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16. ABSTRACT

I suppose that one reason for having a title on a technical paper is to raise questions which the paper is supposed to answer. In this case, it would seem that the title presupposes a discussion on why one should perform laboratory tests on aggregates and assumes that the reader is familiar with this material called "aggregates". It might be well however to make sure that we do all agree on the nature of the material and so perhaps we should define the term before we discuss the need for performing laboratory tests. All of you know, of course, that the full name is "mineral aggregates" and it was undoubtedly adopted by someone who felt that professional engineers would never get anywhere by using such simple terms as stone or rock. Geologists and petrographers complicated matters when they found out that a piece of stone large or small consists of one or more minerals, hence is correctly called a mixture or aggregation of minerals. The dictionary says that minerals are "Any chemical element or compound occurring naturally as a product of inorganic processes", and Dana goes on to say that "if exposed to favorable conditions will develop a certain characteristic atomic structure which is expressed in its crystalline form....." Therefore, when an engineer prepares mixtures of rock, sand or gravel, he is actually drawing upon Mother Nature's chemical storehouse, and when he adds Portland cement, asphalt, or other ingredients, he is further complicating the mixture of crystalline and amorphous chemical compounds and the stage is set for both physical and chemical changes or reaction.

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LABORATORY TESTS ON AGGREGATES

By
F. N. Hveem
Materials and Research Engineer

57-04

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State College of Washington, Pullman, Washington
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By

F. N. Hveem*

I suppose that one reason for having a title on a technical paper is to raise questions which the paper is supposed to answer. In this case, it would seem that the title presupposes a discussion on why one should perform laboratory tests on aggregates, and assumes that the reader is familiar with this material called "aggregates". It might be well however to make sure that we do all agree on the nature of the material and so perhaps we should define the term before we discuss the need for performing laboratory tests. All of you know, of course, that the full name is "mineral aggregates" and it was undoubtedly adopted by someone who felt that professional engineers would never get anywhere by using such simple terms as stone or rock. Geologists and petrographers complicated matters when they found out that a piece of stone large or small consists of one or more minerals, hence is correctly called a mixture or aggregation of minerals. The dictionary says that minerals are "Any chemical element or compound occurring naturally as a product of inorganic processes", and Dana goes on to say that "if exposed to favorable conditions will

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develop a certain characteristic atomic structure which is expressed in its crystalline form....." Therefore, when an engineer prepares mixtures of rock, sand or gravel, he is actually drawing upon Mother Nature's chemical storehouse, and when he adds portland cement, asphalt, or other ingredients, he is further complicating the mixture of crystalline and amorphous chemical compounds and the stage is set for both physical and chemical changes or reactions.

Most of us have been familiar with rocks from childhood; from the days when we threw small stones at the neighbor's cat or sometimes at his kids. Also, during our formative years in school, we may have been told that there were "sermons in stones" or if we were fortunate enough to live in the country and go barefoot we learned about stone bruises; nevertheless by and large, rocks and pebbles were all too commonplace and presented little to intrigue the imagination. Before we had advanced enough to pay income tax, life was simpler for most of us, and our language and terminology reflected this simplicity. In those days, rocks were simply rocks for which we found only occasional use. Sands were more intriguing and those living near major streams, lakes or the ocean found sand a really admirable substance. I doubt however that many of us stopped to think that sand grains were nothing more than small sized stones or pebbles.

In a manner similar to their professional brethren in the law or in medicine, engineers confuse people at times with their language and terminology. It is to be feared that they often confuse themselves. For example, the asphalt paving engineer usually recognizes three forms of granular materials identified as coarse aggregate, fine aggregate and filler, and this distinction in terms leads to the inference that there are also important differences in properties of the materials.

It is, of course, easy to poke fun at people who use long words, but the professional man, and especially the engineer, has an obligation to be precise and exact in his language, hence engineering specifications properly refer to coarse aggregates, fine aggregates or filler instead of just simply saying gravel, sand or dust. However, in spite of terminology, so-called filler dust is nothing more than minute particles of stone, and when man's vision is expanded by use of the microscope, all of the apparent differences between fine dust, sand and coarse aggregate tend to disappear. When derived from the same parent stone, coarse aggregates, sand and filler will be found to have the same mineral composition and, therefore, be made up of the same chemical compounds. Figure 1 illustrates a piece of granitic rock, the four minerals that make up a typical granite, together with the chemical formulas for each of the minerals present.

The next step is to recognize that calling earthy materials by such names as silt, loam or clay does not change the fact that here again we are talking about small particles of stone. It is true, however, that clays and other classes of finely divided soil particles which are a product of weathering usually have become intermingled with many forms of organic material, and the very process of disintegration has tended to separate and segregate many of the primary constituents of the stone. For example, the disintegration of granite is usually due to the decomposition of the mineral, feldspar, which is converted into the clay mineral, kaolinite. So while granite that has been finely crushed by artificial means still contains portions of all the minerals, decomposition by weathering processes will leave the hard quartz particles, hornblende and perhaps biotite mica, to form the granular disintegrated granite while the decomposed feldspar has been largely removed and washed away by water, especially in the upper horizons of the soil. On the other hand, quartz consists of the single mineral, silica, SiO_2, which is extremely hard and resistant to abrasion and wear, but is subject to attack by certain alkalis which may slowly convert crystalline quartz into other forms of silica.

In the sedimentary rocks such as shales and sandstones, clay particles and sand grains may be recemented to form massive stone that differs markedly from the parent stone from which the fine particles were originally derived.

The foregoing brief remarks mention only a few of the great variety of materials that exist on the surface of the earth. The more inert and resistant of these chemical compounds or minerals have persisted in spite of ages of weathering and attack of the elements. These highly resistant combinations of minerals are therefore what we mean by the term rock or stone, or what engineers call "mineral aggregates". Figures 2, 3, 4, and 5 present specimens of four different classes of rock; namely, igneous, volcanic, sedimentary and metamorphic.

In general, engineers are inclined to feel that problems in chemistry should be left to the chemist and there is some justification for this view because it is true that a great many engineering works have been constructed by men with little or no knowledge of the science of chemistry. With some justification, engineers may feel that there are enough problems to be met in the realms of physics and mechanics, and that they can well leave to others the question of chemical phenomena -- especially as there is more than one field of chemistry involved.

Therefore, let us see if mineral aggregates present any problem or variation in their physical properties. First, the most easily recognized is the question of shape, and it is easy to perceive the difference between rounded water worn pebbles and the angular shapes characteristic of most crushed stone. Most contractors have encountered the specification stipulation that elongated or flat particles are "verboten". So far as I know, the reasons why flat or elongated particles are objectionable have never been made too clear, but it is certainly true that they are frowned upon, probably for the reason that such pieces of stone will pass through plant screens corresponding to the least dimension with the result that the pieces are much larger than had been intended.

For a great many engineering applications, crushed stone and gravels are used more or less interchangeably, although for some purposes crushed stone is considered superior. This preference is most marked when materials are being considered for granular bases for roads and perhaps the least discrimination exists when materials are being proposed for portland cement concrete. This seems to lead logically to the question of what are the significant differences between crushed stone and gravel. First, it might seem that the primary difference rests in the question of angularity on the presumption that angular particles are more "stable" than rounded ones. However, an examination will show that in the majority of cases crushed stone particles also have a rougher surface texture than the water worn gravels. There is a great deal of evidence to indicate that particle surface texture is a far more important variable than is over-all particle shape. Figure 6 shows stone particles of different shape and degree of angularity. Figure 7 shows particles having different degrees of surface texture or roughness.

