Chapter 15

CONSTRUCTION MATERIALS

15.1 PURPOSE AND USES OF AGGREGATES

15.1.1 *Aggregates Used without the Addition of a Cementing Material*

Aggregates are used by themselves, that is, without the addition of a cementing material, in such applications as bases or sub-bases for flexible and rigid pavements. In the case of a base for a rigid pavement, the purpose of the layer may be to prevent **pumping**, to cover a frost-susceptible material, or to improve the general drainage characteristics of the section. Load-carrying capacity of the base layer is not a primary consideration in the choice of a material. Rather, gradation is the primary consideration. In the case of bases and sub-bases for flexible pavements, however, load-carrying capacity is a primary factor in the selection of materials. Here, too, gradation plays an important role, but, in addition, the material used in any particular layer of the flexible pavement system must reinforce those layers beneath it and must be capable of withstanding and transmitting the load to which it will be subjected. Strength tests such as the triaxial compression test and the California Bearing Ratio Test (CBR) are commonly used to evaluate such materials.

Aggregates by themselves frequently make up the entire pavement structure. This type of pavement, sometimes referred to as the low-cost road, is one "*in which a layer of predominantly granular material is placed on the natural soil to serve as a wearing course or a base course for a relatively thin flexible surface*". Again, the requirements for these materials are mainly gradational requirements, with perhaps a restriction placed on the plasticity of the material passing the No. 2000 sieve. The emphasis here is on the maximum use of local materials.

Aggregates are also used without the addition of cement for shoulder material. The main requirements in this application are again gradation and stability. Naturally, all shoulders are not composed of uncemented graded aggregates. The trend towards paved shoulders has progressed rapidly.

15.1.2 *Aggregates for Bituminous Pavement Layers*

There are many types of bituminous pavement layers used by various highway agencies. The situation with regard to bituminous mixtures is not so simple as it may appear with Portland Cement Concrete (PCC) mixtures. In the latter case there is one basic type of mixture for slab construction, whereas there is a multiplicity of types of mixtures in the former. In spite of the many types of bituminous layers that

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are used, the ideal aggregate for bituminous construction, regardless of class or type, would have the following characteristics :

1. strength and toughness,
2. ability to crush into chunky particles, free from flakes, slivers, and pieces that are unduly thin and elongated,
3. low porosity (however, it should not be completely lacking in porosity),
4. hydrophobic characteristics, and
5. particle size and gradation appropriate to the type of construction.

15.1.3 *Aggregate in Fresh, Plastic Concrete*

When concrete is freshly mixed, the aggregates really are suspended in the cement-water-air bubble paste. Behavior of this suspension (i.e., the fresh, plastic concrete), for instance, ease of placement without segregation causing rock packets or sand streaks, is crucially influenced by selection of the amount, type, and size gradation of the aggregate. Depending upon the nature of the aggregates employed, a fairly precise balance between the amount of fine and coarse-sized fractions may have to be maintained to achieve the desired mobility, plasticity, and freedom from segregation, all lumped under the general term 'workability'. Selection of mixture proportions should aim to achieve optimum behavior of the fresh concrete consistent with developing desired properties in the hardened product.

15.1.4 *Aggregates in Hardened Concrete*

The aggregates contribute many qualities to the hardened concrete. The strength-giving, binding material holding concrete together results from the chemical union of the mixing water and cement and is, of course, the basic ingredient. This hardened cement-water-air bubble paste would, by itself, be a very unsatisfactory building material, not to speak of its high cost. Indicative of the cost is the observation that if such a paste were used alone with the water contents of average concrete, it would contain from about 10 to 13 tons of cement per cubic yard. The paste, subsequent to initial hardening, unless restrained by contained aggregates, undergoes an intolerable amount of shrinkage upon drying. The exposed portions of such pastes dry out first, and differential shrinkage between the outside and inside portions often results in cracking. The presence of aggregates provides an enormous contact area for intimate bonding between the paste and aggregate surfaces. Rigidity of the aggregates greatly restrains volume change of the whole mass. Shrinkage of concrete is only about one-tenth that of paste. Thus, the aggregate is not only cost-conserving but is really essential.

In some cases, cement grouts containing little or no aggregate are employed successfully for underground work where severe drying is not expected. Expanding agents are also used to compensate for shrinkage, where drying is anticipated such as in grouting tendons in post-tensioned, pre-stressed members.

It is an inescapable conclusion that aggregates are not simply fillers used to dilute the expensive water-cement paste and thus make a cheaper product. Economics are important, but significant improvements in the workability of the fresh concrete are contributed by proper choice of aggregates. Such a choice influences the highly important properties of the hardened concrete such as volume stability, unit weight, resistance to the destructive environment, strength, thermal properties, and pavement slipperiness.

A major use of aggregates in the highway industry is, of course, in Portland Cement Concrete for rigid-pavements, slabs, bridges, and other structures. Aggregates for concrete should be physically and chemically stable. It was earlier stated that the properties of an aggregate were primarily dependent upon its mineralogic composition, internal texture, and internal structure. These factors then influence the concrete-making quality of an aggregate to a major degree. The general requirements of aggregates for Portland Cement Concrete are as follows : size, distribution and interconnections of voids; surface character and texture; gradation; internal texture and structure; mineral composition; and particle shape.

Probably no other physical characteristic of an aggregate has such an important effect on the water requirements and workability of fresh concrete mixtures as the gradation or particle size distribution. These factors profoundly influence a large number of other important concrete properties. Particle shape also affects concrete workability, segregation, and bleeding.

15.2 AGGREGATE QUALITIES OF CONCERN

1.	Gradation	6.	"D" cracking potential
2.	Maximum size	7.	Alkali reaction potential
3.	Surface properties	8.	Deleterious substance
4.	Particle shape	9.	Resistance to wear
5.	Soundness	10.	Affinity to bituminous materials

15.2.1 *Test for the Evaluation of the Quality of Aggregates*

Not only do aggregates from different sources differ widely in their composition and properties, but samples from the same source may also show considerable variation. For determining the suitability of aggregates, the following acceptance tests are commonly in use :

Sieve Analysis

The grading required in a road aggregate varies according to the purpose for which it is to be used. The results of sieve analysis are normally required for comparison with the specification of the American Society for Testing Materials ([ASTM] C-136).

Soundness Test

The soundness of an aggregate is commonly evaluated by accelerated soundness tests using either (1) sodium sulfate or magnesium sulfate (ASTM C-88) or (2) the freezing and thawing method of the

American Association of State Highway and Transportation Officials ([AASHTO] T-130). Aggregates that stand up well in these tests can be expected to give satisfactory performance.

Flotation Test

Coal, lignite, and other deleterious material can be separated from an aggregate on the basis of low specific gravity. Natural aggregates are separated into two groups : those which float in liquid, and those which sink in liquid. The lighter aggregates are undesirable (ASTM C-123).

Friable particle Test

This test is used to determine the amount of soft particles, such as clay lumps, in the aggregate (ASTM c-127 and C-128).

Alkali Reaction

The mortar bar test (ASTM C-227), measuring expansion and the amount of silica dissolved in a standard N_aOH solution (ASTM C-289) is used to determine the alkali reaction potential of aggregates.

Abrasion Test

The most commonly used abrasion test is the Los Angeles Abrasion Test (ASTM C-535).

Aggregate-Bitumen Affinity Test

These tests include the Stripping Test and the Immersion-Compression test (ASTM D-1075).

One of the important classifications of aggregates is that based on size. Size classification is invariably controlled by specifications that will dictate the distribution of particle sizes to be used for a particular mixture. Figure 15.1 illustrates a typical specification controlling the size distribution or gradation of an aggregate for an asphalt concrete mix. For convenience, the ordinate is plotted as per cent by weight passing a given size on an arithmetic scale; the abscissa is the particle size plotted to a logarithmic scale. Generally, the size distribution is determined by dry sieve analysis.

Various terminologies have been used to describe the size distribution of aggregates. Typical gradations, together with their descriptive nomenclature, are illustrated in Figure 15.2. In addition to the descriptive nomenclature shown in this figure, aggregate quite often is referred to as coarse aggregate, fine aggregate, and filler. In this discussion, coarse aggregate will be referred to as material retained on the No. 4 sieve; fine aggregate will be referred to as that material passing the No. 4 sieve. While not referred to in these notes, filler is usually the material passing the No. 200 sieve. Also related to the size distribution of an aggregate are several other concepts which are described in the following passages.
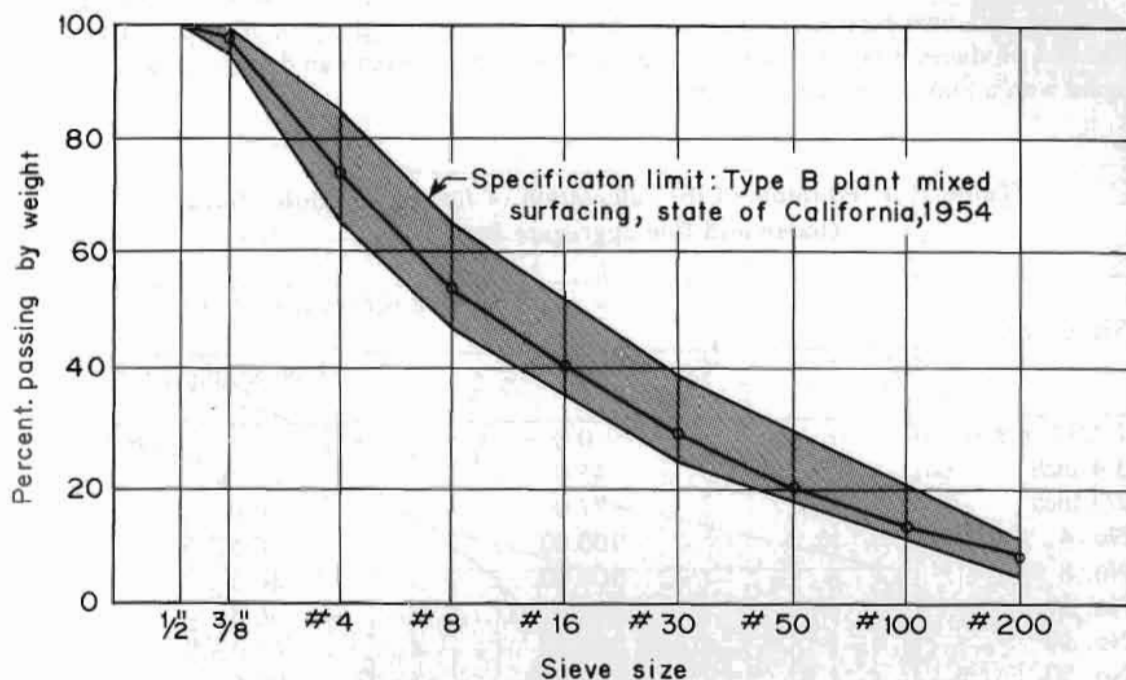
Fig. 15.1 Typical gradation specifications

Fineness Modulus

The fineness modulus (FM) of an aggregate grading is a useful, descriptive number from which an idea of the relative coarseness or fineness of the aggregate grading may be obtained. The fineness modulus is computed by adding the cumulative percentages retained on each sieve of the logarithmic sieve series (6 inches, 3 inches, 1 1/2 inches, 3/4 inch, 3/8 inch Nos. 4, 8, 16, 30, 50, 100) and dividing the result by 100. It is a term most commonly associated with aggregates for PCC. An example of the calculation of the fineness modulus for a coarse aggregate and a fine aggregate (FA) is shown in Table 15.1.

Maximum Density

The size distribution of an aggregate may be specified by the formula:

$$p = 100 \ (d/D)^n$$

where,

p	=	percentage of material by weight that passes a given sieve having openings of width d,
D	=	the maximum particle size of a given aggregate, and
n	=	an exponent upon whose value coarseness or fineness of gradation depends.

275

From this formula one can calculate the percentage of material of any given fraction for an aggregate of a given top size for some particular value of n. Studies have shown that, for n = 0.5, a gradation is determined that produces maximum density. Figure 15.3 shows a maximum density gradation curve for an aggregate with a maximum size of 1.5 inches.

