materials is discussed subsequently.

Thixotropy develops to a degree in almost all sols, but the rate of formation and break-down and its strength vary greatly with the particle size, particle shape, surface activity, exchangeable cation, concentration, nature of the liquid phase, electrolyte content, and other factors. Among clay minerals, the property is most easily demonstrated in bentonite-water slurries. For sodium-montmorillonite, 80 milliliters of water can be added to 1 gram of clay and the mixture forms a gel which will not flow from a test tube 8 mm in diameter 1 minute after cessation of agitation. In similar tests 30 milliliters of water can be added to 1 gram of kaolinite; whereas, only 16 milliliters of water can be added to 1 gram of muscovite of the same grain size (Winkler, 1949; 1943). Thixotropy of bentonite is reduced if alkali ions are replaced by Ca⁺⁺ or Ba⁺⁺ and is eliminated by complete removal of alkali ions and their replacement by H⁺ or polyvalent ions (Freundlich, 1935; Houwink and Burgers, 1939). As is well known, bentonite-water slurries are used as deep-well drilling fluids, because thixo-

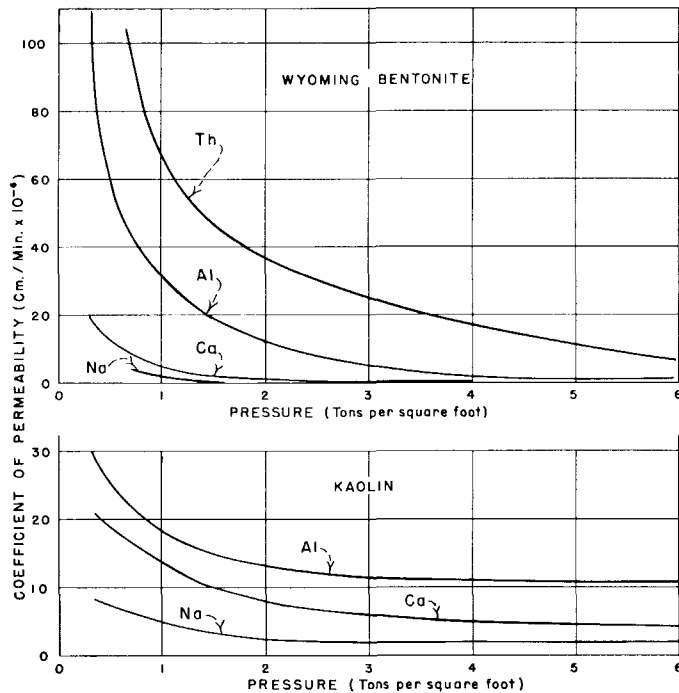


FIGURE 21. Effect of exchangeable cation on permeability of kaolin and Wyoming bentonite (Samuels, 1950).

tropic setting of the slurry prevents rapid settling of the cuttings after temporary stopping of the rotation of the bit.

In a thought-provoking article, Aekermann (1948) describes the significance of thixotropy in soil mechanics properties of glacial clays of Norway. The clays range from fat clay to fine sand of low clay content, and consist predominantly of particles in the range from 2 to 20 microns. The finest fractions are predominantly composed of particles in the range from 0.05 to 0.20 micron. The sand and silt fractions are mainly quartz and feldspars. Mica and clay minerals are concentrated in the finest fractions. No montmorillonite clays were identified. Laboratory tests of clay-water mixtures demonstrate the thixotropic setting of sols of the glacial clays with rest. Because of the great significance of thixotropic strength in establishing stability of these soil masses at high water content, Aekermann (1948) proposed an additional consistency limit comparable to those proposed by Atterberg. He designates the quantity "stiffening limit."

The "stiffening limit" is the boundary between the quick and liquid consistencies. At water contents greater than the liquid limit an apparently stable soil is maintained by thixotropic strength and hence can be liquefied suddenly by vibration, overloading, or other disturbances.

The "stiffening limit" is defined as the water content (expressed as percent by weight of dry soil) at which a thoroughly stirred thixotropic soil still flows under its own weight in a test tube of 11 mm diameter after exactly 1 minute of rest. The liquid limit of thixotropic Norwegian fat clays generally is above 40 percent, whereas the "stiffening limit" ranges from 65 percent to very high values. Lean coarse clay (silt) of the same

electrolyte content, and containing the same clay minerals as the fat clay, becomes syrupy at water contents as low as 20 percent, and the "stiffening limit" always is lower than 100. The lean coarse clay has a greater ability to flow because it liquefies at a lower water content. Ability to flow is inversely proportional to thixotropy. Low liquid limit (mostly in the range 30 to 60 percent) indicates weak thixotropy, whereas high "stiffening limit" (mostly over 100 percent) indicates high thixotropy. Norwegian quick clays possess a liquid limit less than 56. Because of its high degree of thixotropy, a fine clay with high optimum moisture content and optimum concentration of electrolytes may become more highly liquid, and thus more likely to flow, than the coarse clay or silt. The "stiffening limit" of several clays and shales occurring in the United States is indicated in table 11 in relation to mineralogy and Atterberg consistency limits.

Gelling time is closely related to concentration of the sol. Winkler (121) summarized data for sodium montmorillonite-water slurries as follows:

$\frac{\text{Volume of the liquid}}{\text{Volume of the solid}}$	Gelling time (minutes)
33	1
34	6
36	45

Thixotropic properties occur even in cohesive soils composed largely of sand and possibly containing less than 5 percent of clay minerals. Distinct thixotropy has been demonstrated in certain quick sands and loess, the latter containing about 3 percent montmorillonite (Freundlich and Juliusburger, 1935). It is entirely likely that thixotropy contributes to stability at low moisture content of loess in western Nebraska. The structure of the loess is preserved by films of montmorillonite upon the grains of silt and fine sand. With wetting, this loess is subject to considerable consolidation as the result of collapse of the original open fabric.

In clayey soils, thixotropy is strongly influenced by electrolyte content. Winkler (1943) demonstrates increase in thixotropy of aqueous suspensions of mica and kaolinite by addition of NaCl and KCl; and reduction by addition of BaCl₂ and CaCl₂. For aqueous sols of sodium montmorillonite, originally air dried, increasing concentration of NaCl, KCl, NaOH, and KOH up to 1.0 N continuously decreased thixotropy. When maintained moist without drying prior to preparation of the slurry, sodium montmorillonite attained a maximum thixotropy with potassium hydroxide at 0.65 normal.

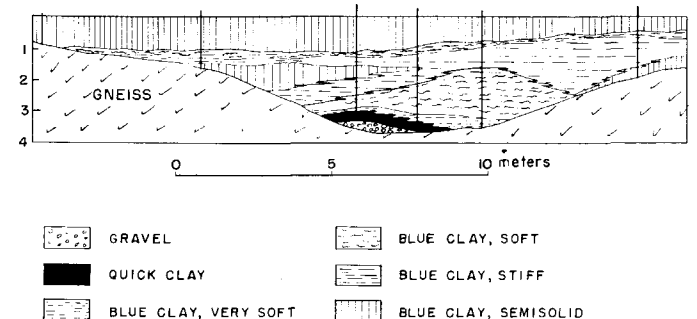


FIGURE 22. Development of a zone of quick clay through leaching of electrolytes by drainage into an underlying gravel stratum (Aekermann, 1950).

For hydrogen montmorillonite a definite maximum in thixotropy is observed in water slurries in which the concentration of KOH is about 0.05 N. Simultaneously, sediment volume and swelling attain a maximum. At this concentration of KOH, the H^+ of the original acid montmorillonite is neutralized (Freundlich, 1935; Houwink and Burgers, 1939). As is noted by Marshall (77) two zones of thixotropy can be developed in aqueous slurries of montmorillonite: one at low electrolyte content and one at high electrolyte content, the two zones being separated by a range of concentration in which thixotropy is small.

Rosenquist (1946) found thixotropic strength development in clays with addition of up to 3-percent sodium chloride solution, but with further additions the quick clays lost their ability to flow. The quick condition is recovered with removal of the excess salt. Rosenquist's experiments correlate with observation of zones of quick clay containing water of minimum electrolyte content, and the occurrence of quick clays overlying permeable gravels (fig. 22). Through decrease in thickness of adsorbed water films with decrease in concentration of electrolyte, a plastic clay can become quick without changing total water content. With other clays and other solutes, quick clays might develop through increase in salt content of interstitial water.

Shear Resistance

Resistance to shearing stress is developed in soils by particle interlocking, meshing of irregularities on particle surfaces, adhesion, cohesion, and cementation by secondary minerals, such as iron oxides, carbonates, quartz, opal, and chalcedony, which are deposited interstitially. Clay minerals are of fundamental importance in establishing shear resistance of earth materials. At low water content, restricted water films subject the mass to compressive stresses of considerable magnitude and thus increase shear resistance. However, increasing degree of saturation by introduction of water decreases the internal compressive stress arising in water films. Moreover, if degree of saturation is increased by rapid consolidation of the earth material with loading, shear resistance of the material is reduced by pore water pressure. Consequently, shear resistance of earth materials depends not only upon the structural integrity of the solid constituents, but also upon the ability of the material to drain contained water and air as readjustment of the structure takes place in response to load.

Clay minerals and the fabric of granular earth materials play critical roles in both phenomena. Winterkorn and Moorman (1941) have found the shear resistance of cohesive soils to be approximately a logarithmic function of the moisture content in the lower part of the plastic range. Shear tests of soils containing differing clay minerals and clay minerals with differing exchangeable ions demonstrate the interrelation of structure and permeability in control of deformation of the test specimen. With loading of specimens of a beidellite (Putnam) clay, Winterkorn and Moorman (1941) show greatest deformation in the sodium modification and smallest for the modifications containing calcium, hydrogen, and potassium. In triaxial shear tests performed on the same soils at maximum density, and optimum moisture content, but without achievement of equilibrium, de-

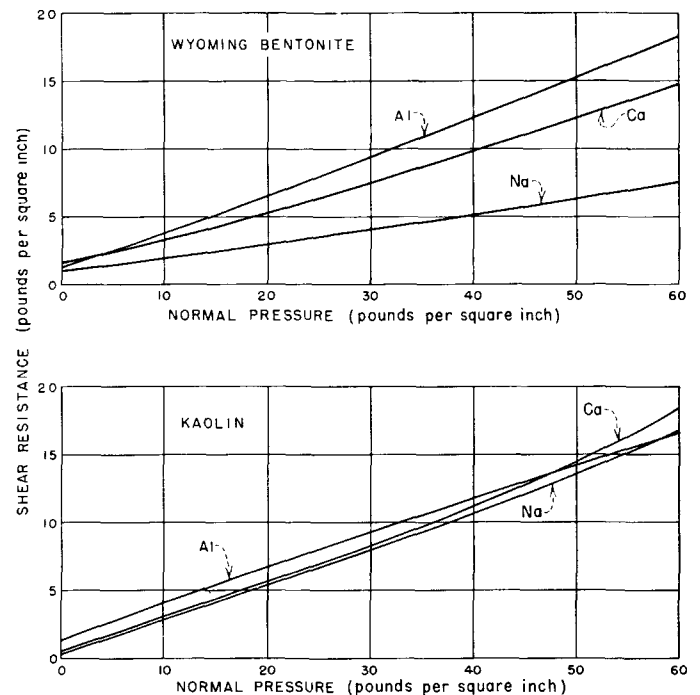


FIGURE 23. Effect of exchangeable cation on shear resistance of kaolin and Wyoming bentonite (Samuels, 1950).

formation of the sodium clay is less than that of the hydrogen clay because drainage of the sodium clay was greatly impeded by its very low permeability. Correspondingly, the internal friction of the sodium clay is low because of the high pore pressure and consequent anomalously low compressive stress linking elements of the fabric together.

Loosely cemented silts and sands possessing an open fabric are especially susceptible to loss of shear resistance with disturbance by vibration or rapid changes of load while saturated. Intergranular braces, so typical of many loesses, soften with wetting and lose cohesion. Loose or poorly cemented sands and silts are subjected to "spontaneous liquefaction" with shifting of the grains to more stable positions while the voids are filled with water (Terzaghi and Peck, 1948; Terzaghi, 1950).

In reverse, marked resistance to shearing is developed with rapid application of shearing stress to saturated, loose, noncohesive or slightly cohesive earth materials which possess a closely packed fabric (Terzaghi and Peck, 1948; Green and Weltmann, 1946). Disturbance of the fabric necessarily results in increase in bulk volume and dilation of the voids. The material then appears dry and hard, as, for example, in the familiar experience of walking upon saturated sand on the ocean shore. In their undisturbed condition, dilatant materials flow readily if not stressed rapidly. With release of the applied stress, the original compact fabric is restored, presumably by compressive stress arising in the capillarity of interstitial water. These phenomena are developed especially in silts and sands. Dilatancy is significant in drilling because the mass of cuttings settled compactly in the hole commonly expands (dilates) against the drill rods or pipe when an attempt is made to withdraw the tools (Larsen, 1946). Jarring momentarily re-establishes the compact fabric and permits progressive

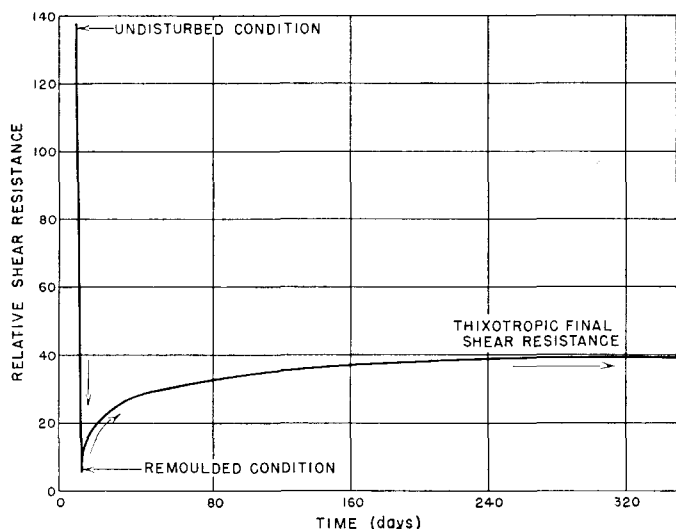


FIGURE 24. Changes in shear resistance of plastic glacial lake clays with remolding and rest (Ackermann, 1948).

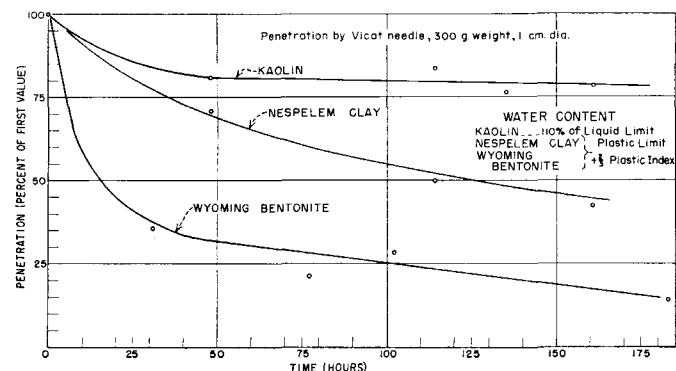


FIGURE 25. Thixotropic development of penetration resistance in clays.

freeing of the pipe or rods. Dilatancy as a factor in soils mechanics is described further by Terzaghi and Peck (1948).

Clay mineral constituents of earth materials increase sensitivity of shear resistance to moisture content. The range of moisture content at maximum shearing resistance decreases as the clay minerals become increasingly abundant, and as intergranular friction is reduced.

The role of shear resistance in controlling density of soils remolded with given compactive effort must not be overlooked in study of stress-strain phenomena in earth materials. The moisture content yielding maximum cohesion is so low the workability of the material is poor and low void ratio and high density in the remolded specimen are attained only with great difficulty. To obtain both high density and high shear resistance Johnson and Davidson (1947) recommended compaction at optimum moisture content, followed by drying to the moisture range producing maximum shear resistance.

In studies of Wyoming bentonite, Samuels (1950) demonstrated increasing shear resistance with the exchange of cations in the series, sodium < calcium < aluminum (fig. 23). Shear resistance of sodium, calcium, and aluminum modifications of kaolin is essentially identical and similar to the shear resistance of Wyoming bentonite containing aluminum as the exchangeable cation. By

replacement of naturally occurring hydrogen, calcium, and sodium in the Putnam soil with potassium, Winterkorn and Moorman (1941) increased the angle of friction from 19° to 22° . The effect of exchangeable cation upon the angle of friction of kaolin is negligible.

Shear resistance is increased in clayey materials by development of thixotropic strength, but this element of shear resistance is lost with disturbance of the fabric by vibration or rapid strain (Hvorslev, 1939). With disturbance of natural structure by crushing and kneading, plastic clays become softer; and clays owing their plasticity largely or entirely to thixotropy become liquid. With remolding and rest, thixotropic strength increases shear resistance at a decreasing rate, the shear resistance ultimately reaching a constant value which is only a fraction of the shear strength of the undisturbed material (fig. 24). Strength gain is very slow after 4 weeks of rest. The proportion of original strength regained varies widely with the nature of the material. The original strength arises in cementation, particle interlocking, interparticle cohesion, and stable water films developed through geologic time. These features are regained only partially or not at all. Strength regain with time was observed in illitic and micaceous Norwegian glacial clays by Hvorslev (1939) and by Ackermann (1950); and for montmorillonite clays in Germany by Winkler (1949), and in Mexico City, Mexico, by Zeevaert (1947, 1949) and by Cummings (1930). Construction experience with a thixotropic fill material is described by Hirashima (1948).

Thixotropic stiffening of clay develops increased resistance to penetration. In laboratory tests, resistance to penetration is increased most rapidly for Wyoming bentonite and least for a kaolin; whereas intermediate values were obtained for a glacial lake clay (Nespelem formation, near Coulee City, Washington) containing montmorillonite, illite and hydrous mica, and a vermiculite-chlorite (fig. 25).

In nature and in engineering practice, landslides or slope failures are the commonest demonstration of inadequate shear resistance in earth materials. Although any natural material will fail on slopes under extreme conditions, poorly cemented sands and silt, with or without clay mineral fractions, and fractured expansive clays



FIGURE 26. Landslide in granite containing abundant zones and seams of beidellite, Anderson Ranch Dam site, Idaho.

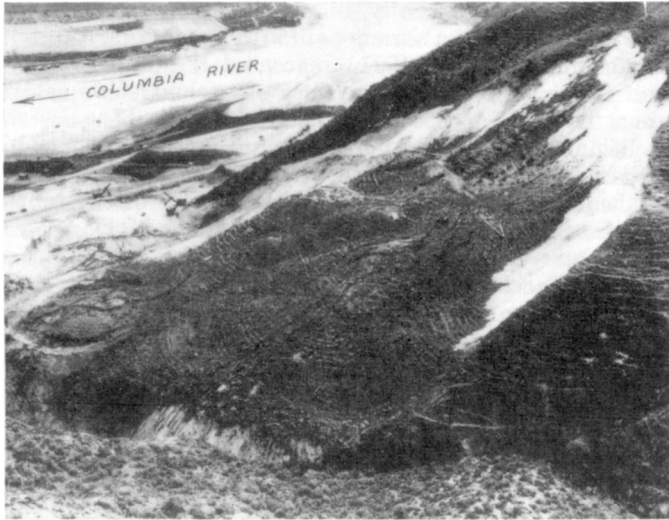


FIGURE 27. Landslide in the Nespelem formation at the left abutment of Grand Coulee Dam site, Washington, as the result of excavations at the toe of the natural slope.

are most susceptible to collapse as a result of: (1) changes of packing caused by stress change associated with loading or unloading, vibration, undermining, or rapid draw-down of an adjacent body of water; (2) decomposition of intergranular braces, granular interlocking, or adhesion by weathering or other chemical action; (3) decrease of intergranular friction, cohesion, and adhesion by introduction of water and development of pressure in pore water; and (4) decrease of intergranular friction, cohesion, and adhesion by swelling with hydration of crystals of expansive clays within interstices of the material (Terzaghi, 1950). At Anderson Ranch Dam, Idaho, seams of tan beidellite cut the granodiorite to depths in excess of 300 feet beneath the original surface. With unloading of the toe of the natural slope in the course of excavation of the site and with penetration of water from rain and snow, successive sliding occurred at the left abutment (fig. 26). Soles of the slides were coated with the beidellite which cracked and curled through shrinkage following exposure. At the left abutment of Grand Coulee Dam, sliding in the Nespelem formation followed progress of excavation (fig. 27).