A third property of mineral aggregates that may have a marked influence upon the behavior or suitability for engineering purposes is the question of porosity or absorption, and a closely related or parallel property is that of density of the stone, usually expressed in terms of specific gravity. Figure 8 shows stone particles having different degrees of porosity. Figure 9 is a cross section of a porous stone showing the degree to which paving asphalt has been absorbed into the interior of the particle. These, then, are the principal physical properties of the individual stone particles - shape, surface, texture, porosity, and density.

There are very few cases where engineers use stone particles in which all are the same size. The only example that comes readily to mind is the use of standard Ottawa sand as a means for testing cement and as a standard in the concrete mortar test. It is true, of course, that there is something attractive to the eye in a large mass of particles or grains that are very uniform and of the same size and shape. People are intrigued by heaps of corn, masses of ball bearings, and perhaps even more so by chests full of pearls or gold coins. However, for most engineering purposes, rock particles are assembled in a wide range and variety of sizes usually graduated from the very smallest measured in microns up to the coarse particles measured in inches. This collection of stone particles is usually classified by means of a sieve analysis and the sequence of sizes is generally referred to as the grading of the aggregate. Sieve analyses are not difficult to make and are among the first tests performed by the average young civil engineer. It is also a pretty simple matter to plot the results on a chart in order to study or examine the "grading curve". It sometimes seems, however, that the very simplicity of the process and familiarity with grading curves leads to the belief that there is nothing particularly involved or mysterious. A simple grading curve, however, can provide a great deal of valuable information to the engineer, and it can also conceal many significant relationships. Figure 10 illustrates some of the wide variety of gradings that have been encountered with mineral aggregates. Figure 11 shows a grading curve that has been found to be satisfactory for a variety of purposes.

It may seem that I am a little slow in getting down to the question of why should laboratory tests be performed on mineral aggregates. The sieve analysis just mentioned above is, of course, one of the first and simplest of the laboratory tests, and engineers have long realized that it is important to determine and control the grading of aggregates. Many tests are by no means new. For example, in the Proceedings of the American Society of Civil Engineers for November 1947, Mr. Jacob Feld quotes from a treatise on Soil Classification presented over 300 years ago, in which John Evelyn recommended the use of "the best auxiliaries of microscopes, lotions, <u>strainers</u>, calcination, triturations and grindings" in order to identify the various materials of the earth. Some of these old "auxiliaries" are still in use although today strainers are generally referred to as sieves or screens.

Here again terminology becomes involved because the operation which the lay engineer would call "determining aggregate grading" might be described by the scientist as the determination of the granulometric composition. Of course, there is usually a difference between the gradation of the aggregate as received and the grading which is considered best for a particular purpose. This leads to the question of what is best and what considerations determine that one gradation may be better than another. Without going into great detail, it may be said that the following factors may be influenced by the grading of the aggregate. Workability and the ease with which the mixture can be placed under a given set of circumstances; the amount of asphalt in the paving mixture or the amount of water in portland cement concrete often need to be varied according to the gradation. The surface texture of bituminous pavements is affected by the amount and type of coarse aggregate and proportions are usually critical when the gradation contains an excessive amount of fine particles or dust.

Performance of a sieve analyses, however, and an intelligent study of the results requires information on another property, namely, the specific gravity. If all particles of stone and sand were of equal density or had the same specific gravity, the matter would not be as important. However, it often happens that the sand particles have a specific gravity different from the coarse stone. As sieve analyses are determined by weighing the amounts of each size as separated by the sieves, it is necessary to know the specific gravity of each fraction in order to compare aggregate gradations. Figure 12 illustrates the marked differences that can exist when aggregates of different specific gravity are combined. In terms of weight, the gradation of all four samples shown in Figure 12 would be identical. It is obvious, however, that the relative volumes of the fine and coarse fractions can vary considerably.

This is perhaps a good place to emphasize one of the fundamental relationships that must be considered in all engineering work dealing with the laboratory analysis and the field proportioning or batching of mineral aggregates. This is the fact that virtually all of the important relationships depend upon the relative volumes and not upon the weight. In some instances the bulk volume or weight per cubic foot of the granular material is significant, but for most work the important relationships in proportioning rest upon the absolute volumes of the various particle size groups. This is especially important in portland cement concrete for example. It may be asked then if this is true why are all specifications based upon weight percentages and why are plants controlled by means of scale weights rather than by volume. It has been amply demonstrated that proportioning by volume is nearly always unreliable or erratic because many factors influence the degree to which granular materials will bulk. It has been found by long experience that the most reliable method, either for laboratory or for construction control, is to weigh all materials at the time of proportioning. But when establishing the weights to be used, an engineer must make allowances for any differences in the volume-weight relationships. This means that whenever a given combination includes materials that are measurably different in specific gravity, then two different sets of figures must be calculated for the aggregate grading, one based on relative volumes which conforms to the theoretical or specified grading, the other corrected for variations in specific gravity to give the actual weights of each fraction which must be combined. The need for this correction is very often overlooked, especially in bituminous work.

Having demonstrated the need for laboratory tests to determine the grading of the aggregate and need for knowledge of the specific gravity to correctly evaluate the grading, we may then consider other properties of the aggregate; for example, the question of absorption or porosity. Aggregates that are absorbent obviously have holes or pores and consequently are nearly always below the average in density or specific gravity. However, absorption can present variables and complexities as there can be a considerable range in the size as well as the volume of the pores. For example, an aggregate particle may have a considerable volume of pore space but the capillaries may be so minute that only a liquid of very low viscosity can penetrate deeply.

There have been various methods used to evaluate porosity, the oldest and most common is by means of soaking in water which is reasonably satisfactory for concrete aggregates. However, it can be shown that the amount of water absorbed does not necessarily indicate or parallel the amount of organic liquid such as road oil, for example, that could be taken up, and as asphalts are organic liquids derived from petroleum it becomes desirable to evaluate the absorption by some similar liquid.

Many years ago we developed the test known as the Centrifuge

Kerosene Equivalent or CKE method for evaluating the total surface including the pores in the coarse aggregate. This method, too, however is not entirely free from discrepancies because kerosene may penetrate deeply into stone having very fine pores but the penetration of asphaltic materials will naturally vary with the viscosity of the asphalt. Therefore, while the CKE method may give a fairly reliable indication of the amount and rate of absorption of the more liquid asphalts, it often happens that the heavier paving grades will not be absorbed at the same rate. However, if the pores are relatively large, then the CKE evaluation will be satisfactory for all grades of asphalt. It may therefore be seen that even such a simple property as porosity must be broken down into three distinctions - the volume of the pores, the size of the pores, and whether or not there is any differential or preferential absorption between water and organic liquids. Figure 13 illustrates the hand operated centrifuge used to evaluate the surface capacity which includes porosity.