Table 15.1 Example of the calculation of fineness modulus for a coarse and fine aggregate for concrete

Sieve size	Cumulative percentage retained	
	Coarse aggregate	Fine aggregate
1 1/12 inches	0.0	
3/4 inch	45.0	
2/3 inch	77.0	0.0
No. 4	100.00	0.5
No. 8	100.00	10.5
No. 16	100.00	36.3
No. 30	100.00	68.3
No. 50	100.00	91.6
No. 100	100.00	98.4
	Z = 722.0	Z = 305.6

Source: University of Washington 1985

Fineness Modulus (Coarse aggregate) FM_{CA} = 722.0/100 = 7.22
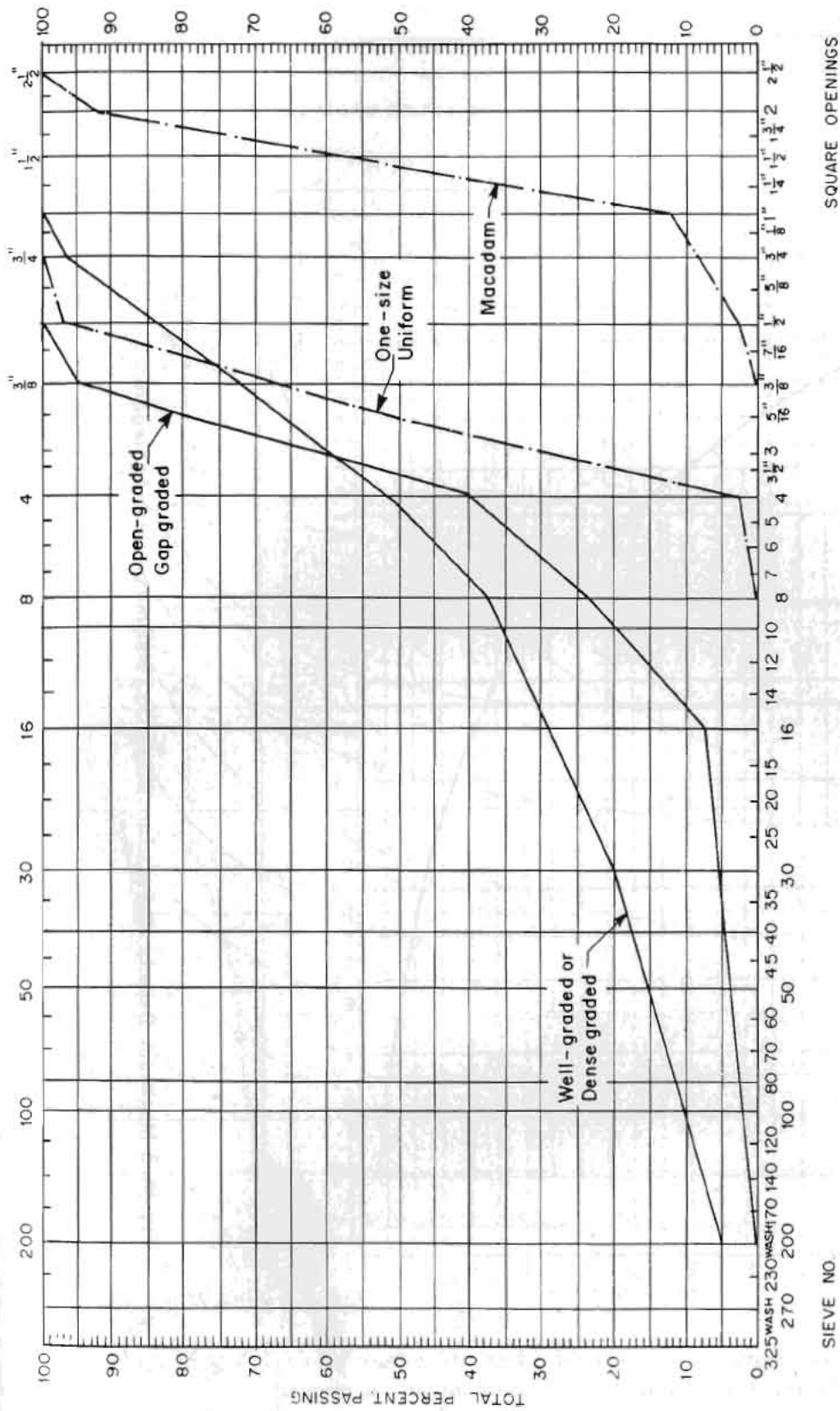Fineness Modulus (Fine aggregate) FM_{FA} = 305.6/100 = 3.06

Aggregate Voids

Many references to "voids in aggregates" are made in literature dealing with the use of these materials. Confusion sometimes results because of a lack of understanding of terminology. One must distinguish here between **voids** (more properly, **pores**) in a piece of aggregate and the void system in a loose or compacted aggregate mass that makes up the space between aggregate pieces. The former is a characteristic that influences such things as specific gravity and absorption of a material (see ASTM Designations C 127 and 128), while the latter may influence the design of a PCC mixture or bituminous concrete mixture using the material (see ASTM Designation C 30).

15.2.2 Maximum Size Aggregate in Concrete

Figures 15.4 to 15.6 are data from a research report showing the effect of varying the maximum size of aggregate (dense graded mixes) with the cement content. The net result is that, as strength increases with age or cement content, the optimum size of aggregate decreases. Therefore, various economies may result if available aggregate sources are limited in size.

Fig. 15.2 Typical aggregate gradations

Source: University of Washington 1985

277

THE ASPHALT INSTITUTE

Project ___CETS 464___
Location _____
Date ___9-26-85___

Sample No. _____
Source _____
Materials ___Max Density Grad___

AGGREGATE GRADING CHART

Maximum Density Curve for 1 1/2 in. Maximum-size Aggregate

TOTAL PERCENT PASSING
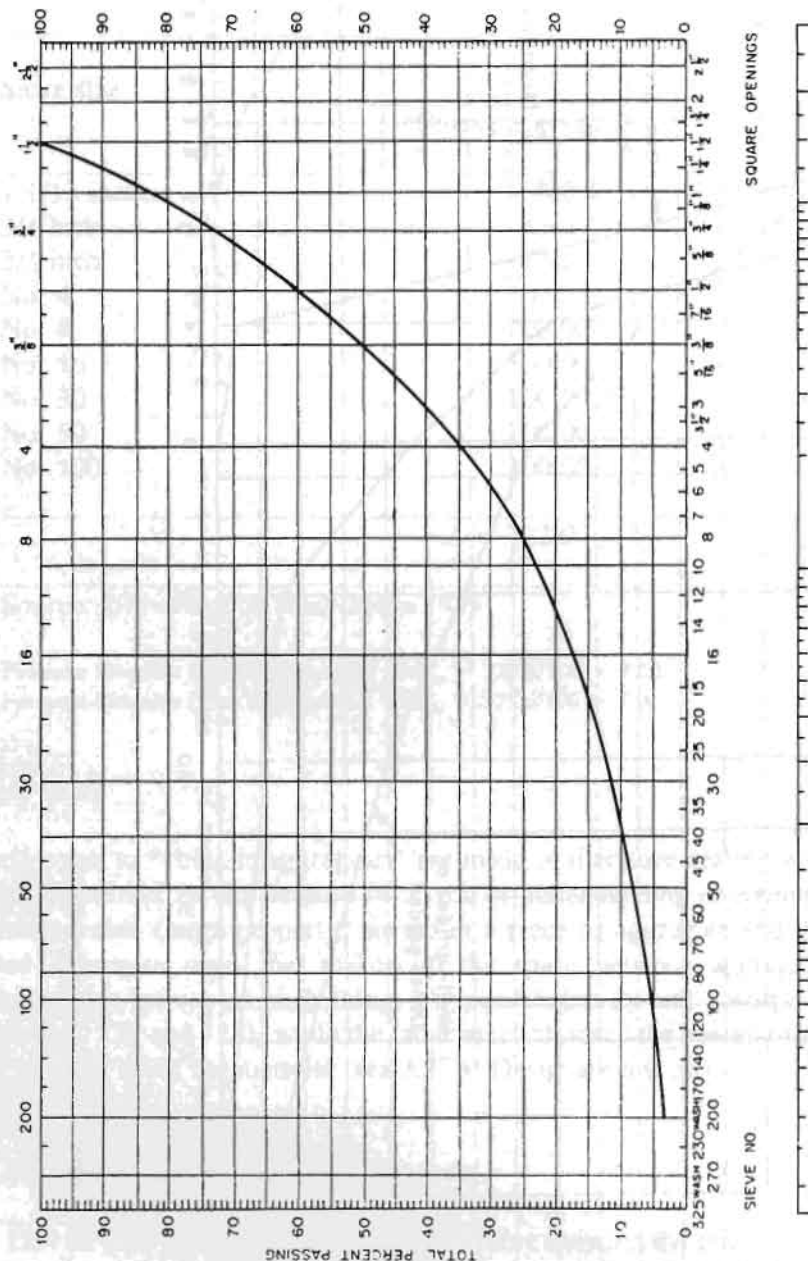
SIEVE NO.

SQUARE OPENINGS

Fig. 15.3 Maximum Density Curve for 1 1/2 in. Maximum-size Aggregate

Source: University of Washington 1985

Fig. 15.3 Maximum density curve for 1.5 in maximum-size aggregate

EACH POINT REPRESENTS AN AVERAGE OF 4-18x36-INCH AND 2-24 x 48-INCH CONCRETE CYLINDERS TESTED AT 28 DAYS
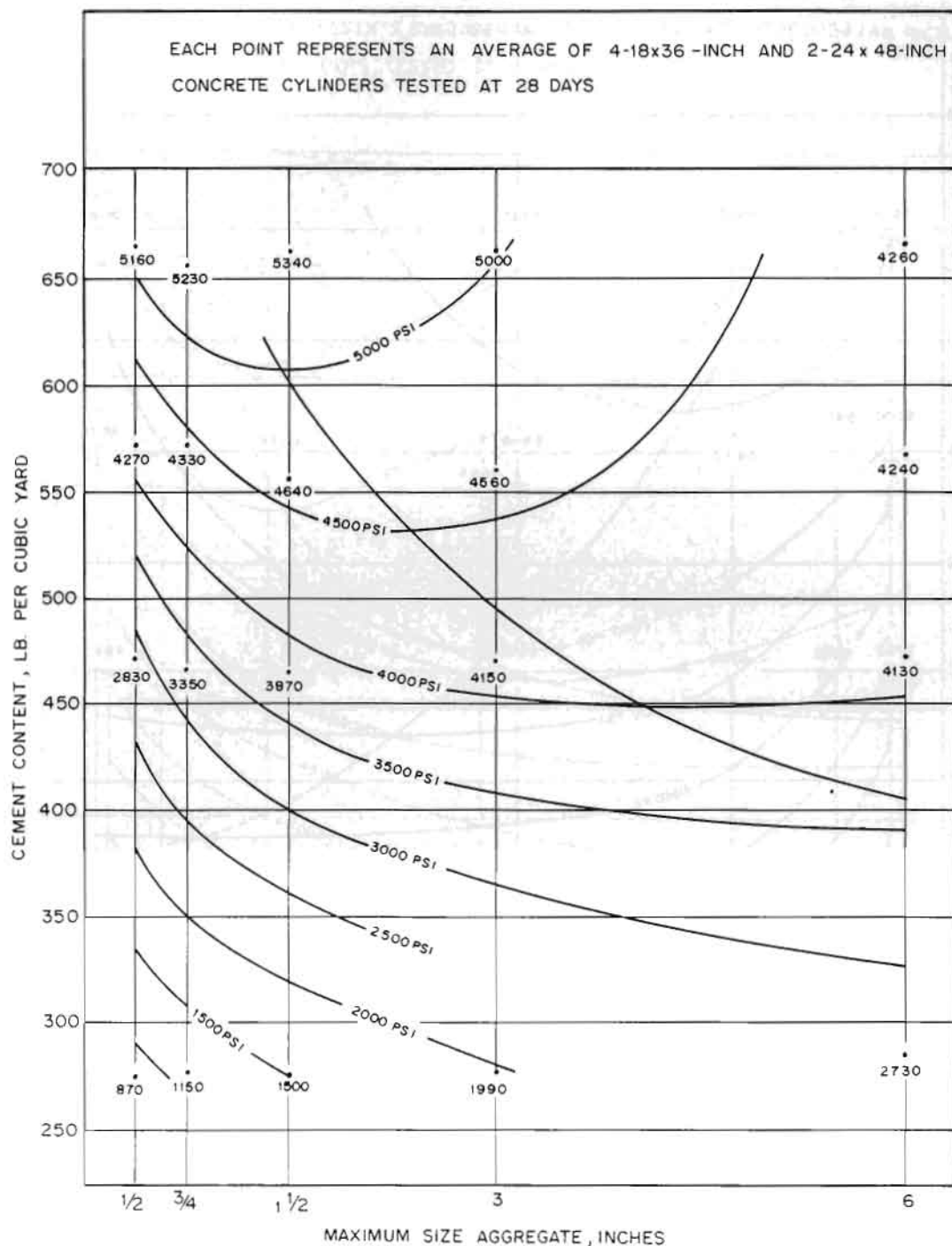
Source: University of Washington 1985

Fig. 15.4   Compressive strength decreases with increasing maximum size aggregate for minimum cement content (28 day-old specimens)

279

EACH POINT REPRESENTS AN AVERAGE OF 4-18 x 36-INCH AND 2-24 x 48 INCH
CONCRETE CYLINDERS TESTED AT 90 DAYS
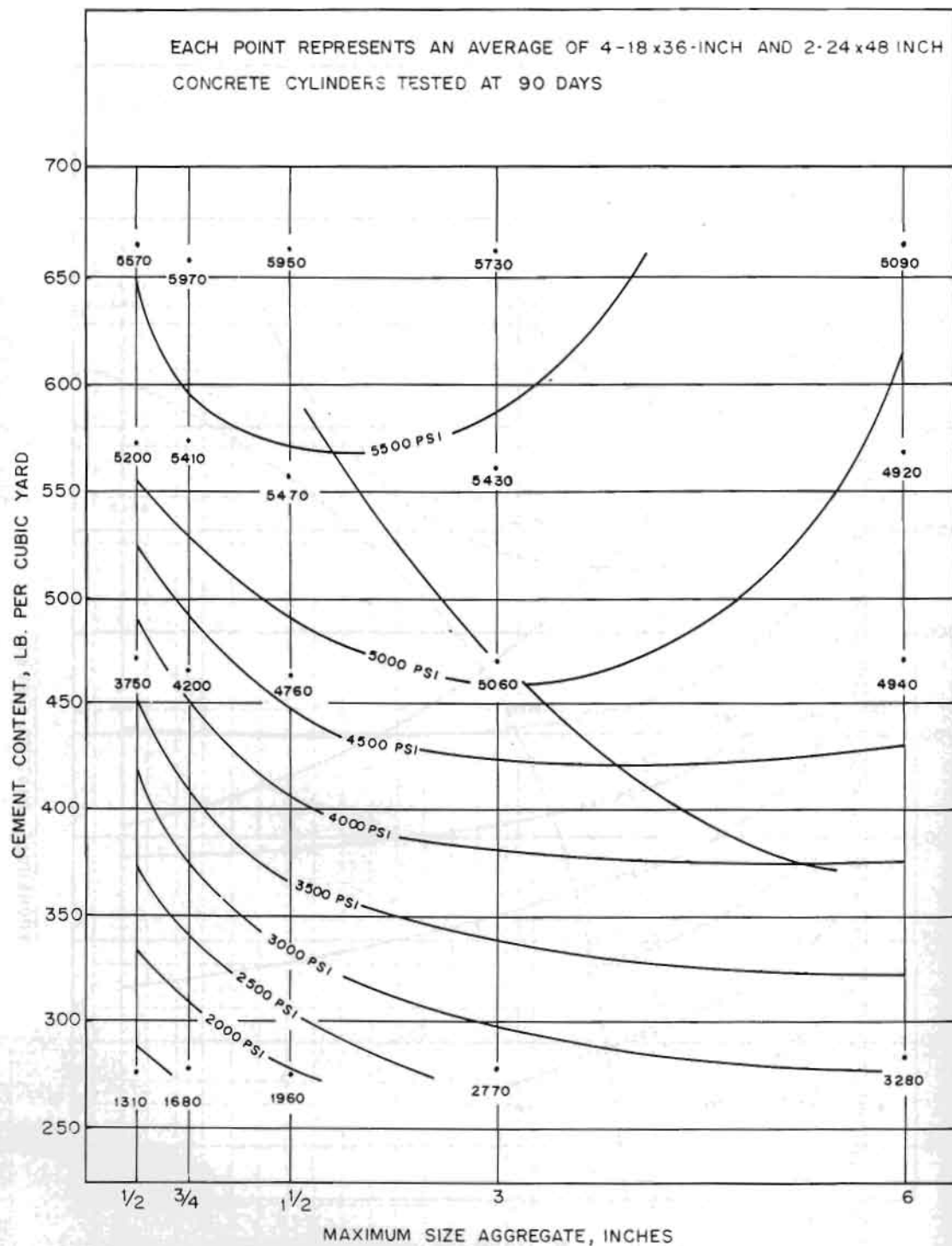
Source: University of Washington 1985

