

Basic Aggregates

by

Robert C. Beste, PG

Aggregates are the major constituents of concrete (making up about 75 to 80 percent), asphaltic concrete (making up about 95 percent) and road and railroad base and bedding materials.

“Every kind of rock and every mineral species that occurs on this planet as a solid, grain, or mass - except ice - is potentially subject to evaluation for use as aggregate. However those substances that can significantly affect the performance of concrete, asphalt and ballast for better or worse when they occur as aggregate constituents are more important to identify, and among these, those that occur most frequently are of the greatest interest.”¹

A *Mineral* is a naturally occurring solid element or compound, exclusive of biological formed carbon components. It has a definite composition, or range of composition, and an orderly internal arrangement of atoms known as *Crystalline Structure*, which gives it unique physical and chemical properties, including a tendency to assume certain geometric forms known as *Crystals*.

A *Rock* is any naturally formed, consolidated material (but not soil) composed of two or more minerals, or occasionally of one mineral, and having some degree of chemical and mineralogic constancy, which is able to be represented as a sample of the unit.

Aggregates are normally processed from rock, however, some minerals can be processed as aggregate. This has given birth to a new term, *Industrial Minerals* which is synonymous with Sand, Crushed Stone, Clays, and other commercially used natural products.

Aggregates can be classified in three ways: *Size*, *Density*, and *Origin*.

Aggregates classified by **Size** or usually broken into two categories roughly divided at the #4 sieve: *Coarse Aggregates* and *Fine Aggregates*. Either of these two categories can be *Clean* graded (with the lower sized particles removed in processing) or *Full* graded (with the lower sized particles retained in processing - also called *Minus Stone*). These sizings may be specified by a nominal *Top Size* or by a specific Gradation Size number designation.

Aggregate classified by **Density** are classified into three categories: Normal Weight Aggregates, Lightweight Aggregates, and Heavy Weight Aggregates. The most commonly used type used in concrete are **Normal Weight** Aggregates which generally range in density from about 2.45 to 2.90 in specific gravity.

Lightweight Aggregates are generally below 2.0 in specific gravity and are widely used in lightweight concrete where weight is a critical factor in the design considerations of a

¹Dolar - Mantuani, L., 1983, Handbook Of Concrete Aggregates

structure. Most lightweight aggregates are produced from products such as expanded shale but some natural sources do exist.

Heavy Weight Aggregates are used in concrete to increase the weight of the concrete or to provide shielding in concrete for nuclear power plants. In railroad ballast Heavy Weight Aggregates are used for steep grades to better hold the roadbed. In the past most heavy weight aggregates have been produced from Iron Oxide ores but increasing heavy slags such as copper slags have been used in these applications. In fact only recently have lead slags been discontinued for use in these applications. Heavy Weight Aggregates range in density from about 3.0 to 5.0 in specific gravity.

Aggregates classified by **Origin** can be classified by how the rock was formed or *Rock Type*. They can also be classified by how they are processed.

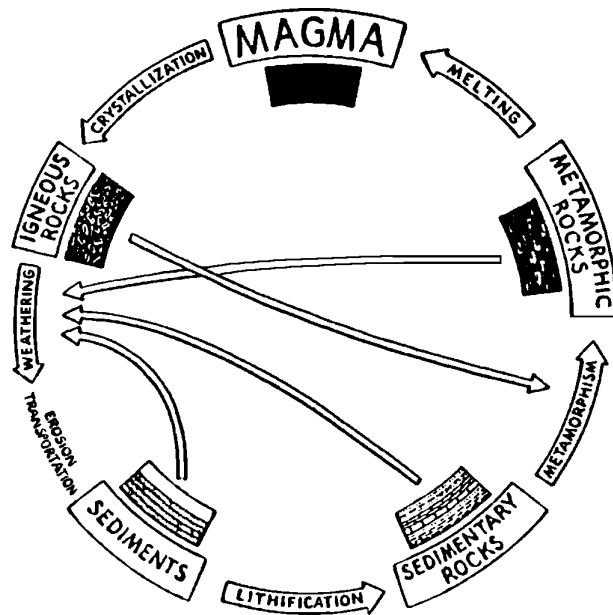
Aggregates classified by rock type (excluding man-made aggregates) fall into one of three types of rock: Igneous, Sedimentary, or Metamorphic.