Fractures formed by orogenic or epeirogenic movements, creep, drying shrinkage, and syneresis contribute to slope instability by weakening the material and by facilitating entry of water into zones which otherwise might remain unsaturated or even dry. Wetting of disturbed and partially dried clays usually results in slaking even though the undisturbed clay with original moisture content would resist slaking. The slaked material along fractures decreases shear resistance of the mass and thus contributes to possible failure. Fractures in otherwise stable material can be produced by swelling of adjacent or interbedded expansive clays (Terzaghi, 1950).

Sands and silts interbedded with lean or fat clays afford access of water to otherwise impervious masses. The Nespelem formation occurring on the shores of Lake Roosevelt, impounded by Grand Coulee Dam, Washington, apparently exemplifies this action in their catastrophic failure following rapid draw-down of the water level.

Thixotropy increases shear resistance of materials and so inhibits shear failure until failure begins. Thixotropic strength is a treacherous phenomenon, for catastrophic failure can be induced by vibrations of passing trains, blasting, or construction activities (Winkler, 1943; Ackermann, 1948). Although no detailed field studies have been made of the physical-chemical phenomena involved, there is little doubt that the landslides developed in the Nespelem clays are influenced by thixotropy, because clays supporting vertical slopes and appearing stiff and compact prior to disturbance, approach the liquid condition with excavation by power shovels or similar disturbance and large waste piles assume an angle of repose of 2° or 3° . Natural moisture content of these clays sometimes exceeds the liquid limit. The Nespelem clays contain montmorillonite, illite, and hydrous mica, together with vermiculite-chlorite (fig. 16). Thixotropic properties of the Nespelem clay are demonstrated by tests of changing penetration resistance with time (fig. 25) and observation of stiffening at water content greater than the liquid limit.

Shear resistance due to thixotropy is dependent upon concentration and kind of electrolyte held in the interstitial water. This phenomenon was discussed previously. Ackermann (1948) and Rosenquist (1946) have found that, with the solutions characteristically occurring in Norwegian blue clays containing hydromicas as the predominant clay mineral, thixotropy is decreased as electrolyte concentration decreases. As a consequence, stiff plastic clays are converted to quick clays of lower consistency through leaching of electrolytes from near-surface zones and from clays overlying gravels of high transmittancy (fig. 22). In other situations, thixotropy

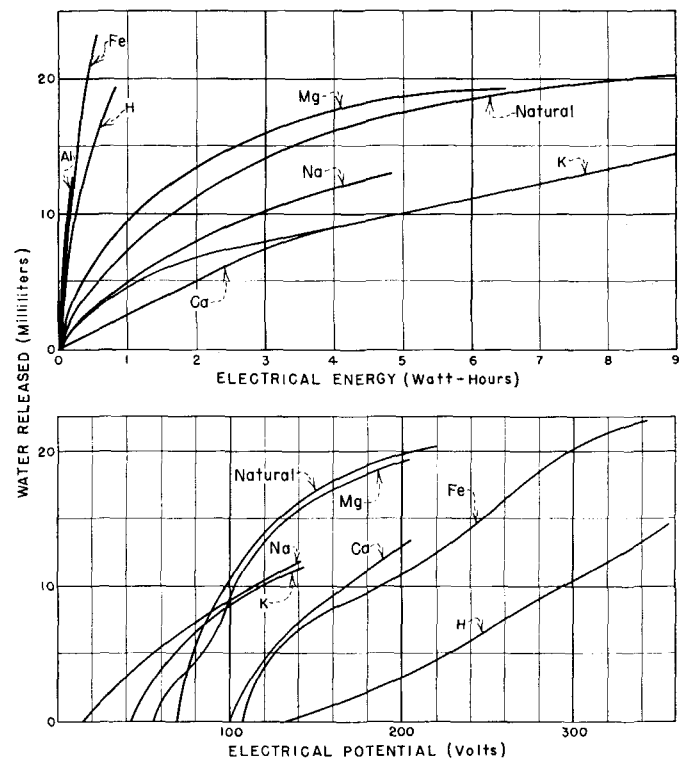


FIGURE 28. Effect of exchangeable cation on electro-osmotic yield of a kaolinite soil (Winterkorn, 1947).

might be increased by changes in concentration of electrolytes in interstitial water.

Increased shear resistance in highway subgrades has been obtained economically by various types of chemical and physical-chemical treatment. Stabilization of clays requires binding of the particles by agents resistant to water or waterproofing by agents which permit maintenance of sufficient cohesion by water originally contained in the material. Cementing action can be obtained by several inorganic and organic binding agents, each with particular ranges of application, controlled largely by the surface-chemical properties of the earth material. Winterkorn (1948) has classified earth materials and complementary agents as follows:

Surface-chemical character of the soil	Complementary chemical admixture
1. Complex iron and aluminum silicates with SiO_2 : R_2O_3 ratio greater than two; the clay particles are typically charged negatively	1. Organic cations (ammonia derivatives and substances which may react with particle surfaces through hydrogen linkage)
2. Complex iron and aluminum silicates with SiO_2 : R_2O_3 ratio less than two and complex hydrous iron and aluminum oxides. The negative charges are less and positive charges are greater than for soils of Group 1	2. Organic anions, such as soluble soaps, saturated and unsaturated fatty acids, and resin acids. Antioxidants are recommended to assure durability
3. Particle surfaces covered by lignaceous and proteinaceous organic matter	3. Substances forming synthetic resins with humus materials
4. Saline and alkaline soils	4. Field unexplored
5. Peat and muck	5. Substances forming synthetic resins with organic matter or which themselves form resins

For quantitative data and the limitations pertaining to these methods, the reader is referred to the definitive writings of H. F. Winterkorn and his associates (1946). Recent work on stabilization of soils by dispersants is reported by Lambe (1954a) and Lambe and Michaels (1954).

Stabilization of highway subgrades by introduction of divalent or trivalent inorganic ions, such as calcium hydroxide or salts of calcium, aluminum, or iron, has been investigated extensively but best results have been obtained so far with calcium hydroxide (Callaway and Buchanan, 1951). Although these methods have yielded satisfactory results in highway subgrades, where only a few inches of material must be treated, stabilization of clay foundations of buildings, dams, bridges, and similar large works by mechanical admixture or hydraulic injection of chemical agents, has not proved feasible because of the quantity of material in place to be treated and the characteristically very low permeability. For successful treatment of a soil mass the agent must permeate the soil fabric rather than merely penetrating fractures transecting the formation. Physical-chemical treatment of loess in place has been described by Denisov (1951).

Extensive investigations have been conducted on electro-osmotic and electrochemical stabilization methods in many laboratories of the United States, England, Germany, France, Russia, and elsewhere (L. Casagrande, 1937; 1939; 1947; 1949; Endell, 1935; Preece, 1947; Erlenbach, 1936; Endell and Hofmann, 1936; Kolbuszewski, 1952; Schaad and Haefeli, 1946; Vey, 1949;

Spangler, 1949; Karpoff, 1953). In accordance with observations originally made by Reuss in 1808, adsorbed cations, together with the adjoining water in interstices of clays, will move toward the cathode in an induced electrical field, a process designated as electro-osmosis. If continued sufficiently long, the naturally occurring cations are replaced by hydrogen and significant quantities of water are moved from portions of the material, or may be removed entirely, if desired, at the cathode. Shear resistance is increased by replacement by hydrogen of ions, such as sodium, which tend to increase zeta potential and water-adsorbing capacity of clays, and also by removal of the interstitial water. If a temperature gradient exists or is induced by the electrical potential, thermo-osmotic transfer of water will occur simultaneously.

Winterkorn (1947) has demonstrated widely differing effectiveness of electro-osmosis with change of exchangeable cation in a kaolinite soil from near Hagerstown, New Jersey (fig. 28). For given power consumption, aluminum, ferric iron, and hydrogen modifications released more water than did the calcium, potassium, and sodium soils, magnesium soils being intermediate. However, the calcium, ferric iron, aluminum, and hydrogen soils require greater voltage at given current intensity (30 milliamperes) for given water release than did the sodium, potassium, and magnesium soils.

At given electrical potential and dielectric constant and viscosity of the pore water, the volume of electro-osmotic flow increases with zeta potential and decreases as the size of the capillary decreases. Consequently, in sodium clays with high zeta potential and high dispersion, conductance is high and electro-osmotic yield is low. Conversely, for ferric iron and aluminum modifications, the zeta potential is low and dispersion is less; but when the low zeta potential is compensated by higher induced potential gradient, electro-osmotic flow is more rapid and is accomplished with less power consumption than for the sodium modification.

During electrochemical treatment, electro-osmosis is supplemented by action of chemicals introduced at the anode or cathode, either in solution or by decomposition of the electrodes. Electro-osmotic transfer of water inevitably accompanies electrochemical treatment of earth material. In addition, both electro-osmosis and electrochemical treatment involve limited movement of charged, colloidal particles, such as fragments of clay mineral crystals toward the anode. Moreover, complex crystals, such as montmorillonite, can be partially decomposed at higher potential gradients.

Electro-osmotic treatment is especially applicable to dewatering of silts and clays in which electro-osmotic permeability is equal to or greater than hydraulic permeability (L. Casagrande, 1949). In clays, electro-osmotic permeability (expressed as centimeters per second at 1 volt per centimeter) usually is several thousand times the hydraulic permeability at unit hydraulic gradient.

In their present state of development, electro-osmotic methods are not competitive with ordinary methods of foundation or slope control, such as dewatering by drains or well points, or use of sheet piling or, for foundations, use of any of several types of piles or footing designs to support the structure. However, where other methods have failed, electrical methods of soil

Table 12. Compressive strength of synthetic soils.

Mixture (percent by weight)			Moist specimens			Air dry specimens				
Wyoming bentonite ^a	Kaolin ^b	Sand ^c	Density (lbs./ft. ³)	Water content (percent)	Compressive strength (psi)	Density (lbs./ft. ³)		Water content (percent)		Compressive strength (psi)
						Initial	Final	Initial	Final	
100	----	----	77.7	17.1	55.5	79.5	87.2	20.0	7.0	195.2
25	----	75	105.8	14.4	42.0	108.2	112.1	18.1	1.3	541.0
25	25	50	107.8	13.9	85.9	107.5	116.6	19.6	2.6	563.5
----	25	75	111.2	13.6	9.1	108.9	114.7	17.8	0.1	76.5
----	100	----	89.9	14.2	100.3	86.1	85.4	17.8	0.4	65.6

^a Predominantly Na-montmorillonite from near Osage, Wyoming.

^b From near Bath, South Carolina.

^c Equal parts by weight of No. 50 to No. 100 and minus No. 100 fractions of sand from Clear Creek near Denver, Colorado.

stabilization have proved successful at reasonable cost. For examples of application, cost, procedures, and theoretical treatment the interested reader is referred particularly to the writings of L. Casagrande (1947, 1949), of Preece (1947), and of others (Steinfeld, 1951; Karpoff, 1953).

Unconfined Compressive Strength

Unconfined compressive strength depends upon many aspects of fabric and composition, including size, shape, and gradation of constituents; their mutual relations; size, shape, and distribution of voids; and the content of water and air. These factors control the response of earth materials to loading, including elastic and plastic adjustments, as well as shear failure.

Clay minerals are significant in response of earth materials to loading because, when dry, they develop relatively high strength through formation of adhesive and cohesive bond throughout the mass. Introduction of small proportions of clay minerals to a sand or silt greatly increases compressive strength, the maximum strength of the mixture exceeding that of either the sand or silt or the clay alone (table 12). The strength of such mixtures increases more rapidly with small additions of montmorillonite minerals in contrast to kaolinite, halloysite, or illite types, in response to the finer particle size distribution and greater dispersion of the montmorillonite minerals.

Johnson and Davidson (1947) determined the maximum unconfined compressive strength of synthetic soils containing calcium kaolinite, sodium kaolinite, and sodium bentonite, with results as follows:

Mixture	Maximum compressive strength, psi	
	At optimum moisture and maximum density	After air drying (at about 70° F) for 7 days
Calcium-kaolinite mixture	14.2	92.4
Sodium-kaolinite mixture	20.2	138.5
Sodium-bentonite mixture	70.8	952.5

The increased strength of the sodium-kaolinite mixture in contrast to the calcium-kaolinite soil, is regarded as due to greater dispersion and hence more effective distribution of the sodium clay component. The much greater fineness and dispersity of the sodium bentonite continues the same trend, the clay mineral being very

efficiently distributed as a binding agent over surfaces of granular constituents of the mixture. With drying, the kaolinite mixtures increase six to sevenfold in strength, whereas the bentonite mixture increases more than thirteenfold, a clear demonstration of the effectiveness of the compressive action of restricted moisture films in reinforcing the specimen. This type of structural control of strength of earth materials is exemplified by loess (figure 29).

In tests of sodium bentonite and bentonite in which the sodium is replaced by calcium, Samuels (1950) has demonstrated the relationship of compressive strength to moisture content. At a moisture content less than 50 percent of dry weight, sodium bentonite shows the greater strength; with moisture content between 50 percent and 75 percent, the strength is about equal; and at moisture content over 75 percent, the sodium bentonite again exhibits the greater strength. The comparatively high compressive strength of the sodium bentonite at moisture content below 50 percent probably is the result

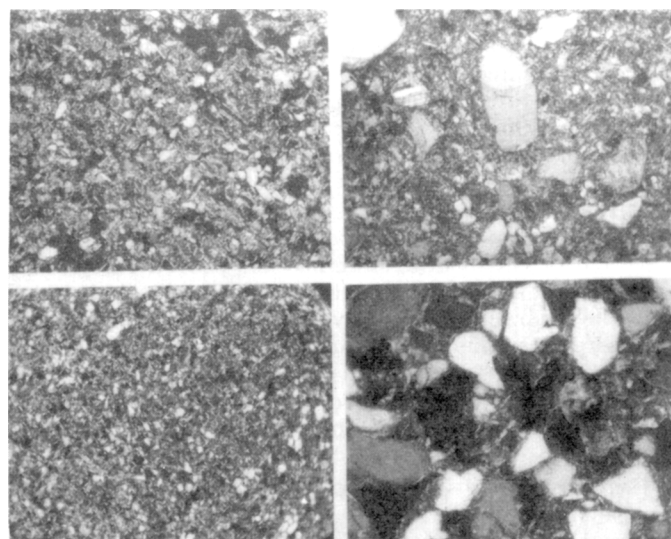


FIGURE 29. Photomicrographs of thin sections showing fabric of loess (upper left), clayey, silty, fine sand (upper right), remolded loess (lower left), and clayey sand (lower right), (load-consolidation curves a, c, e, and f in fig. 30). Nicols crossed. Magnification 60x.

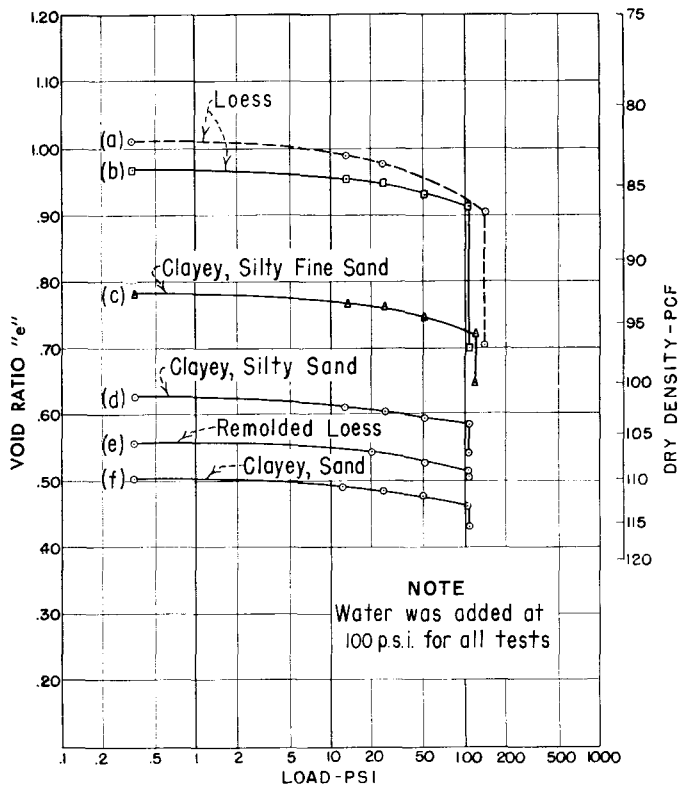


FIGURE 30. Consolidation of undisturbed loess, remolded loess, and sand with loading and wetting (cf. fig. 29).

of cohesion of the specimen produced by tension in water films. With moisture content in the range 75 to 143 percent, calcium bentonite approaches the liquid limit; whereas throughout the range of moisture contents investigated (up to 143 percent), sodium bentonite always is well below the liquid limit.

Studies by Hendricks, Nelson, and Alexander (1940) on Mississippi bentonite modified by exchange of various cations, demonstrate that calcium montmorillonite containing 36 percent of water is in equilibrium with an atmosphere at 90-percent relative humidity (table 4). Consequently, at and below this water content, the water is adsorbed and does not possess the properties of free water. This is consistent with Samuels' (1950) observation of modest compressive strength (28 psi) at water content slightly above this value (40 percent of

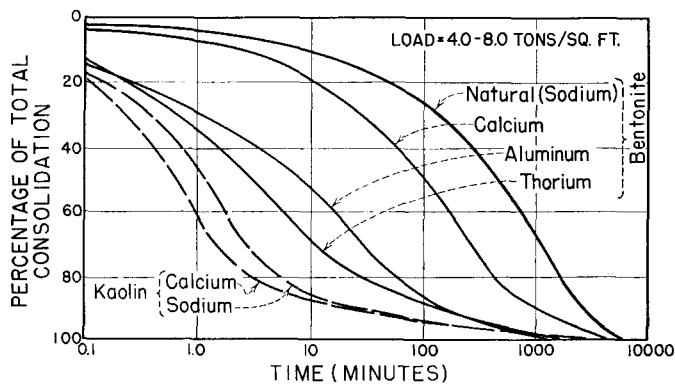


FIGURE 31. Rate of consolidation of kaolin and Wyoming bentonite modification (Samuels, 1950).

dry weight). However, sodium montmorillonite contains only 28 percent of water while in equilibrium with air at 90-percent relative humidity, and the compressive strength of the sodium-bentonite tested by Samuels is seen to decline precipitously at moisture contents just above this value (44 to about 60 percent). If the calcium bentonite were as fine as the sodium modification, compressive strength of the calcium modification would be considerably higher than that of the sodium type. With moisture content equivalent to one-fourth that of the respective liquid limits, the strength of natural bentonite is about 2 psi; whereas, that of the calcium modification is about 23 psi.

Consolidation

Consolidation of the earth materials with loading represents adjustment of the internal structure of the solid framework by rotation and sliding of the constituents and displacement of fluids (air or water or both) from the consolidating mass. For natural earth materials, consolidation as a result of structural adjustment is rarely large and is significant only in materials of very low unit weight, such as loess, volcanic ash, and organic soils. The rate and magnitude of this consolidation are increased greatly by wetting and consequent decrease in shear resistance of the soil constituents, especially if expansive clay minerals are an essential binding agent. Curves in figure 30 demonstrate the resistance of dry loess to consolidation with loads as high as 100 psi, and the great consolidation of the material with wetting while under load. The related fabrics are illustrated in figure 29. The low clay mineral content and high void ratio permit rapid drainage of pore fluids with consolidation of loess.