Fig. 15.5   Compressive strength decreases with increasing maximum size
aggregate for minimum cement content (90 day-old specimens)

280

EACH POINT REPRESENTS AN AVERAGE OF 4-18x36-INCH AND 2-24x48-INCH CONCRETE CYLINDERS TESTED AT 1 YEAR

(Y-axis: CEMENT CONTENT, LB. PER CUBIC YARD)

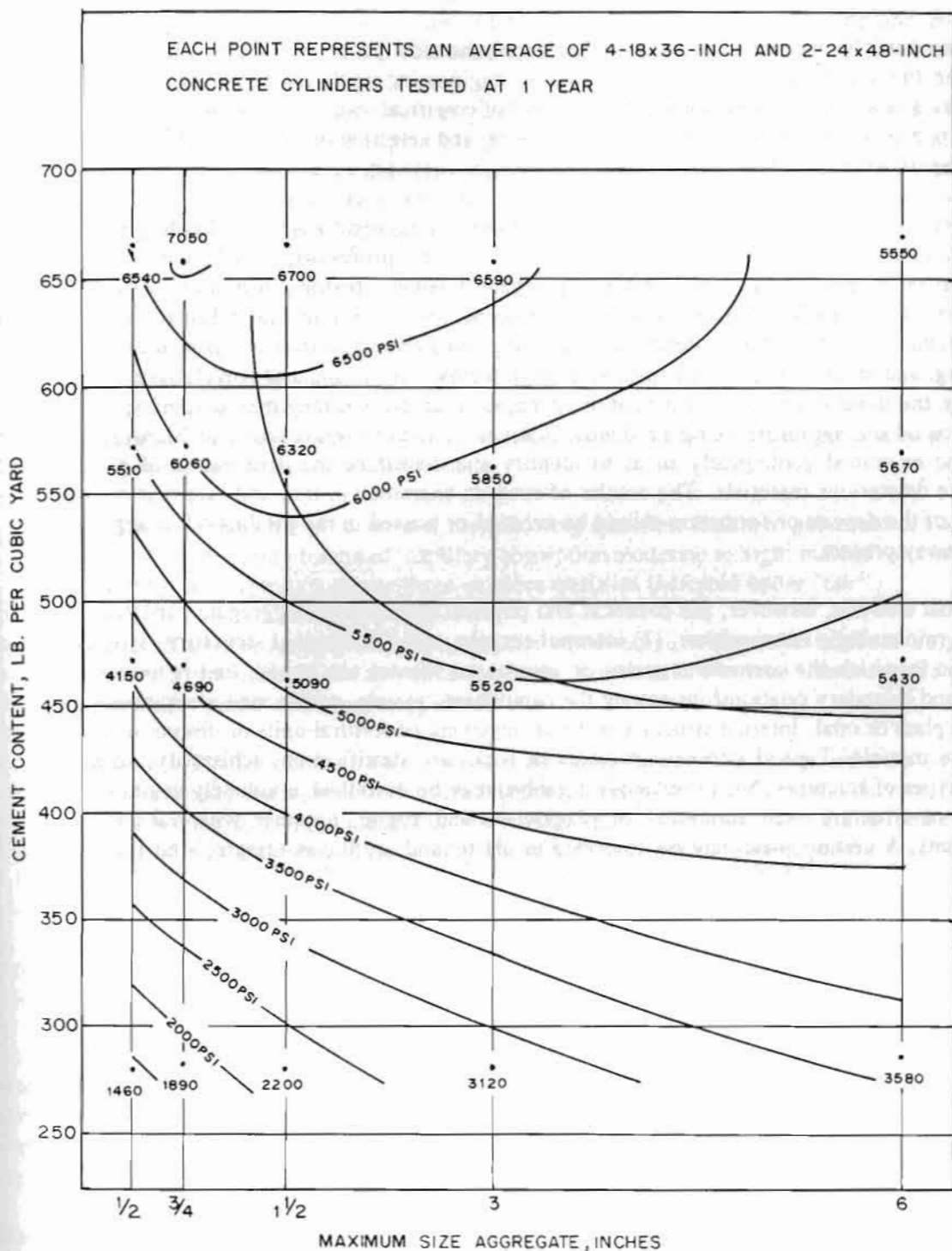(X-axis: MAXIMUM SIZE AGGREGATE, INCHES)

Source: University of Washington 1985

Fig. 15.6   Compressive strength decreases with increasing maximum size aggregate for minimum cement content (one year-old specimens)

15.3   PROPERTIES OF AGGREGATES

Aggregate particles possess a series of physical and chemical properties which, together with grading, determine the suitability of the aggregate for an engineering application. An understanding of these properties is essential as a basis for the development of empirical tests, for establishing specification limits based upon such tests and, in general, for evaluation and selection of aggregates for use under specific conditions of service.

The physical and chemical properties of particles of mineral aggregates arise in (1) **the geological history of the sand or gravel** or of the rock formation and (2) **the processing to which the materials were subjected** in the production of the finished aggregate. **Geologic history** includes the origin or mode of formation of the rock types as well as subsequent processes such as folding, faulting, jointing recrystallization, hydrothermal alteration, weathering, erosion, deposition of secondary substances, such as coating, and so on. The geologic features of rock formations or sand and gravel deposits are important factors in the development and operation of aggregate sources, and they may determine the quality and limitations of the aggregate being produced. Sources of mineral aggregates for highway construction should be examined geologically so as to identify and determine the distribution of any unsound or otherwise deleterious materials. The results of such an examination may indicate that certain zones or portions of the deposit or formation should be avoided or wasted in the production of aggregates for use in a highway project.

In the final analysis, however, the chemical and physical properties of aggregate particles depend upon their (1) **mineralogic composition,** (2) **internal texture,** and (3) **internal structure.** Internal texture is the fabric in which the constituent grains or amorphous masses are joined, that is to say, the mutual, spatial, and boundary relationships among the component crystals, grains, and amorphous phases, e.g., volcanic glass or opal. Internal structure is the arrangement of textural units or discontinuities within the aggregate particle. Typical internal structures of rocks are stratification, schistosity, vesicularity, and various types of fractures. So, for example a gabbro may be described as coarsely crystalline in texture, massive in structure, and composed of plagioclase and augite, together with various other minor constituents. A certain shale may be described as clastic and argillic in texture, stratified and fissile in structure, and composed of an illite-type (hydromica) clay and specific proportions of silt and sand of a certain petrographic identity.

Mineralogic composition, internal texture, and internal structure of rocks (or earth materials in general) relate specifically to the geologic conditions of origin and to subsequent geologic history. Because of this relationship, the petrographer almost always can determine the origin and geologic history of a rock from an examination of representative particles. Igneous rocks are formed by solidification of molten siliceous materials intruded into the crust of the earth or extruded upon its surface. If the melt cools very slowly, the igneous rock will be wholly crystalline and a coarse crystalline texture like that of granite may result. If the melt cools rapidly a portion or the entirety of the material may solidify as glass before crystallization can be completed.

Sedimentary rocks develop by grain-by-grain accumulation of particles. The particles are joined together during geologic time by secondary processes of cementation, consolidation, or crystallization so that a coherent rock is produced. Metamorphic rocks form by crushing, fragmentation, and recrystallization of previously existing rocks as a result of geologic processes at elevated temperature, pressure, or shearing stress. The texture and internal structures that result reflect the nature of the original rock and the environmental conditions under which the metamorphism is consummated.

Aggregates vary widely in lithologic and mineralogic composition, both because of the nature and distribution of geologic formations and because of the selective action of weathering and erosion in destroying certain rocks and minerals and concentrating others.

Within each petrographic classification, such as granite, basalt, sandstone, or schists, a wide variation of composition, texture, and structure is possible. Hence any rock types produce particles that may be either sound or unsound physically, or deleteriously reactive or innocuous chemically as a constituent of concrete aggregate. The terms descriptive of the degrees of physical and chemical quality of the aggregate particles may be defined as follows :

1. Satisfactory : Particles are hard to firm, relatively free from fractures, and not chiplike; capillary absorption is very small or absent; and the surface texture is relatively rough.

2. Fair : Particles exhibit one or two of the following qualities : firm to friable; moderately fractured; capillary absorption small to moderate; flat or chiplike; surface relatively smooth and impermeable; very low compressibility; coefficient of thermal expansion approaching zero, or being negative in one or more directions.

3. Poor : Particles exhibit one or more of the following qualities: friable to pulverulent, slake when wetted and dried; highly fractured; capillary absorption moderate to high; marked volume change with wetting and drying; combine three or more qualities indicated under 'fair'.

4. Innocuous : Particles contain no constituents that will dissolve or react chemically to a significant extent with constituents of the atmosphere, water, or hydrating Portland Cement while enclosed in concrete or mortar under ordinary conditions.

5. Deleterious : Particles contain one or more constituents in significant proportion that are known to react chemically under conditions ordinarily prevailing in Portland Cement, concrete, or mortar in such a manner as to produce significant volume change, interfere with the normal course of hydration of portland cement, or supply substances that might produce harmful effects upon concrete or mortar.

As a consequence of its mineralogic composition, texture, and internal structure, each rock or mineral particle in aggregate is characterized by a suite of physical and chemical properties that determines the response of the particle to environmental conditions and thus its performance in engineering service.

15.3.1 *Physical Properties*

The physical properties of aggregates have important engineering significance. Included are such properties as porosity, permeability, surface texture, thermal, volume change, and others.

Porosity, Permeability, and Absorption

The internal pore characteristics are the most important properties of aggregates. The size, abundance, and continuity of pores influence or control such qualities as strength, elasticity, abrasion resistance, surface texture, specific gravity, bond with cementitious binder, resistance to freezing and thawing action, and the rate and magnitude of various cement-aggregate reactions.

Surface Texture

Surface texture of an aggregate particle is the fabric or pattern and the relative roughness or smoothness of the periphery. Surface texture encompasses all of the physical features of the rim and their dimensions, both areally and radially, and details of the form of the surface, such as the relative planeness, curvature, and rugosity. Clearly, surface texture depends upon the internal texture, structure, abrasion, and leaching to which the particle has been subjected.

Surface texture influences the bond developed between an aggregate particle and the cementing material in concrete. Table 15.2 shows the results of bond tests to indicate the effect of the surface texture of aggregate on bond strength in tension. The surface texture of aggregate also influences the water requirement of Portland Cement for a given consistency.

Volume Change with Wetting and Drying

The volume change of PCC with wetting and drying is influenced by aggregate in three general ways. First, in particles containing clay minerals of the expanding lattice type, such as the montmorillonites and some illites, wetting and drying leads to progressive increase in volume of the particle at any selected level of moisture content. Second, particles of high compressibility, such as certain weak sandstones, fail to resist drying shrinkage of Portland Cement paste and so permit inordinate shrinkage of concrete. Third, certain aggregates, because of their particle shape and surface texture, increase the water requirement for a given consistency and thus increase drying shrinkage. In areas where aggregates contributing to drying shrinkage of concrete are likely to be proposed for use, a wetting-and-drying test should be included in the standard specifications of the highway department.

Table 15.2   Effect of surface texture on bond strength (aggregate embedded in cement briquets)

Surface texture of aggregate	Bond Strength in Tension, psi		
	28 days in water	28 days in water, then 28 days in air	28 days in water, then 28 cycles of wetting and drying
Rough, porous	350	260	235
Rough	240	275	230
Rough	215	300	245
Fairly rough	250	185	160
Smooth	120	45	
Smooth, conchoidal	285	170	45
Very smooth	195	40	25

Source: University of Washington 1985

Thermal Properties

The thermal properties of aggregates that are of significance to the performance of PCC are 1) coefficient of expansion, 2) specific heat, and 3) conductivity. These properties are not significant in bituminous pavement or for aggregates used as sub-base materials.

In mass concrete construction, specific heat, conductivity, and diffusivity must be considered in the design of cooling systems, and these properties of the proposed aggregates may influence the selection of the Portland Cement for the project. In pavement concrete these properties are not of significance.

The thermal coefficients of expansion for aggregates as a whole, and for those of individual particles, may be of importance in concrete highway structures. Of primary concern is the difference in (1) expansivity of the aggregate particle and of the concrete and (2) in the expansivity of the coarse aggregate and of the mortar or cement paste. A difference of 3.0×10^{-6} per degree Fahrenheit in the thermal coefficient of expansion of the coarse aggregate and that of the mortar can reduce freezing and thawing resistance considerably. Difference in the thermal coefficient of expansion between the aggregate and cement paste, low compressibility of the aggregate particles, and an inferior cement-aggregate bond are thought to contribute to the expansion and deterioration of concrete highway pavements and other structures containing the so-called sand-gravel aggregates in Kansas, Nebraska, Iowa, and Missouri, USA.

In general, however, the thermal properties of aggregates are of minimal importance as a factor in aggregate selection for concrete construction on highway projects.