Having discussed the need for testing to determine the gradation, the specific gravity and porosity, we now come to the question of surface texture. There are direct tests for the first three mentioned, but significant differences in surface texture are not so easily measured. While either markedly rough or obviously smooth, polished particles can be detected by inspection or by feel, there are many intermediate stages not easily evaluated. The real reason for this difficulty is the fact that surface irregularity is not always the major consideration. The real significance lies in the question of resistance to sliding. It can be shown that some surfaces that appear rough or irregular do not offer any unusual resistance to sliding between particles and other stones that may appear rounded and water worn can display a very significant resistance. This means then that the only means for correctly evaluating the effect of surface texture so far as stability is concerned is to perform tests that will reflect the frictional resistance. Such a test is the stabilometer, Figure 14, which, while it is said to measure stability, actually measures with reasonable accuracy only one of the factors that contributes to the overall stability of paving mixtures; namely, the interparticle friction. Furthermore, in an asphaltic mixture it evaluates what may be called the residual friction or the algebraic sum of + friction and - lubrication allowing for the influence of compaction and the lubricating effect of any asphalt or other material present. It can easily be shown that particles of dry stone or sand in contact offer variable resistance to sliding, depending upon whether the material is a rough textured particle such as sandstone or basalt on one hand, or smooth polished substances such as quartz or flint on the other. Nevertheless, the initial friction can usually be modified by the presence of viscous liquids such as asphalt, and as the engineer is only concerned in the behavior of a paving mixture after the aggregates are combined with asphalt, the property of interparticle friction is best evaluated on specimens representing the compacted pavement in place. Tests will show that rock and sand grains having rough surface textures resembling sandpaper will show higher friction resistance or stability and can be lubricated less readily than smooth, polished particles.

Thus far we have not discussed the effects of particle shape; that is, whether angular particles are more stable than rounded or spherical ones. A limited number of tests have been performed attempting to settle this point. For example, in our own laboratory samples of rounded, smooth quartz gravel were crushed and tested in the stabilometer both before and after crushing. Little difference in stability value was found and it may be observed that the broken fractured surfaces of quartz particles are virtually as smooth as are the water worn surfaces. By way of contrast, tests on a certain sample of crushed ledge rock indicated no greater stability than the quartz gravel although the particles were extremely angular, having many square, sharp corners. The flat surfaces however were obviously smooth and glassy in texture. In a third case rounded stream gravel of basaltic rock was found to develop very high stability even though all particles were nearly spherical in shape. However, a careful examination showed that these rounded particles offered a great deal of resistance to sliding when pressed tightly together by hand. A recent paper by B. A. Vallerga presented before the National Sand and Gravel Association in Los Angeles, February 11-14, 1957, presents additional evidence that particle surface texture is a much more important variable than is particle shape.

In summary then, it can be stated that all observations of performance and of tests measuring interparticle friction indicate that the shape of the particle is of relatively minor consequence although undoubtedly there must be some effect. It seems reasonable that other things being equal a mass of cubes would be more stable than would a mass of ball bearings. However, mineral aggregates are neither cubes or spheres and it appears that the texture of the stone, especially of the plane surfaces, is the most important variable.

While precise test measurements are not available, it must also be recognized that this question of surface texture has an influence upon the behavior of concrete mixes.

It is perhaps well to emphasize that while it is not difficult to test aggregates in the laboratory and establish numbers for many of these properties, the effort may be largely wasted unless the engineer understands how these properties affect their use in engineering work. Thus a rough surface texture is desirable to develop high stability in bituminous mixtures but it can be objectionable in portland cement concrete because it requires more water to produce workability and high water cement ratios make poor concrete, both in terms of strength and in durability.

All of the discussion thus far has neglected one of the properties of stone which has long been considered of primary importance. I refer to the matter of hardness. Virtually all specifications today carry requirements limiting the loss in such testing devices as the Los Angeles Rattler. These rattler tests are hardness tests and are, of course, aimed at eliminating the softer and weaker stone types and there is no doubt that some such evaluation is necessary. It is true, however, that the emphasis on hardness has been shifted in recent years and there is also room for doubt whether existing methods evaluate this property properly.

So much for purely physical properties or relationships. Grading, porosity, particle surface texture and shape, specific gravity and hardness - these may be classed as among the rather general requirements as all these properties are important regardless of the particular type of construction. In addition, there are certain special tests to determine properties that are important in certain applications and perhaps not in others. For example, it is important to have "sound" aggregate if portland cement concrete structures are to be durable and withstand freezing and thawing. The sodium sulfate soundness test has long been used for this evaluation. This cannot be classed as one of the more satisfactory tests because there are many discrepancies between the test results and the actual performance of materials. While this test is performed by alternate immersion of the aggregates in sodium sulfate solutions and then drying, the action is almost wholly mechanical or physical. In other words, these solutions enter the pores in the stone and the expanding crystals that are formed tend to fracture or disrupt the stone in much the same manner as would the freezing of water into ice.

Differences in chemical composition do emphasize themselves however in the so-called reactive aggregates. Here it has been found that certain alkalies present in greater or less degree in all portland cement may react with certain aggregates to produce an expansive by-product. This problem may be met in two different ways, either by testing the aggregates to determine whether any reactive materials are present or by eliminating portland cements that are high in alkali. Tests of this sort fall in the borderline between classical physics and chemistry and we are here dealing with a phenomena that is variously described as being in the field of colloidal chemistry or surface chemistry. The mineral opal, for example, is one of the most potent causes for trouble in the cement-aggregate reaction, and opal is one of the few colloidal gels found in nature. Figure 15 illustrates the extensive cracking and virtual failure of a concrete stadium due to the presence of reactive aggregate in combination with a high alkali content of the portland cement used.

In this same field of physico-chemical phenomena we encounter differences in the ability of mineral aggregates to retain a coating of asphalt in the presence of water. Here again this performance cannot be predicted from a simple chemical analysis as we are dealing with differences in adhesion tension between the asphalt and the surface of the particles. Such laboratory tests as stripping tests, swell tests and water asphalt preferential tests are among those devised to evaluate aggregates to determine their ability to hold asphalt against the action of water. Figure 16 shows particles stripped of asphalt after a period of immersion in water.

It should be apparent by this time that there is no single test to determine whether a mineral aggregate is a "good" aggregate or a "poor" aggregate. Therefore, the question of whether or not a material is good or poor depends entirely upon the use to which it will be put and, as is the case with all engineering materials, it is necessary for the engineer to know what properties of materials are necessary for the particular purpose. The only way to find out whether or not the aggregates have the desired properties is by means of laboratory tests. It usually requires a separate test for each property.