At higher content of clay minerals, the size of voids and their continuity are decreased so that pore pressures develop unless application of load is very slow. Consolidation is dependent mainly upon drainage of air and water from voids. Consequently, permeability is the critical control of consolidation rate. Samuels (1950) found consolidation rate of Wyoming bentonite to increase in order $Na < Ca < Al < Th$, and consolidation rate for kaolin to be $Na < Ca$ (figure 31). This sequence is the order of increasing permeability in these clays at this loading (fig. 21). As reported by Preece (1947), Cooling has demonstrated the dependence of consolidation of bentonite upon exchangeable cations. At given load up to 5.0 tons per square foot, void ratio decreases in the order sodium > calcium > thorium > aluminum. At slightly greater loads, the void ratio of all modifications is in the range of 1.3 to 1.5. The compressibility is greatest for sodium and decreases in the order sodium > calcium > aluminum > thorium, the latter two exhibiting similar rates. Similar data for beidellite soil were developed by Winterkorn and Moorman (1941), the consolidation varying as follows: sodium > calcium > magnesium > potassium > hydrogen.

With normal fabrics, earth materials containing kaolinite or illite as the predominant clay mineral consolidate less than do those containing members of the montmorillonite group. Samuels (1950) demonstrates the lesser consolidation of kaolin in contrast to bentonite (fig. 32), the change of void ratio for the sodium kaolin with loading from 0 to 8 tons per square foot

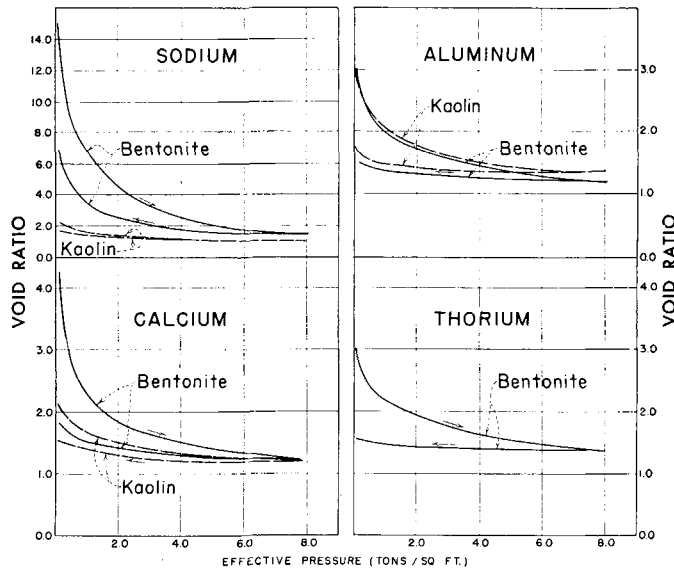


FIGURE 32. Relation of exchangeable cation to consolidation of kaolin and Wyoming bentonite (Samuels, 1950)

being only $\frac{1}{14}$ that of the sodium bentonite. The compressibility decreases in the order aluminum > hydrogen > calcium > sodium. This sequence is essentially the reverse of that exhibited by bentonite, the difference apparently arising in the distinctly different proportions of particles less than 1 micron in the cationic modifications of the two soil types. For the bentonite, the fraction smaller than 1 micron is about 90 percent for the sodium modification, 81 percent for the calcium type, and 60 percent for the aluminum type. For kaolin, the less than 1 micron fraction ranges only from 82 percent for the hydrogen and aluminum types to 88 percent for the sodium type. Thus, for the kaolin, the influence of decreasing zeta potential from sodium to aluminum is not masked by widely differing particle size. The initial void ratio increases from the sodium modification of the kaolin to the aluminum modification because of increasing random aggregation with increase in attractive forces between the particles. The high initial void ratio of the aluminum modification correlates also with the higher liquid limit (figure 19) and probably with a higher con-



FIGURE 33. Settlement of a building as the result of consolidation of montmorillonite clays in the foundation, Mexico City, Mexico. Courtesy of A. E. Cummings (1947).

tent of pore water. This point has been emphasized by Johnson and Davidson (1947).

Earth materials containing montmorillonite-type clays may consolidate or expand with addition of water, depending upon the adsorptivity of the clay mineral and its swelling potential, the original density of the material, and the load. For example, the sodium bentonite from the Mowry formation, Tiber Dam site, increased from 109 pounds per cubic foot to 112 pounds per cubic foot, with loading to 45 psi at natural moisture content. With addition of water, the unit weight decreased to 111 pounds per cubic foot as a result of hydration of the montmorillonite constituent. With decrease of load to 3.5 psi, the sample expanded to 94 pounds per cubic foot. With increments of load above 45 psi, after addition of water, comparable samples increased as much as 7.5 pounds per cubic foot during increase in load to 220 psi.

Most spectacular of settlement problems in engineering are found in Mexico City, Mexico, which is underlain by layers of montmorillonite clay, tuff, gravel, sand, silty clay, and boulder clay. Zeevaert (1947, 1949) reports progressive settlement of the area of the city at an average rate of 5 inches per year. Many large buildings have settled as much as 10 feet since construction (fig. 33), as a result of compression of zones of soft to stiff clay, which are as much as 130 feet thick. Typical water content of the clays ranges from 500 to 700 percent of dry weight, and void ratio is as high as 14.0. Rate of settlement has increased since ancient times not only because of loading incidental to growth of the city but also because of drainage of groundwater. Removal of groundwater increases loading of deep-lying strata by loss of buoyancy of zones emerging above the water table and increases the ease of drainage of loaded clay layers. Successful protective measures so far depend upon design of the foundation, compensation for loading by variable excavation and use of piles to equalize settlement for each structure (Zeevaert, 1947; Cummings, 1947).

Loess deposits also are subject to great consolidation although their granular fabric is very different from that of montmorillonite clays and shales. Their unexpectedly high compressive strength while dry is readily lost with wetting because of breakdown of the argillie intergranular braces of montmorillonite. Under the load of a 50-foot embankment at Trenton Dam, Nebraska, wetted loess consolidated a total of 1.54 feet during the first 2 months following completion of construction.

Swelling with Hydration

Adsorption of water by clays leads to expansion or swelling. Its magnitude varies widely, depending upon the kind and amount of clay minerals present, their exchangeable ions, electrolyte content of the aqueous phase, particle size distribution, void size and distribution, the internal structure, water content, superimposed load and other factors. Two mechanisms are involved: (1) a relaxation of effective compressive stress related to enlargement of capillary films and (2) osmotic imbibition of water by expanding lattice clays.

Expansion of clays as the result of enlargement of capillary films is essentially the reverse of drying shrinkage, although the original volume at given water content

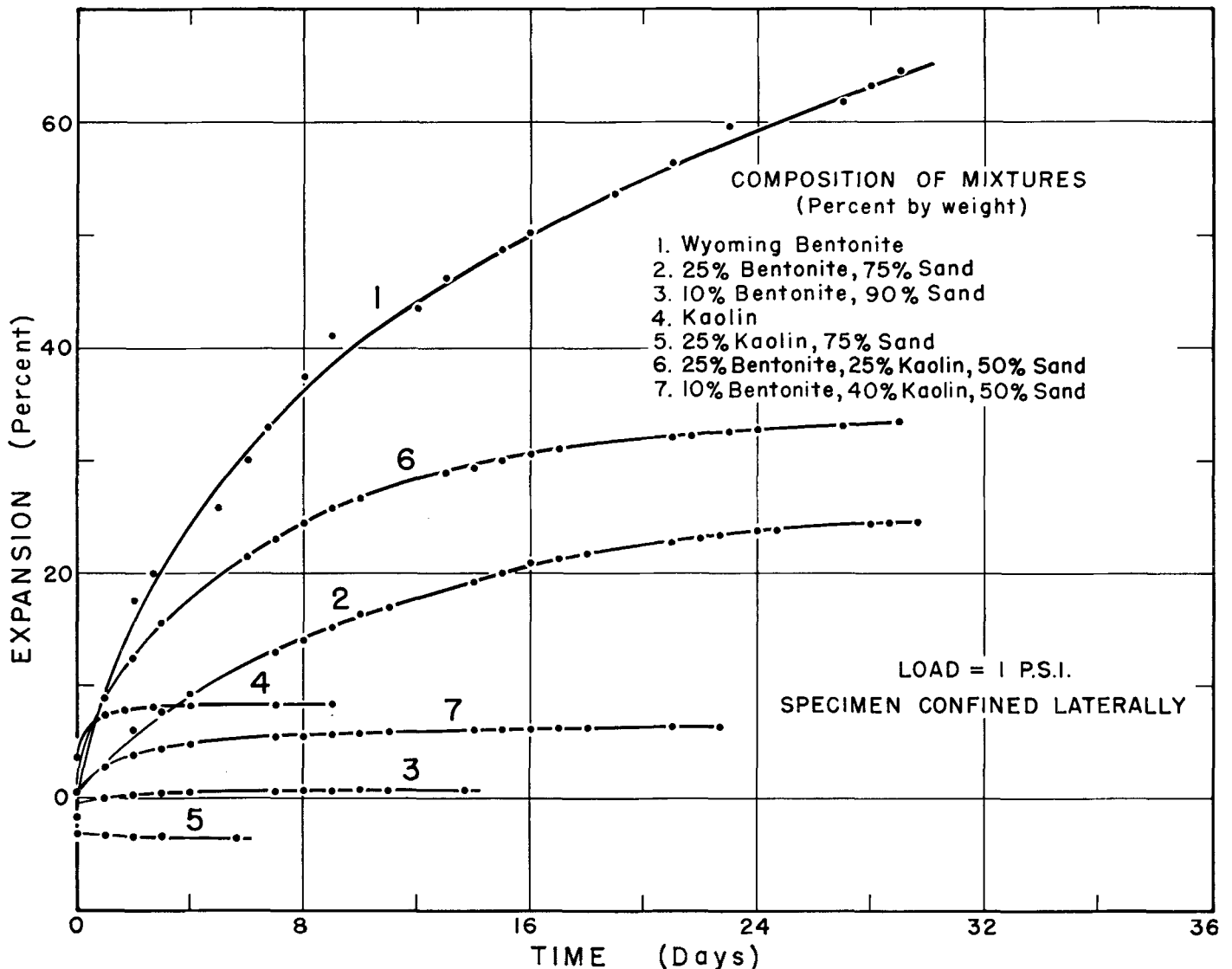


FIGURE 34. Volume change of bentonite-kaolin-sand mixtures with wetting.

usually is not recovered because of permanent changes in internal texture and structure during the shrinkage process. In tests of calcium and sodium kaolin—synthetic soil mixtures at optimum moisture content and maximum density, Johnson and Davidson (1947) observed water absorption of 1.5 percent and 1.7 percent, respectively, during a 4-day soaking period with resulting linear expansion of 0.12 percent and 0.085 percent, respectively. Under identical conditions Wyoming bentonite expanded 0.94 percent while sorbing 2.4 percent by weight of water.

Tests of synthetic mixtures of Wyoming bentonite-kaolin-sand, reveal the expansive potential of sodium bentonite. Under a load of 1 pound per square inch, with lateral restraint, Wyoming bentonite expanded 66 percent during 33 days of sorption of water and was apparently still expanding at the conclusion of the test (fig. 34). A mixture containing 25 percent sodium bentonite expanded 0.94 percent while sorbing 2.4 percent under the same conditions. In a test of a mixture of 25 percent bentonite, 25 percent kaolin, and 50 percent

fine sand, the specimen expanded 33.5 percent. The greater expansion of the latter mixture in contrast to the first mixture arises in a more dense fabric and hence greater effectiveness of given expansion of the bentonite constituent. The data demonstrate similar relationships for the mixture containing 10 percent bentonite.

With sorption of water by expanding lattice clay minerals, such as members of the montmorillonite group and some types of illite, expansion as a result of enlargement of water films is supplemented by expansion as a consequence of adsorption of water along the 001 inter-layer space and upon edges of broken crystals. The capillary compressive forces increase inversely as the radius of the capillary decreases. Consequently, the expectable compressive forces are greatest for finest-grained materials. Therefore, the greatest expansion is expected from montmorillonite-type clays, not only because of expanding lattice but also because of relief from higher compressive stresses.

With sifting of materials containing montmorillonite into polar liquids, expansion takes place, the magnitude

Table 13. Free swell data on clay and clay-like minerals.

Clay minerals	Location	Free swell ^a in water (percent)
Ca-Montmorillonite	Forest, Mississippi	145
	Osage, Wyoming ^b	125
	Willow Creek Dam, Colorado	95
	Davis Dam, Arizona	45-85
Na-Montmorillonite	Osage, Wyoming	1400-1600
Na-Hectorite	Hector, California	1600-2000
Ca-Beidellite	Friant-Kern Canal, California	80
	Wellton-Mohawk Canal, Arizona	110
Na-Beidellite	Wellton-Mohawk Canal, Arizona	310
K-Illite	Fithian, Illinois	115-120
	Morris, Illinois	60
	Tazewell, Virginia	15
Mixed clays ^c	Grand Coulee Dam, Washington	120-140
Kaolinite	Mesa Alta, New Mexico	5
	Macon, Georgia ^d	60
	Langley, North Carolina	20
Halloysite	Santa Rita, New Mexico	70
Muscovite	North Carolina	25
Vermiculite	Libby, Montana	50
Pyrophyllite	Staley, North Carolina	40
Talc	Providence, Rhode Island	30
Serpentine	Warren County, New York	10

^a Test based upon swell in water of 10 cc of crushed material passing No. 30 screen and retained on No. 50 screen.
^b Ca-montmorillonite prepared in laboratory from Na-montmorillonite (bentonite).
^c Contain montmorillonite, illite, jeffersite, and chlorite.
^d Contains small amount of montmorillonite.

of which is dependent upon the amount of clay present, the composition of the clay, the presence or absence of cementing materials, the exchangeable cations, electrolyte content of the liquid, the molecular size and structure of the liquid, and the interaction of molecular forces of the liquid and solid. For the clay minerals, the free swell in water is in the series montmorillonite > illite > halloysite > kaolinite (table 13). The free swell of beidellite is distinctly less than that of montmorillonite and commonly equal to or greater than that of illite. For materials such as pyrophyllite, talc, and muscovite, the reported free-swell values are probably too high, for the platy shape of the particle prevents efficient packing of the sample.

With clays of montmorillonite type, the swelling decreases greatly with exchange of sodium for other univalent ions or for divalent or trivalent ions. For Wyoming bentonite, Baver and Winterkorn (1935) observed decreased swelling in the sequence: sodium > lithium > potassium > calcium > magnesium > hydrogen. For beidellite soil, the sequence was found to be lithium > sodium > calcium > barium > hydrogen > potassium, the latter demonstrating binding of the lattice by potassium in the 001 interlayer space of beidellite.

A series of free-swell tests were performed using Na-montmorillonite (Wyoming bentonite) in various liquids (table 8). No definite correlation between the dielectric constant and the degree of swelling was

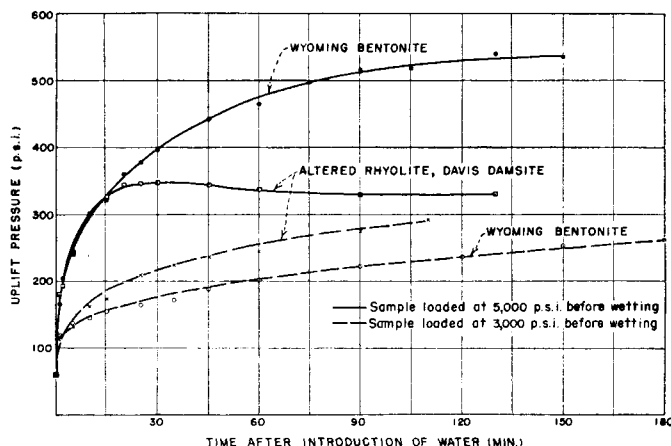


FIGURE 35. Uplift pressure developed by hydration of Wyoming bentonite and an altered rhyolite containing montmorillonite, after initial loading (after Holland, personal communication).

observed, although the swelling tended to increase with an increase in the dielectric constant. The particles of montmorillonite remained intact in most of the liquids. Very slight dispersion occurred in carbon tetrachloride, diethyl ether, acetic acid, acetone, and glycerol. Disintegration was almost complete in water and formamide. Examination of table 8 indicates that the dielectric constant of the liquid will not account alone for the variations in swelling. Of significance also are the dimensions of the liquid molecules; the ability of the liquid molecules to build layers between the packets of the clay mineral crystals; and characteristic molecular forces, such as distortion polarization and orientation polarization, both of which influence the dipole moment of the molecule.

In a moist atmosphere, montmorillonite soils adsorb water, and the crystals swell as the result of hydration of certain exchangeable cations and development of layers of water molecules in the 001 interlayer space. Hendricks, Nelson, and Alexander (1940) found the relative adsorption of a Mississippi montmorillonite clay to be as follows (table 4):

Relative humidity, 5 percent—magnesium > calcium > lithium > strontium > barium > hydrogen > sodium > cesium > potassium

Relative humidity, 40 percent—calcium > strontium > magnesium > hydrogen > lithium > barium > sodium > potassium > cesium

Relative humidity, 90 percent—calcium > hydrogen > lithium > strontium > magnesium > barium > sodium > potassium > cesium

The avidity for water of magnesium, calcium, lithium, strontium, and barium clays at very low humidity is evident and is correlative with hydration of the exchangeable cations. The work demonstrated that sodium, potassium, cesium, and hydrogen ions are not hydrated. With increase of relative humidity from 5 percent to 90 percent, the adsorption by the modifications containing nonhydrating cations increases eightfold to thirteenfold, whereas the adsorption by modifications containing hydrating ions increases only fourfold to sevenfold. The increase in adsorbed water correlates with an increase in the "c" dimension from a fraction of an Ångström unit for the potassium modification to 5.7 Ångströms for the sodium type, the latter corresponding to an increase of 58 percent in the volume of the

unit cell. At saturation without loading, the "c" dimension exceeds 30 Angstroms and dispersion of the sodium to individual packets follows with agitation. For hydrogen and calcium modifications, the "c" dimension does not greatly exceed 20 Angstroms, even in a saturated atmosphere.

With immersion of sodium montmorillonite in distilled water, complete dispersion does not occur in the absence of agitation. Rather, a maximum swelling occurs when equilibrium is achieved between the attractive forces between the plates of the clay minerals and the osmotic pressure developed in the intervening water layer. With agitation, separation of the individual platelets of the montmorillonite takes place, and a dispersed sol is developed.

The change in bulk volume taking place in earth materials with wetting and drying is influenced considerably by original density, the shrinkage increasing and expansion decreasing with decreasing original density, other factors of texture and structure and composition being held constant. For example, in tests of the Porterville clays near Porterville, California, owing its activity to heidellite, total volume increase from a dry to saturated condition ranged from 2.0 percent to 21.6 percent, with variation in dry density from 74.1 pounds per cubic foot to 96.5 pounds per cubic foot. Moreover, the pressure developed in maintaining the volume constant ranges from 5.1 psi to 146.6 psi in the same series.

If samples of expansive clays are subjected to initial loads of high magnitude, tremendous swelling pressures are developed. Unpublished data obtained by W. Y. Holland (fig. 35), in the Bureau of Reclamation laboratories during design studies for Davis Dam, Arizona-Nevada, demonstrate pressures as high as 540 psi developed in Wyoming bentonite originally compressed at 5,000 psi and subsequently wetted following a period of unloading sufficient to permit relaxation of the specimen. An altered rhyolite containing high proportions of montmorillonite developed pressures in excess of 330 psi under the same conditions. Initial loading of the clays at 3,000 psi instead of 5,000 psi produced lesser swelling pressures.

Consolidometer tests of undisturbed clays and shales containing illite or montmorillonite-type minerals in the clay fraction indicate potential hydration pressures as high as 15 tons per square foot (table 14). Expansive clays and shales have caused significant distress in engineering structures in many parts of western United States and also in other countries, notably South Africa, Palestine, Burma, Australia, and India (Wooltorton, 1950; Jennings, 1950; Holtz and Gibbs, 1953; Felt, 1950). Distress arises with introduction of water to the foundation materials after construction. Water can be introduced by hydraulic flow, capillarity, vapor transfer in response to gradient in relative humidity, and thermosmosis. The action commonly follows seasonal cycles of wetting and desiccation (Wooltorton, 1950). Criteria for recognizing expansive soils from soil mechanics properties are described by Holtz and Gibbs (1953).