Data on thermal coefficients of expansion of rocks, concrete, and Portland Cement Paste are summarized in Table 15.3. Note that serious difference in expansivity of the cement paste and that of the aggregate is to be expected only with rocks of very low expansivity. Rocks characterized by a linear thermal coefficient of expansion of 1.0×10^{-6} per degree Fahrenheit or less include granites, limestones, and marble.

Strength and Elasticity

High strength and elasticity of the particles are desirable for road metal and ballast because the rate of disintegration is minimized and the stability of the compacted course is maximum. However, for PCC, optimum results may be obtained by a compromise between strength and elasticity - so low that the strength of the concrete suffers and drying shrinkage is excessive - and level of strength and elasticity - so high that the adjustment of volume change of the concrete takes place primarily in the cement paste and along cement-aggregate boundaries, rather than moving uniformly throughout the concrete. Near-surface portions of pebbles and sand grains may be seriously weakened by weathering even though the interior of the grains is not modified significantly. The strength and elasticity of aggregate are not reflected proportionately in the strength and elasticity of the concrete.

A factor in the strength and elasticity of aggregate particles is the degree to which the particles are fractured either internally or because of the process of crushing by which the aggregate is manufactured. Fractures contribute to a breakdown of particles during handling and processing and to fragmentation in ballast or road metal and in the surface of bituminous pavements. Internal fracturing of aggregate particles makes a final screening operation, just prior to use of the aggregate, especially necessary in order that the desired grading can be maintained.

Table 15.3 Thermal coefficient of expansion of some rocks, * concretes, and Portland Cements (expansion per degree Fahrenheit, in a range of from -4° to 212°F)

Materials	No. of specimens	Range in mean linear thermal coefficient
Granites	27	1.0 to 6.6
Diorites and andesites	17	2.3 to 5.7
Gabbros, basalts, diabases	15	2.0 to 5.4
Sandstones	24	2.4 to 7.7
Quartzites	20	3.9 to 7.3
Dolomites	7	3.7 to 4.8
Limestones	65	0.5 to 6.8
Siliceous limestones	6	2.0 to 5.5
Cherts	9	4.1 to 7.3
Marbles	29	0.6 to 8.9
Slates and argillites	5	4.5 to 4.8
Portland Cements, neat	10	5.9 to 9.0
Concretes	27	3.6 to 6.8

Source: University of Washington 1985

* All coefficients of rocks were obtained on dry specimens

Density

The density of an aggregate particle is dependent upon the true density of its mineral constituents and upon the porosity. The density of a porous material may be defined to include in its volume all, some, or none of the volume of the pore space. Thus, there are such terms as bulk, apparent, and true specific gravity. The bulk density (dry basis) of common rocks ranges from about 1.6 to 3.2.

Bulk density or bulk specific gravity of specific rock types can be correlated with approximate ranges of porosity and, commonly, also with degrees of soundness, such as resistance to freezing and thawing breakdown. Such correlations are empirical but, with proper control and evaluation, are of great value in aggregate selection in specific areas.

Hardness

The resistance of an aggregate to abrasion and degradation is controlled by the hardness of the mineral constituents, by the firmness with which the individual grains are cemented or interlocked together, and the frequency of fracturing (see above). Particles composed of minerals of a low degree of hardness may be designated as 'soft'; those which are easily disintegrated because of poor cementation or intensity of fracturing may be designated as 'weak'. Weak and soft particles are objectionable in aggregate because

they break down during processing, changing the gradation of the aggregate from that contemplated, and are susceptible to continuing disintegration during services as a result of impact, abrasion, and weathering.

Particle Shape

The shape of aggregate particles may significantly affect the engineering performance of the aggregate. The workability of concrete, the strength, asphalt demand, and workability of asphaltic mixtures, as well as the frictional characteristics of graded aggregate mixtures, are but a few examples of the influence of particle shape on the quality of aggregate.

The size and shape of rock and mineral particles in aggregate depend to a considerable extent upon the presence and spacing of natural partings and cleavage in the parent formation. It is for this reason that certain formations characteristically produce more or less equidimensional, slabby, or elongated forms in certain size fractions and why it is not possible to obtain substantial production of large-sized aggregate from certain sources. The shape of particles depends also upon the relative strength, elasticity, and abrasion resistance of the rock or mineral and upon the natural or artificial processes whereby the aggregate is produced. It is common to find certain rock and mineral types in an aggregate represented by subangualar or even well-rounded particles, whereas other rock and mineral particles in the same sample are angular.

Two relatively independent properties, sphericity and roundness, control particle shape. Sphericity describes the relation of the surface area of the particle to its volume or the relative volume of the particle and that of the circumscribing sphere. Roundness measures the relative sharpness or angularity of the edges and corners of the particle.

Coatings

A coating is a layer of substance covering a part of the entirety of the surface of an aggregate particle. The coating may be of natural origin, such as mineral deposits formed in sand and gravel by groundwater, or artificial; such as stone dust resulting from crushing and handling. Natural coatings usually do not cover the entire surface of pebbles and sand grains; rather, they tend to concentrate at the bottom of the particles as they lie in the deposit. Coatings usually are composed of silt, clay, and calcium carbonates; carbonate, organic matter, iron oxides, opal, manganese oxides, alkali and alkali-earth sulfates, and soluble phosphates have been identified.

The coating materials may be essentially inert chemically, or they may be potentially deleterious. Many coatings are physically weak, porous, absorptive, and poorly bounded to the aggregate particles. In such instances they may seriously impair the quality of the aggregate for the intended use.

15.3.2 Chemical Properties

The chemical properties of aggregates are frequently of great engineering significance.

Solubility

Few rocks, gravels, or sand that would be considered seriously for use as aggregate contain a sufficient proportion of water-soluble substances to affect the quality of the aggregate in service. Nevertheless, occasional formations and deposits of sand and gravel contain concentrations of water-soluble substances, such as gypsum, in the form of coatings or seam fillings, sufficient to cause difficulty in PCC. Such substances can be detected by petrographic examination or by qualitative chemical tests; they may be revealed by efflorescence at natural exposures of the formation or deposit.

Oxidation, Hydration, and Carbonation

Various unstable minerals are susceptible to oxidation, hydration, or carbonation if exposed to the atmosphere. These effects are insignificant for road metal, ballast, or bituminous construction, if ordinary caution is used in selection of the materials. However, PCC may become unsightly or distressed by these actions. Susceptible substances include from sulfides (marcasite, pyrite, and phrrhotite), ferric and ferrous oxides in clay-ironstone particles, free lime (C_aO), free magnesia (M_gO) in industrial products and wastes, and certain zeolites.

15.4   SPECIFICATIONS AND PROPERTIES

A specification may be defined as a concise description, preferably in measurable terms, of the significant characteristics of a material. The determination of such needs, in terms of characteristics that can be set up easily in a specification, requires logical thought based on sound chemical and engineering principles.

Requirements should be set forth in a clear, detailed but concise manner and should be quantitative rather than qualitative to reduce to a minimum decisions based on personal opinion.

There are five important requisites of a specification :

1.	accuracy and precision,	4.	flexibility, and
2.	workability,	5.	acceptability.
3.	suitability,		

A specification should never be considered as final or complete. Frequently an outmoded specification will prove a greater deterrent to progress than no specification at all. Any specification should be examined periodically, in view of technical advances in manufacture, testing, and use requirements.

Specifications for any material represent the purchaser's or user's conception of those characteristics of the material which are necessary for the successful use of the product in his application. Preparing a specification for a material is not a simple matter. It is frequently very difficult to put into specific quantitative terms the properties that the material should and should not possess. There is an ever present danger of specifying too rigidly and the consequences of that are higher prices. In addition, one may know well what specific characteristics of an end product are desirable but, in preparing specifications for components of that end product, may not know with the same certainty the properties of the components that determine the ultimate success of the end product.

This is sometimes the case with mineral aggregates. Take, for example, aggregates for portland cement concrete for a highway pavement. A desirable aggregate for this application is one that will make workable, then strong, durable concrete. However, present-day methods are not always adequate to perform this evaluation. The relatively recent discovery of concrete failures caused by the presence of certain forms of silica support the contention that there may still be present in aggregates certain very important characteristics hitherto ignored and unknown.

This should not imply, however, that specifications for aggregates are at the level of guesswork. There are many, perhaps most, aggregate properties that can be specified on a firm scientific basis. Aggregate specifications are dynamic. They are constantly being refined and improved as new research takes place and further experience is gained.

15.4.1 *Local Specifications and Their Importance*

Many of the examples of specifications for aggregates are those of national rather than local character. Such specifications must necessarily be broad. Hence, they should be regarded primarily as guides rather than as absolute standards. There are many mistakes that may be made by using or imposing a general specification in all areas of the country. First of all, the aggregates differ. Secondly, the climate may differ, so a material which may be extremely deleterious in one area may be completely innocuous in another.

15.4.2 *Quality Requirements for Aggregates*

Under "quality requirements" one can list all usual specification provisions other than those dealing with gradation. Quality requirements can be divided into five distinct groups.

1. General quality requirements
2. Abrasion resistance
3. Soundness
4. Restrictions on 'deletrious' constituents
5. Special requirements

It is the purpose of this section to discuss each of these five types of quality requirements, giving reasons for each.

General

Most specifications for aggregates for use in PCC, bituminuous mixtures, or in similar classes of use begin with a paragraph heading such as "Description", "General Characteristics", "General Requirements", or something similar. It is the purpose of the paragraph, first, to describe in general terms the type of material considered to be acceptable and, second to collect in one place those rather nebulous requirements that undoubtedly influence the acceptability of the material but for which a good quantitative testing method test does not exist.

For example, the following is an extract from the first paragraph of a specification dealing with coarse aggregates called 'Description' :

"Coarse aggregates.... shall be composed of clean, tough, durable fragments of crushed limestone or dolomite, crushed or uncrushed gravel, or slag, free from an excess of flat, elongated, thinly laminated, soft or disintegrated pieces and free from fragments coated with dirt or other objectionable matter" (ASTM Designation [33-49]).

Similarly, ASTM Designation C 33-49 presents the general characteristics of coarse aggregate for concrete as follows :

"Coarse aggregate shall consist of crushed stone, gravel, blast-furnace slag, or other approved inert materials of similar characteristics, of combinations thereof, having hard, strong, durable pieces, free from adherent coatings and conforming to the requirements of these specifications" (ASTM Designation [33-49]).

Currently, however, ASTM Designation C 33-55T does not contain such indefinite requirements as "hard, strong, durable pieces," etc. This later revision of the specifications for concrete aggregates attempts to put all desirable qualities into definite terms and, as such, is a more practical type of specification. This is a desirable trend, and, no doubt, as technology progresses, aggregate specifications will continue to be refined to produce better definitions in all areas.

Abrasion Resistance

The qualities of material known as **hardness** and **toughness** have historically been regarded as essential to good aggregate. The properties of hardness and toughness are very closely related. Hardness is made up, in part, by abrasion resistance and toughness is generally understood to mean the power possessed by a material to resist fracture under impact.

At present, practically all (if not all) highway agencies specify a limit on abrasion resistance of aggregate which is based on the Los Angeles' test. The actual maximum loss specified may vary from place to place and, of course, will also vary depending upon the use to which the coarse aggregate will be put. For example, ASTM Designation C 33-55T cites a maximum loss of 50 per cent whereas ASTM Designation D 692-54 specifies that coarse aggregate for bituminous-concrete surface courses will have a maximum loss of 40 per cent. It is significant to note that ASTM Designation C 33-55T also states that:

"Coarse aggregate having an abrasion loss greater than 50 per cent may be used, provided the aggregate produced satisfactory strengths in concrete of the proportions selected for the work".

There is recognition of a current trend, on the part of some people, away from rigid abrasion-resistance specifications for coarse aggregate for PCC.

Soundness

The soundness of aggregates or their resistance to the forces of weathering is undoubtedly one of the most important considerations in the selection of a material for highway construction. The primary exposure

that one is concerned with is alternate freezing and thawing. Somewhat less frequently one may be concerned with the resistance of materials to alternate heating and cooling, wetting and drying, or the action of aggressive waters. Most specifications for aggregates in cold climate areas should include a provision for soundness that is designed to ensure the selection of a material that is durable in freezing and thawing.

The most common soundness requirement for aggregates (both coarse and fine) is based on the sodium or magnesium sulfate soundness test (ASTM Designation C 88-55T). This method may be used for acceptance of material but rejection should be based on other determinations such as freezing and thawing tests.

Freezing and thawing tests of the aggregate are also commonly used as the basis for a soundness specification. No ASTM test method exists for this, although there is an AASHTO standard method in existence (T 103-42).

In the particular case of aggregates for PCC, soundness in freezing and thawing is sometimes specified on the basis of results of tests in which concrete, made with the aggregate, is exposed to alternate freezing and thawing and the deterioration of the concrete is noted (ASTM Designations C 290, 291, 292, and 310). Specifications based on this type of test appear to be better founded than those based on a sulfate soundness test.

Restrictions on Deletrious Constituents

It is generally recognized that the presence of certain substances in aggregates for PCC is undesirable. These substances, if present, would tend to decrease the durability of the concrete and make it less abrasion-resistant than would otherwise be the case, cause pop-outs, or inhibit strength gain. Specifications for such aggregates, therefore, normally contain a section in which the deletrious materials are named and a limit placed on the amount of each that is allowable.

Obviously, the same deleterious substances do not occur in all locations and even materials that are called by the same name may differ in their effect on concrete from one area of the country to another. Hence one cannot list all deleterious materials with fixed allowable percentages of each. The most commonly recognized deleterious materials are clay lumps, coal and lignite, soft organic impurities, lightweight particles, and material finer than the No. 200 sieve. Some specifications list in detail each type of substance with a corresponding limiting percentage. Others may set up a general category based on a physical property rather than on specific names. For example, ASTM Designation C 33-55T contains the following Table (15.4).