Igneous rocks are formed by crystallization of liquid rock or Magma in the earth.

Sedimentary rocks are formed from small pieces of existing rock which has been broken down and moved by rivers and wind. These sediments were then deposited and cemented together by natural processes.

Metamorphic rocks are pre-existing rocks which have been changed by great pressure and heat (but not the point of re-melting). The rock cycle diagram to the right illustrates the inter-relation of rocks.²

Aggregates classified by processing are man made such as Slags, Expanded Shales, Manufactured Sand, etc.



All aggregates can be characterized by two components Size and Physical & Chemical Properties. This is very much the same way shoes are sold. Size is denoted by a specific Gradation or sizing much the way shoes have different sizes large to small. Physical & Chemical Properties are not un-like the different types of shoes, i.e. Slip-ons, Dress shoes, Tennis Shoes, etc. As in shoes, you can wear the same sized shoe but it would not be proper to wear Tennis Shoes to a Banquet, nor could you wear Tennis Shoes to the court 3 sizes too big. Properties which affect an aggregates performance are shown on pages 3 to 5.

²Leet, L.D. & Judson, S., 1963, Physical Geology; 3rd Ed.

Effects of Aggregate Properties on Concrete, Asphaltic Concrete and Ballast

Properties	Aggregate Desirable Characteristic	Aggregate Objectionable Characteristic
Physical Properties		
Texture		
Crystallinity	Crystalline	Partially or Entirely Glassy
Grain Size	Medium to Fine	Large
Intergranular Bond	Interlocked with Good Bond	Coarse grained minerals, Poor Bond
Packing of Grains	Dense	Loose
Granularity	Medium to Fine	Conglomerate
Cementation	Well Cemented	Poorly Cemented
Cementing Medium	Silica, Carbonates	Clay, Limonite, Halides
Structure		
Continuity of Structure	Massive	Fissile, Foliated, Shistose
Stratification	Thick Layered, Widely Stratified	Thin Layered, Highly Stratified
Parting Joints	Widely Spaced	Narrowly Spaced
Mechanical Properties		
Sound when hit with hammer	Rings	Sounds Dull
Compactness	Compact	Loose
Hardness	High Mohs Hardness, Hard	Low Mohs Hardness, Soft
Toughness	Interlocked grains, Tough	Weak
Compressive Strength	High Strength	Low Strength
Modulus of Rupture	High Strength	Low Strength
Elasticity	Elastic	Non-Elastic
Resistance to Abrasion	High Resistance, Hard	Low Resistance, Soft
Resistance to Impact	High Resistance, Strong Granular Interlock	Low Resistance, Weak Granular Interlock
Resistance to Polishing (asphalt)	Slight polishing over time	Easily polishes
Internal Fracturing	Free of micro- and macrocracks	Easily broken, high micro- and macrocracks, crack due to Cleavage, Laminated
Properties Influencing Physical Stability		
Volume Stability	Low Compressibility	High Compressibility
Density	High Density	Low Density
Vugginess	Slight	Very Deeply Vuggy
Porosity	Low Porosity, Compact	High Porosity
Pore Size & Quality	Few Pores > 0.2 Microns or Pores < 0.04 Microns	Many Pores 0.2 - 0.04 Microns
Distribution of Pores	Even Distribution	Uneven Distribution
Permeability	Low, Impermeable	High, Permeable
Water Absorption	Slight	High