Spectacular distress is widespread in Texas in the vicinity of Austin and Dallas where the Eagle Ford shale and Taylor marl underlie the surface (Felt, 1950; Giesecke, 1922; Simpson, 1939; Dawson, 1953). The Eagle Ford shale contains about 35 percent of clay minerals including calcium-montmorillonite, illite, and kao-

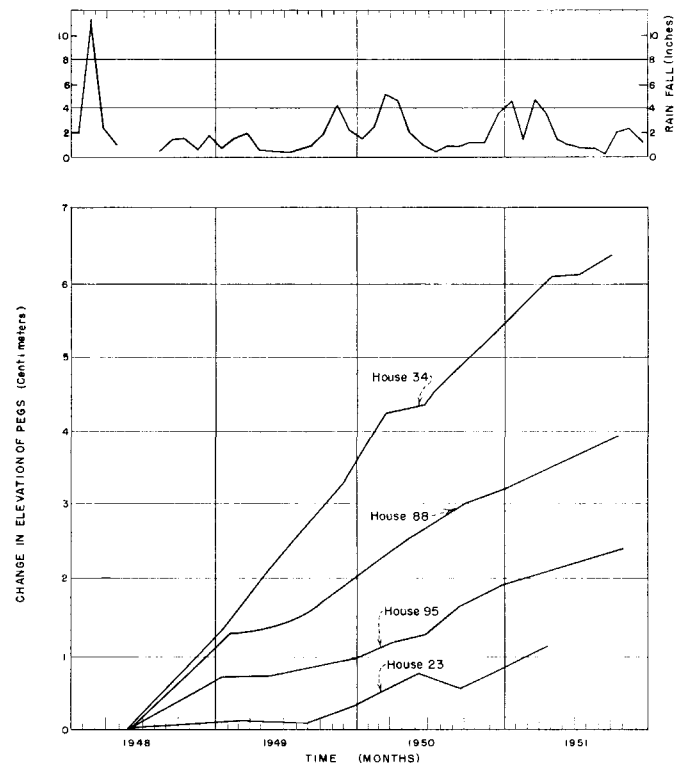


FIGURE 36. Uplift of buildings by expansion of illite clay as the result of hydration, Pretoria, South Africa (J. E. Jennings, 1950, with additions).

linite (fig. 14). A very high swelling pressure arises in the combination of the swelling clay and a compact fabric which develops full effectiveness of the expansion of the montmorillonite constituent. Drying as the result of exposure and growth of vegetation extends to depths as great as 15 feet. Dawson (1953) reports differential uplift as much as 2.4 inches of structures with resulting cracking of walls and foundations and misalignment of doors and windows and other distress. Satisfactory foundations thus far require the founding upon piles penetrating to stable material below the weathered layer.

Similar distress related to a calcium-illite soil are reported by Jennings (1950) in Pretoria and adjacent areas of South Africa. Uplifts as much as 6.4 centimeters in about 3 years are reported for light structures, the uplift relating only generally to incidence of rainfall (fig. 36) because of extraneous supply of water to the foundation by drain pipes broken as the result of movement of the soil and buildings. Uplift typically is a doming action with maximum deflection occurring in the center of the building. Shattered slickensided clay affected by drying and atmospheric temperature variations extends to depths as great as 27 feet. In addition to hydraulic flow the increase of moisture content results from vapor or capillary transfer, possibly in response to reduced temperature in the ground beneath the building in contrast to the temperature of the surrounding ground at equivalent depth. Jennings reports a temperature difference of 5° F. The uplift probably is the result of both expansion of clay minerals and relief of capillary stresses.

The largest reported uplift resulting from swelling of expansive clays or shales is described by Mielenz and

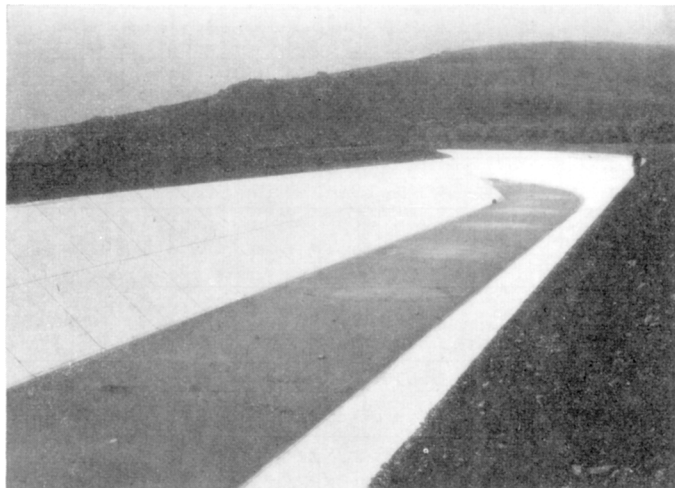


FIGURE 37. Displacements of concrete lining by swelling of beidellite clay in the subgrade. Friant-Kern Canal, near Lindsay, California.

Okeson (1946) in an investigation of foundation displacements on the Malheur River Siphon near Ontario, Oregon. Seepage of irrigation water and run-off into parts of the foundation resulted in progressive but irregular uplift which locally exceeded 1 foot within 3 years after construction. The sodium bentonites of the Idaho formation developed uplift pressures of 7,200 pounds per square foot and at one point lifted not only the siphon but 38 feet of alluvial sand and silt as well. Where saturated prior to construction, the foundation yielded to small consolidation.

Most susceptible to uplift and displacement are light slabs such as highway pavements, canal linings, spillways, and basement floors (figs. 37 and 38). Distress along the Friant-Kern Canal involves the Porterville clay. Heaving and cracking involving side slopes only occurred along the Delta-Mendota Canal, California, in sections traversing the expansive clays of the Tulare formation. Differential uplift of 3 to 7 inches for concrete slabs are common in many parts of the western United States, and are reported locally to exceed 12 inches in areas of Texas underlain by the Taylor marl (Felt, 1950 and 1953).



FIGURE 38. Cracking and bulging of concrete lining by swelling of beidellite clay in the subgrade. Friant-Kern Canal, near Lindsay, California.

Remedial measures are difficult and expensive in most situations. Three approaches are possible: (1) preventing increase in moisture content beneath the structure by moisture barriers, drains, and vents; (2) prewetting to equalize moisture content and reduce later expansion of foundation materials; (3) excavation of the expansive earth materials and their replacement by stable materials in sufficient depth to minimize uplift by the remaining foundation materials and (4) chemical treatment to prevent penetration of water into the foundation or to reduce swelling characteristics. Moisture barriers and drains are feasible if the offending waters penetrate from the surface or move in well-defined subsurface channels. Unfortunately, however, many examples of distress relate to vapor or capillary transfer vertically or laterally from zones of higher water content. Control of such moisture movement frequently is economically unfeasible so that appropriate measures require either special design or expedient repair.

As a result of extensive studies of differential uplift of highway pavements overlying the Taylor marl near Austin and Dallas, Texas, Felt (1950, 1953) concluded that severe heaving can be prevented by prewetting by ponding areas underlain by dry expansive soils. It was found necessary to continue the ponding at a given site for 1 month or longer. During ponding the moisture content of subgrade materials increased 6 percentage points on the average (from 13 to 19 percent) in the top 7.5 feet. Satisfactory wetting of subgrade materials could not be achieved by introduction of water at 4-inch-diameter drill holes on 5- or 6-foot centers. Minor heaving was found to be controlled by early clearing of vegetation from the right-of-way and proper control of moisture content and density of subgrade materials during grading operations.

Overexcavation and replacement of expanding clays with stable material is effective only if the uplift pressure is so small that loading sufficient to maintain uplift within design limits can be accomplished with moving of a reasonable amount of earth. This is not true for many structures where uplift pressures of several tons per square foot occur in the foundation materials. However, uplift pressure is reduced greatly with slight expansion of clays and shale; and moreover, expansion is reduced greatly by even slight increase in loading (Holtz and Gibbs, 1953). Experience with foundation design of structures located upon expansive clays and shales is described by Woollorton (1950), by Jennings (1950), and by Holtz and Gibbs (1953).

Dramatic results have been obtained in laboratory tests by chemical treatment of expansive soils. Unfortunately, introduction and distribution of significant quantities of treating agents into the formation in place particularly the relatively impermeable expansive clays and shales has so far proved impossible. Davidson (1949; and Glab, 1949) has reduced swelling pressure of the montmorillonite soil by factors ranging from 4 to 18 by introduction of 1.29 to 9.66 percent of Armac T, a water-soluble cationic amine acetate. In other work, calcium hydroxide admixed with montmorillonite and beidellite clays has proved effective in greatly reducing hydration expansion. Goldberg and Klein (1953) demonstrate reduction of swelling pressure from about 9 to about 5 psi by admixture of 8 percent of calcium hydroxide with sodium bentonite, and from about 7 to 1.5

psi for the beidellite-containing Porterville clay (fig. 39). Similar effects are attained by the introduction of divalent or trivalent inorganic cations to expansive clay in which sodium is the dominant exchangeable cation. Laws and Page (1946) achieved favorable results in treatment of kaolinite and illite soils with sodium silicates, but the swelling of montmorillonite was increased. Introduction of stabilizing cations into formations in place could be accomplished to a degree either by hydraulic injection or by electrochemical treatment. However, successful treatment of significant masses of clay or shale in place has yet to be demonstrated.

Drying Shrinkage

Drying of originally moist clays leads to a diminution of volume as a result of (1) decreasing size of the unit cell of expanding lattice minerals (if present), and (2) increasing compressive stresses originating in capillary forces and adsorbed water films. Clays of the kaolinite group, and to a lesser extent the illite group, show little or no volume change of individual crystals and essentially all of the drying shrinkage arises in compressive capillary forces and externally adsorbed water films. Under ideal conditions, the capillary forces are inversely proportional to the radius of the channelways permeating the clay. Since the size of the smallest capillary intimately penetrating the clay will be on the same order of size as the finest particles and usually will be smaller, the compressive capillary forces increase rapidly with decreasing particle size.

In tests of synthetic calcium and sodium kaolinite soils Johnson and Davidson (1947) observed higher

shrinkage limit and shrinkage ratio* for the sodium modification, although the difference was not pronounced. The higher shrinkage limit seemingly relates to restraint of shrinkage of the cohesive sodium kaolinite by the sand and silt and a consequent cessation of shrinkage at a higher water content than that attained by shrinkage of the more granular calcium-kaolinite soil. Shrinkage limit of the sodium-bentonite mixture is higher and the shrinkage ratio lower than for the kaolinite mixtures, again probably because of restraint of shrinkage by the sand and silt.

In drying of clays containing expanding lattice-type minerals, shrinkage is identified with both individual clay crystals and the mass as a whole. Both effects are more pronounced in montmorillonite-type clays than in those of kaolinite type or illite, because of the typically greater fineness, thicker adsorbed water film on the periphery of crystals, and the expulsion during drying of water originally held along the 001 spacing. Values of shrinkage limit for highly expansive soils are difficult to reproduce because of irregular fracturing of the materials. Winterkorn and Moorman (1941) report a range of shrinkage limit of a beidellite soil from 19.4 to 11.8 percent in the following order: potassium > aluminum > hydrogen > magnesium = calcium > sodium. Shrinkage ratio varied from 2.08 to 1.80 in the order sodium > magnesium > calcium > aluminum > hydrogen > potassium. In tests of modifications of Wyoming bentonite, Samuels (1950) found the shrinkage limit to be as follows: calcium > sodium > aluminum for specimens containing dry volumes of 56.5, 54.7, and 53.8 cc per hundred grams dry weight.

Study of shrinkage of synthetic mixtures of sodium bentonite and kaolinite with fine sand reveals significant influences of fabric upon volume change with drying (tables 10 and 15). In the bentonite-sand mixtures, development of grain-to-grain contact prevents excessive shrinkage of mixtures containing less than 25 percent of bentonite. This is most pronounced in the mixture containing 10 percent of bentonite, in which optimum distribution of the montmorillonite as grain coatings stabilizes an open fabric at the shrinkage limit. With 50 percent or more of bentonite, shrinkage of the mixture is controlled by the properties of the bentonite. With 25-percent bentonite, the shrinkage limit is 24.9 percent, whereas this limit is only 6.9 percent for the mixture containing 50-percent bentonite. A comparable change occurs in shrinkage ratio. Similar results are obtained in bentonite-kaolin-sand mixtures containing 25 to 40 percent of bentonite.

In similar tests of kaolin-sand mixtures, the shrinkage limit of kaolin alone is high (25.3 percent), but decreases markedly with addition of sand. Sand decreases the shrinkage limit by substitution of only slightly porous grains for highly porous volumes of kaolin. With the existence of an endoskeleton, as in mixtures containing 75 percent or more of sand, the volume of voids at the shrinkage limit increases slightly through restraint of shrinkage by the granular fabric, and the shrinkage ratio decreases progressively because the small propor-

* Shrinkage limit is the moisture content (percent of dry weight) at which a reduction in moisture content will not cause a decrease in volume of the mass, but at which an increase in moisture content will cause an increase in volume of the mass. Shrinkage ratio is the bulk specific gravity of the dried soil used in determining the shrinkage limit (Allen, 1942).

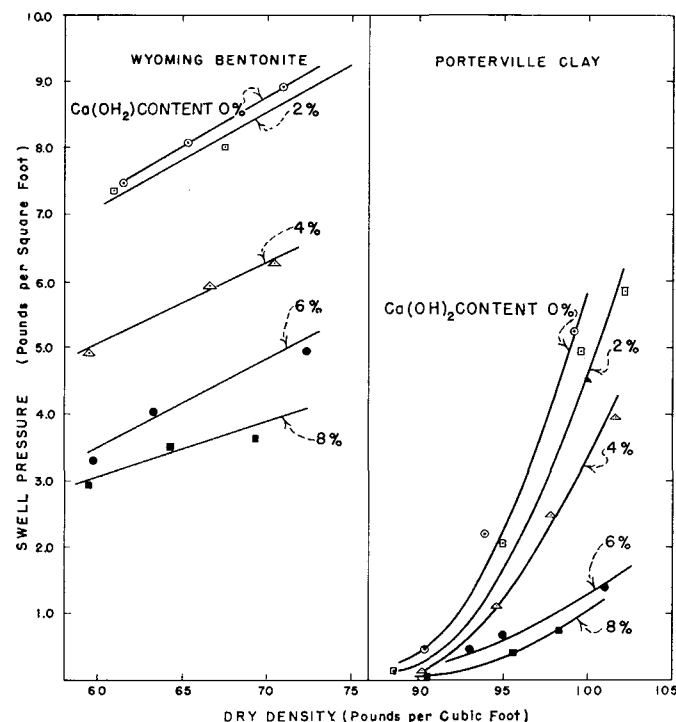


FIGURE 39. Effect of calcium hydroxide on swelling pressure of Wyoming bentonite and Porterville clay by hydration (Goldberg and Klein, 1953).

Table 14. Uplift pressure observed on various expansive clay and shales.

Clay mineral	Petrographic type	Geologic formation and locality	Maximum observed uplift pressure ^a (tons/sq ft)
Na-Montmorillonite	Claystone	Idaho formation, near Ontario, Oregon	3.6
	Shale	Colorado shale, near Shelby, Montana	2.0
	Clay	Alluvium, near Yuma, Arizona	11.0
Mixed cation montmorillonite	Shale	Eagle Ford shale, near Dallas, Texas	15.0 ^b
	Clay	Porterville clay, near Porterville, California	10.5
	Clay	Alluvium, near Patterson, California	8.0
	Clay	Alluvium, near Antioch, California	4.9
Ca-Illite	Clay	Alluvium, Pretoria, South Africa	5.0 ^c

^a Load required to prevent vertical expansion of laterally confined specimen.

^b From Dawson (1953, in press).

^c From Jennings (1950).

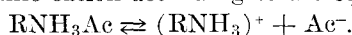
tions of kaolin do not fill the intergranular spaces. Coatings on the grains are poorly developed.

Voids content at the shrinkage limit of bentonite-kaolin-sand mixtures increases progressively, although slightly, with decrease of bentonite content from 47.5 to 40 percent. The values obtained in this range are similar to the shrinkage limit of bentonite alone because of separation of the granular elements of the fabric.

With bentonite content of 25 percent (kaolin constituting 25 percent and sand 50 percent by weight of the mixture) shrinkage limit is high (24.4 percent), as the result of stabilization of the fabric by grain coatings composed of montmorillonite, and the presence of intermixed montmorillonite and kaolinite in intergranular spaces. Although the shrinkage limit of this mixture almost equals that of the bentonite-sand mixture containing 25 percent of bentonite, the shrinkage ratio is much higher. This relationship demonstrates the restraint of internal shrinkage cracking by mixed expansive and nonexpansive clays in the fine fractions of a sandy soil. Such a mixture is capable of excessive expansion with rehydration (fig. 34) and development of swelling pressure.

With kaolin content above 25 percent and bentonite content less than 25 percent, both shrinkage ratio and shrinkage limit are reduced. This relationship indicates some restraint of volume shrinkage by the sand and coarse fractions of the kaolin, but it shows as well the development of internal cracking in the soil mass. Such a mixture is capable of but limited expansion with rehydration (fig. 34).

Shrinkage of earth materials can be altered by treatment with organic surface-active agents. In tests of a kaolinite soil, Davidson and Glab (1949) decreased shrinkage by admixture of a fatty acid amine acetate, whose dissociation in water leads to release of a large organic cation according to the equation



With addition of the agent in amounts up to 3 percent (by dry weight of the soil), shrinkage limit increased progressively from 14.9 to 25.1 percent, and shrinkage ratio simultaneously decreased from 1.77 to 1.46.

In similar tests of a montmorillonite soil, Davidson (1949) produced a decrease in shrinkage by use of

six water-soluble cationic organic compounds.* Rosin Amine-D Acetate and Ammonyx T were particularly effective, the shrinkage limit being increased progressively from 6.0 to about 37 percent and 28 percent by addition of 16.11 percent and 13.08 percent by dry weight of the soil of the two compounds, respectively.

Shrinkage is critically important in the development of properties of earth materials and in engineering performance. Excessive shrinkage accompanying drying of cohesive earth materials containing expanding lattice clay minerals leads to the development of crumbs or aggregations, and thus gives rise to fine and medium argillic fabrics. These are exemplified by the beidellite-containing Porterville clay (figs. 6 and 11). Drying in expansive clays can occur to depths in excess of 25 feet. Woollorton (1950) has summarized the role of drying shrinkage in control of fabric and permeability of expansive montmorillonitic and illitic soils of Burma, and the associated distress of engineering structures.

Cracking as the result of drying shrinkage of earth materials leads to disruption of structural integrity of the mass (fig. 40). Drying is accelerated by the accompanying increase of exposed surface, and water easily penetrating to depths following precipitation results in excessive slaking and expansion in the formation in place. Such cyclical volume change accelerates creep of superficial deposits on slopes. Moreover, loss of cohesion within the mass can aggravate development of landslides, particularly following long periods of drought (Ladd, 1934). Slides of this type have been observed in canal sections lined with expansive clays exhibiting high drying shrinkage. Drying cracks extending to depths of several feet commonly become partially filled with sand and silt from the surface. With expansion of the clay, during, rehydration, the jacking action can be destructive to adjacent retaining walls or foundations.

Shrinkage of soils adjacent to structures decreases support, as, for example, under highway pavement or canal linings. Certain montmorillonite "adobe" soils in central California recede as much as 2.5 inches from adjacent concrete during dry weather. As a result, differential settlement of the structures is a common phe-

* Armac T, Armac 18D, Armac 12D, Rosin Amine-D Acetate, Amine 220, and Ammonyx T. All yield monovalent cations on dissolution in water, except Amine 220 whose cations are divalent.

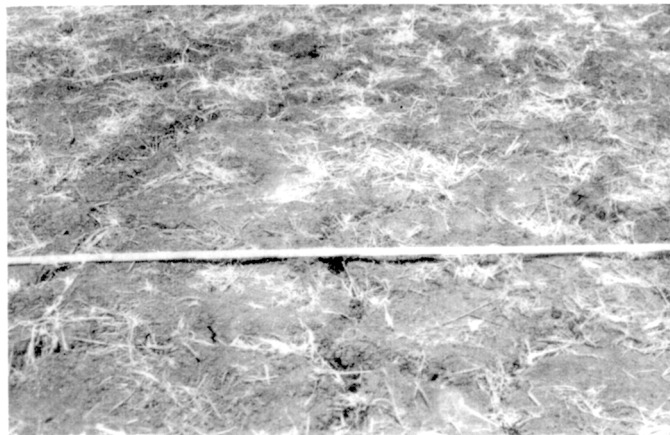


FIGURE 40. Shrinkage cracks in the exposed surface of the Porterville clay, near Lindsay, California. The cracks are easily visible to depths of more than two and a half feet.

nomenon. Resulting cracks permit excessive penetration of water from the surface into foundation or subgrade materials. Moreover, the linear shrinkage can cause cracking of asphalt membranes designed to prevent seepage into subgrades. For example, shrinkage of the montmorillonite-containing Denver and Laramie formations, near Denver, Colorado, necessitates repeated resealing of edges of pavements to maintain adequate surface drainage. Excessive shrinkage of clays destroys many types of protective coatings on buried pipe installations.