In this case, instead of a detailed list of such items as shale, shells, and other light and soft materials, the specification lists the general categories of soft particles and lightweight particles. In any case the specification should recognize, by class or by name, those substances which may be harmful and limit the amount of each to a level consistent with the quality of concrete which is sought. For other uses of aggregates on highways, the restrictions on deletrious constituents are frequently not as rigid as they are for aggregate of PCC. For example, ASTM Designation D 692-54, the Standard Specification for Crushed Stone, Crushed Slag, and Gravel for Bituminous Base and Surface Course of pavements, does not include a section on deleterious substances but contains only a statement under the heading "General Characteristics", that the course aggregate *"shall consist of hard, strong durable pieces, free from*

adherent coatings.... " This recognizes that small amounts of materials such as shell, chert, etc., are not as harmful to bituminous concrete as they are to PCC. It is assumed, then, that other specification provisions, such as those for soundness and abrasion, will eliminate aggregates containing harmful quantities of objectionable substances.

Table 15.4 Limits for deleterious substances in coarse aggregates for concrete

Item	Maximum Per Cent by Weight of Total Sample
Clay lumps	0.25
Soft particle	5.0
Chert that will readily disintegrate (soundness test, 5 cycles)	1.0
Material finer than No.200 sieve	1.0*
Oven-dry material floating on a liquid having a specific gravity of 2.0	1.0**

Source: ASTM Designation C33-55T

* In the case of crushed aggregate, if the material finer than the No. 200 sieve consists of the dust of fracture, essentially free from clay or shale, this percentage may be increased to 1.5.

** This requirement does not apply to blast-furnace-slag coarse aggregate.

It should be stated, however, that some agencies specify aggregates on the basis of class rather than on the basis of use and may employ the same class of aggregate for PCC and some high type of bituminous construction. In this case, specification provisions that are primarily intended for the control of quality of concrete aggregates may be imposed upon aggregates for bituminous construction, and vice versa.

Special Requirements

Under this heading may be listed a number of items that are sometimes included in specifications, often simply a general statement, but sometimes with quantitative limits attached. Some of the most common of these are :

a. a Statement limiting the presence of flat and elongated pieces in coarse aggregate;

b. a "service requirement" provision that may say, in effect, that even if the aggregate conforms to all other requirements of the specification, if it has been shown to give poor field performance it can be rejected: on the other hand, it may be acceptable if it has had a satisfactory service record in the past,

c. aggregates for use in bituminous mixtures may be required to pass a stripping test;

d. aggregates for use in bituminous mixtures may have to meet a specification requirement on minimum percentage of crushed pieces, and

e. blast-furnace slag may have to meet a requirement for minimum unit weight.

15.5   AGGREGATE CALCULATIONS

15.5.1 *Sieve Analysis Data*

In the presentation of data for the results of sieve analyses, the aggregate gradation is generally expressed as a percentage of the total weight of the material passing a given sieve size. To obtain this information, material is passed through a number of sieves and the weight of material retained on each sieve is determined. The method for calculating the aggregate gradation, based on the results of a sieve analysis, is shown in the example in Table 15.5.

15.5.2 *Combining Aggregate Gradings*

In the majority of situations, the gradation of an aggregate from a particular source does not conform to the limits defined by a given grading specification. In the production of hot asphalt concrete, aggregate, after being dried and heated, is separated into 3 or 4 size fractions. In this case it is also necessary to combine the materials from each of the storage bins to meet the specifications for the particular job. The simplest means by which the proper combination can be obtained is by a trial-and-error procedure and is illustrated in Tables 15.6 and 15.7. This particular situation might be linked to a hot-mix plant with a two-bin separation of aggregate, plus a bin for mineral filler. In deciding the proper proportions of the aggregates to use by the trial-and-error procedure, one can quickly obtain at least approximate percentages of the various materials by studying the various sieves to ascertain which aggregate will control the quantity of material passing a particular sieve.

As an example, assuming 5 per cent of aggregate C is to be used (200 mesh sieve controlling), then aggregate B would contribute the majority of material passing the No. 8 sieve. Approximately 35 per cent of material B would be required.

Thus, as a first trial, try 5 per cent of C, 35 per cent of B, and 60 per cent of A and determine whether this combination will produce the desired grading.

Checking the column for the combination against the specification limits it can be seen that the assumed proportions are satisfactory since the combination in all cases lies within the grading limits. If the combination was outside the limits for a particular size, it would then be necessary to modify the percentages somewhat and proceed as before.

Table 15.5   Example illustrating aggregate gradation determination based on sieve analysis data

Sieve Size	Weight Retained on Sieve (gm)	Cumulative Wt. Retained (gm)	% Retained	% Passing
3/4 "	0	0	0	100
3/8 "	80	80	8	92
No 4	120	200	20	80
8	100	300	30	70
16	150	450	45	55
30	90	540	54	46
50	90	630	63	37
100	170	800	80	20
200	110	910	91	9
pan	90	1000	100	-

Table 15.6 Example of three aggregates to be combined to meet specification limits

Sieve Size	Specification Limits	% Passing By Weight		
		Aggregate A	Aggregate B	Aggregate C
1"	100	100	100	100
3/4"	95-100	95	100	100
3/8"	65-80	45	100	100
No4	45-60	12	100	100
8	30-45	3	85	100
30	15-25	0	48	100
200	3-7	0	7	80

Table 15.7 Example of trial-and error procedure for combining aggregate

Sieve Size	Aggregate A	Aggregate B	Aggregate	Combined (A) + (B) + (C)
1"	100 x .60 = 60	100 x .35 = 35	100 x .05 = 5	100
3/4"	95 x .60 = 57	100 x .35 = 35	100 x .05 = 5	97
3/8"	45 x .60 = 27	100 x .35 = 35	100 x .05 = 5	67
No.4	12 x .60 = 7	100 x .35 = 35	100 x .05 = 5	47
8	3 x .60 = 2	85 x .35 = 30	100 x .05 = 5	37
30	0 x .60 = 0	48 x .35 = 17	100 x .05 = 5	22
200	0 x .60 = 0	7 x .35 = 2	80 x .05 = 4	6
	60 % (A) +	35 % (B) +	5 % (C) =	Comb.

15.5.3 *Two Graphical Methods for Blending Aggregates*

i) *Straight-Line Method*

This method, which is recommended by both the Road Research Laboratory, Great Britain, and the Asphalt Institute, U.S.A., is widely used. The method is illustrated in Figure 15.7 showing a diagram with vertical percentage scales for the two aggregates and horizontal scales for the proportion of the aggregates in the final mix. Points on the vertical scales, corresponding to the percentages passing the various sieves, are connected by straight lines in respect of the same sieve sizes. To exemplify the method, aggregates A and B, as described in Table 15.8 and Figure 15.8, have been represented on the diagram.

According to the method described by the Road Research Laboratory, a vertical line is drawn through the point where the sloping line representing a certain sieve intersects the horizontal line representing the percentage of material required in the specification to pass this sieve. The intersection of the vertical line with the horizontal axes defines the proportion. This method takes into account only one point on the grading curve which the aggregate is required to approximate. By repeating the procedure for other sieve sizes, however, the mix representing the closest approximation can be estimated.

A better procedure, when grading limits are specified, is to draw the percentage ranges allowed for each sieve on a scale corresponding to the vertical scale of the diagram. By sliding this scale over the sloping line of the diagram, the proportion of the two aggregates can be determined where possibly all the sloping lines fall within the respective ranges specified. In Figure 15.8 the specification limits are shown with solid lines, while the material outside of the specification is dashed. In terms of the envelope specified in Table 15.8 and reproduced in Figure 15.8, this condition is fulfilled for a proportion of 0.45 A + 0.55 B with the exception of the percentage passing sieve No. 200. Addition of fines is required to comply with the requirements of sieve No.200. This method can be used to great advantage when more than one grading specification may be considered. A vertical, sliding scale can then be made for each specification, and the one chosen to which a combination of the two materials at hand can be closest approximated.

When, on the other hand, a large number of controls to approximate one given specification are made, another procedure is advantageous : points on the vertical scales, corresponding to the percentages passing the various sieves, are marked with pins and corresponding sieve sizes on the two axes are joined by strings. The sliding specification scale is placed under the threads and moved to a position where the greatest number of threads crosses within the specified limits. Again, the proportion of A and B are read off on the horizontal scales.

The straight-line method, as described by the Asphalt Institute, involves mixing three aggregates. In this procedure, two straight-line charts are joined together. The best combination of two aggregates is found on the one chart and this combination is then combined with the third aggregate on the second chart. This way of combining may not necessarily lead to the best combination of the three aggregates, and the method so employed is more cumbersome than certain other methods.

ii) Rothfuchs' Method

The method development by Rothfuchs is, no doubt, one of the most useful graphical procedures, as it is reasonably quick and simple and can be applied to mixtures of any number of components. Rothfuchs' Method will be briefly described by considering the four materials A, B, C, and D, the sieve analysis for which is given in Table 15.9 and the grading in Figure 15.9.

1. The cumulative curve of the required aggregate grading (median of envelope) is plotted, using linear ordinates for the percentage passing but by choosing a scale of sieve aperture size so that the grading plots are a straight line. This is readily done by drawing an inclined straight line and marking on it the sizes corresponding to the various percentages passing (line M in Fig. 15.10). It may be noted that, if the grading of the median complies with the formula, the horizontal scale will be exponential. More specifically, if $n = 0.45$, the diagram obtained will be the Bureau of Public Roads' Chart. If $n = 0.5$, the horizontal scale will be divided according to the square root of the sieve (a way of presentation often used and which complies with the Fuller Curve). Refer to Figure 15.10.

2. The gradings of the aggregates to be mixed are plotted on this scale. It will generally be found that they are not straight lines (curves marked A, B, C, and D).

3. The straight lines that most nearly approximate to the grading curves of the single aggregates are drawn. This is done by selecting for each curve a straight line, so that the areas enclosed between it and the curve are a minimum and are balanced about the straight line (curves marked A', B', C' and D').

4. The opposite ends of these straight lines are joined together (large dashed lines) and the proportions for mixing can be read off from the points where these joining lines cross the straight line representing the required grading. From Figure 15.10, it is seen that this method yields the proportions:

$$0.25 \text{ A} + 0.25 \text{ B} + 0.43 \text{ C} + 0.07 \text{ D}.$$

The grading for this combination is calculated in Table 15.9 and plotted in Figure 15.9. Had Material B been omitted, we would have had :

$$0.44 \text{ A} + 0.49 \text{ C} + 0.07 \text{ D}, \text{ and}$$

finally, had only materials A and C been used, we would have had:

$$0.44 \text{ A} + 0.56 \text{ C}.$$

Considering for a moment the theoretical basis for Rothfuchs' Method, by approximating the individual sieve grading curves to straight lines, these lines are aligned with the specification median through multiplication with the factor representing the proportion of each aggregate in the mixture.
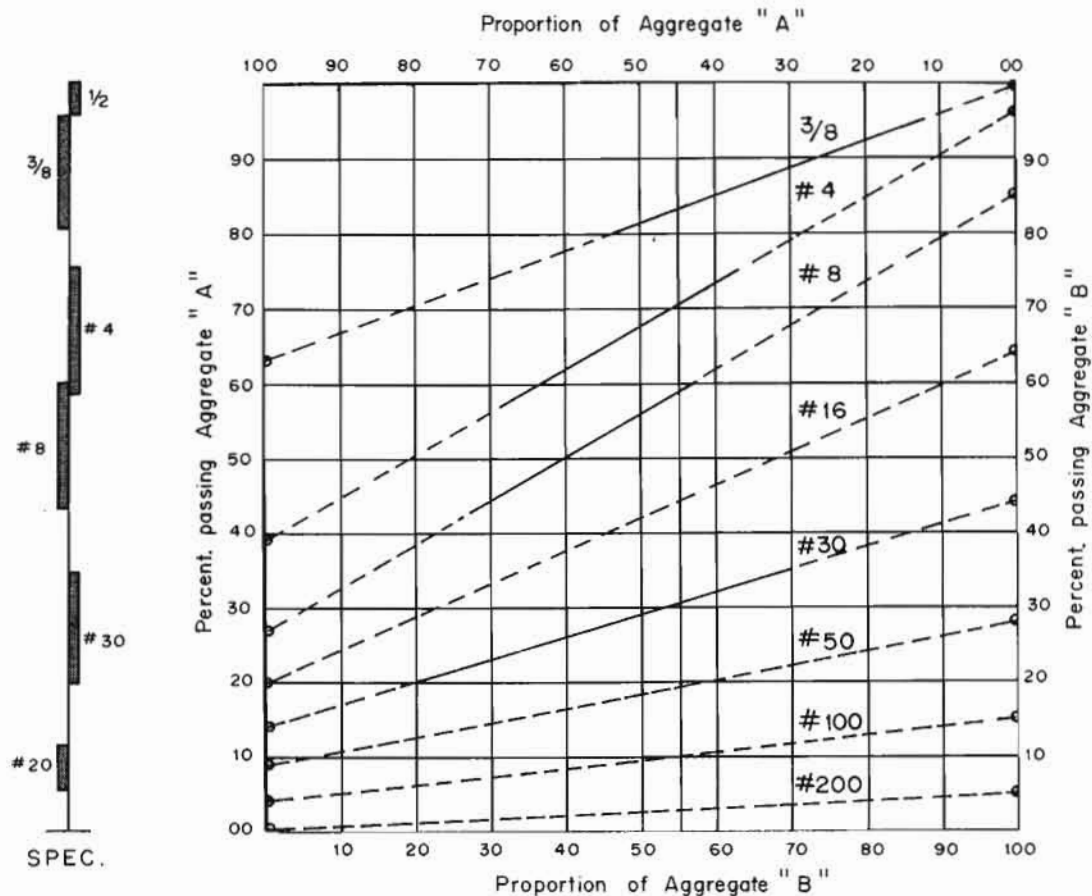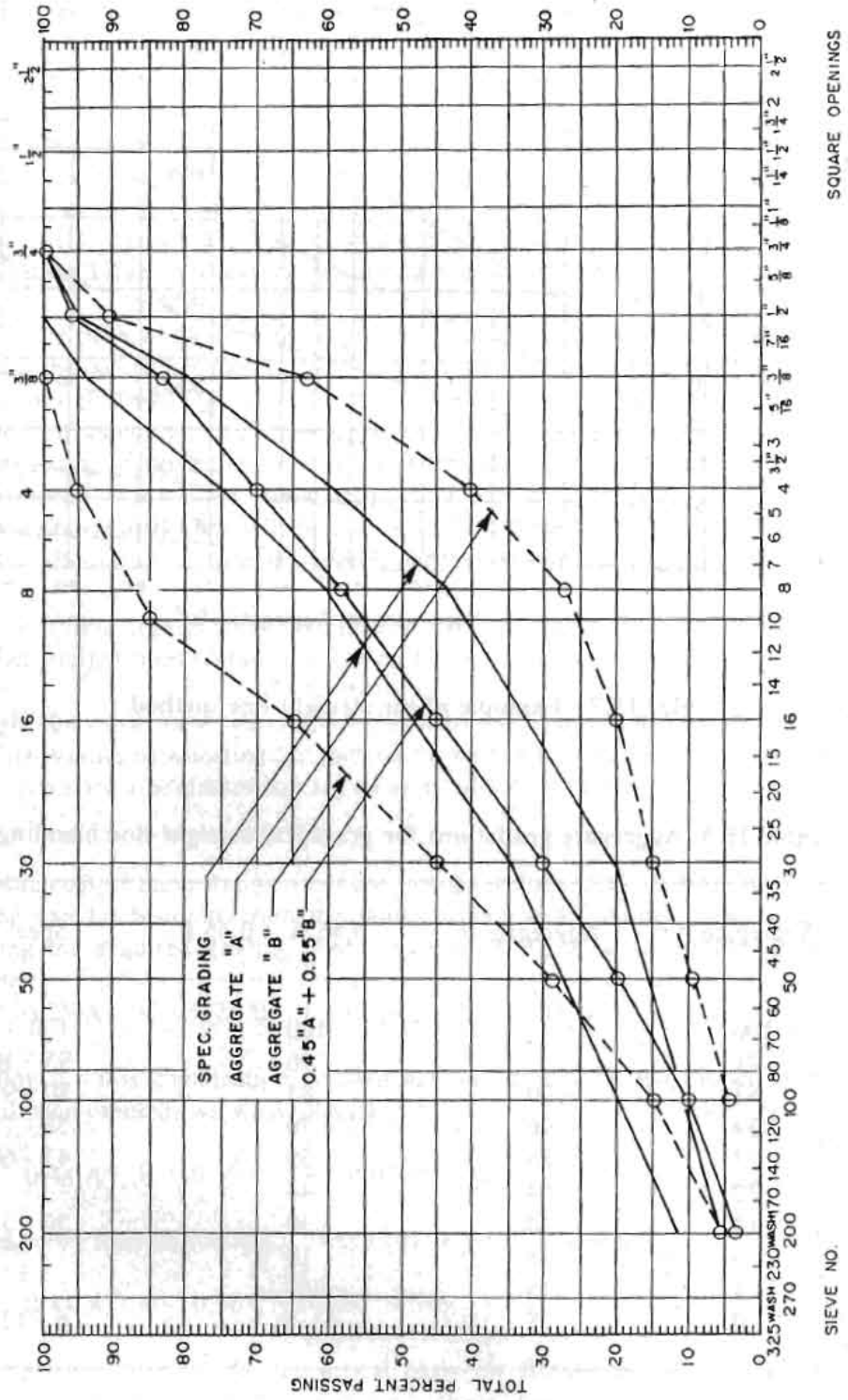
Fig. 15.7   Example of the straight-line method