Properties Influencing Physical Stability (continued)		
Solubility in Water	Insoluble	Soluble
Sensitivity to Water	No significant Volume Change or disintegration on wetting	Expands on wetting, flakes or disintegrate in water
Susceptibility to wetting & Drying	Resistant to disintegrating due to wetting and drying cycles	Disintegrate in water
Susceptibility to freeze-thaw Damage	Low; High frost resistance	High; Low frost resistance
Volume stability on heating & cooling	Stable	Unstable
Coefficient of Thermal Expansion	High; compatible with that of cement paste	Very Low
Chemical Properties		
Compositional Stability		
Chemical Stability (activity)	Practically Stable	Unstable
Surface Reactivity (concrete)	Non-reactive or very slightly reactive	Reactive with formation of unstable products
Reactivity with cement paste (concrete)	Non-reactive or slightly reactive, non-expansively reactive	Reactive with excessive expansion
Chemical Reactivity	Insensitive to external environment	Highly sensitive to environment: oxidizes, hydrates, carbonates or forms sulfates
Volume stability in acids & bases	Stable	Unstable, Swells
Volume instability do to ion exchange	Cation exchange minerals absent	Cation exchange minerals present
Color stability	Stable	Unstable, discolors easily
Coatings, Incrustations	Unreactive	Reactive
Weathering or Alteration products	Unreactive	Reactive
Specific Bulk Aggregate Properties		
Particle Shape (sphericity)	Cubic	Oblong and/or Flat
Angularity	Angular to Sub-Rounded	Sharp Angular or Well Rounded
Surface Texture	Rough, Rugged	Very Smooth
Adherence (bond) of particles to cement paste or asphalt (coating, incrustation)	Good adherence, Good Bond	Poor adherence, Poor Bond
Packing capacity of particles (concrete, asphalt)	High capacity with small or few large interparticle voids	Low packing capacity with many large interparticle voids
Unit Mass	Relatively High	Low Unit Mass
Rock Cement Value of fines (ballast)	No or Little Cement Value	High Cement Value
Resistivity (ballast)	High Resistivity, passes little AC or DC current	Low Resistivity, easily passes AC or DC current

Effects of Aggregate Properties on Concrete, Asphaltic Concrete and Ballast

Complex General Properties		
Mineralogical and Lithological compositional properties	Desirable minerals and rocks present	Harmful minerals and rocks present (concrete: sulfates, sulfides, Zeolites, Magnesite, etc.; ballast: schistose & high mica rock)
Distribution of minerals, rock constituents, textures & structure	Homogeneous, uniform	Heterogeneous
Physical & Chemical condition due to weathering and/or alteration	Insignificant changes in texture, structure, or composition; reactive products absent	Significant changes in texture, structure, or composition; reactive products or physically harmful products present
Alumina Content (carbonates)	Very Low	High
Mica Content (igneous & metamorphic rocks)	Very Low	High
Surface of particles	Fresh, Clean	Weathered, <i>Dirty</i> coated with clay minerals, rock dust or organic matter
Contaminants	None or few slightly harmful contaminants present	Large amounts of objectionable or few very objectionable contaminates present
Material finer than 75 μm	Few, physically or chemically not harmful; low clay fines	Large amounts of physically or chemically harmful; high clay fines

Adapted from: Handbook of Concrete Aggregate, Dolar-Mantuani, L. and including data from

Ballast Selection and Grading, Raymond, G.P., Boon, C.J. and Lake, R.W

Effects of Particle Characteristics on Behavior of Granular Material, Selig and Roner;

Iowa Pore Test, Dubberke and Marks

The relationship of Aggregate Durability to Trace Element Content, Dubberke and Marks

Absorption and other properties of carbonate rocks affecting soundness of aggregate, Harvey, Baxter, Fraser & Smith

Alumina Content of Carbonate Rocks as an index to Sodium Sulfate Soundness, Baxter and Harvey

Igneous Rocks

Igneous Rocks are generally hard durable aggregates. This varies with the individual mineral assemblage of the rock itself. Igneous rocks are usually very low in absorption. For aggregate with an absorption value above 1%, the strong possibility of adverse weathering is present which should signal the need for further testing. A general chart for Igneous Rock types is contained on page 7. As a general rule for unweathered aggregates, finer grained (or Aphanitic) material performs better in the areas of resistance to impact and abrasion than larger grained (or Phaneritic) material. Coarser grained igneous rocks tend to break more easily on crystal boundaries. In the area of mineral assemblage, Basalts tend to be more durable than granite.