Syneresis

Syneresis is the spontaneous separation of an initially homogeneous colloidal system into two phases—a coherent gel and a liquid (Heller, 1937). Shrinkage of the gel phase is equal to the volume of the liquid expelled (Ferguson and Applebey, 1930). Syneresis is reversible unless coagulation of the colloidal phase proceeds too far (Heller, 1937). Three varieties of syneresis were recognized by Heller (1937): (1) Syneresis by reduction in swelling as the result of dehydration of hydrophilic particles; (2) syneresis by agitation through development of gels from dense geloids settled by gravity or centrifuging, or through formation of an emulsion of geloids; and (3) syneresis by contraction.

The phenomenon is best developed in concentrated and strong gels and is pronounced in fine-grained sediments, such as chalks, marls, and colloidal clays, especially those of sodium montmorillonite type (Jungst, 1934; Braune and Richter, 1949). Shrinkage as the result of syneresis is accompanied by cracking, distortion, and hardening of the clay-water system. The process gives rise to an appearance suggestive of drying shrinkage. In laboratory experiments Jungst (1934) reports fissuring to depths up to 3 cm in sediments 12 cm thick, the cracks being as much as 3 mm wide at the surface. The sediments were continuously covered with water during the test. He also observed numerous special details of the secondary fabric in clays, including mounds, pits, cones, grooves, and spirals, which might easily be mistaken for features of sedimentation or fossils in geologic formations. Considerable research has been performed in study of syneresis in silica gel, agar-agar, and dye stuffs (Heller, 1937; Ferguson and Applebey, 1930; Plank and Drake, 1947; Rossi and Marescotti, 1936; Bonnell, 1932; 1933; 1933a; Gapon, 1930), but

little has been accomplished in elucidating this property in clays and shales.

The rate and degree of development of syneresis depends upon the original concentration of the colloidal phase, the temperature, the acidity or alkalinity, and the concentration of electrolytes (Ferguson and Applebey, 1930; Jungst, 1934; Braune and Richter, 1949; Plank and Drake, 1947; Rossi and Marescotti, 1936; Bonnell, 1932; 1933; 1933a; Gapon, 1930). In clays, fabric is important. Jungst (1934) found that an intermediate content of colloidal clay and electrolyte is conducive to most rapid and pronounced syneresis. An addition of sand to colloidal clay increased syneresis, a maximum being attained with 30 percent by weight. No shrinkage or expulsion of water was evident in clay-sand mixtures containing 80 percent or more of sand.

Syneresis is a condensation of gels which, in clays, apparently demonstrates the drawing together of hydrated colloidal particles of clay minerals under the influence of van der Waals' forces and electrostatic attraction, with partial destruction of adsorbed water layers (Talmud and Suchovolskaya, 1931). In a clay-water mixture of low electrolyte content, fragments of crystals of clay minerals are surrounded by a diffuse cloud of cations held by the net negative charge on the lattice and by anions (especially OH^-) fixed at broken prism edges of the lattice. Water molecules are held in this zone in such volume as to cause osmotic equilibrium between it and the surrounding free water solution. For weakly held monovalent cations such as Na^+ , the diffuse cloud of adsorbed ions is thick and the residual negative charge of the system is high. With more tightly bonded monovalent cations, such as H^+ and K^+ , especially with illite and beidellite after drying, and with divalent and trivalent ions, the diffuse cloud of ions and water molecules is less thick and the negative charge of the clay mineral is more nearly balanced by the charge of the cationic counterions. Similarly, addition of electrolytes to the clay-water system will extract water from the diffuse cloud of cations and a new osmotic equilibrium will be established with a water hull of lesser volume and thickness.

Although a net negative charge remains upon the entire hydrated clay particle (including both clay solid and counterions), the peripheral position of the cations causes a repulsive effect in the immediate vicinity of the periphery of the adsorbed water hull toward cations in the free water or toward the cations similarly associated with other particles of clay in the clay-water system. In a suspension of Na-montmorillonite and distilled water, the repulsive forces at this peripheral position in the adsorbed water hull are sufficiently great to prevent coagulation.

However, in clay-water systems of more concentrated type, proximity of the particles gives rise to van der Waals' forces of significant magnitude, which tend to draw the particles together in spite of the repulsion of the diffuse cationic hulls of adjacent particles. Moreover, according to Hauser and Le Beau (1946) the free water contains a net excess of positive charge which represents cations in equilibrium with cations within the adsorbed water hull upon the clay particles. They postulate that these "interact and form groups of ions which have a greater charge associated with them. Thus,

Table 15. Shrinkage and expansion of synthetic soils with loss and gain of water content.

Mixture (percent) by weight			Drying shrinkage					Expansion with wetting					Total volume change ^d (percent)
Wyoming bentonite ^a	Kaolin ^b	Sand ^c	Density (lbs./ft. ³)		Water content (percent)		Shrinkage (percent)	Density (lbs./ft. ³)		Water content (percent)		Expansion (percent)	
			Initial	Final	Initial	Final		Initial	Final	Initial	Final		
100			70.2		38.1		29.6	72.0	38.9	43.4	99.5	66.0	95.6
25		75	107.0	112.9	19.7	1.9	5.4	107.0	85.8	20.0	35.0	24.7	30.1
10		90	108.3	111.3	19.6	0.8	2.3	107.8	107.1	20.5	20.8	0.7	3.0
25	25	50	105.5	117.9	20.1	2.3	11.5	104.7	78.4	20.4	40.1	33.5	45.0
10	40	50	106.7	123.1	19.5	0.6	12.9	106.7	100.4	20.0	24.3	6.3	19.2
	25	75	108.0	121.7	19.3	0.0	11.2	109.2	113.2	19.4	17.0	-3.5	7.7
	100		97.8	97.5	19.3	0.0	-0.8	96.4	89.2	19.3	31.0	8.1	7.3

^a Predominantly Na-montmorillonite from near Osage, Wyoming.

^b From near Bath, South Carolina.

^c Equal parts by weight of No. 50 to No. 100 and minus No. 100 fractions of sand from Clear Creek near Denver, Colorado.

^d Sum of shrinkage and expansion.

these groups may act as nuclei about which the colloidal particles may condense, owing to forces of an electrical nature. On the basis of this idea, if orientation and condensation do take place, this will occur up to the point where the attraction forces between the basic charge on the particles and the ions in the dispersion medium are balanced by the forces of repulsion between the ions in the diffuse layer and the ions in the dispersion medium. Thus, a rigid gel may form, which may be made fluid by redistributing the ions in the system." The redistribution might be accomplished by shaking or stirring.

To the attractive electrostatic forces mentioned by Hauser and Le Beau (1946) must be added the van der Waals' gravitational forces. The close approach of the particles will cause a contraction of the cationic diffuse layer of each particle. This contraction of the diffuse layer can be accomplished only by expulsion of water. This excess water is extruded from the clay-water mass as the volume decreases in the course of syneresis. The electrolyte content of the water expelled during process of syneresis is different from that of the original suspension (Rossi and Marescotti, 1937). Glasstone (1946) believes the extruded water to be water held by capillary forces between heavily hydrated particles constituting the framework of the gel. Much work remains to be done before the mechanism of syneresis and its causes and conditions are explained fully.

Syneresis is a widespread phenomenon whose development usually passes unrecognized because of its superficial resemblance to drying shrinkage. Its significance in engineering performance of earth materials remains to be evaluated. Failure of bentonite membrane linings, even while under water or buried beneath saturated earth, might occur as a result of syneresis. The phenomenon develops cracks which are so typical of claystone and shale formations in place, especially those containing members of the montmorillonite and illite groups. Syneresis is a common cause of difficulty in testing and control of drilling muds (Larsen, 1946). The relation of syneresis to other properties of clays and shales is discussed at appropriate places in the text.

Frost Heaving

Frost heaving is raising of the ground surface by development of bodies of ice within the soil. The magnitude of the uplift depends upon the capillarity and transmittancy of the soil, the rate of freezing, surcharge or loading, and the ground-water conditions. Detailed studies of frost heaving are reported by Taber (1929; 1930) and by Beskow (1947; 1948) upon whose work many of the following comments are based. Taber demonstrated conclusively that frost heaving is caused by movement of water into the freezing zone in an amount equal to the uplift. Expansion of water with freezing virtually is insignificant in the process. Indeed, lenses can be produced by freezing of soils saturated by liquids which contract upon freezing, such as nitrobenzene and benzene.

Under given conditions of temperature, surcharge, and water availability, the rate and magnitude of heaving depends upon the fabric of the soil (table 16). From detailed studies, Beskow (1947) concluded that heaving will not develop in soils containing less than 30 percent by weight of fractions passing the 0.062 mm sieve or less than 55 percent by weight of fractions passing the 0.125 mm sieve. For most soils, heaving will not develop if fractions passing the 0.062 mm sieve constitute less than 50 percent of the material. More fundamentally, frost heaving depends upon the capillarity of the soil, that is its ability to sustain capillaries of considerable vertical continuity. For the loose packing achieved at the liquid limit, a capillary rise less than 1.0 meter identifies non-heaving sediments; at maximum density of packing, the minimum capillary rise for frost-heaving soils was found by Beskow to be 1.25 meters. Under small loads, such as are sustained by most soils at the freezing zone, capillary rise must exceed 1.5 meters with loose packing or 2.0 meters with packing at maximum density. Normal frost-heaving soils sustain a capillary rise in the range 2 to 20 meters.

Admixture of clay with sand makes frost heaving possible (Plank and Drake, 1947). With a 5-percent addition of fat clay, frost heaving can occur; with 10- to 20-percent addition, frost heaving is well developed.

Table 16. Relation of soil properties to frost heaving.^a

Soil group		Average particle size (mm)	Amount passing sieve (percent)		Capillarity ^b (meters)
Nature of frost heaving	Soil type		0.062 mm	0.125 mm	
Non-frost heaving	Sediment	0.1	30	55	<1
	Moraine		15	22	
Frost heaving only superficial and with very high ground-water table	Sediment	0.1-0.07	30-50		1-1¼
	Moraine		30-50		
Frost heaving through road base with very high ground-water table	Sediment	0.08-0.05	15-25	22-36	1¼-2½
	Moraine		15-25	22-36	
Normal frost-heaving soils with frost boils to depths to ground water up to 1½ meters for sediments, and up to 1 meter for moraines	Sediment	<0.05	750		2-20
	Moraine		725	736	
Frost-heaving clays, but not liable to boils	Sediment				20-?
Non-frost-heaving stiff clays	Sediment				

^a From Beskow (1935).

^b Capillary height for packing at the liquid limit.

However, with larger additions of a fat clay, frost heaving decreases, becoming virtually zero with 40-percent addition. The process can be visualized as follows: with addition of small amounts of clay, the sand grains are coated and continuous water films of considerable thickness are developed; yet the fabric is open and highly permeable, and ice lens formation is marked. With increasing clay content above 20 percent, voids progressively are more filled, and permeability is decreased to virtually zero at 40-percent clay content.

The fabric most conducive to frost heaving lies intermediate between fine sand or coarse silt and stiff clays, which inhibit lens formation because of their extremely low permeability. Tests by Endell (1935; 1941) demonstrate the relative effect of kaolin, sodium bentonite, and calcium bentonite upon the rate of frost heaving in synthetic mixtures of quartz dust and the clay minerals (fig. 41). The rate of heaving is reduced the most with

sodium bentonite and least with kaolin, a clear reflection of decreasing transmittancy of the material.

Taber's (1929; 1930) hypothesis of heaving requires progressive migration of fluids through capillary passages into a narrow zone (or zones) of freezing within which lenses of frozen fluid accumulate. In the freezing process, water first is frozen in openings of large size, such as cracks and root holes, because the freezing point of free water is higher than that of adsorbed water. However, with continued decline of temperature, the outermost films of adsorbed water finally are oriented into the adjacent surfaces of ice crystals, thus reducing the thickness of the adsorbed water films separating the ice and the soil particles. Because equilibrium previously had been established between the forces transmitted through the adsorbed water and the load to which the soil fabric is subjected, the thickness of the adsorbed film separating the ice crystal and the adjacent soil particle is re-established by transmission of water from adjacent unfrozen films. By this process large volumes of ice can accumulate in one or more lenses if the movement of the freezing isotherm is slow compared to the rate of introduction of water from an external source. If the rate of freezing is rapid, only small lenses result or the mass is frozen homogeneously before water transfer can be accomplished on a significant scale. Clearly, even with a slow freezing rate, lens formation can be restricted or prevented by inadequate transmission of water to the freezing zone, either through want of water or low permeability of the fabric. It is interesting to note that fine stratified ice lenses can develop in stiff moist clays and shales by redistribution of water within the material, even if external sources of water are not available (Beskow, 1947). In this process heaving is practically absent. However, extraction of water from portions of the material simulates drying as a consequence of evaporation. Shrinkage cracks may form, disrupting original fabric and stimulating the onslaught of slaking with rewetting.

The size and spacing of ice lenses also depend upon fabric of soils (Beskow, 1947). In silty soils ice layers are clean and parallel to the freezing surface. The

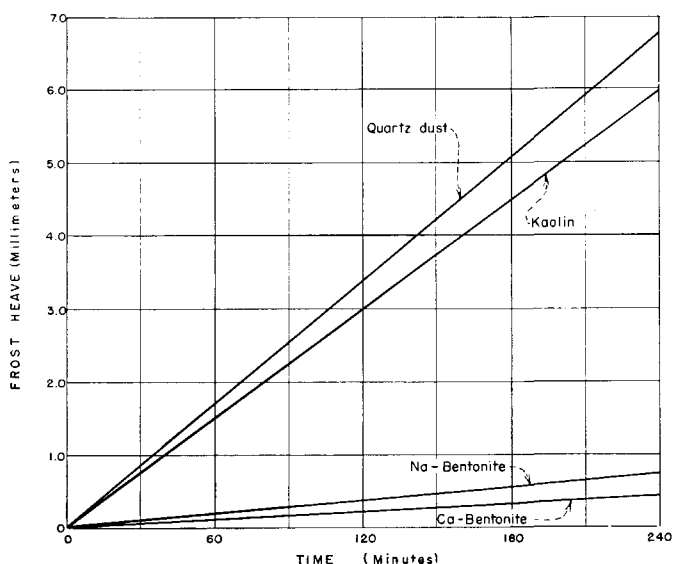


FIGURE 41. Relation of mineralogic composition and fabric to rate of frost heave (Preece, 1947; Endell, 1941).

coarser the silt, the less ice will accumulate, both in thickness, continuity, and spacing of the layers. In a fine silt, the ice layers typically are a few tenths of a millimeter thick, a few centimeters in lateral extent, separated a few millimeters, and oriented mutually parallel, giving a streaked appearance. The coarser the silt, the finer the structure of the ice layers until, with a grain size predominantly in the range 0.06 to 0.10 mm, the ice layers disappear entirely. Coarser soils freeze homogeneously.

In clays, the ice layers are thick and widely spaced, uniform groups lying parallel to the freezing surface and being more distinct and thicker, the more colloidal the clay. Thick ice layers commonly develop in clays at discontinuities, especially planes of stratification. In varved clays subjected to slow freezing, many thick and uneven ice layers grow simultaneously in several laminae. Cracks that occur in the dried upper part of clays commonly are filled with ice above the frost line, but accumulation of ice causes the cracks to widen and extend downwardly several centimeters below the freezing zone. In undisturbed claystones and shales, the impermeability frequently prevents development of ice lenses in the mass but yet significant heaving can occur by growth of ice layers along joints and other fractures by drawing of water from external sources through the fracture system.

Variations in fabric and water availability cause differential growth of ice lenses, hence can produce differential heaving of overlying or adjacent engineering structures. Clearly, differential displacement is more critical than uniform movement. Fortunately, the potentialities for stress development in materials as the result of frost heaving are relatively small. Taber (1929; 1930) was able to inhibit ice lense formation by application of surface loads of about 215 pounds per square inch.

Sensitivity of Clays to Remolding

Excavation and recompaction of earth materials partially or completely destroys original fabric of clays and shales. Simultaneously, capillary and adsorbed water films are disrupted. The degree of permanent change effected in the soil properties by manipulation depends upon the work done in disturbing a unit volume of the material, the original fabric, and the nature of the binding agent originally supporting the fabric. If the binding agent is mineral matter of low solubility, such as iron oxides and silica, originally deposited from solution in voids and upon grain boundaries, the change will be essentially irreversible. If the original structure is stabilized by moisture films, the remolding might effect only temporary changes, which diminish as the moisture distribution progressively approaches that of the original material. Similarly, if the binding agent is composed of highly soluble salts, strength lost by wetting and working will be regained wholly or in large part with drying, or, indeed, the strength of remolded material may be greater than that of the original soil (Winterkorn and Tchebotarioff, 1947). Reversibility of binders was discussed previously under "Cementation."

The strength of clay stabilized by thixotropic development in the solid-water system can be lost almost completely by agitation, vibration, or application of shearing stress. With moisture content in excess of the liquid limit, soils liquefy as a result of disturbance. The thixo-

tropic structure redevelops with rest at rates depending upon the physical-chemical properties of the constituents, the fabric of the soil, electrolyte content of the water phase, and the water content.

In a study of the sensitivity of clays to remolding, Winterkorn and Tchebotarioff (1947) conclude that decrease in compressive strength with remolding is due to destruction of cementing minerals; and that increase in compressive strength with remolding is due to (1) break-down of secondary aggregates with consequent increase in surface area available for adsorption, (2) rearrangement of particles into a more stable fabric, and (3) destruction of planes of weakness or fractures. Clays unaffected by remolding appear to owe their cohesive properties to capillary water films and to the action of hydrophilic reversible colloids. Loess is especially sensitive to remolding, the disturbed loess typically possessing about one-half the compressive strength of the undisturbed loess at the same porosity (Denisov, 1946).

Sensitivity of soils to drying and wetting depends in large part upon the hydrophilic or hydrophobic properties of the clays and their volume change with change in water content. The phenomena associated with slaking are discussed subsequently.

Slaking

Slaking is the disintegration of materials as the result of change of water content. Under natural conditions, slaking proceeds until single grains or particles and water-stable aggregations are produced. In the natural evolution of geologic deposits of clays and shales, slaking results from rewetting after partial removal by evaporation of stable adsorbed water films which are at equilibrium within the fabric.

A complex series of actions is involved in the slaking process. With initial drying the shale or clay first is compressed by capillary forces whose magnitude depends upon the size of the pores, their abundance, and the surface tension of the interstitial water. As compressive forces of large magnitude develop, shear failure with resultant cracking will occur if discontinuities of fabric create surfaces of weakness and variable capillary potential within the material. With continued drying below the shrinkage limit, the larger capillaries are progressively emptied by the smaller. In this process differences of compressive stress related to differences of fabric are accentuated and cracking increases. These cracks disrupt the fabric and facilitate rapid entry of water when rewetting occurs.

With complete removal of capillary water by drying, water is confined to films upon surfaces of the solid particle and at points of contact. Tension in these films and other forces (see below) effect strong cohesion in the shale or clay, even in the absence of mineral cements. At equilibrium with ambient air the thickness of the water films depends upon the relative humidity and the surface-chemical properties of the particles.

With rewetting of dried clay or shale, the adsorbed water films are increased in thickness, expansive clay minerals swell, and air is compressed in the interior under the force of penetration of water along capillaries (Yoder, 1936). All of these actions contribute to internal stress and slaking. In the absence of expansive clay minerals, the increasing thickness of adsorbed water films is significant in slaking only in loose sands and

silts. With rewetting, weak aggregations of sand and silt grains, stabilized only by water films, collapse under the force of gravity. Similarly, in clays and shales, minor splitting along fractures might occur in response to the decrease in cohesion effected by enlargement of adsorbed films.