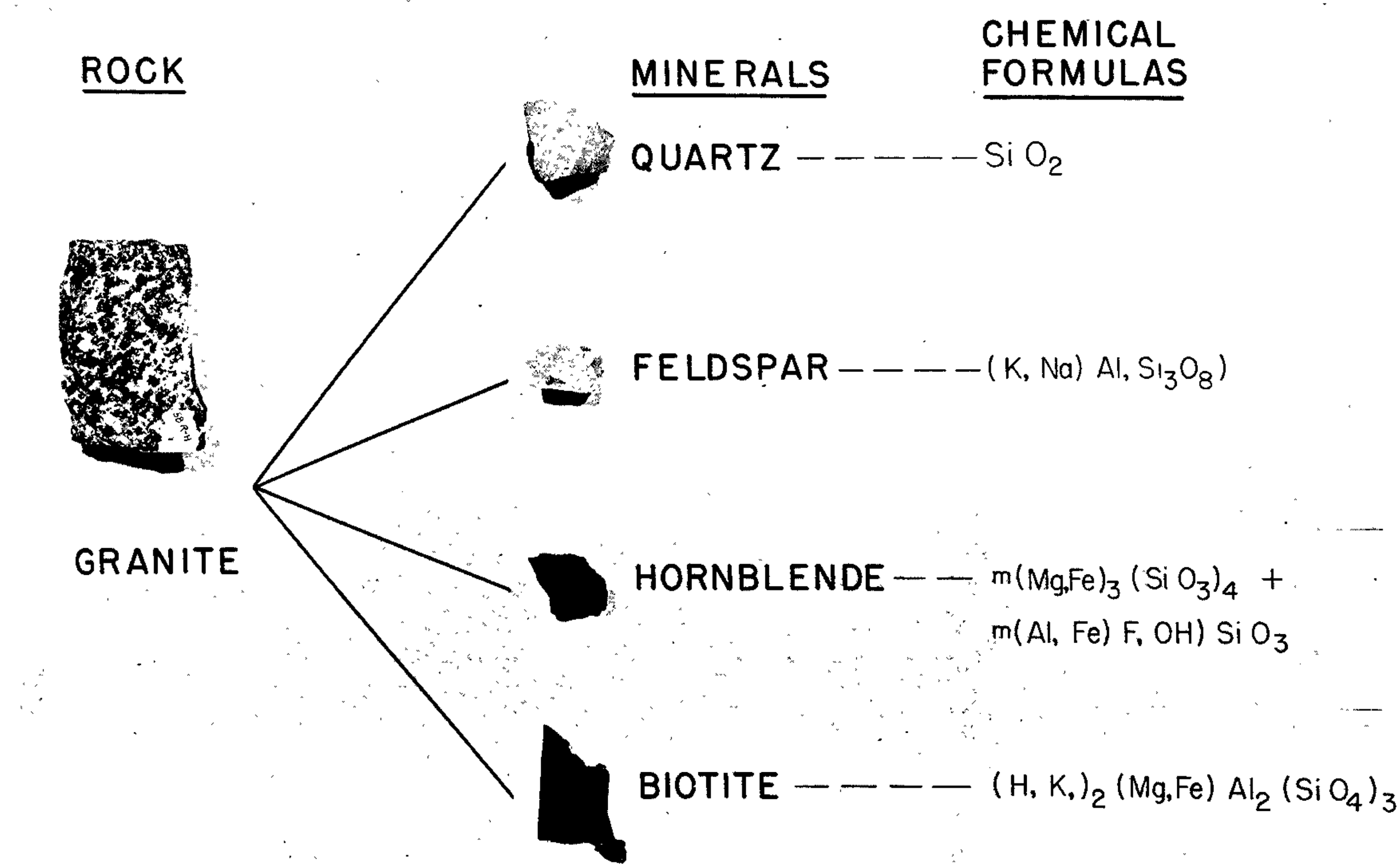
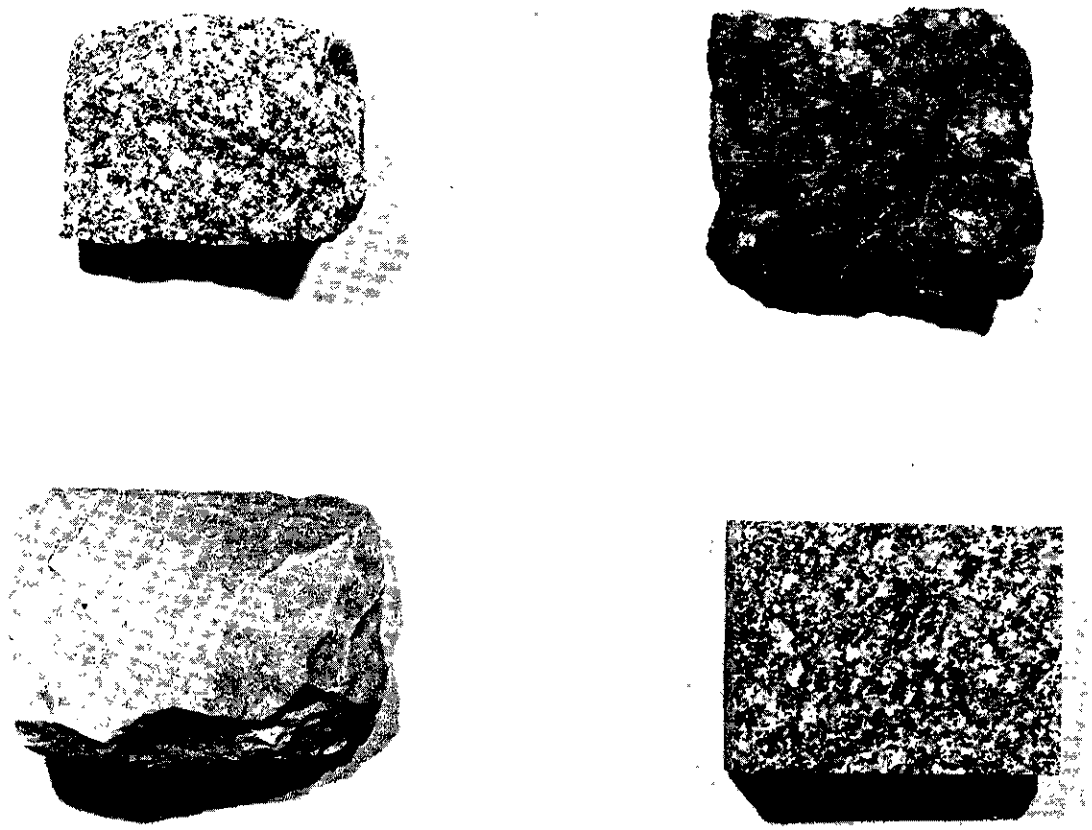

ROCK
MINERALS
CHEMICAL FORMULAS
QUARTZ — SiO_2
FELDSPAR — $(K, Na) Al, Si_3O_8)$
HORNBLENDE — $m(Mg,Fe)_3 (SiO_3)_4$ +
$m(Al, Fe) F, OH) SiO_3$
BIOTITE — $(H, K,)_2 (Mg,Fe) Al_2 (SiO_4)_3$
GRANITE