Considerations in quarrying Igneous rocks are Oxidized Zones and boundary Chill Zones. These Zones will normally have less desirable Physical Properties than the interior of the rock mass. Because of their brittleness, internal fracturing of this rock type is a factor which can greatly reduce rock durability. These micro-fractures are usually not apparent to the naked eye. An example of this is the fact that two physically appearing Basalts can be the most durable or least durable in a group of different stone types.

Mica and other platy minerals reduce durability in Igneous (and Metamorphic) Rocks. They provide an easy parting plain for the fracture of the particle.

Certain minerals contained in Igneous Rocks can be reactive with higher alkali cements. Some rocks which have been reported as Alkali-Reactive Siliceous Rocks in the past are Andesites, Basalts, Dacites, Granites and Rhyolites. This does not mean that these categories are always reactive, but because enough Igneous Rock has been found to be reactive, either the deposit should be tested (best by the mortar bar method with the local cement) for possible reactivity or concrete made from untested aggregates should be limited to low alkali cement and/or fly ash.

Metamorphic Rocks

Metamorphic Rocks can be categorized into two major groups: Non-Directional Structure which is massive or granular (caused by contact metamorphism and therefore less widespread), and Directional Structure which is lineate or foliated (caused by regional metamorphism). Of the two types, Non-Directional Structured stone is preferable to Directional Structured stone as aggregates. Some examples of these rock types are found on page 8.

The mineral assemblage of the rock again will effect durability and other physical properties. Softer minerals and platy minerals reduce the durability of the stone. The degree of Metamorphism also affects durability, the higher the level of metamorphism the higher the durability.

Most Gneisses have some Schistose material contained with it. As the Schistose material increases, durability is reduced.

Generalized Chart of Igneous Rock Types

Darker Color » » »	Light Colored Minerals with K Feldspar > 2/3 of the total Feldspar. Mainly K Feldspar, Quartz, and mica with minor amounts of dark minerals.	Mostly Light Colored Minerals with K Feldspar 1/3 to 2/3 of the total Feldspar. Mainly Feldspar, Quartz, and mica with minor amounts of dark minerals.	Light and Dark Colored Minerals (salt & pepper) with Na Feldspar > 2/3 of the total Feldspar. Mainly Na Feldspar, dark minerals, with some Quartz, and dark mica	Mainly Dark Colored Minerals with Ca Feldspar > 2/3 of the total Feldspar. Mainly Ca Feldspar, dark minerals, with little Quartz, and some Olivine	Dark Colored Minerals with little or no Feldspar. Mainly iron rich dark minerals and Olivine
Phaneritic (large crystal size)	Granites , Syenites and Nephelene Syenites	Monzonite	Granodiorite and Diorite	Gabbro Diabase and Theralite	Peridotite
Porphyritic (mixed large and very small crystals)	Granite Porphyry , Rhyolite Porphyry , Syenite Porphyry, Trachyte Porphyry, Phonolite Porphyry	Monzonite Porphyry and Latite Porphyry	Granodiorite Porphyry, Diorite Porphyry , Dacite Porphyry and Andesite Porphyry	Gabbro Porphyry , Basalt Porphyry and Theralite Porphyry	Peridotite Porphyry and Limburgite Porphyry
Aphanitic (very small crystal size)	Rhyolite , Trachyte and Phonolite	Latite	Dacite and Andesite	Basalt and Theralite	Limburgite

(Note. The most rock types are highlighted in bold print.)