All significant slaking of clays and shales results from swelling of clay minerals or development of internal air pressure. The relative importance of each depends upon the amount and swelling potential of the clay minerals and upon the fabric. Clays and shales containing expansive clay minerals will swell with or without spalling and disintegration if penetrated by water. Clays and shales containing only nonswelling clay minerals will spall and disintegrate without notable swelling if penetrated by water. Kaolinite, halloysite, and many hydrous mica clays and shales commonly are so compact as to defy penetration by water. They remain intact indefinitely when submerged. Dry shales and clays containing expansive minerals might react very slowly because of their impermeability, but swelling or slaking ultimately occurs.

With immersion in water, air-dry sodium bentonite does not disintegrate; rather, it slowly swells and flocculant growths appear upon the surface. With swelling, the size of the piece increases severalfold, and ultimately its form is lost by slumping. However, complete dispersion of the bentonite through the water phase does not occur, even though the bulk volume of the bentonite increases manyfold. Air-dry calcium montmorillonite is prone to rapid expansion with simultaneous disintegration into small aggregations. With brittle montmorillonite-type clays and shales, the spalling can be explosive. Air-dry potassium montmorillonite begins at once to swell and spall with considerable release of air bubbles as each new crack is formed. The spalled pieces continue to disintegrate until only small aggregations remain. Air-dry illite shales and clays begin at once to disintegrate by spalling. Air is released with the formation of each new crack. The slaking proceeds until a mass of chips and flakes of moderate size remain. Porous kaolins spall and ravel at varying rates, air usually escaping with each spall.

If the air-dry clays are evacuated prior to immersion in water, spalling and slaking occur in expansive clays in a manner similar to that experienced without evacuation. However, slaking commonly is more rapid, although less complete. After evacuation, kaolin containing no expansive minerals does not slake.

These observations demonstrate that compression of air in capillaries is the only significant force causing slaking of nonexpansive clays. In expansive clays air pressure and differential expansion combine to effect slaking. Sands and silts containing expansive or nonexpansive clay minerals will respond as do the related clays. For example, loess bound by grain coatings and interstitial montmorillonite slakes immediately either with or without previous evacuation. In granular fabrics, expansion of the clay constituent decreases cohesion and intergranular friction.

Significant slaking occurs on wetting only if the air-dry condition is approached. In tests of the beidellite-containing Carlisle shale occurring at Cedar Bluffs Dam site, near Ogallah, Kansas, a minimum of 16 to 32 minutes of drying at 50 percent relative humidity and 70° F

was necessary to induce softening and slaking following immersion. Slaking increased with further drying time, being complete following immersion in water after 24 hours of drying.

Clayey materials usually do not slake in nonpolar liquids, such as benzene. If a variety of liquids is used, rapidity and degree of slaking tends to increase with increasing dielectric constant of the liquid. This is true even after drying of the clay at 200° C, a temperature found to completely remove the adsorbed water. The fact that clays and shales, susceptible to slaking under ordinary conditions, remain cohesive after drying at 200° C indicates that forces other than the tension of water films are involved in the binding of particles together. Increasing degree of slaking with increasing dielectric constant of the penetrating liquid suggests that the forces are electrostatic. Consequently, it is not necessary to assume that materials, which slake in water but resist slaking in liquids not miscible with water, do so only because stabilizing water films remain in the fabric. Slaking of clays and shales in water depends upon both weakening of electrostatic binding forces between particles and development of internal tensile stresses in the fabric by expansion or air pressure.

Slaking of clays, claystones, and shales cause many minor difficulties at engineering sites (Burwell, 1950). Slopes ravel progressively following exposure by excavation and are prone to erode badly with run-off or if acted upon by waves or currents of reservoirs or canals. Shales and clays permitted to dry before placing of concrete slake if later saturated, thus destroying bond of the concrete to the foundation. Terzaghi (1950) cites slaking of newly exposed clays in open cuts as causing landslides by decreasing shearing resistance of the materials. Measures to prevent excessive slaking usually involve placing a protective cover, such as concrete, earth materials, or asphalt, immediately after excavation to grade. Slaking also is reduced by electro-osmotic and electrochemical treatment and by introduction of organic cations which develop hydrophobic qualities in the clay (Davidson, 1949; and Glab, 1949).

CLAYS AND SHALES IN CONCRETE MATERIALS

Clays in Natural Aggregate and Crushed Stone

Clay minerals are almost universal constituents of natural sand and gravel and crushed stone. They occur as disseminated crystals or masses, or as veinlets in sedimentary, metamorphic, and igneous rocks of all types (Rhoades and Mielenz, 1948; Knight, 1949). For example, granites and granite gneisses of the Rocky Mountains of Colorado and Wyoming commonly contain disseminated crystals, veinlets, and seams of clay minerals, including kaolinite, illite, montmorillonite, and halloysite, either singly or in various combinations. Basalts of the Columbia Plateau of Washington almost universally contain nontronite with or without montmorillonite and saponite as a result of deuteric, hydrothermal, and epigene alteration of original glass, palagonite, ferromagnesian minerals, and plagioclase. This alteration may be uniformly distributed through pebbles, or it may be accentuated at the periphery of pebbles as a result of weathering after the gravel was deposited (fig. 42). In that area, sands typically carry nontronite-containing basalts, grains of almost pure

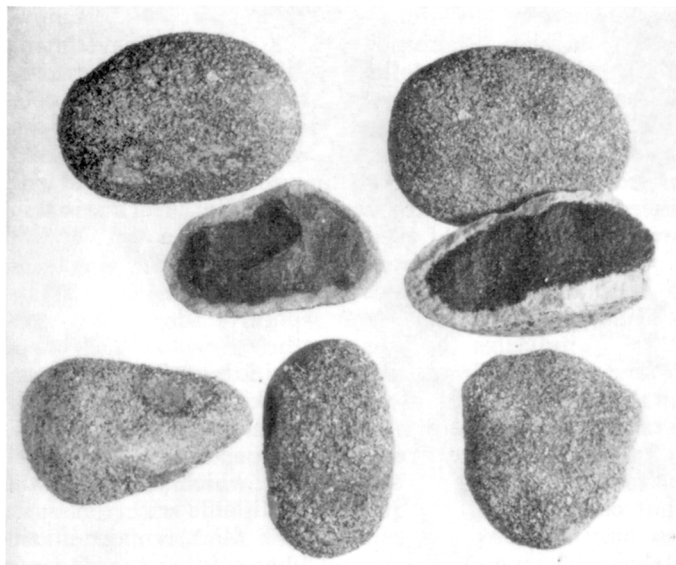


FIGURE 42. Basalt gravel showing development of weathered rims in which palagonite is leached and partially altered to nontronite and iron oxides.

nontronite, and, less commonly, flakes of montmorillonite with or without intermixed halloysite. Limestones from many areas contain clay minerals, either disseminated within or between crystals of calcite or concentrated along solution channels (Loughlin, 1928). In the vicinity of San Diego, California, the Poway conglomerate locally contains pebbles of dacite and andesite which are deeply altered to montmorillonite-type clay.

Alteration evident in natural aggregates may develop in the original rock formation or after deposition of the sand and gravel. Alteration of natural aggregates in place is especially dangerous because deepest decomposition occurs at the periphery of the particles where the cement must bond.

Depending upon the kind, amount, and distribution of clay minerals in aggregate, several deleterious actions might arise in the concrete. Adsorption of water is increased and resistance to freezing and thawing and wetting and drying of the concrete is reduced. If expansive clays are present, wetting and drying can produce deleterious volume change of concrete (Rhoades and Mielenz, 1948; Knight, 1949). Strength and wear resistance of the concrete can be decreased critically. Break-down of the aggregate during handling and mixing is aggravated, and water requirement is increased and the strength is reduced. Changing gradation during mixing is a characteristic of the Poway conglomerate where excessive amounts of altered volcanic rocks are present.

Clay minerals occur also in natural aggregate as constituents of highly clay particles, such as shales, claystones, argillaceous concretions, and clay balls. Clay balls are rounded lumps of clay occurring in gravel or coarse sand, having been developed by rolling and molding of plastic clay by stream action; they generally contain sand and fine gravel particles. Argillaceous ferruginous concretions are particularly abundant in sands and gravels of North and South Dakota and adjacent parts of Wyoming and Nebraska. Chips and

flakes of shale are common, minor constituents of sands and gravels, particularly those carrying locally derived materials not yet subjected to long continued attrition and impact. Clay balls are common in Colorado in coarse sand and gravel or small streams draining areas in which the Mancos shale is exposed.

In addition to accentuating the deleterious action experienced with disseminated clay and clay seams in aggregate, the highly argillaceous materials commonly occur as lightweight particles which segregate towards the surface during placing and finishing of concrete. Moreover, shales commonly produce flat and slabby pieces which may segregate and produce oriented zones which decrease workability and require use of additional sand, cement, and water in the mix. Sodium and potassium clays of high cation exchange capacity, such as montmorillonoids, can release alkalis into the solutions permeating the mortar by exchange reactions with calcium, thus possibly contributing to alkali-aggregate reaction.

Clays occur also in natural aggregates as coatings upon the particles. These coatings decrease bond with cement and their removal during handling and mixing increases the fines in the aggregate by continuous break-down. Removal of plastic clay coatings frequently is costly, both in development of the necessary plant and in its operation and control. Phelps (1952) reports progress in use of deflocculating agents to displace clay coatings from aggregate more effectively than could be accomplished by washing with water alone. Various kinds and concentrations of reagents are used, most wide-spread success being found with sodium silicates. The aggregate is fed into a pool or into a classifier where the water is added together with the dispersing agent. The aggregate is agitated continuously and the clay is discharged with effluent water over a weir. In one installation, aggregate containing as much as 25 percent by weight of material passing the No. 325 sieve is said to be deslimed with use of a deflocculating agent at a cost of \$0.04 per ton of feed. Moreover, capacity of the plant is increased by treatment of the aggregate, one plant reporting an increase of 75 percent in capacity at a cost of \$0.01 per ton. The type of agent, its rate of addition, and other features of the process depend upon the composition and amount of clay and its mode of occurrence. Consequently, the requirements must be established individually for each installation.

Clays and Shales as Sources of Lightweight Aggregate

Production and use of both natural and manufactured lightweight aggregate for concrete, mortar, and plaster is a rapidly expanding industry. Clays and shales are processed into satisfactory lightweight aggregate of several types which are marketed commercially under the trade names such as Haydite, Rocklite, Gravelite, Cel-Seal, and others (Cordon and Hickey, 1948; Price and Cordon, 1949; Tuthill, 1945; Kruge et al., 1949; Petersen, 1950). Firing is accomplished in rotary kilns or sintering machines. In either process the raw material is heated rapidly to the range between incipient and complete fusion. Bloating or vesiculation is accomplished by entrapment of released gases by the viscous, partially fused clay or shale. Clays and shales are fired alone after crushing and sizing, or after admixture with iron oxides or carbonaceous material. Research

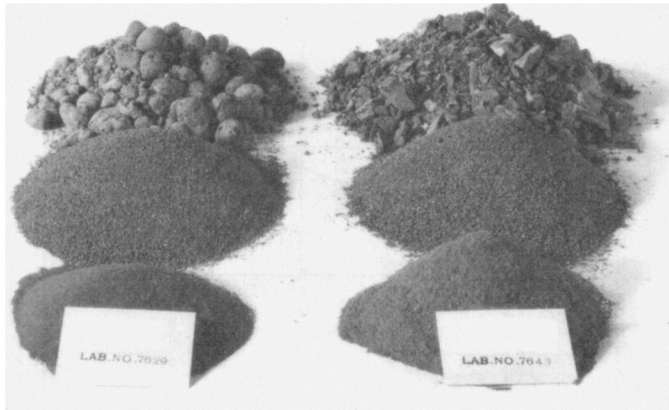


FIGURE 43. Coarse and fine Rocklite (left) and Haydite lightweight aggregate.

and development of materials, methods, production equipment, and additional uses is actively in progress.

Haydite is manufactured as both coarse and fine aggregate, and has been used most extensively of all clay- and shale-type lightweight aggregates, commercial manufacture having begun in 1920. After being crushed to pass the $1\frac{1}{2}$ - or 1-inch sieve, the shale or clay is fired in a rotary kiln at 2,000° F to 2,100° F until a desired degree of vesiculation is achieved (Tuthill, 1945). The clinker material is then crushed to desired sizes (fig. 43). Very good structural concrete can be made with properly manufactured Haydite, the unit weight ranging from 100 to 110 pounds per cubic foot, and the compressive strength ranging from 4,000 to 5,000 psi, depending on the cement content of the mix (Cordon and Hickey, 1948; Price and Cordon, 1949). The concrete is resistant to freezing and thawing and wetting and drying. Expansion as the result of alkali-aggregate reaction is negligible. Bulk dry weight of the coarse aggregate ranges from 35 to 49 pounds per cubic foot.

Rocklite is produced by firing of crushed and screened shale or clay in a rotary kiln at about 2,170° F (Tuthill, 1945). During the firing, originally irregular pieces vesiculate and expand to rounded pebble-like forms, and a finely porous skin of high strength about 1 mm thick is developed at the periphery (fig. 43). Very good structural concrete can be produced with Rocklite aggregate, the unit weight varying from 90 to 100 pounds per cubic foot, and the strength ranging from 1,000 to 5,000 psi (Cordon and Hickey, 1948; Price and Cordon, 1949). Resistance of the concrete to freezing and thawing and wetting and drying is satisfactory. Expansion as the result of alkali-aggregate reaction is negligible. Bulk dry weight for the coarse aggregate ranges from 37 to 44 pounds per cubic foot.

Gravelite is manufactured by extruding prepared clay or shale through a multiple die to form cylinders which are cut to desired length (Price and Cordon, 1949). Sizes below three-eighths inch are prepared by mixing the clay with sufficient water to agglomerate the clay into small particles. The pellets or particles then are sprayed with fuel oil and fired in a rotary kiln. The finished product is composed of spherical, vesicular particles. Bulk, saturated surface-dry weight is 40 to 45 pounds per cubic foot for the coarse aggregate, and about 55 pounds for the fine aggregate. Concrete containing only Gravelite as aggregate weighs 75 to 85

pounds per cubic foot; with natural sand as fine aggregate, weights range from 95 to 110 pounds per cubic foot (Cordon and Hickey, 1948). Gravelite was used in construction of the upper deck of the San Francisco-Oakland Bay bridge.

Cel-Seal lightweight aggregate is produced by mixing small proportions of iron oxides and carbonaceous material in the raw clay; the mass then is made plastic with water. The mixture is extruded as round pugs from a multiple die. Small billets are produced by cutting the pugs with a rotating wire. Billets of selected sizes are passed through a revolving cylinder in which they are rounded and coated with a pulverized refractory clay (Price and Cordon, 1949). The pellets then are expanded by vesiculation in a rotary kiln at a temperature above the fusion point of the clay of the pellet and below the fusion point of the coating. Each particle of the finished product is round and smooth. Bulk dry weight ranges from 15 to 30 pounds per cubic foot. Concrete containing graded Cel-Seal aggregate weighs 50 to 90 pounds per cubic foot.

Nodulite is a lightweight aggregate produced from Florida fuller's earth (Tuthill, 1945). In the process, the fuller's earth is dried and pulverized and then fed into a large revolving drum, where spraying with water effects a crude pelletizing action producing lumps ranging from $\frac{1}{16}$ to about 1 inch in size. The nodules are coated with fine silica sand to prevent adhesion. Firing is accomplished at about 2,000° F in a rotary kiln. Bulk dry weight of the finished coarse aggregate ranges from 42 to 46 pounds per cubic foot.

Despite extensive investigations of the process and controls of expansion of clays and shales in production of lightweight aggregate, little information on the fundamental phenomena involved has been published. Most comprehensive are the investigations of Conley, Wilson, and Klinefelter (1948) and of C. M. Riley (1951). Riley has compiled numerous references on bloating of clays and shales. Expansion and vesiculation of clays and shales occurs during firing in the range from about 2,000° to 3,100° F, but the results obtained for a particular material depend upon the rate of heating, the temperature, the kiln atmosphere, residency in the kiln, and other factors.

Expansion and vesiculation require (1) presence of one or more substances which release gas after fusion has developed sufficient molten material to prevent its ready escape, and (2) that the molten material be of sufficient viscosity to retain the expanding gas. Riley (1951) concluded that the viscosity of the melt produced by firing is determined essentially by the bulk chemical composition of the raw material. Using data published by Conley and associates (1948), as well as original information, he defined a range of composition based upon the oxides SiO_2 , Al_2O_3 , and the total of CaO , MgO , FeO , Fe_2O_3 , and $(\text{K}, \text{Na})_2\text{O}$, in which optimum viscosity of the melt could be expected. All bloating clays and shales among some 80 investigated by Conley were found to contain at least 5 percent of compounds of iron alkalis and alkaline earth, these, together with carbon, being substances thought to act as fluxes and the major producers of gas. If other factors are constant, increasing alumina content increases the refractory quality of the material and decreases vesiculation.

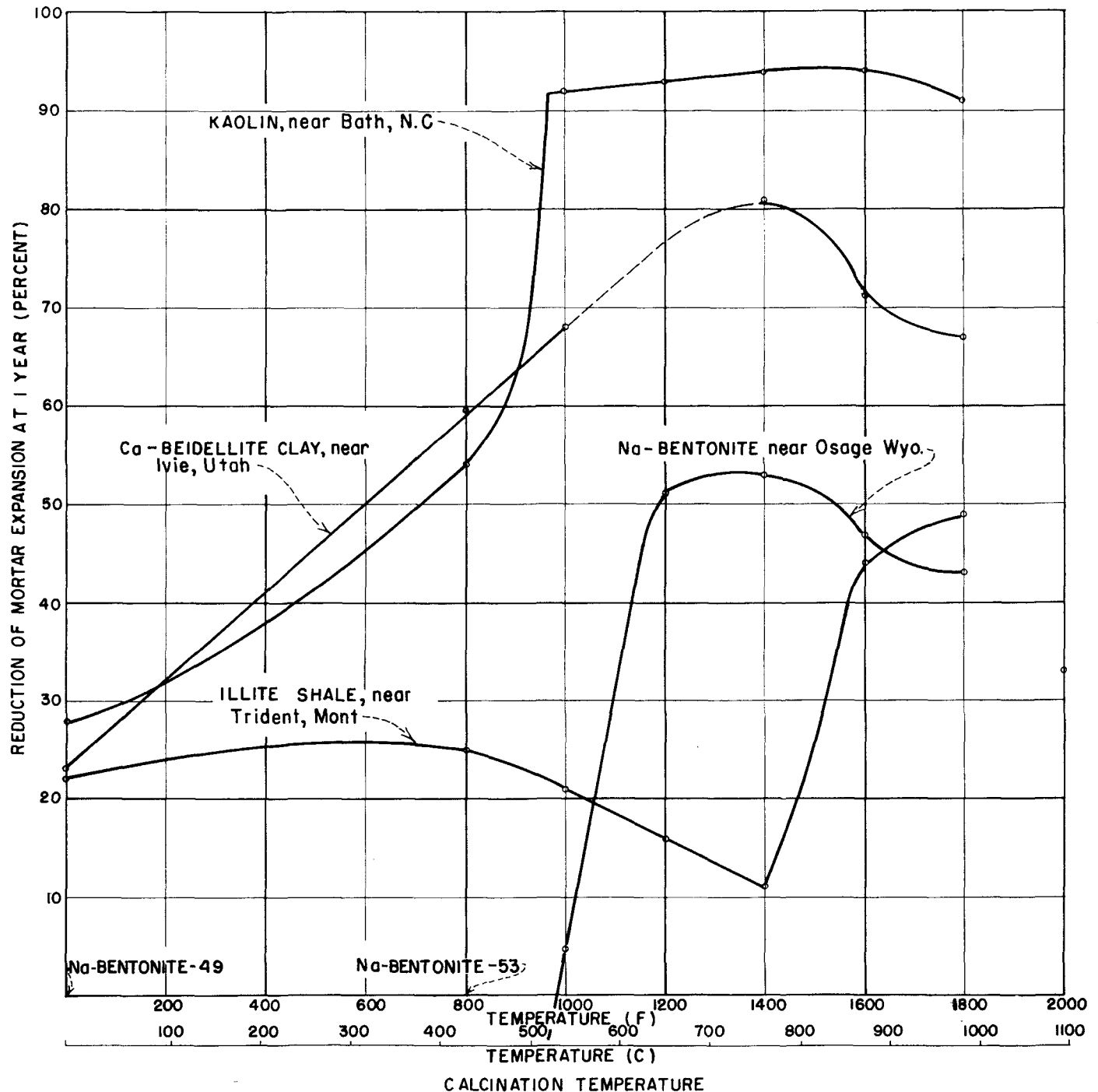


FIGURE 44. Effect of calcination of clay and shale pozzolans on expansion of mortar as the result of alkali-aggregate reaction.