Figure 1

Figure 2



IGNEOUS

Figure 3

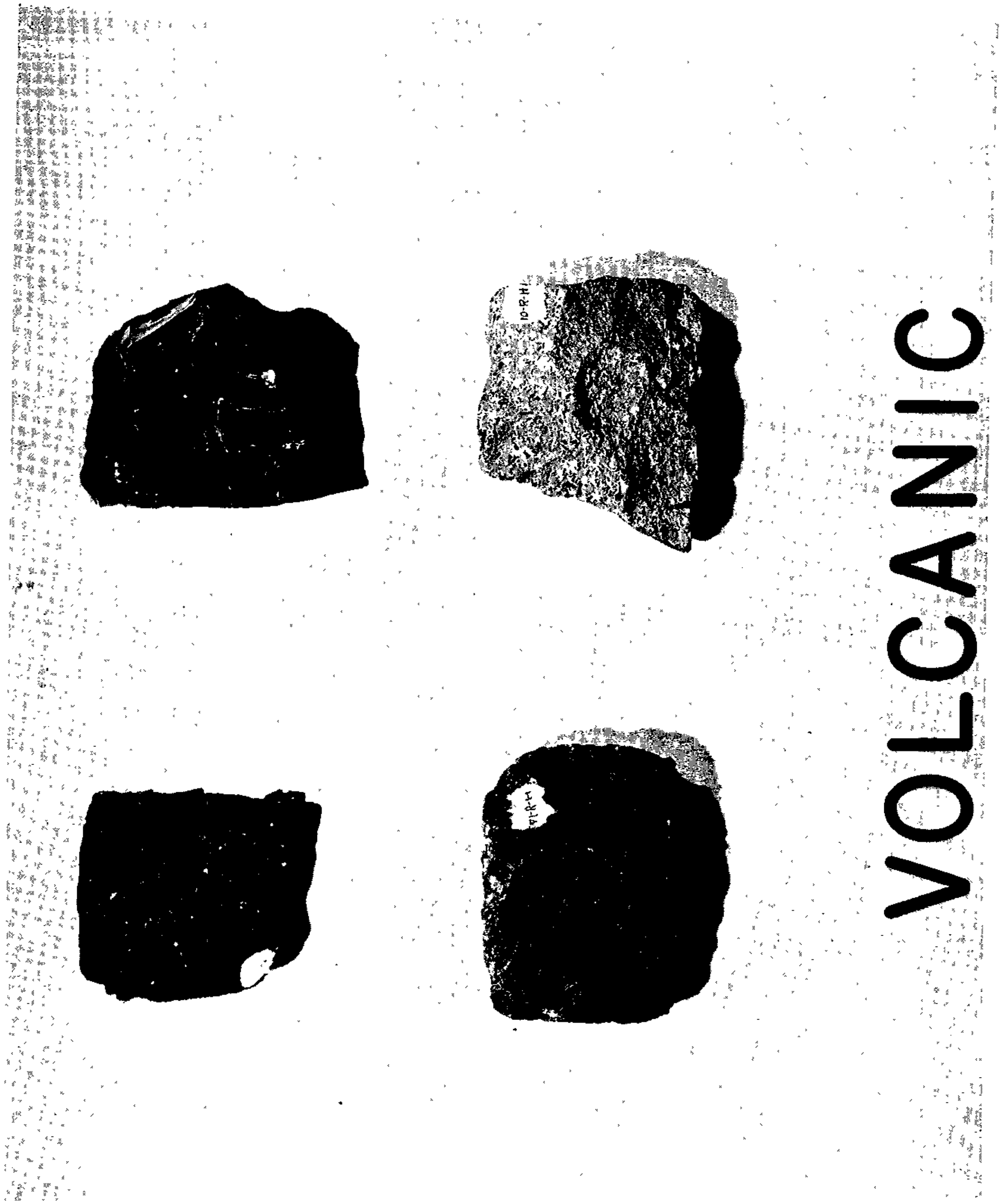
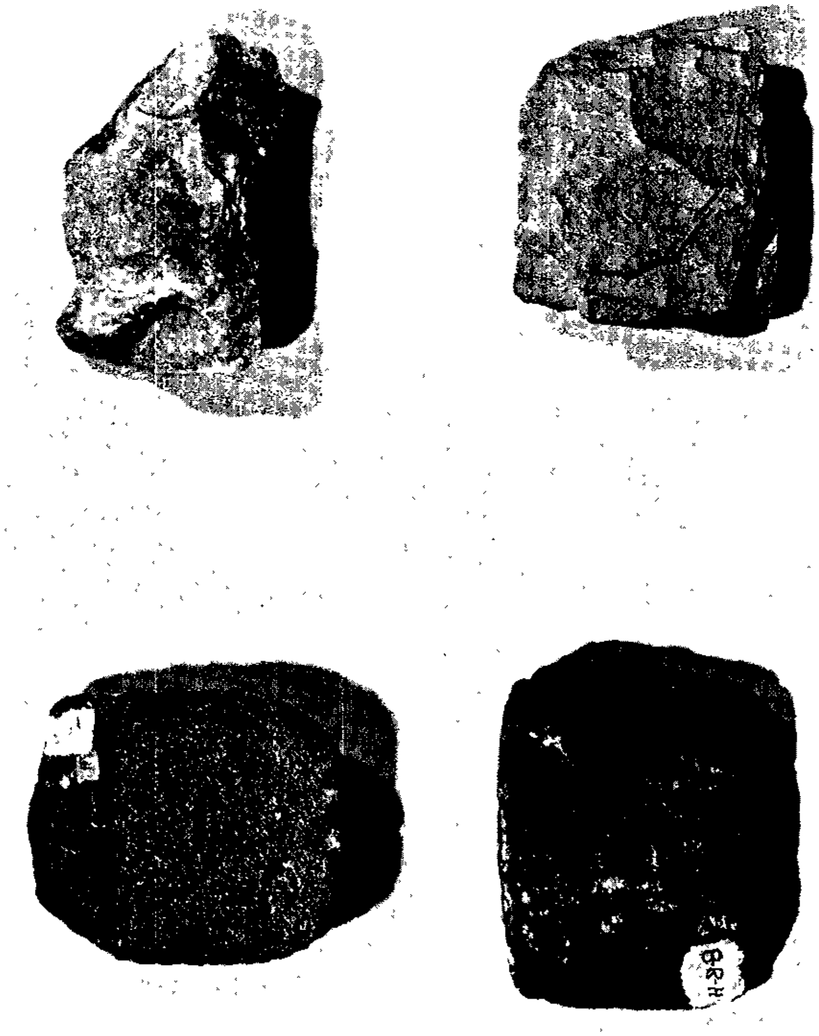
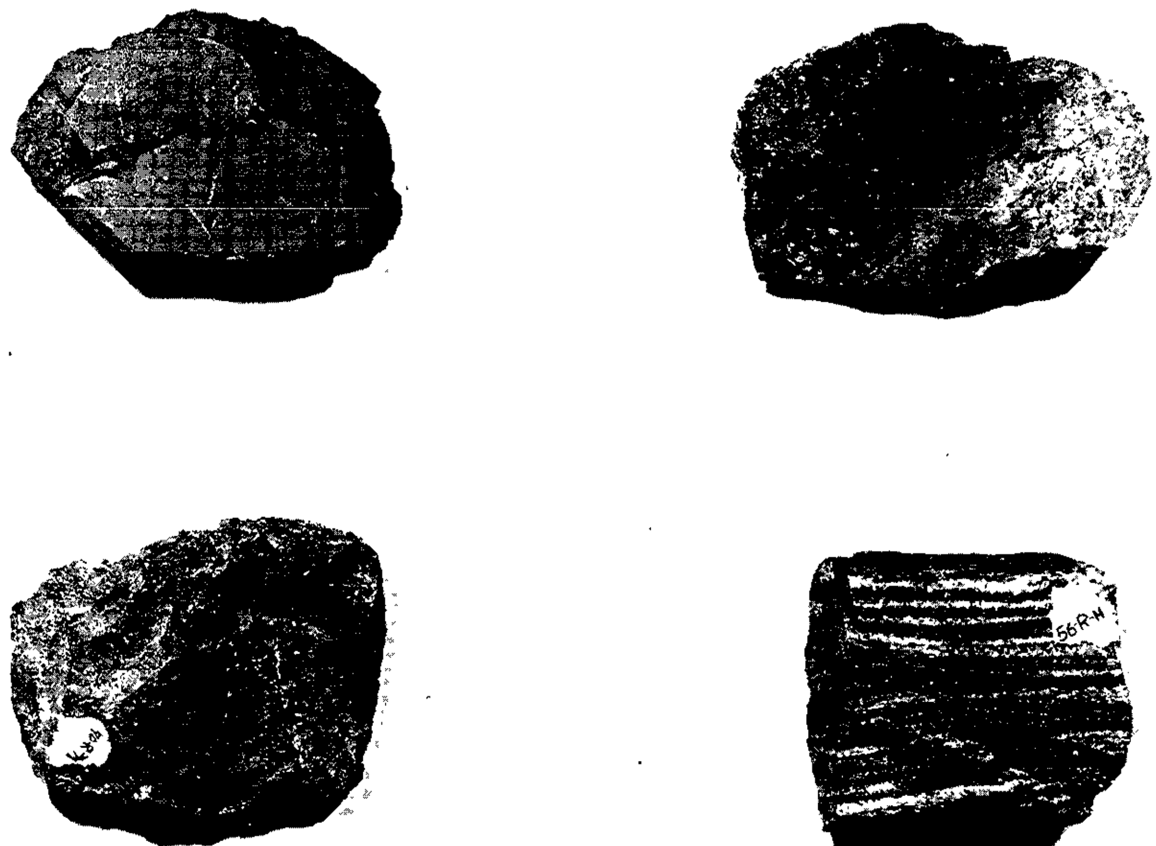