Generalized Chart of Metamorphic Rock Types

	Non-Directional Structure Contact Metamorphism	Directional Structure - Regional Metamorphism		
		Slaty	Phyllitic	Schistose
Metamorphism » » »				Gneissose
Light Color	Metaquartzite, Marble and Hornfels		Phyllite (an intermediate state between Slate and Schist)	Quartzite Gneiss and Granulite
Intermediate Color (including red or brown)	Metaquartzite, Marble, Hornfels and Serpentine			Granite Gneiss, Granodiorite Gneiss, and Biotite Gneiss
Dark Color (including green)	Metaquartzite, Marble, Hornfels and Serpentine	Slates		Diorite Gneiss

(Note. The most rock types are highlighted in bold print.)

Certain minerals contained in Metamorphic Rocks can be reactive with higher alkali cements. Zeolites have been found to be harmful due to their tendency to exchange ions in their crystal lattice (causing an increase in volume). Periclase (MgO a high temperature metamorphic mineral found in marble formed from dolomitic limestones) can be reactive and expansive. It easily alters to Brucite ($Mg(OH)_2$). Some rocks which have been reported as Alkali-Reactive Siliceous Rocks in the past are Granite-Gneiss, Granodiorite-Gneiss, Hornfels, Phyllites, Quartzites and Schists. This does not mean that these categories are always reactive, but because enough Metamorphic Rock has been found to be reactive, either the deposit should be tested (best by the mortar bar method with the local cement) for possible reactivity or concrete made from untested aggregates should be limited to low alkali cement and/or fly ash.

Limestones and Dolomites

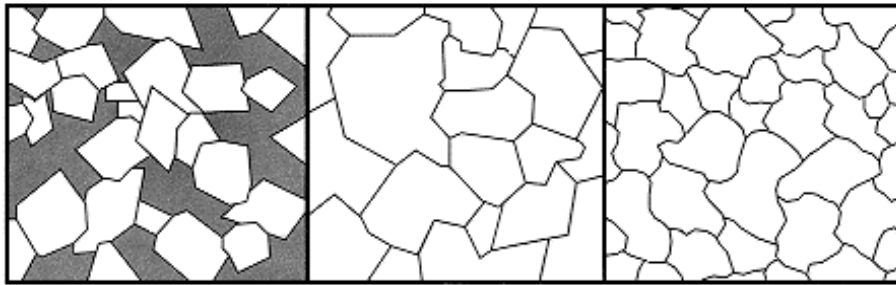
Limestones and Dolomites are the most widespread Sedimentary Rocks used for aggregates. These are made of primarily of Calcium and Magnesium Carbonates. Very few limestone's or dolomites are pure compounds. True *High Lime* Limestone are used in chemical applications such as stack de-sulfurization. Normally, besides impurities such as Iron, Silica and Alumina; they most always have some blend of Calcite ($CaCO_3$ the major constituent of Limestone) and Dolomite ($CaMg (CO_3)_2$ the major constituent of Dolomite). This creates a series in rocks from Limestone to Dolomite (shown below, considering only the mix of Calcium and Magnesium Carbonates).

True Limestone	Dolomitic Limestone	Limy Dolostone	True Dolomite
Containing 95% or more Calcite and less than 5% Dolomite	Containing from 50% to 90% Calcite and 10% to 50% Dolomite	Containing from 50% to 90% Dolomite and 10% to 50% Calcite	Containing 90% or more Dolomite and 10% or less Calcite

Limestones come in many types and grain sizes, i.e. crystalline, fossiliferous, etc. Generally they are compact and low in absorption, lighter in both color and density than true Dolomites. They can change to Dolomitic Limestones by the process of Dolomitization.

Dolomitization is the process whereby limestone is wholly or partly converted to dolomite rock or dolomitic limestone by the replacement of the original calcium carbonate with magnesium carbonate, usually through the action of magnesium-bearing water (seawater or percolating meteoric water). It can occur penecontemporaneously or shortly after deposition of the limestone, or during lithification at a later period. It is commonly accompanied by recrystallization and by shrinkage of volume (as much as 11% if the original limestone) leading to the formation of pores, cavities, and fissures. Limestone which have become dolomitized are usual higher in absorption, softer, and has a higher L.A. Abrasion loss than their parent limestones. This type of rock is usually used for base stone, or if the Magnesium content is high enough, for fluidized bed material. Examples of this process are seen in the uppermost ledges of quarries or along seams which carry water laterally through the formation.