Table 15.8 Aggregate gradations for graphical straight-line blending

Sieve Size	Aggregate A	Aggregate B	0.45 A + 0.55 B	Spec
3/4"	100	-	100	100
1/2"	91	-	96	95 - 100
3/8"	63	100	83	80 - 95
No.4	39	96	70	58 - 75
8	27	85	59	43 - 60
16	20	64	44	-
30	14	44	30	20 - 35
50	9	28	19	-
100	4	15	10	-
200	0	5	3	6 - 12

Fig. 15.8   Results of graphical blending, two aggregates

298

Table 15.9 Aggregate gradation for Rothfuchs' Method of blending

Sieve Size	Spec. Grading	Required Grading	A	B	C	D	Rothfuchs' Method 0.025 A + 0.25 B + 0.43C + 0.07 D
1/2 "	95 - 100	98	100				100
3/8 "	80 - 99	88	79	100			95
No. 4	58 - 75	67	18	68	100		72
8	43 - 60	52	6	11	95		52
16			2	3	60	100	34
30	20 - 35	28	1	2	41	95	25
50			1	2	31	66	19
100			1	1	22	39	13
200	6 - 12	9	1	1	20	30	11

15.6 AGGREGATE PROPERTIES AND BEHAVIOUR PECULIAR TO BITUMINOUS MIXTURES

Particle surface texture is even more important when considering the resistance to deformation of asphalt-coated aggregate particles. The point is illustrated schematically in Figure 15.11 which suggests why, for two mixtures with the same film thickness of asphalt, irregular surfaced aggregate should be expected to develop the greater frictional resistance for a given contact pressure.

Angularity of particles may influence, to a lesser degree, the interparticle friction. Test results indicate that angular material exhibits higher strength in comparison to a rounded aggregate of the same source at the same constant void ratio. Unfortunately, in these comparisons, the angular material is usually produced from rounded material by crushing. Hence, the effect of angularity is to a certain extent masked by the change in particle surface texture produced by crushing.

Particle angularity influences the compaction of asphalt mixtures; that is, a mix containing an angular aggregate will compact under a given compactive effort to a lesser degree than will a mix containing a rounded aggregate. It is possible, however, that an angular aggregate may permit a greater degree of compaction, particularly when heavy rollers are used. The mix made with the rounded material may actually shove and push excessively under the roller and decompact.

Angularity, however, may be beneficial when the pavement is subjected to traffic, since all available evidence indicates that the mix containing the more angular materials are less susceptible to densification under heavy traffic and subsequent reduction in load-carrying ability. However, this may be also influenced by particle surface texture rather than by angularity.
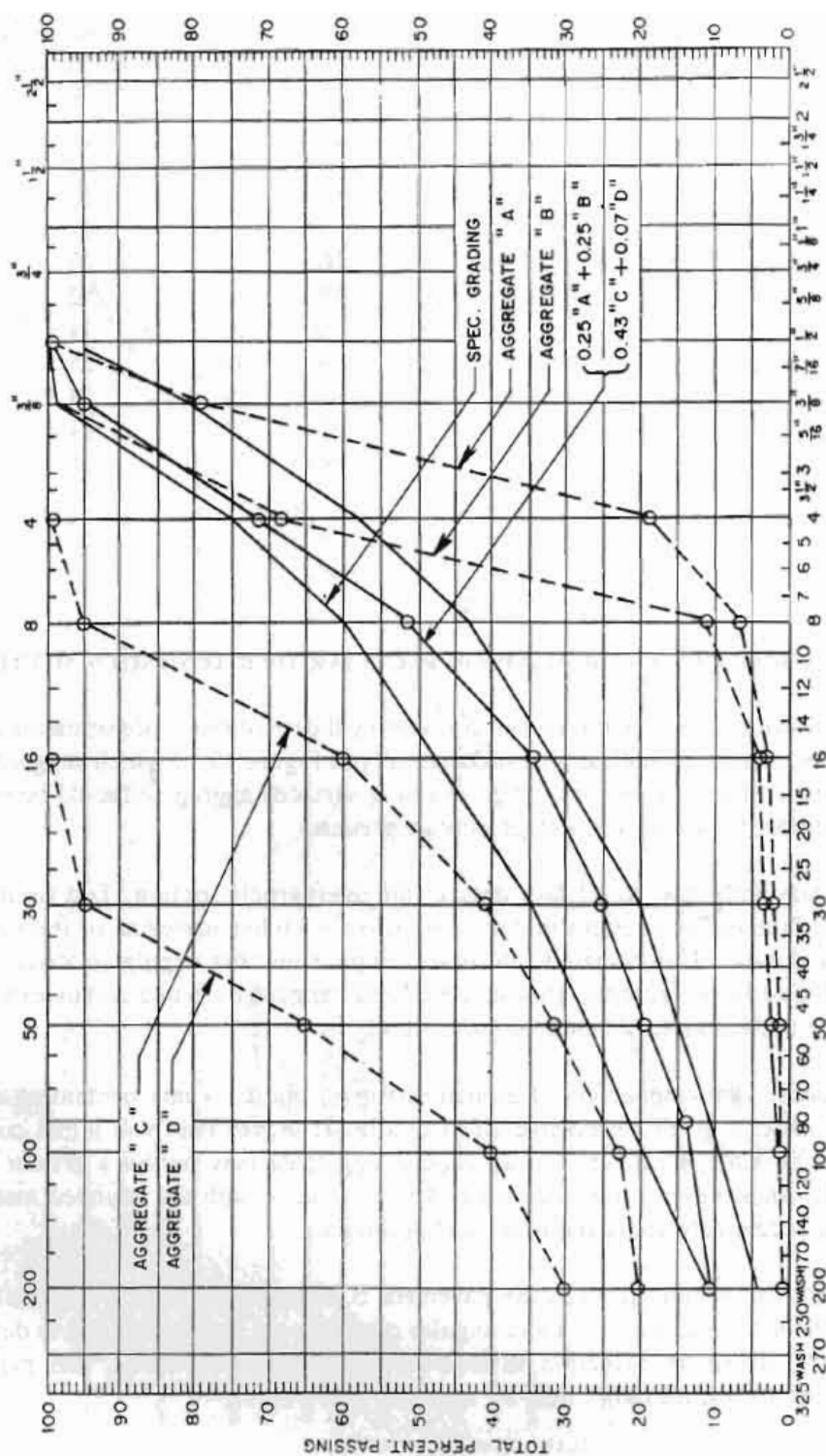
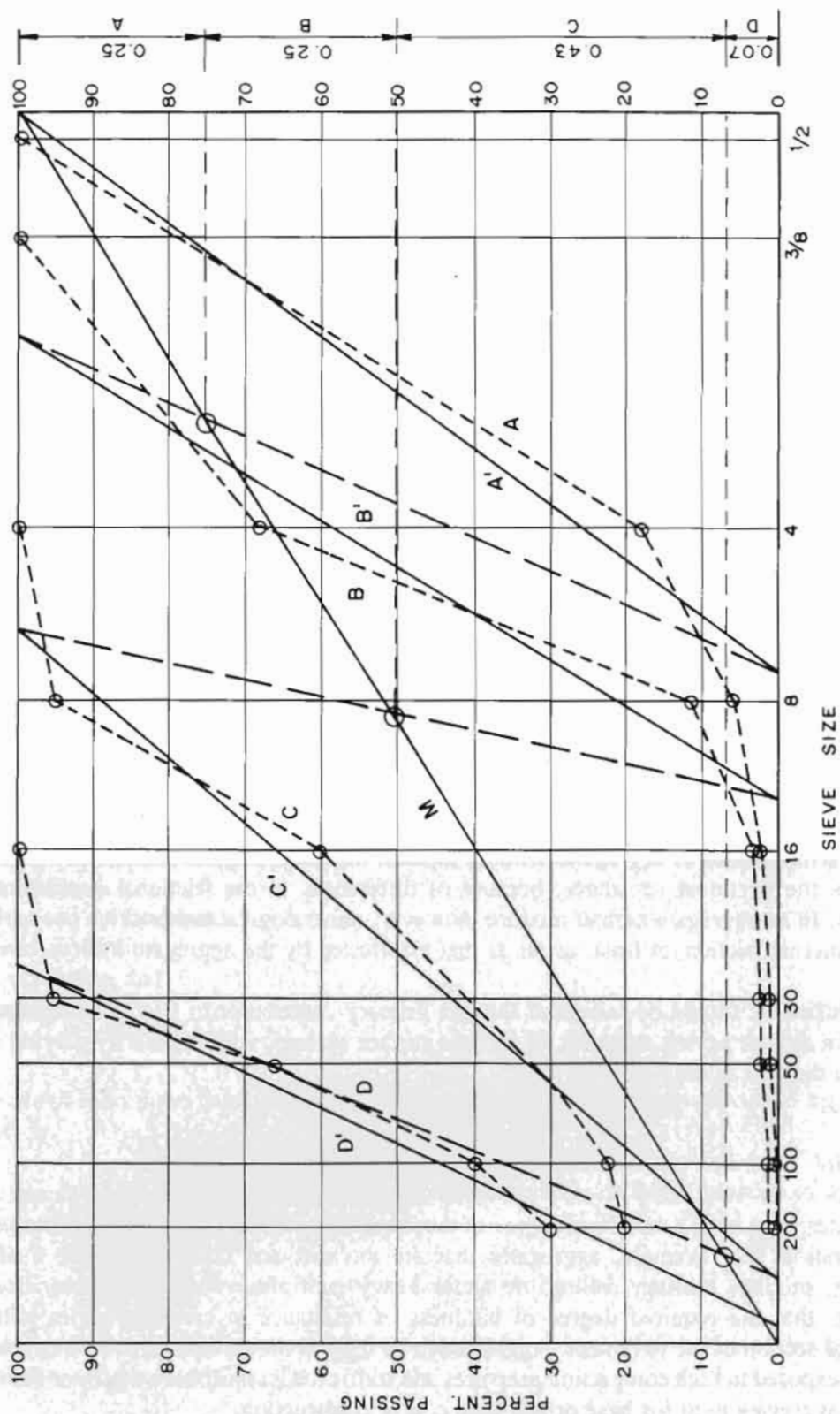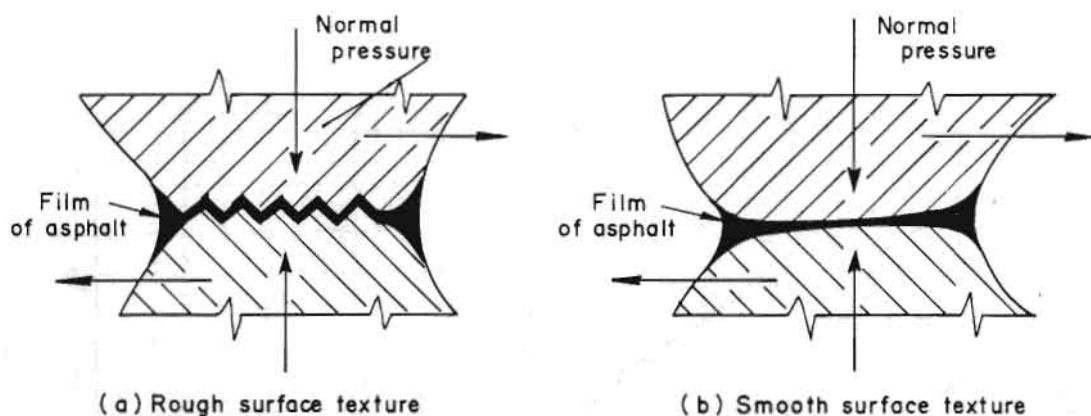Fig. 15.9 Gradations of four aggregates to be blended

Fig. 15.9 Gradations of four aggregates to be blended

Fig. 15.10 Example of blending using Rothfuchs' Method

Fig. 15.11 Comparison of contact surface of aggregates with different texture

Particle size appears to have little effect on interparticle friction, at least in laboratory investigations. In actual pavements, however, due to limited thickness, structural effects may cause particle size to have an influence on the interparticle friction of the composed aggregate asphalt mixture. Particle gradation will influence internal friction to a certain extent. The denser the gradation of aggregate, the more contact areas in the compacted aggregate mass; hence, the greater the frictional resistance.