Figure 4



SEDIMENTARY



METAMORPHIC

Figure 5

Figure 6

CHARACTERISTIC SHAPES OF AGGREGATE PARTICLES

PARTICLE SURFACE TEXTURES

Very-Rough Rough Smooth Polished

Figure 7

Figure 8

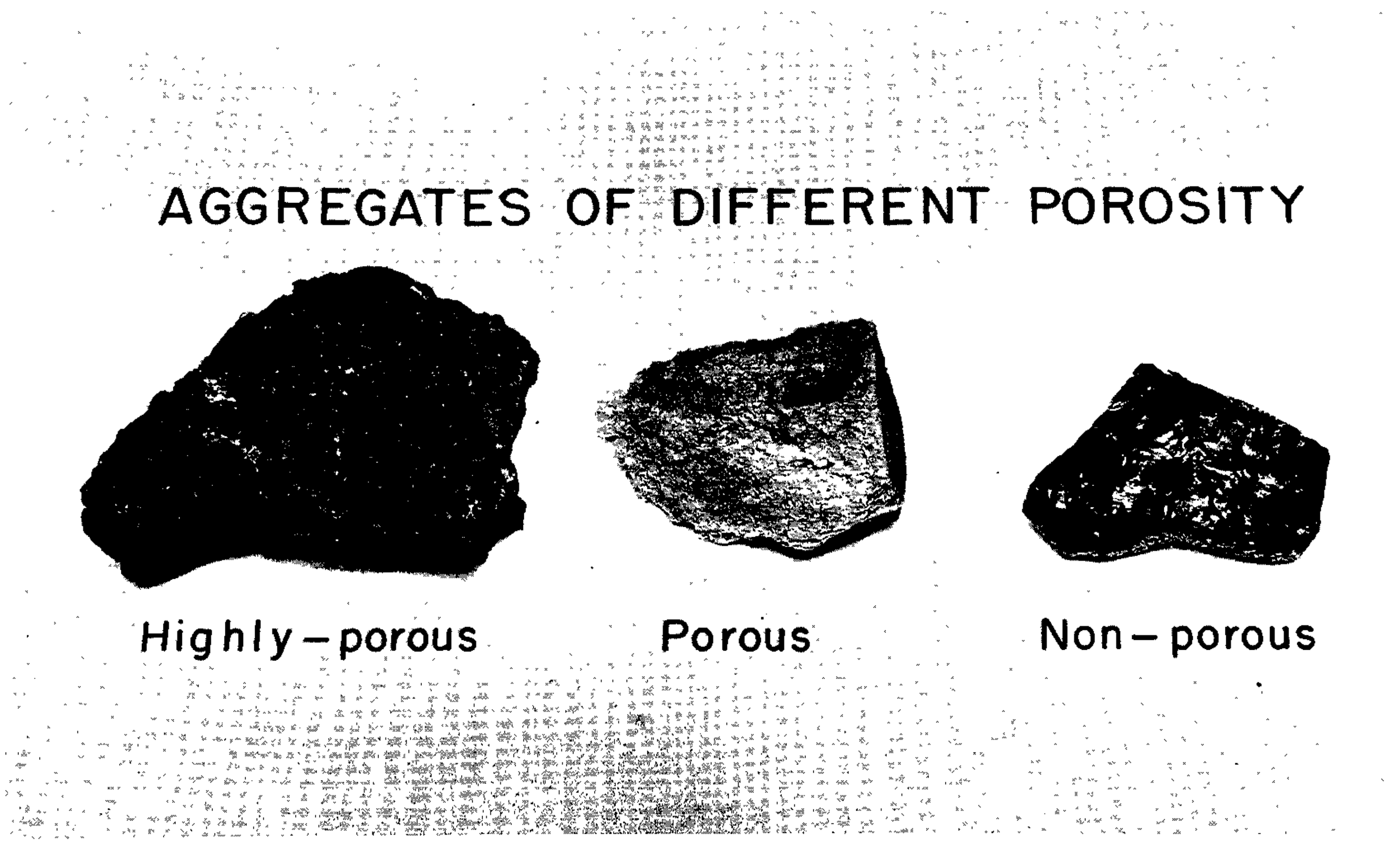

AGGREGATES OF DIFFERENT POROSITY
Highly-porous
Porous
Non-porous

Figure 10

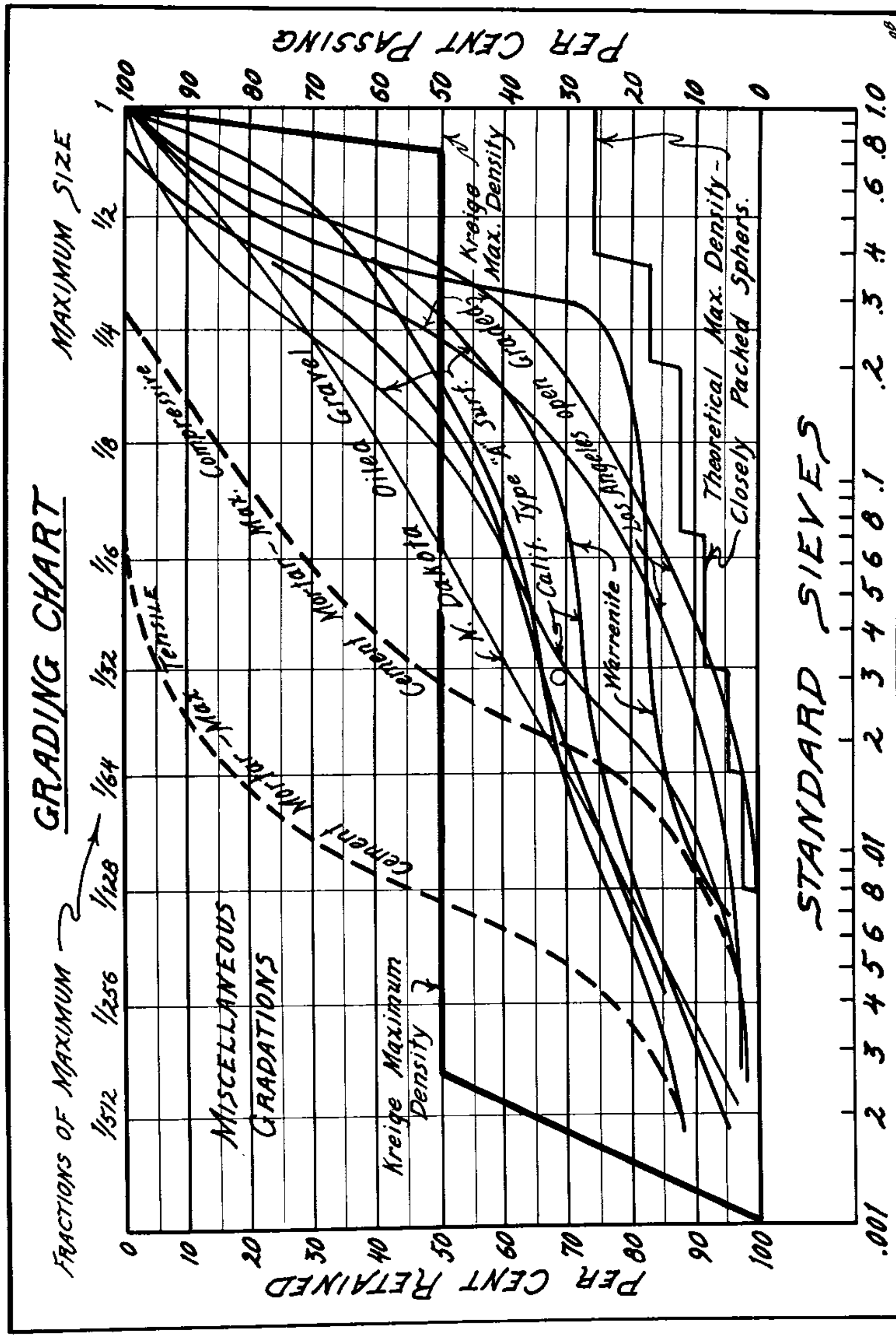
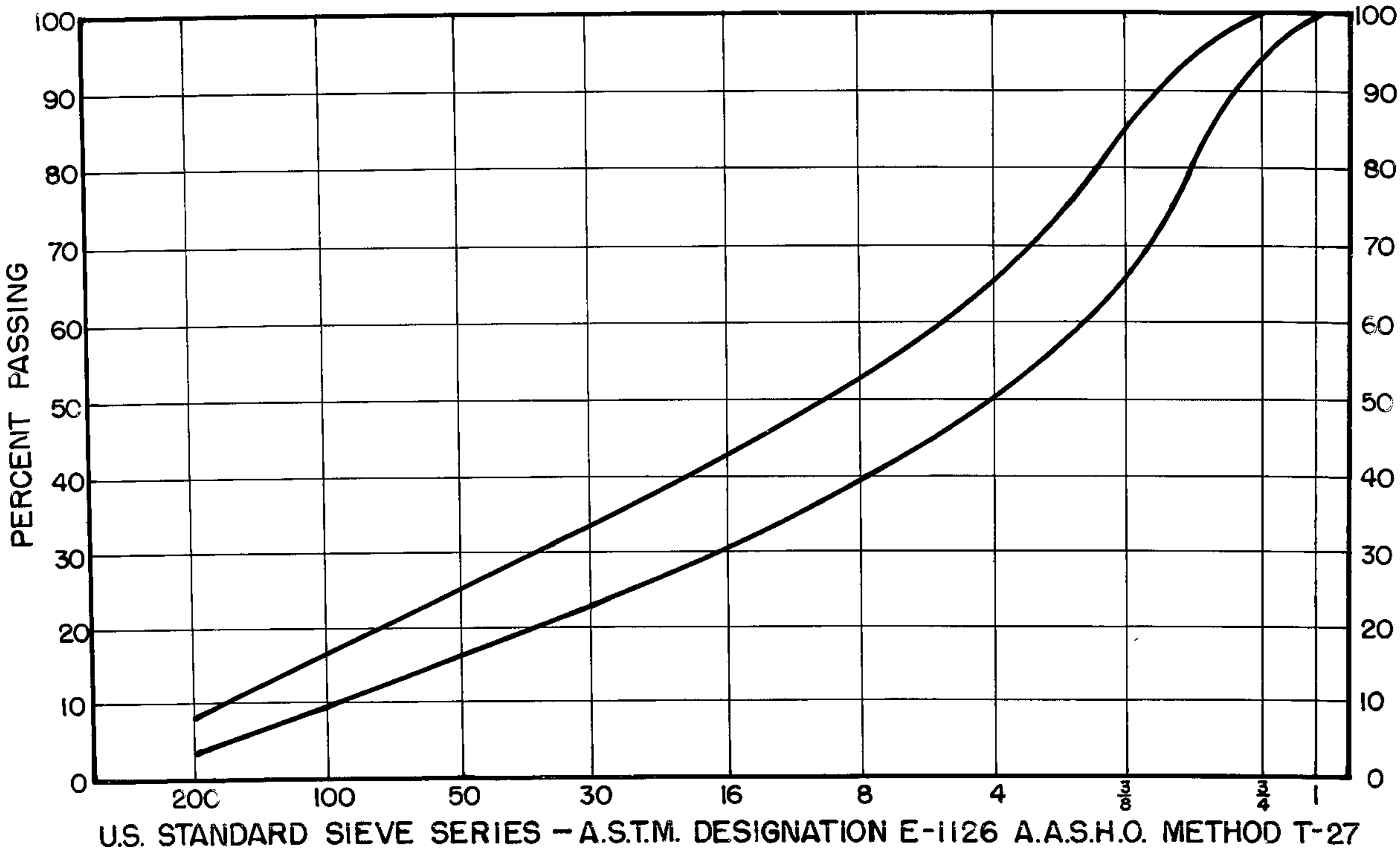

GRADING CHART
FRACTIONS OF MAXIMUM
MAXIMUM SIZE
1/512
1/256
1/128
1/64
1/32
1/16
1/8
1/4
1/2
1
PER CENT PASSING
100
90
80
70
60
50
40
30
20
10
0
PER CENT RETAINED
0
10
20
30
40
50
60
70
80
90
100
STANDARD SIEVES
.001
2
3
4
5
6
8
.01
2
3
4
5
6
8
.1
.2
.3
.4
.6
.8
1.0
MISCELLANEOUS GRADATIONS
Kreige Maximum Density
Kreige Max. Density
Theoretical Max. Density - Closely Packed Sphers.
Cement Mortar - Max. Tensile
Cement Mortar - Max. Compressive
Oiled Gravel
N. Dakota
Calif. Type "A" Surf.
Warrenite
Los Angeles open
Grade "B"