Dolomites are categorized into three types³:



Plainer E Dolomite

Crystal Structure: Straight
Euohedral Crystal faces
Least Dense
Porosity: High

Plainer S Dolomite

Crystal Structure: Subhedral
Crystal faces
Density: Medium Density
Porosity: Medium

Non-Plainer Dolomite

Crystal Structure: Anhedral
Crystal faces
Density: Very Dense
Porosity: Very Low

Plainer S Dolomites and Non-Plainer Dolomites are best suited for the building industry. Only Non-Plainer Dolomites are well suited for railroad ballast. Dolomites are generally darker in color and heavier than true Limestone. They are also more resistance to chemical attack than Limestones.⁴

Limestones and Dolomites many times do quite well on impact tests such as the L.A. Abrasion but are not sufficiently hard to produce low loss during wear or abrasion tests such as the Mill Abrasion test. This has led to most railroads having a prejudice against using carbonate rocks for mainline ballast, especially limestone. Many limestones fines also have higher cement values than dolomites. of Igneous Rocks and most Metamorphic Rocks have no cement value. This aids in the ability of the ballast to remove worn stone from the roadbase that collects moisture which causes damage to the sub-base. These fines, while not generally conductive themselves, retain moisture and reduce the resistivity of the ballast as a whole. This can create signal problems.⁵

Some Carbonates can be reactive with higher alkali cements. Carbonates with roughly equal amounts of calcite and dolomite and which also have amounts of illite clay in their matrix can sometimes be reactive. The reaction is caused by a reverse dolomitization which causes the dolomite to revert to brucite ($Mg(OH)_2$, with a net volume reduction) followed by an uptake of water by the illites causing expansion. Iron sulfides such as pyrite and marcasite are also reactive causing expansion and staining. Some other Sedimentary Rocks which have been reported as Alkali-Reactive Siliceous Rocks in the past are Arenites, Argillites, Chalcedony, Chert, Dolomite, Dolostones, Flint, Graywacke, Opal, and Siltstones. This does not mean that

³Greg and Sibley, 1987, Journal of Sedimentary Geology

⁴Lamar, J.E., Limestone For Sewage Filter Beds, 1929

⁵Signals are transmitted through one track and back through the other with the engine functioning as a moving shunt. Reduced resistivity allows the signal to pass from track to track through the ballast.

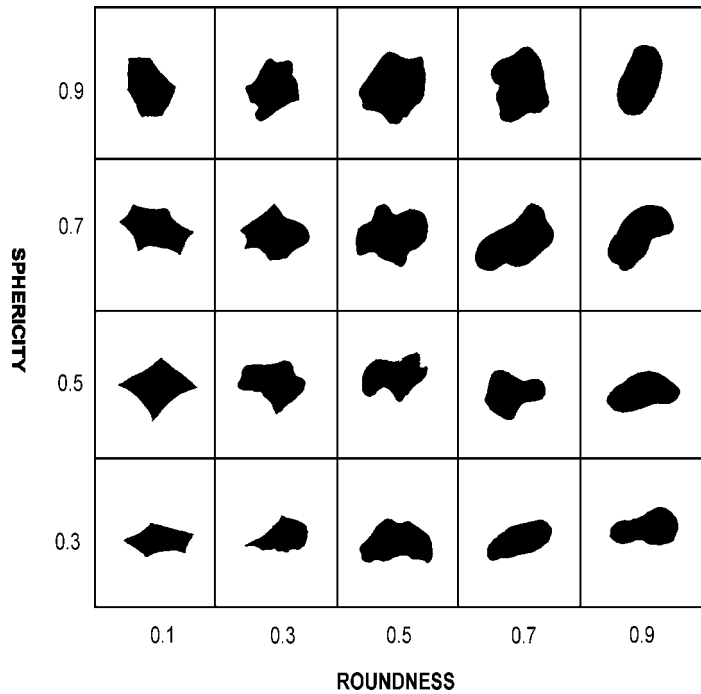
these categories are always reactive, but if a large clay or quartz content is present there is an increase of potential for expansion and either the deposit should be tested (best by the mortar bar method with the local cement) for possible reactivity or concrete made from untested aggregates should be limited to low alkali cement and/or fly ash.