The clays and shales classified by Conley and associates as "bloaters" contain less than 25 percent of Al_2O_3 , but three-fourths of the nonbloaters likewise contain less than this amount of Al_2O_3 . Their work demonstrated that determination of pH is 90 percent correct in identifying propensity for vesiculation, the nonbloaters producing a water slurry with pH less than 5, whereas bloaters produce a water slurry with pH greater than 5. This relation probably relates to the nature of the exchangeable cation and the cation exchange capacity of

the clay or shale, the alkalis and alkaline earth serving constructively as fluxes in the firing process.

In the firing of natural clays and shales, gas undoubtedly is evolved by several processes (Jackson, 1924; Hostetter and Roberts, 1921; Orton and Staley, 1909). Austin, Nunes, and Sullivan (1942) identified H_2O , CO_2 , and SO_3 as gases evolved from several bloating clays. In addition, it is likely that CO , O_2 , and possibly H_2 are evolved in vesiculation of many clays and shales. Riley (1951) concluded that the most significant re-

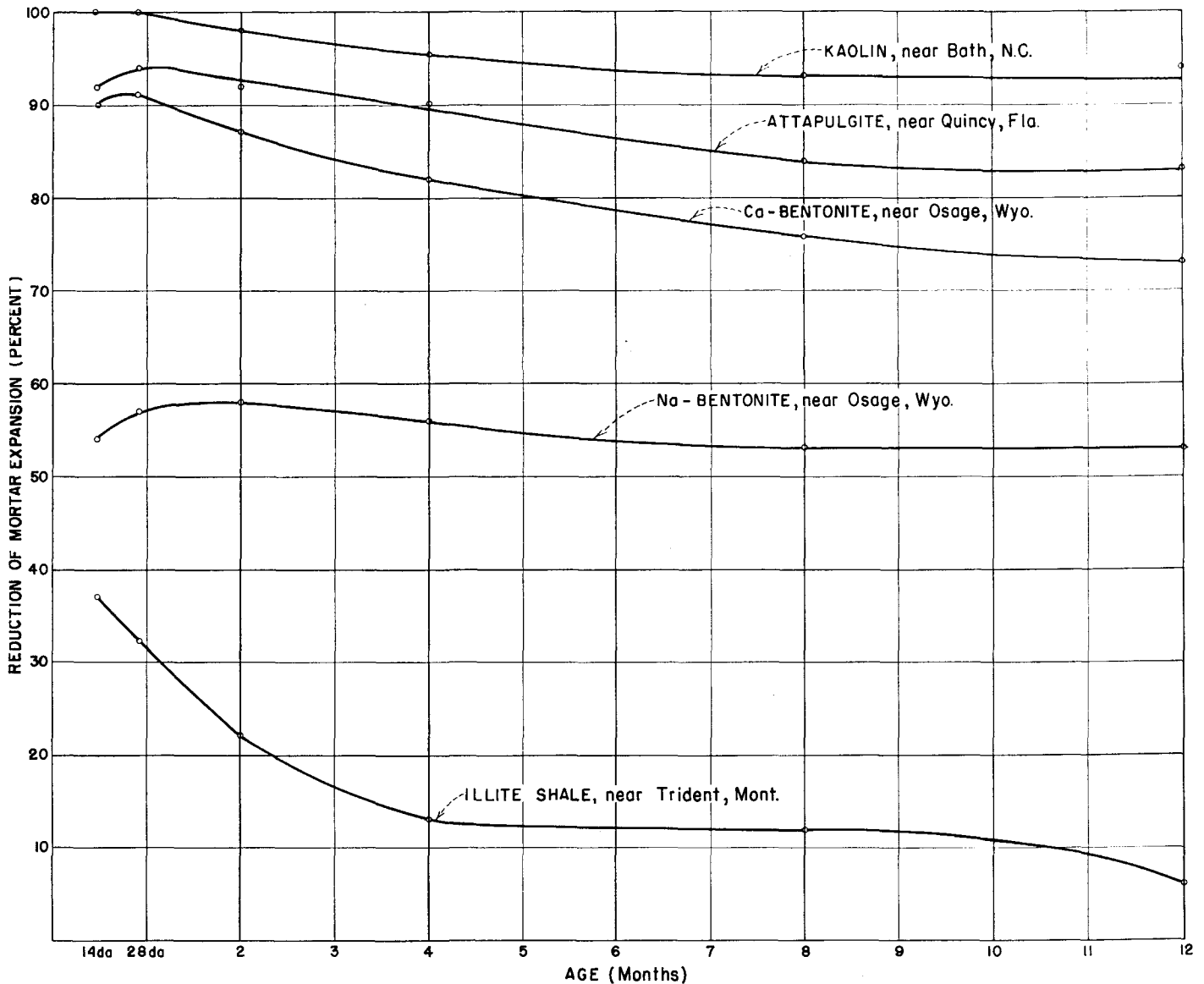
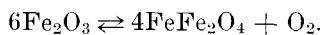


FIGURE 45. Effect of clay and shale pozzolans after calcination at 1400° F upon expansion of mortar as the result of alkali-aggregate reaction.

action involved in generation of gas is partial reduction of ferric oxide according to the equation:



The ferric oxide is furnished by original limonite or hematite present in the raw shale or clay or by decomposition, with or without oxidation, of original ferric or ferrous compounds, most notably including biotite, amphiboles, montmorillonite-type or illitic clays, chlorite, and other clay and clay-like minerals. These relationships demonstrate the need for mineralogic analysis in the investigation of clays and shales as sources of lightweight aggregate.

Calculation indicates that at least 7.6 percent by weight of Fe_2O_3 must be available from these sources for adequate vesiculation if this source alone furnishes gas (Riley, 1951). Complex silicates, such as micas, amphiboles, and the clay and clay-like minerals, probably also release O_2 , H_2 , and H_2O as the result of other re-

actions. Experiments by Conley and associates (1948) and by Riley demonstrate that gases are evolved by reactions of dolomite, pyrite, sulfur, sulfates, and carbonates of the alkalis and alkaline earths, and possibly calcite. Less than 1 percent by weight of these minerals is required for adequate vesiculation. Carbon undoubtedly contributes to gas formation during firing of some carbonaceous clays and shales.

The fabric of the original clay or shale is significant in the expansion process. Most beneficial is a dense, relatively impervious fabric which resists shrinkage during heating and retards release of vapors and gases before fusion effects a seal in the particles. The fabric is especially significant in firing of carbonaceous clays and shales, inasmuch as a porous, open fabric permits ready burning out of the carbon, whereas a dense fabric retards oxidation by the kiln atmosphere and retains CO and CO_2 produced by reaction with interstitial water or with water or oxygen released by dehydration or de-

composition of hydrated compounds or hydroxylated silicates.

Most promising as sources of lightweight aggregate are shales and clays containing illite, beidellite-type members of the montmorillonite group, and vermiculite-chlorite. These minerals approximate the composition found by Riley (1951) to yield the melt of optimum viscosity. They almost always contain significant amounts of iron in their lattice and are typically admixed with varying amounts of limonite and hematite. Unlike members of the kaolin group, they typically contain moderate proportions of alkalis and alkaline earths which serve as fluxes in the firing process. The potentialities for expansion and vesiculation of clays and shales of these mineralogic types have been demonstrated both in the laboratory and in commercial enterprise.

Clays in Pozzolans

Pozzolans are siliceous or siliceous and aluminous materials, natural or artificial, processed or unprocessed, which, though not cementitious in themselves, contain constituents that will combine with lime in the presence of water at ordinary temperatures to form compounds which have a low solubility and process cementing properties (U. S. Bur. Reclamation, 1949; Lea, 1938). Use of pozzolans as a replacement for part of the portland cement in concrete has come into prominence in recent years and is increasing. Within recent years, certain pozzolans have been found to participate in chemical and physical-chemical reactions with alkalis (Na_2O and K_2O) released during hydration of portland cement (Hanna, 1947; Mielenz et al., 1950). As a consequence, deleterious reactions involving the alkalis, such as the alkali-aggregate reaction, are inhibited or prevented.

Mielenz, Witte, and Glantz (1950) and Mielenz, Greene, and Schieltz (1951) have classified pozzolans into five "activity types," depending upon the substances responsible for the pozzolanic action, as follows:

- Activity Type 1 ----- Volcanic glass
- Activity Type 2 ----- Opal
- Activity Type 3 ----- Clay minerals
- Activity Type 3a ----- Kaolin group
- Activity Type 3b ----- Montmorillonite group
- Activity Type 3c ----- Illite group
- Activity Type 3d ----- Mixed clays with vermiculite-chlorite
- Activity Type 3e ----- Palygorskite
- Activity Type 4 ----- Zeolite
- Activity Type 5 ----- Hydrated aluminum oxides

In the natural condition, clay minerals are nonpozzolanic or only weakly pozzolanic. However, with calcination, particularly in the range $1,200^\circ$ to $1,800^\circ$ F, partial dehydration and crystallographic changes result in significant reactivity with lime and alkalis for most types of clay (figs. 44 and 45). Although certain calcined clays control or markedly reduce expansion of mortar as the result of alkali-aggregate reaction, water requirement typically is excessive and strength development is usually low, especially for pozzolans of Activity Type 3b (figure 46).

The kaolin group of minerals disintegrate with partial dehydroxylation to one or more aluminous and siliceous substances which are largely amorphous microscopically and by X-ray diffraction. With slow heating of kaolinite, water is lost progressively between 600° and 930° F, at which temperature collapse of the crystallographic struc-

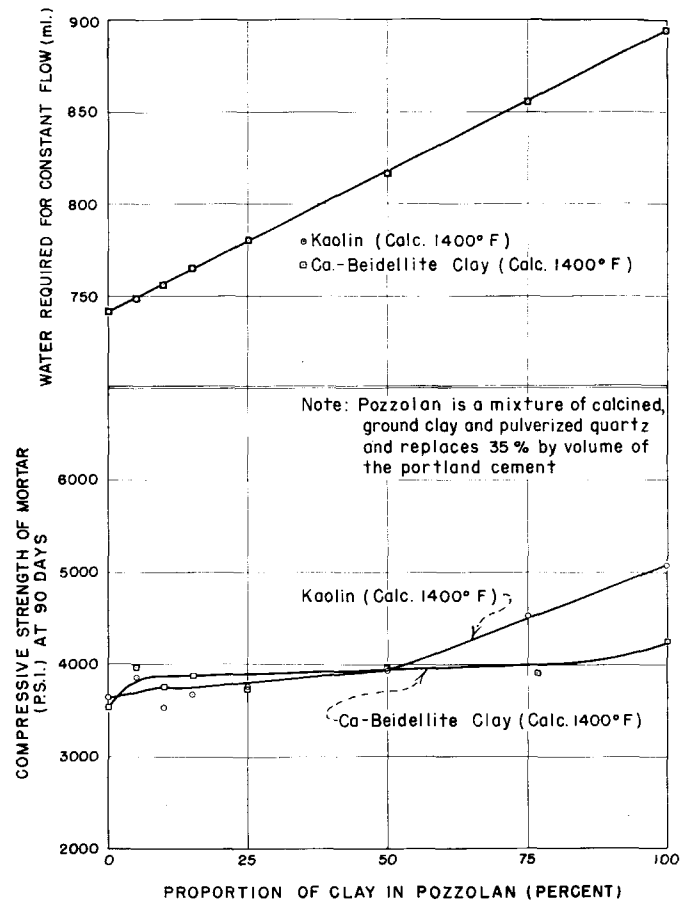


FIGURE 46. Effect of calcined clay pozzolans on water requirement and compressive strength of portland cement mortar.

ture begins (fig. 47) (Nutting, 1943). Disintegration may occur at temperatures as high as $1,225^\circ$ F if the kaolinite is heated rapidly (Parmelee and Rodriguez, 1942). This disintegration proceeds rapidly between 930° and 950° F, with liberation of H and OH ions as water. With disintegration of the crystalline structure an amorphous aluminous and siliceous substance is produced. As the temperature increases, an exothermic reaction occurs at about $1,800^\circ$ F, possibly as the result of crystallization of gamma-alumina, and gamma-alumina can be identified by X-ray diffraction analysis. At about $1,825^\circ$ F, mullite ($3\text{Al}_2\text{O}_3 \cdot 2\text{SiO}_2$) and/or gamma-alumina form, the relative amount of each depending largely upon the degree of order existing in the original clay mineral. After calcination at $2,000^\circ$ F, the gamma-alumina has disappeared. With continued heating at $2,750^\circ$ F, a mixture of mullite, cristobalite, and silica glass is produced, the precise temperature of complete mullitization and the content of glass depending upon the kind and abundance of impurities (Parmelee and Rodriguez, 1942). For pure kaolinite, the weight loss during calcination exceeds 14 percent (Nutting, 1943).

The course of dehydration and recrystallization of anauxite is similar to that of kaolinite, except that dehydration begins at about 625° F and proceeds rapidly with disintegration of the crystallographic structure between 750° and 950° F, virtually complete dehydration being accomplished between $1,200^\circ$ and $1,475^\circ$ F,

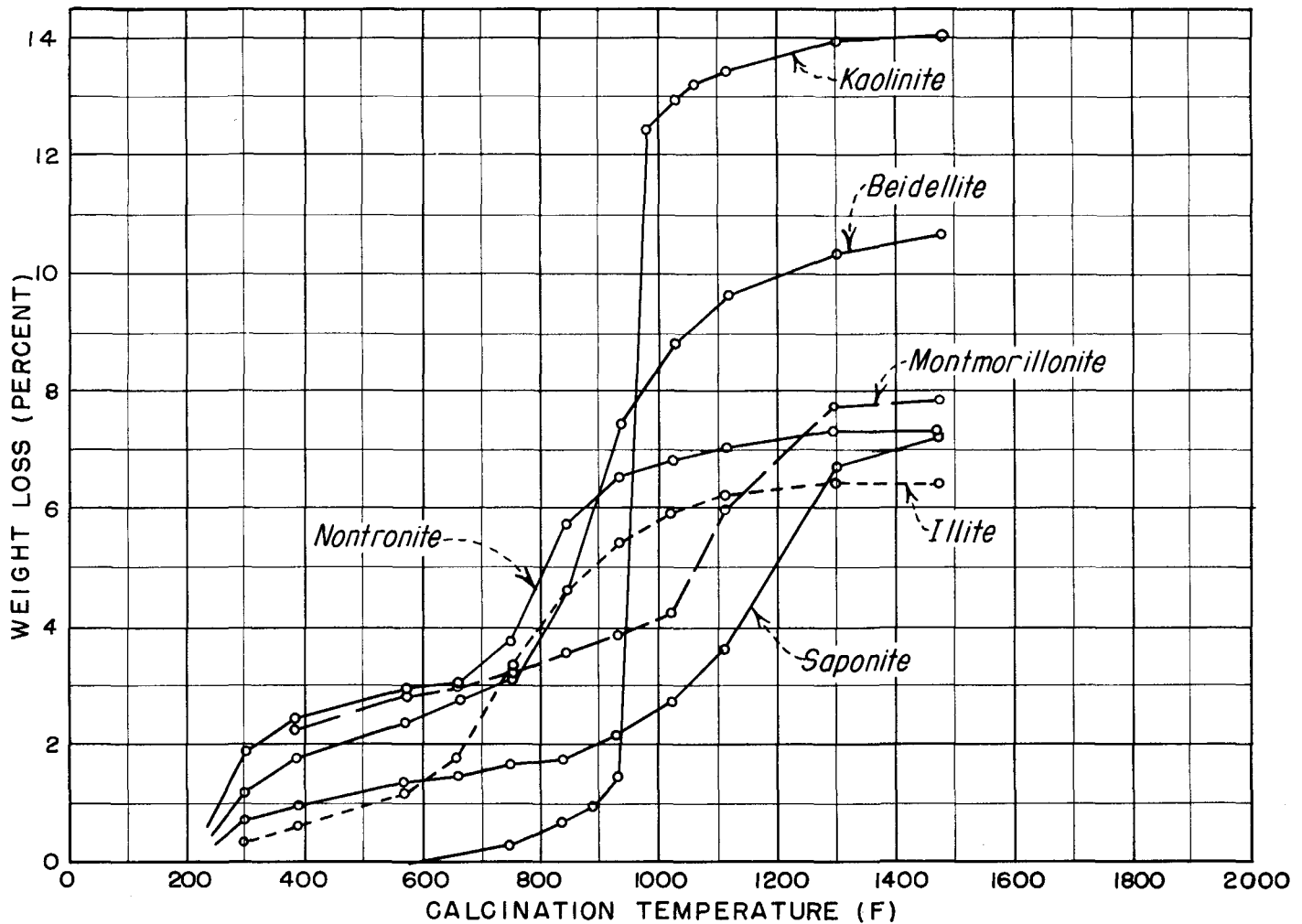


FIGURE 47. Weight change of clay minerals during calcination (Nutting, 1943).

depending upon the composition of the original anauxite (Nutting, 1943).

The pozzolanic properties of kaolin undergo remarkable change, both physically and chemically, with calcination (Mielenz et al., 1950). Water requirement decreases from 72.8 to 46.0 percent for tested materials calcined at 2,000° F. Neither initial nor final set of the lime-kaolin paste occurs at an age up to 14 days unless the kaolin is calcined at or above 800° F. Beginning of crystallization of gamma-alumina and later of mullite during calcination at 1,600°, 1,800°, and 2,000° F increases the time necessary for set of the lime-kaolin paste to be accomplished. At an age of 28 days, the mortar strength increases almost uniformly with calcination of the kaolin; but the maximum strength is equivalent to only 85 percent of the strength of the control mortar.

Test data indicate that crystalline kaolinite is comparatively ineffective in controlling alkali-aggregate reaction, but the amorphous siliceous and aluminous substance produced with collapse of the crystalline structure after calcination between 1,000° and 1,600° F is highly effective, the optimum calcination temperature being 1,400° to 1,600° F (fig. 44) (Mielenz et al., 1950).

This substance apparently is a compound rather than a simple mixture of siliceous and aluminous glass, inasmuch as the solubility of the silica remains very small until gamma-alumina forms at 1,800° F, probably with resulting decomposition of the amorphous compound and formation of readily soluble silica (Mielenz et al., 1950). However, formation of gamma-alumina causes a decrease in the effectiveness of the kaolin in controlling mortar expansion. At 2,000° F, mullite forms, and the effectiveness of the material in reducing alkali-aggregate reaction probably would be decreased further.

With calcination, montmorillonite first loses free water and, then, between about 300° and 950° F, water adsorbed on or between lattice planes of the clay crystals is released (fig. 47) (Nutting, 1943). Beginning at about 950° F, H⁺ and OH⁻ ions of the lattice structure of the clay are lost, the rate of loss being high as the temperature rises to about 1,200° F. Dehydration continues slowly at higher temperatures and is essentially complete at 2,000° F. However, the rate of dehydration with progressive heating depends upon the chemical composition, degree of alteration, and exchangeable cations of the clay. Typical montmorillonites lose from about 4.6 to about 9.8 percent in weight between 212° and 1,475° F.