Void ratio, or degree of packing (compaction), will influence internal friction in the same manner as gradation; that is, the lower the void ratio, or the greater the degree of packing, for a given aggregate gradation, the greater will be the frictional resistance of the aggregate mass. The presence of asphalt will modify this relationship.

In compacted masses of aggregates without asphalt, the mineralogical composition of the aggregate may influence the frictional resistance, because of differences in the frictional coefficients of the various minerals. In an aggregate asphalt mixture, however, mineralogical composition probably has little effect on the internal friction, at least, as far as that manifested by the aggregate itself is concerned.

In conclusion, it should be reiterated that the primary contributor to frictional resistance of aggregate, for use in asphalt paving mixtures, is particle surface texture, with angularity playing a lesser role than has been thought in the past.

Durability

Aggregates must have a sufficient degree of those qualities necessary to resist crushing, degradation, and disintegration. For example, aggregates that are too soft and crush under the loads applied during handling, mixing, placing, rolling, or under heavy traffic may be undesirable. It should be noted, however, that the required degree of hardness or resistance to crushing varies with location in the structural section of the pavement. Aggregate to be used in the asphalt concrete surfacing, which will be directly exposed to high compaction pressures and traffic loads, must have a greater resistance to crushing than an aggregate used for base or sub-base course construction.

Aggregates for asphalt-paving mixtures must also exhibit resistance to degradation. By degradation we mean the production of fine material (usually material passing the # 100 and # 200 mesh screens) by mechanical action such as that produced by repeated application of traffic loads or by excessive handling prior to mixing. Hardness of aggregate is not necessarily related to degradation, since hard particles may wear excessively. Excessive abrasion of aggregate in an asphalt pavement produces fine material which may be either uncoated or insufficiently coated with asphalt and, in turn, can lead to disintegration of the surface.

Disintegration is the breaking down of aggregate particles due to chemical action and usually requires the presence of water to accelerate this action. Fortunately, however, when aggregate is coated with asphalt, disintegration is either minimized or eliminated entirely. Hence, in a well-designed asphalt concrete, disintegration of the aggregate is not as important as in the case of untreated aggregates for base course construction.

Disintegration is related to the mineralogical composition of the aggregate. For example, it is possible that the aggregate may contain minerals that, due to the action of water, will break down into clayey materials. In untreated base courses, this will result in loss in frictional resistance and increased resilient deformations under the action of traffic which, in turn, can lead to cracking of the pavement.

Wettability

Exposure to water is a condition to which all road-building aggregates are subjected. For good performance, any aggregate selected should be reasonably free from any detrimental effects on strength, durability, or flexibility caused by the presence of water. In the case of asphalt-coated aggregates, it is desirable that the aggregate will be of such a nature that water will not displace the asphalt from the aggregate surface. Hence, proper adhesion between the aggregate and the asphalt must be obtained, particularly in the presence of water. Properties of aggregates considered to affect adhesion are:

- surface, texture,
- surface coatings,
- particle size and surface area,
- porosity and absorption,
- chemical reactivity, and
- surface energy.

At present, there are at least three theories regarding the water resistance of asphalt-coated aggregates. These theories are :

i.   chemical reaction concept: acidic components of asphalt react with basic minerals of aggregate to form water insoluble compounds;

ii.   mechanical concept: emphasizes the role of surface roughness and porosity; and

iii. surface energy concept: adhesion resulting from interfacial energy relationships at the aggregate, asphalt, water, and air interfaces.

Considering first the chemical reaction concept, when a solid is wetted by a liquid, absorption occurs at the surface and is followed by a chemical reaction between absorbed material and constituents of the solid phase. For an asphalt to show good adhesion to a solid, the asphalt must contain certain acid or polar compounds and must produce a water insoluble reaction compound. An acidic stone (e.g., quartz) cannot react with an acid oil. Basic oxides (limestones), however, can react with acid oils.
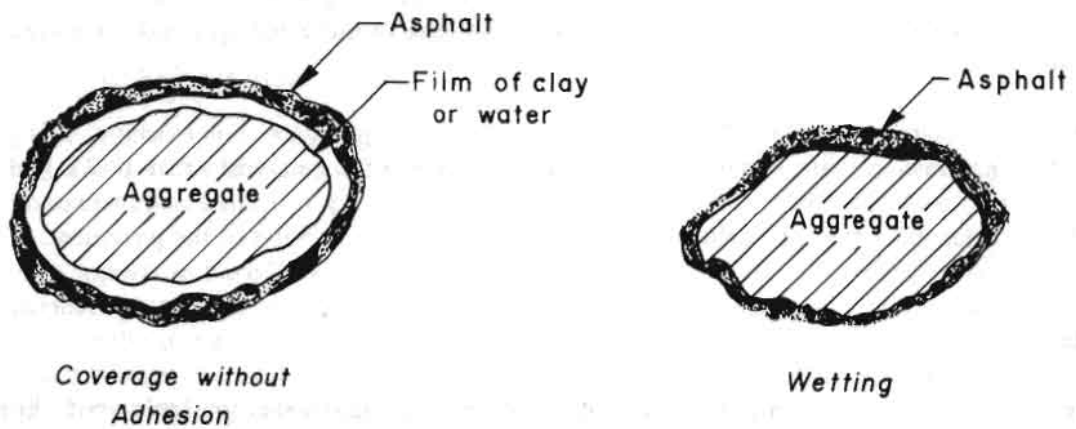

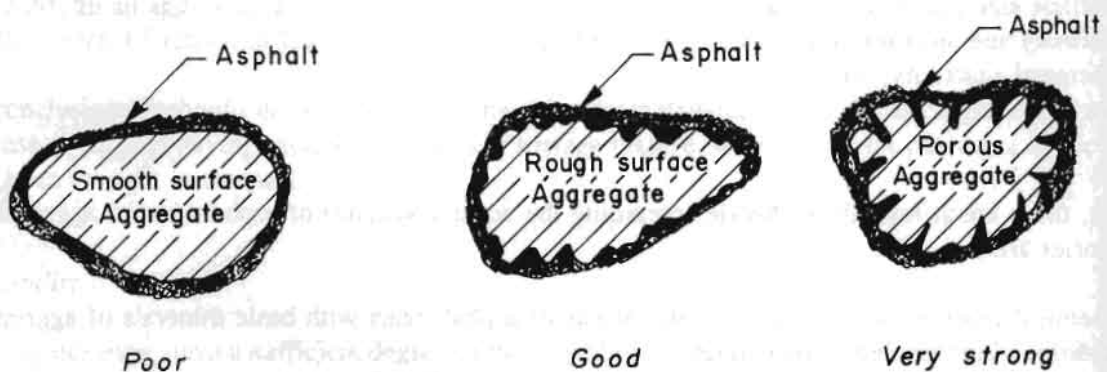Fig. 15.12 Effect of surface film on aggregate coverage

Fig. 15.13 Effect of aggregate surface texture on adhesion

According to the mechanical theory, the composition of the rock is important only to the extent that it affects surface texture. It is thought that the rougher the surface texture, the better the adhesion. Porous aggregates usually show better adhesion to asphalt, due also in part to mechanical interlock. In the case of porous materials, however, it is difficult at times to remove the water from the pores during the drying process. This may be a detriment with respect to adhesion.

Surface coatings also affect adhesion and fall into the mechanical interlock concept. If a layer of clay surrounds the aggregate particle, it is possible to develop coating of the aggregate, but the asphalt will not actually contact the aggregate particle. A film of water surrounding the aggregate particle will also produce a similar result.

Various aspects of the mechanical theory are illustrated in Figures 15.12 and 15.13. The surface energy concept, in part, makes use of the classical theory of wetting to explain adhesion. In the presence of water, the chemical theory states that :

$$r_{SW} = r_{SB} + r_{WB}\cos\Theta$$

where,

r_{SW} =   aggregate-water interfacial tension,

r_{SB} =   aggregate-asphalt interfacial tension, and
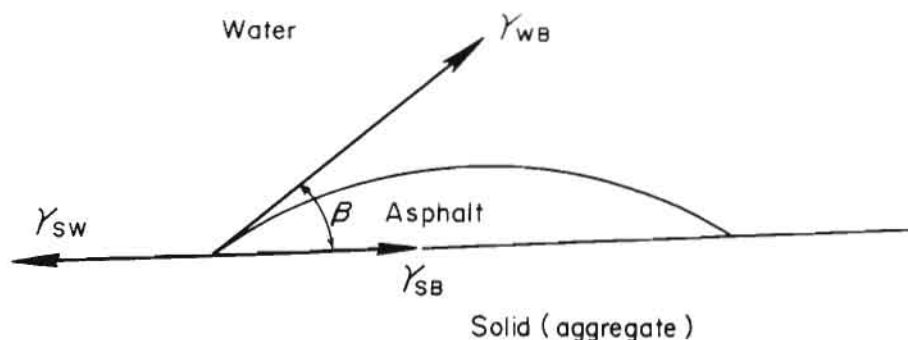
r_{WB} =   asphalt-water interfacial tension.

Fig 15.14 Contact angle in an aggregate, asphalt, and water system

From Figure 15.14 it can be seen that the smaller the contact angle, Θ, the greater is the possibility that the asphalt will flow over the surface of the aggregate and form the desired bond.

This formula is presented primarily to emphasize the importance of interfacial analysis in the study of the effects of water in asphalt mixtures. It should be noted, however, that such a strictly physical approach to adhesion is open to considerable criticism.

The values involved are difficult to measure and their application should be tempered with reservation. Nevertheless, as an attempt to explain the relative abilities of asphalt and water to coat aggregate particles, such a formula provides a valuable foundation for further discussion.

A somewhat more practical approach to an explanation of the adhesion phenomenon is found through use of the principle of polarity. Here one may find basic reasons for the terms commonly used in connection with mineral aggregates, 'hydrophilic' (water loving) and 'hydrophobic' (water hating).

Mineral aggregates, in particular those formed from freshly broken stone, ordinarily exhibit some degree of polarity. This tendency depends upon the chemical and crystalline structure of the material, upon its surface condition, and upon other factors of its physical condition. Figure 15.15 presents a graphical generalization of the possible effects of polarity upon adhesion.

Asphalts are generally rather weakly polarized. In other words, they tend to be weak dipoles. Since water molecules are all dipoles and are thus very active electrically, it is easy to see why water presents such a problem to the paving technologists with respect to stripping failures.

Actually, two conclusions might be drawn in this situation : (1) if an aggregate particle is already coated with water (or some other active dipole), it is impossible for the normal asphalt cement to displace the water and bond to the stone; and (2) if the particle should be coated with an asphalt, it is still possible for the water to later strip the bitumen from the aggregate. Fortunately, these generalizations do not always apply.

In some cases an aggregate-asphalt combination may exhibit polar tendencies which are considerably stronger than the polar action of the same aggregate with water. In such a case, the asphalt would displace water on the surface of the stone and a little stripping action might be expected. Also, the polar tendencies of some bituminous materials tend to increase with age, because of the orientation of polar materials within the main body of the asphalt. Consequently, a certain mixture might happen to be weakly water-resistant shortly after its preparation, but it would later have satisfactory adhesion as polar orientation proceeded (Fig 15.16). Particle size is important when considering the surface energy concept, because the surface areas and surface energy effects for the very fine sizes are large in relation to particle mass.