A General Summary of Engineering Properties of for Rocks is contained on page 12.

Particle Shape in an Aggregate Mix

Particle shape affects interlock of aggregates. A simple graph to estimate particle shape is shown to the right: Aggregates near the center of the chart usually perform best for construction purposes. S & P values for a given aggregate can be useful in predicting aggregate performance when other factors remain equal. Up to a given point, more angular particle have increased surface area (a plus). Past a given point the extremely angular particles tend to degrade on the edges (a minus).

Stockpiling characteristics are also affected by particle shape. The more rounded a aggregate, the less steep the angle of repose.



Summary of Engineering Properties of Rock

Type of Rock	Mechanical Strength	Durability	Chemical Stability	Surface Characteristics	Presence of undesirable impurities	Crushed Shape
Igneous Granite, Diorite, Syenite Felsite Basalt, Diabase, Gabbro Peridotite	Good Good Good Good	Good Good Good Fair	Good Questionable Good Questionable	Good Fair Good Good	Possible Possible Seldom Possible	Good Fair Fair Good
Sedimentary Limestone, Dolomite Sandstone Chert Conglomerate, Breccia Shale	Good Fair Good Fair Poor	Fair Fair Fair Fair Poor	Good Good Poor Good	Good Good Fair Good Good	Possible Seldom Likely Seldom Possible	Good Good Poor Fair Fair to Poor
Metamorphic Gneiss, Schist Quartzite Marble Serpentine Amphibolite Slate	Good Good Fair Fair Good Good	Good Good Good Fair Good Good	Good Good Good Good Good Good	Good Good Good Fair to Poor Good Poor	Seldom Seldom Possible Possible Seldom Seldom	Good to Poor Fair Good Fair Fair Poor

Shales and Clay Minerals

Clay minerals proper are sheet-structure Hydrrous Aluminosilicates that contain Sodium, Potassium, Calcium or Magnesium as exchangeable cations. The crystal lattice is characterized by a few basic sheet units stacked on top of one another.

Properties of Main Clay Mineral Subgroups⁶

Property	Kaolinite (Kandite) Subgroup	Illite Subgroup	Montmorillonite (Smectite) Subgroup
Individual particle size, in μm	4.0 to 0.3 μm	0.3 to 0.1 μm	0.2 - 0.02 μm
Relative water adsorption	Slight	Moderate	Very Large
Principal interlayer cations	(Nil)	Potassium	Calcium, Sodium
Relative ion exchange	Slight	Moderate	Large
Relative permeability	Large	Moderate	Small
Relative plasticity	Slight	Moderate	Large
Refractive Index (range)	1.55 to 1.57	1.54 to 1.61	1.48 to 1.53
Birefringence, mm	~ 0.006	~ 0.03	~ 0.01 to 0.02

Major Problems Presented by Shales and Clay Minerals

Intercrystalline Volume Change. The most important property inherent in all clay minerals is a volume change on wetting and drying. This type of volume change is due to the uptake of water into the crystal surface and the space between crystals.

Intracrystalline Volume Change. This type of volume change is due to water and exchangeable ions entering the crystal lattice and occupying the space between the lattice sheets and between unit layers of crystals.

These actions cause pop-outs in concrete, poor performance in soundness tests, lower resistance to abrasion and impact, and are more susceptible to frost damage. Some shales also carry reactive or expansive materials in their matrix.

⁶Krumbein and Sloss, 1963, p.195, Table 6.2 and Deer et al, Vol. 3, p. 192, Table 30.