Table 17. Effect of calcination on 001 interplanar spacing of montmorillonite-type clays and illite.^a

Calcination temperature (°F)	Interplanar spacing 001 (kX units) ^b					
	Na-Montmorillonite	Beidellite	Beidellite	Nontronite, near Coulee City, Washington	Hectorite, near Hector, California	Illite, Illinois ^c
Raw	14.01	15.11	14.50	15.11	14.54	10.27
800	15.11 and 12.84	— ^d	14.50 and 9.76	9.88	14.54	10.07
1000	12.53	10.27	9.64	9.88	14.54	10.07
1200	9.88 and 12.53	9.83	9.69	9.88	9.64 and 13.78	10.07
1400	9.76	9.83	9.69	9.88	9.64	10.07
1600	— ^e	— ^e	9.69	9.88	— ^e	10.07
1800	—	—	— ^e	— ^e	—	— ^e
2000	—	—	—	—	—	—

^a From Mielenz, Witte, and Glantz (1950).

^b One Ångström = 1.00202 kX units.

^c Crystal structure destroyed.

^d Line too blurred for unique measurement.

^e Sample supplied by W. F. Bradley, Illinois State Geological Survey, Urbana, Illinois.

With the release of H and OH ions from the lattice of montmorillonite, irreversible shrinkage occurs along the c-axis of the crystal (table 17). For example, for the sodium-montmorillonite d(001) decreases progressively with calcination. After calcination at 1,600° F, the clay constituent has disintegrated so that the characteristic X-ray diffraction pattern of montmorillonite no longer can be obtained from the material. Upon disintegration of the crystallographic lattice of the montmorillonite of Wyoming bentonite, spinel and beta-cristobalite form in progressively increasing amounts as the calcination temperature increases from 1,500° to 2,000° F.

The general course of dehydration of beidellite is similar to that of montmorillonite, but loss of H⁺ and OH⁻ ions and shrinkage of the lattice take place at lower temperatures (between about 750° and 950° F), dehydration being essentially complete at 2,000° F (fig. 47) (Nutting, 1943). Depending upon the chemical composition, degree of alteration, and exchangeable cations, beidellite may lose more than 12 percent by weight of water during heating from 212° to 2,000° F. Irreversible shrinkage of the crystal lattice of beidellite begins during calcination at a temperature about 800° F, being completed during calcination at 1,200° F. Disintegration of the lattice apparently begins with calcination at 1,400° to 1,600° F, and after calcination at temperatures of 1,600° to 1,800° F, the atomic arrangement within the crystal of beidellite is destroyed (table 17). During calcination at 1,600° F, beidellite commonly disintegrates completely and spinel crystals of colloidal dimensions form. With heating to 1,800° F, the crystals of spinel increase in size and cristobalite is formed and both minerals persist after calcination at 2,000° F, but a small amount of mullite and other unidentified crystalline compounds also are developed. In general, montmorillonite-type minerals fire first to a spinel if substantial proportions of Al⁺⁺⁺ occur in tetrahedral coordination, whereas quartz or cristobalite occur before spinel if the proportion of Si⁺⁺⁺⁺ approaches 4.00 (Bradley and Grim, 1951).

Nontronite and saponite rarely occur in amounts sufficient to be of interest as a source of pozzolan.

Pozzolans of Activity Type 3b are changed greatly by calcination in the range 800° to 2,000° F (Mielenz et al., 1950). Water requirement is markedly decreased with calcination. For materials of this type water required to produce a lime-pozzolan paste of normal consistency ranges from 32 to 165 percent. The setting time of lime-pozzolan paste decreases markedly with calcination of the pozzolan, usually to a minimum after calcination at 1,000° to 1,400° F. With calcination at higher temperatures, time of set increases. Comparative strength of portland-cement-pozzolan mortar increases with calcination of the pozzolan, the maximum strength being obtained after calcination at 1,200°, 1,400°, 1,600°, and 1,800° F, depending upon the composition of the pozzolan.

The effect of calcination upon the alkali reactivity of pozzolans of Activity Type 3b depends upon the mineralogic identity, chemical composition, and exchangeable cations present in the clay minerals. Sodium bentonite has been found to be comparatively ineffective in controlling alkali-aggregate reaction (Mielenz et al., 1950), apparently because the presence of exchangeable sodium prevents the clay from reducing the concentration of alkalies in the solution permeating the portland-cement mortar (figures 44 and 45). If naturally occurring sodium is replaced by calcium in Wyoming bentonite, the clay is effective in controlling alkali-aggregate reaction after calcination at 1,400° F (fig. 45).

The change in activity of montmorillonite-type clays with calcination relates to the crystallographic changes occurring with the heat treatment. Shrinkage of the montmorillonite and beidellite crystals from 14 or 15 kX units to 9.69 or 9.88 kX units (table 17), during calcination at temperatures ranging from 800° to 1,200° F, relates to increased reactivity with alkaline solutions and particularly a greater capacity of the clay to adsorb and hold alkali ions. Calcination from 1,200° to 1,600° F leads to destruction of the clay and formation

of comparatively stable compounds with resulting decrease in alkali reactivity of the pozzolan.

With calcination, illite clays lose free water between about 90° and 212° F (fig. 47) (Nutting, 1943). Adsorbed water is lost between 212° and 575° F, and dehydroxylation of the lattice occurs with heating above 575° F. Complete dehydration is accomplished at about 1,300° F. The details of dehydration and lattice change with calcination vary with composition, alteration, and exchangeable cations of the illite. The dimensions of the crystallographic lattice respond less to calcination than do those of the montmorillonite-type clays (table 17). Calcination from 212° to 1,600° F produces little change in X-ray diffraction patterns of two specimens analyzed, other than slight changes in position and intensity of line (table 17). After calcination from 1,600° to 1,800° F, the lattice has disintegrated with production in one specimen of spinel, quartz, and other unidentified compounds. Calcination at 2,200° F of a shale containing illite-type clay with muscovite, together with considerable calcite, dolomite, and quartz, produced a mixture of glass (*n* greater than 1.548), diopside (CaMg SiO_3)₂, quartz, and a small proportion of unidentified substances.

Pozzolans of Activity Type 3c are affected significantly by calcination in the range from 800° to 1,800° F. Water requirement is decreased moderately, especially after destruction of the clay by calcination at 1,800° F (Mielenz et al., 1950). For pozzolans of this activity type producing set of lime-pozzolan paste, time of set is reduced to a minimum by calcination of the pozzolan at 1,400° F. Compressive strength of lime-pozzolan mortar is improved slightly or moderately by calcination, maximum strength occurring after destruction of the clay component by heating at 1,800° F. Illite-type clay pozzolans investigated show little change in alkali reactivity with calcination in the range 800° to 1,800° F, and fail all tests (figs. 44 and 47).

The mixed clays with vermiculite-chlorite are clayey silts and clays which contain a complex mixture of clay minerals which constitutes 30 to 50 percent of the whole. They are distinctly inferior as pozzolans. X-ray diffraction analysis of a typical sample of the material indicates that the vermiculite-chlorite constitutes about 66 percent, beidellite-nontronite about 22 percent, and illite about 11 percent of the mixture. During calcination, the beidellite-nontronite and illite respond as indicated for these minerals in the previous paragraphs. Vermiculite-chlorite represents a series transitory between vermiculite and typical chlorite, the position of any given member of the sequence depending upon the relative proportions of hydrated exchangeable magnesium and water as against brucite ($\text{Mg}(\text{OH})_2$) in the interlayer space (Brindley, 1951). Irreversible dehydration may begin as low as 800° F if excessive interlayer water is present. At 1,600° F disintegration usually is complete. Pozzolans of Activity Type 3d show only slight change in reactivity with calcination up to 1,800° F. None developed set with lime while raw and many show no final set with lime after calcination at 1,000° F. Compressive strength of mortar ranges from inferior to good, the maximum strength being developed after calcination of the pozzolan at 1,800° F. No data are available on alkali-reactivity of pozzolans of Activity Type 3d.

Sparse data are available for palygorskite (Activity Type 3e). Tests have established the effect of calcined (1,400° F) and ground Floridin (Attapulugus clay) on mortar expansion resulting from alkali-aggregate reaction. Satisfactory results were obtained (fig. 45). During differential thermal analysis, Floridin loses adsorbed water in two stages at about 300° and 480° F (Kerr et al., 1949). Dehydroxylation proceeds between about 845° and 1,025° F. A sharp exothermic reaction at about 1,650° F marks the development of spinel.

Clays and shales are the source material of several pozzolans produced commercially or in pilot operations at several plants (Mielenz et al., 1951). Most notably, the siliceous shales of the Monterey formation of California, which owe their pozzolanic activity both to opal and beidellite, have been produced in a calcined condition and marketed by the California Cement Company at Colton, California, and by the Santa Cruz Portland Cement Company at Davenport, California. An oil-impregnated shale of Activity Type 3b occurring in the Monterey formation near Casimaria, California, has been used after calcination both in Cachuma Dam, near Santa Barbara, by the Bureau of Reclamation, and in Big Creek Dam No. 7, near Fresno, California, by the Southern California Edison Company. Mowry shale has been produced experimentally in Wyoming, and was used after calcination in highway test sections by the Kansas State Highway Department. The Eagle Ford shale, near Dallas, Texas, also a representative of Activity Type 3b, has been investigated as a source of pozzolan.

Altered pumicites owing their activity to both rhyolite glass and clay minerals have been produced. An altered pumicite owing a significant portion of its activity to montmorillonite was used in a calcined condition in construction of Falcon Dam, near Laredo, Texas. In investigations for Hungry Horse Dam, Montana, an altered pumicite owing its activity primarily to opal, anauxite, and kaolin was found to be satisfactory.

CONCLUSIONS

Physical-chemical properties control the engineering properties of earth material through mineralogic and compound composition, fabric (texture and structure), and fluids content. Much more remains to be learned about the interrelation of physical-chemical phenomena and engineering performance, but already application of known principles is lagging behind advances being made in the laboratory. Continuing progress is possible only with close coordination of laboratory investigations and field trials.

Study of physical-chemical properties will not replace the soil mechanics tests now widely used to establish quantitatively the response of earth materials to specific physical and hydraulic conditions. However, knowledge of physical-chemical properties of earth materials can aid the engineer by:

1. Anticipating probable performance of earth materials under varying conditions of service and thus aiding development of minimum testing programs
2. Selection of design or construction methods by which difficulties can be avoided or minimized
3. Explaining causes of failure so as to avoid recurrence in new construction
4. Selecting effective procedures for repair and maintenance in the face of difficulties
5. Outlining needed research

Areas of civil and materials engineering in which continuing fundamental and applied research on clays and shales is required to answer immediate engineering needs are:

1. Movement of moisture under structures
 - a. Conditions controlling movement of moisture in earth materials
 - b. Means of controlling movement of moisture in earth materials
 - c. Methods minimizing effects of moisture change on foundation materials
2. Drainage of foundations, subgrades, natural slopes, and embankments
 - a. Conditions controlling drainage of earth materials
 - b. Means of effecting drainage, including electrical methods
3. Stabilization of foundations, subgrades, natural slopes, and embankments
 - a. Physical-chemical phenomena in binding and waterproofing actions, including sensitivity to remodeling
 - b. Methods of controlling shear strength, bearing capacity, water resistance, and durability of water-bearing clays in place, including use of admixtures and agents, and electrochemical procedures
 - c. Methods of controlling settlement of structures on clay formations
4. Control of permeability
 - a. Low-cost earth canal linings
 - b. Methods of reducing permeability of formations in place
 - c. Methods of increasing permeability to improve drainage and reduce development of pore water pressure in clays and shales.
5. Channel stabilization and erosion control
 - a. Conditions controlling erosion of clays and shales in place or in embankments
 - b. Conditions controlling establishment of cohesion in newly deposited clays
 - c. Methods of controlling erosion of clays, including prevention of erosion of clays and shales and inducement of scour in newly deposited clays
6. Calcination of clays
 - a. Production of lightweight aggregate from clays and shales
 - b. Production of pozzolans by heat treatment of clays, shales, and clayey materials

Successful completion of these programs of research demands coordinated investigations in the field and in the laboratory. The properties and the performance of clays must be evaluated in the light of their composition and fabric and the geologic relations of the formations in which they occur. Evaluation of performance must be made with due regard to conditions of service to which the installation might be subjected.

Continuing advance in engineering involving either use of clays as construction materials or construction of works at sites underlain by clays can come only with close cooperation of the engineer, the engineering geologist, the engineering petrographer, and the clay technologist.

ACKNOWLEDGMENTS

The authors wish to express their gratitude to their colleagues of the Bureau of Reclamation for assistance and helpful discussion in the development of this paper. In particular, they recognize the generous cooperation of W. G. Holtz, H. J. Gibbs, and N. C. Schieltz. E. J. Benton and F. H. Geier assisted in compilation of the data.

The authors also are indebted to many individuals and organizations for their generosity in supplying or permitting use of data and illustrations. In this regard they recognize the cooperation of J. E. Jennings, Director,

National Building Research Institute, South African Council for Scientific and Industrial Research; F. M. Lea, Director, Building Research Station, Department for Scientific and Industrial Research, Garston, England; The American Society for Testing Materials; The Highway Research Board; The Reinhold Publishing Corporation; A. E. Cummings, Raymond Concrete Pile Company; H. F. Winterkorn, Princeton University; and Irving Goldberg and Alexander Klein, Institute of Transportation and Traffic Engineering, University of California, Berkeley, California.

The Engineering Laboratories are under the direction of W. H. Price. All design and construction activities are supervised by L. N. McClellan, Assistant Commissioner and Chief Engineer. The Bureau of Reclamation, United States Department of the Interior, as a whole is directed by W. A. Dexheimer, Commissioner.

DISCUSSION

C. G. Dodd:

Has there been any practical application of electro-osmosis to the removal of water from clays for practical soil-mechanics operations?

R. C. Mielenz:

Most of the work has been done in Germany and Russia and very little in this country. I understand that the principle of electro-osmotic dewatering to effect stabilization was used at La Guardia Field during its construction. Preece (1947) has done a great deal of work on electro-osmotic and electrochemical stabilization. The most extensive practical applications were made in Germany during the war, for stabilization of embankments, excavations, and U-boat pens. Electro-osmosis theoretically involves only withdrawal of water without addition of materials to the soil. Conversely, electrochemical stabilization involves both electro-osmotic withdrawal of water and addition of new substances to the soil, either by decomposition of the electrodes or by addition of chemicals added at the electrodes. Electro-osmosis is not permanent unless some supplementary means of preventing return of the water to the dewatered area is installed. The electrochemical process may or may not be permanent depending upon the specific reactions that have taken place.

R. E. Grim:

The process of electro-osmosis is used by the railroads in Holland for dewatering in some of the low areas. There the process goes on continuously. In Sweden paper wicks for dewatering were punched into the ground in the construction of the International Airport between Stockholm and Upsala. The wicks were 5 inches wide and about $\frac{1}{2}$ inch thick and were inserted by a specially developed apparatus.

R. L. Stone:

There has been some work done on application of electrophoresis to the beneficiation of ball clays and kaolins. The rewetting properties of this clay in comparison with one partially dewatered by centrifuging may be of interest. In each case, final removal of water was accomplished by drying at 70° C. When rewetted, as in the formation of casting slips, there was no difference in gel strength and casting rate. A difference did show up in the DTA curves: a deflection was observed at 380° C for the electrophoresized ball clay. No difference, however, was found by chemical or X-ray analyses. It is suspected that the results had something to do with the electron charge.

R. C. Mielenz:

There are several examples of cracking in clay formations, sometimes below the water table, in which drying cannot explain the degree of cracking present, and which might be explained by syneresis. I have not been able to find a satisfactory explanation of syneresis as far as it relates to clays. This process or property has been studied extensively in the organic and inorganic gels and dyestuffs, but little work has been done with clays.

Syneresis is a spontaneous separation of a homogeneous colloidal system into a coherent gel and a liquid. In a study of the geologic significance of syneresis Jünger (1934) describes many features

which have been explained as raindrop prints, drying cracks, ripple marks, and worm trails in clays, chalks, and marls. In 1949 A. S. Carey (1949) described a clay which was intensely cracked both above and below the water table. These cracks might be the result of syneresis.

E. A. Hauser:

Syneresis is most pronounced not in solid structures but in gel structure. There the cause is that we are dealing here not in the colloidal range of dimensions which is not stable, but from the point of view of the diffuse ionic layer surrounding the individual particle. In the solidified state the cause of the shrinkage is that you have a conflict between *van der Waals'* forces of attraction between two solid particles and the still strongly adsorbed dipolar water layer surrounding the individual particle. With time, temperature, and pressure, the *van der Waals'* forces dominate and squeeze out the water resulting in syneresis and cracking.

W. P. Kelley:

We were building a small farm-size reservoir on a rather sandy soil at Riverside which leaked like a sieve. The problem was to find something to seal it that was not too expensive and a series of bentonites was tried. In laboratory testing the materials were spread on large Buchner funnels to a certain depth with a certain head of water. The amazing observation at the time was that after a few days of standing with the head of water on them, cracks began to develop, some of them big enough to let one's finger go through. Later on, some of these bentonites were actually used to seal this reservoir. They worked very well for a while, but later cracks began to develop in the bentonite lining of the wall, so that it had to be done all over again.

T. F. Buehrer:

Are there any other tests besides DTA and color tests to determine suitability of clays for purposes such as canal linings, refractories, and other ceramic uses?

E. C. Henry:

For brick and tile, the physical properties of the clay frequently are more important than the mineralogical properties. If the workability is good, the percentage of water of plasticity not too high, the clay not too sticky, and the drying shrinkage not excessive—so that the pieces will not warp or crack—and the firing behavior satisfactory, the clay will almost certainly be suitable. Physical tests like these are quicker and more decisive than determining the mineral constitution of the clay. For canal linings one would want a swelling type of bentonite, one that will be stable in the swollen condition so that permeability will remain low.

R. C. Mielenz:

The Bureau of Reclamation has under way a lower-cost canal lining program, primarily to develop cheap and more effective ways to reduce seepage from canals. Bentonite has long been used for this purpose, either as very thin membranes of essentially natural bentonite or admixed with local soils. With hydration swelling of the bentonite seals off the pores and reduces the permeability of the lining. For a quick field test, the free-swell test is recommended. This test involves granulation of the dried sample through No. 30 sieve, a bulk volume of 10 cc of the No. 30 to No. 50 sample is sifted into distilled water; and the apparent bulk volume of the wetted material is observed after 24 hours. If the bulk volume does not exceed 6 times the original volume, the material is considered to be inferior or unsuitable for use. Material passing this test is worthy of further testing.

W. T. Cardwell, Jr.:

In the oil industry, we too are interested in the relation between clay swelling ability and sealing ability. In a drilling fluid it is desirable to use a clay that will form only a thin filter cake on the wall of the well, a cake whose low permeability prevents further rapid loss of fluid.

At one time we thought there should be a useful relation between swelling ability and sealing ability, as is assumed in the preliminary selection tests described by Dr. Mielenz. However, we found that the correlation between swelling ability and sealing ability is of the following sort: All clays with high swelling abilities have low permeabilities, and all clays with high permeabilities have low swelling abilities. But some of the clays with poor swelling abilities also have low permeabilities. This shows that if one were trying to pick good sealing clays by means of a swelling test, he would not pick any poor sealers, but he would miss some of the good ones.

R. C. Mielenz:

It is necessary to make some kind of a screening determination because it is expensive to perform the permeability test. The experience cited by Mr. Cardwell is most significant. We are now attempting to develop additional, more critical tests. At present a low swelling, low permeability bentonite will be recognized only by tests of permeability in the laboratory.

B. A. Vallerga:

How does the loss of strength due to thixotropic effects differ from that produced by deformation of a "sensitive" clay?

R. C. Mielenz:

The two might be very closely related. One would anticipate, of course, that a soil which was stabilized in part by thixotropic structure of the water would be a soil that was extremely sensitive to remolding. If the water content of the clay is over the liquid limit, the soil acts essentially as a liquid with vibration or loading sufficient to disrupt the stable water film and destroy the structure. This is true of the Mexico City clays which are montmorillonitic with a natural water content as high as 700 percent and with liquid limits on the order of 450 percent. With the destruction of the structure of stable water films as the result of loading, the clays lose their strength completely, but remolded specimens gain strength with rest.

D. P. Krynine:

How do you measure "sensitivity"?

R. C. Mielenz:

In terms of the strength of the remolded specimen in contract with the strength of the original material.

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