In general, it would appear that all three concepts are necessary to explain the behavior of asphalt and aggregate in the presence of water because chemical reactions may take place, mechanical interlock occurs, and surface energy relationships influence adhesion.
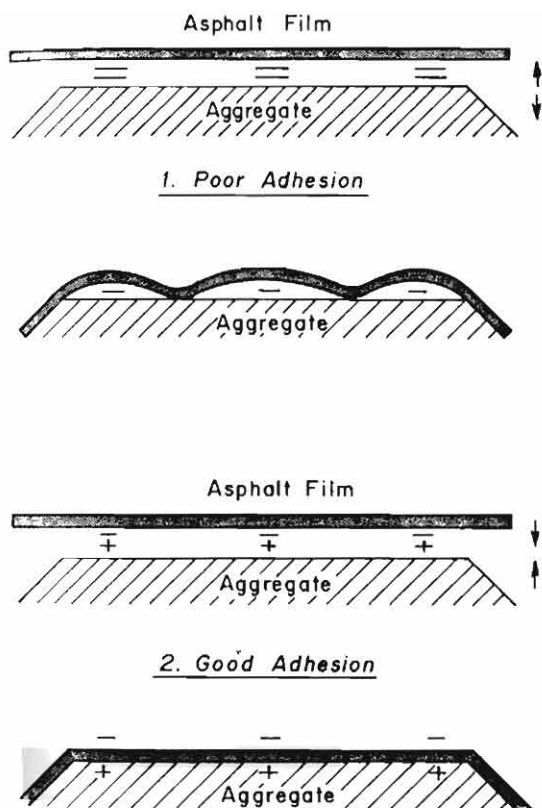
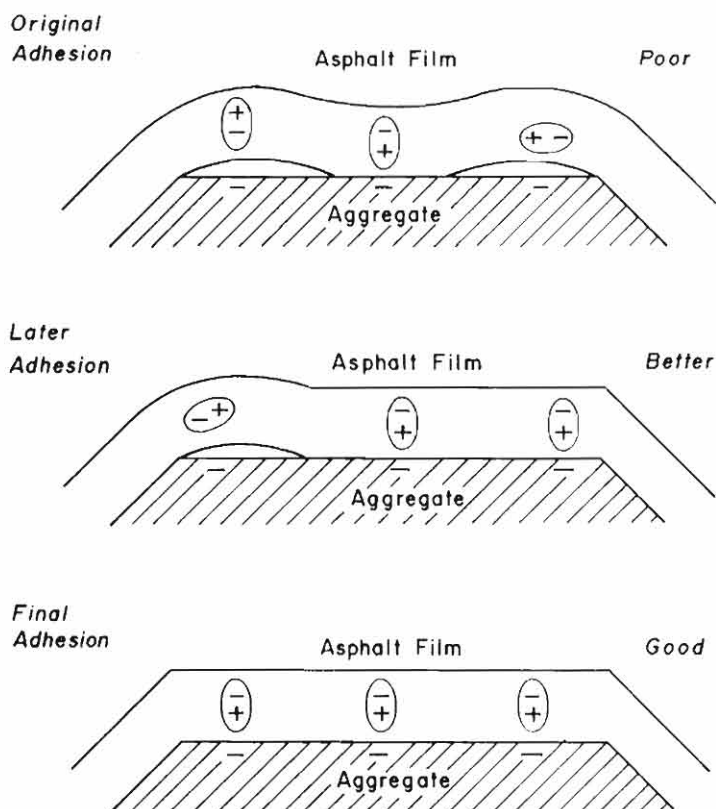Fig. 15.15 Effect of polarity on adhesion

Fig. 15.16 Molecular orientation

15.7 SUMMARY OF PHYSICAL PROPERTIES, ENGINEERING PROPERTIES, AND MINERAL COMPOSITION OF ROCKS (See Tables 15.10, 15.11, and 15.12)

Table 15.10 Average values for physical properties of the principal types of rocks

Types of rock	Bulk	Absorption specific gravity*	Loss of abrasion %	
			Deval % **	Los Angeles ***
Igneous :				
Granite..............	2.65	0.3	4.3	38
Syenite..............	2.74	0.4	4.1	24
Diorite..............	2.92	0.3	3.1	
Gabbro..............	2.96	0.3	3.0	18
Peridotite...........	3.31	0.3	4.1	
Felsite..............	2.66	0.8	3.8	18
Basalt..............	2.86	0.5	3.1	14
Diabase..............	2.96	0.3	2.6	18
Sedimentary :				
Limestone...........	2.66	0.9	5.7	26
Dolomite............	2.70	1.1	5.5	25
Shale...............	1.8-2.5			
Sandstone...........	2.54	2.8	7.0	38
Chert..............	2.50	1.6	8.5	26
Conglomerate........	2.68	1.2	10.0	
Breccia.............	2.57	1.8	6.4	
Metamorphic :				
Gneiss.............	2.74	0.3	5.9	45
Schist.............	2.85	0.4	5.5	38
Amphibolite.........	3.02	0.4	3.9	35
Slate..............	2.74	0.5	4.7	20
Quartzite...........	2.69	0.3	0.3	28
Marble..............	2.63	0.2	6.3	47
Serpentine..........	2.62	0.9	6.3	19

*   After immersion in water at atmospheric temperature and pressure
**   American Association of State Highway Officials (AASHO) Method T3
***   AASHO Method T96.

Table 15.11 Summary of engineering properties of rocks

Types of rock	Mechanical strength	Durability	Chemical stability	Surface charac-teristics	Presence of un-desireable impurities	Crushed Shape
Igneous :						
Granite, syenite						
Diorite..........	Good	Good	Good	Good	Possible	Good
Felaite..........	Good	Good	Questionable	Fair	Possible	Fair
Basalt, diabase						
Gabbro	Good	Fair	Questionable	Good	Seldom	Fair
Peridotite.......	Good	Fair	Questionable	Good	Possible	Good
Sedimentary :						
Limestone						
Dolomite.........	Good	Fair	Good	Good	Possible	Good
Sandstone........	Fair	Fair	Good	Good	Seldom	Good
Chert............	Good	Poor	Poor	Fair	Likely	Poor
Conglomerate						
Breccia.........	Fair	Fair	Good	Good	Seldom	Fair
Shale...........	Poor	Poor	....	Good	Possible	Fair to poor
Metamorphic :						
Gneiss, schists..	Good	Good	Good	Good	Seldom	Good to poor
Quartzite........	Good	Good	Good	Good	Seldom	Fair
Marble...........	Fair	Good	Good	Good	Possible	Good
Serpentinite.....	Fair	Fair	Good	Fair to poor	Possible	Good
Amphibolite......	Good	Good	Good	Good	Seldom	Fair
Slate............	Good	Good	Good	Poor	Seldom	Poor

Table 15.12 Mineral composition of rocks

Name of Rock	No. of samples tested	Quartz	Ortho- class. micro- cline	Plagio- class	Au- gite	Horn- blende	Mica	Cal- cite	Chlo- rite	Kao- lin	Epi- dote	Iron Ore	Remain- der
Igneous rocks													
Granite	165	30	45	(8)			6			(6)			5
Biotite granite	51	27	41	9			11			(7)			5
Hornblende granite	20	23	34	12		13	4		(3)	(10)		(4)	4
Augite syenite	23	(4)	52	7	8		4		(3)	(11)		(3)	4
Diorite	75	8	7	30		27	(4)		(3)	(8)			5
Gabbro	50			44	28	9			(4)	(6)			10
Rhyolite	43	32	45	(3)			(5)		(3)	(3)	(3)	(4)	4
Trachyte	6	(3)	42					(3)	(6)	(14)	(5)	(3)	5
Andesite	67			48	14	6					(8)	(8)	6
Basalt	70			36	35	3				(4)	(3)	(3)	5
Altered basalt	196			32	31							(4)	3
Diabase	29			44	46				(9)	(9)		(4)	6
Altered diabase	231			35	26				(15)			(4)	11
Sedimentary rocks:													
Limestone	875	(6)						83					3
Dolomite	331	(5)						11					2
Sandstone	109	79	(5)							(4)		(9)	3
Feldspathic Sandstone	191	35	26					(3)	(3)	(22)		(4)	7
Calcareous Sandstone	53	46	(3)					42				(3)	6
Chert	62	93											7
Metamorphic rocks:													
Granite gneiss	169	34	35	(4)			20						7
Hornblende gneiss	18	10	16	15	(3)	45	(4)						7
Mica schist	59	36	14	(1)			40						9
Chlorite schist	23	11		10		(5)			39		28	(4)	3
Hornblende schist	68	10	(3)	12		61					(7)		7
Amphibolite	22	(3)		8		70					12		7
Slate	71	29	(4)				55					(5)	7
Quartzite	61	34	(3)				(4)						9
Feldspathic Quartzite	22	46	27	15			(7)		(3)	(10)			7
Pyroxene quartzite	11	29	10		24							(5)	8
Marble	61	(3)						96					1

Source:

b Values shown in parentheses indicate minerals other than those essential for the classification of the rock.

c Includes 10 to 20 % rock glass.

d Limestone contains 8 % of the mineral dolomite : the rock dolomite contains 82 % of this mineral.

e Includes 3 % opal.

f Includes 3 % garnet.

Acidic :   Term applied to igneous rocks containing more than 65 per cent silica (S_iO_2).

Calcareous: Term applied to rocks containing calcium carbonate.

Calcite: The mineral calcium carbonate, C_aCO_3.

Chert: Very fine-grained, siliceous rock containing cryptocrystalline quartz, chalcedony, opal, or a combination thereof. Porous varieties are usually light coloured and have splintery fractures. Dense varieties are hard, have concoidal fracture, greasy lustre, and occur in many colors including white, yellow, brownish stained, or green. The coloured varieties are sometimes called 'jasper' and dense, gray variety called 'flint'. All varieties will scratch glass and cannot be scratched by a knife blade. Some of its constituents may be reactive with cement alkalis, and it should also be considered suspect as concrete aggregate for exposed concrete in cold climates.

Clay: Very fine particles consisting of hydrosilicates of aluminum or magnesium or both. In concrete aggregates, the term frequently refers to these materials occurring as coatings finer than the No. 200 (75 mm) sieve which may be removed by washing. Clay may also occur well dispersed in rocks between laminations so as to weaken the structure or cause the particle to be susceptible to freeze-thaw attack.

Claystone: An indurated clay, having the texture and composition of shale but lacking its fine lamination of fissility, a massive mudstone in which clay predominates over silt, a non-fissile clay shale.

Conglomerate: (1) Rock consisting of rounded pebbles cemented together with finer material. (2) A coarse-grained, clastic sedimentary rock, composed of rounded to sub-angular fragments larger than 2 mm in diameter (granules, pebbles, cobbles, and boulders), set in a fine-grained matrix of sand or silt and commonly cemented by calcium carbonate, iron oxide, silica, or hardened clay, the consolidated equivalent of gravel both in size range and in the essential roundness of gravel and sorting of its constituent particles.

Coral: A general name for any of the large groups of bottom-dwelling sessile, marine invertebrate organisms that belong to the class *Anthozoa*.

Detritus: Fragmental material such as sand, silt, and clay moved from its place of origin.

Diorite: Medium to coarse-grained rock composed essentially of plagioclase feldspar and ferromagnesium minerals.

Dolerite: A basic intrusive rock composed of labradorite and pyroxene and which is characterized by ophitic texture.

Dolomite: The mineral calcium-magnesium carbonate $CaMg(CO_3)_2$. A common rock-forming rhombohedral mineral.

Foliated: More or less parallelism of mineral grains in metamorphic rocks as distinct from the stratified structure of some sedimentary rocks.

Glass: Component of some volcanic rocks resulting from such a rapid cooling from the molten state that no crystal structure is present. Obsidian is a natural glass.

Garnet: A group of minerals, brittle and transparent to sub-transparent mineral, having vitreous lusture, no cleavage, and a variety of colors, dark red being the most common.

Gneiss: A banded or foliated rock (e.g., granite gneiss, diorite gneiss) formed by regional metamorphism in which bands or lenticles of granular minerals alternate with bands or lenticles in which minerals having flaky or elongated prismatic habits predominate. Generally less than 50 per cent of the minerals show preferred parallel orientation and are rich in feldspar and quartz.

Granite: A plutonic rock in which quartz constitutes 10 to 50 per cent of the felsic components and in which the alkali feldspar to total feldspar ratio generally ranges from 65 to 90 per cent. Rock has large grains easily visible to the eye and consisting predominantly of quartz and alkali feldspar.

Hematite: Ferric oxide, Fe_2O_3.

Kaolinite: One of the clay minerals consisting of a hydrous aluminum silicate.

Laterite: A term used for highly-weathered, red subsoil or material rich in secondary oxides of iron, aluminum, or both, nearly devoid of bases and primary silicates and commonly with quartz and kaolinite.

Limestone: A sedimentary rock consisting chiefly of calcium carbonate, primarily in the form of the mineral calcite and with or without magnesium carbonate. Common minor constituents include silica, feldspar, clays, pyrite, and siderite.

Loess deposits: A widespread, homogeneous, commonly non-stratified, porous, friable, slightly coherent, usually highly calcareous, fine-grained, blanket deposit, consisting predominantly of silt with subordinate grain sizes ranging from clay to fine sand.

Magma: Naturally occurring mobile rock material, generalized within the earth and capable of intrusion and extrusion, from which igneous rocks are thought to have been derived through solidification and related processes.

Marble: A metamorphic rock consisting predominantly of fine to coarse-grained, re-crystallised calcite and/or dolomite, usually with a granoblastic saccharoidal texture.

Mudstone: An indurated mud having the texture and composition of shale, but lacking its fine lamination or fissility. A blocky or massive, fine-grained, sedimentary rock in which the proportion of clay and silt are approximately equal.

Peat:
An unconsolidated deposit of semi-carbonized plant occurring in a water-saturated environment, such as a bog or pan, and of persistently high moisture content.

Phyllite:
A metamorphosed rock, intermediate in grade between slate and mica schists. Minute crystals of sericite and chlorite impart a silky sheen to the surfaces of cleavage.

Quartz:
Most abundant form of the mineral silica (SiO_2). Very hard, will scratch glass but cannot be scratched by a knife. Colourless when pure, glassy lusture, with conchoidal fracture.

Quartzite:
There are two types of quartzite (1) A granoblastic metamorphic rock consisting mainly of quartz and formed by re-crystallization of sandstone or chert by either regional or thermal metamorphism. (2) Extremely hard, tough, and stable sandstone. Sand grains have been cemented together with secondary quartz. Excellent concrete aggregate but may crush to thin or elongated pieces.

Sandstone:
A medium-range, clastic sedimentary rock composed of abundant rounded or angular fragments of sand size, set in a fine-grained matrix and more or less firmly united by a cementing material.

Schists:
A strongly-foliated, crystalline rock formed by dynamic metamorphism. It can be readily split into thin flakes or slabs because of the well-developed parallelism of more than 50 per cent of the minerals present, particularly those of lamellar or elongate prismatic habit, e.g., mica and hornblende. It originates from a number of igneous or sedimentary rocks. It is characterized by thin, platy, flat fragments.

Shale:
A fine-grained detrital sedimentary rock, formed by the consolidation of clay, silt, or mud. It is characterized by a thinly laminated structure and a fissility approximately parallel to the bedding. The rock breaks readily into thin layers and is commonly most conspicuous on weathered surfaces. The rock is a poor candidate as a concrete aggregate unless proved otherwise.

Slate:
A fine-grained, low-grade metamorphic rock which breaks easily, not necessarily parallel to laminations. Less suspect as a concrete aggregate than shale.

Colluvium:
Rock fragments of any size or shape derived from, and lying at the base of, a cliff or very steep rocky slope. Talus cones are constituted of colluvium.