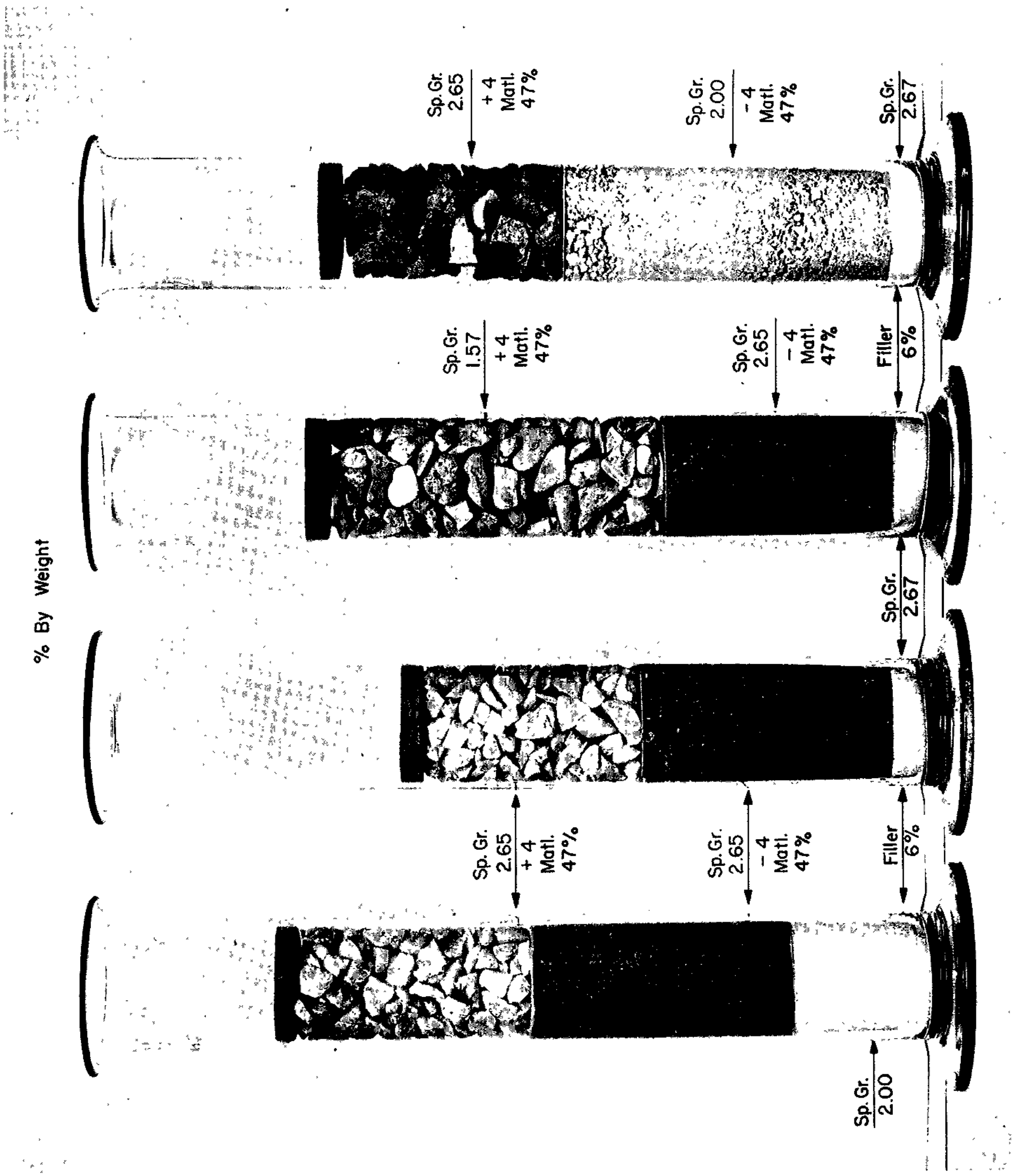
Figure 11

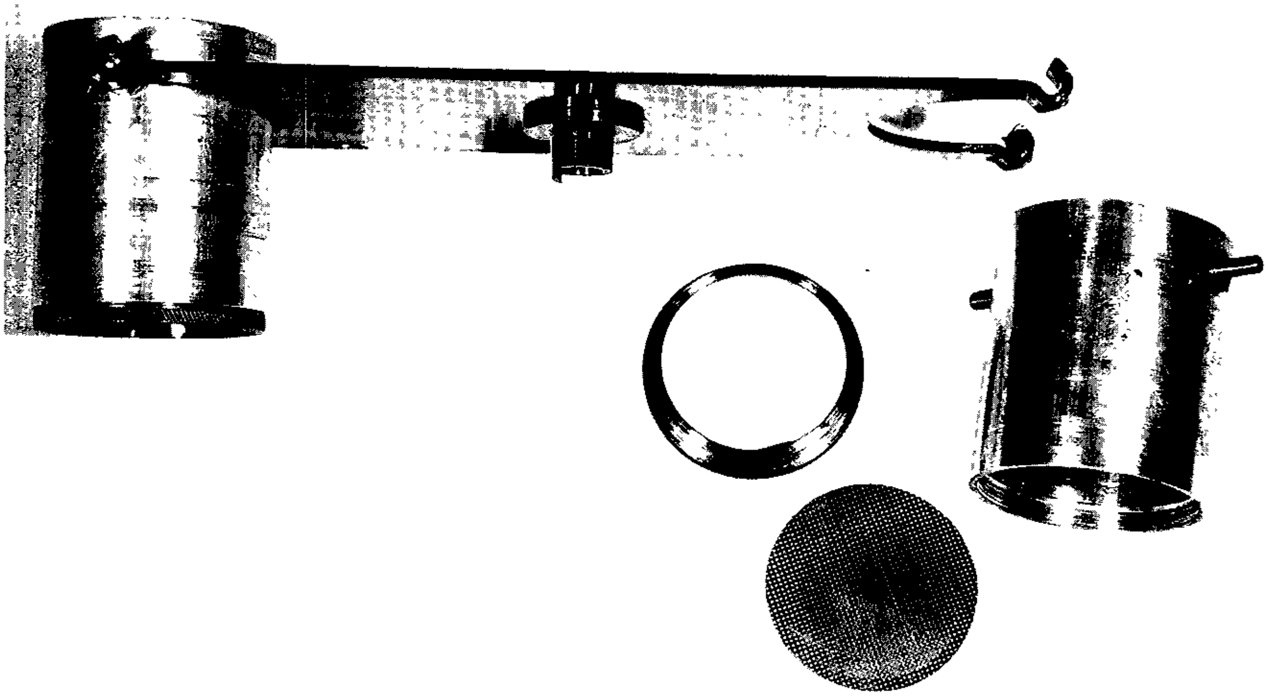
STATE OF CALIFORNIA — DIVISION OF HIGHWAYS

MATERIALS & RESEARCH DEPARTMENT

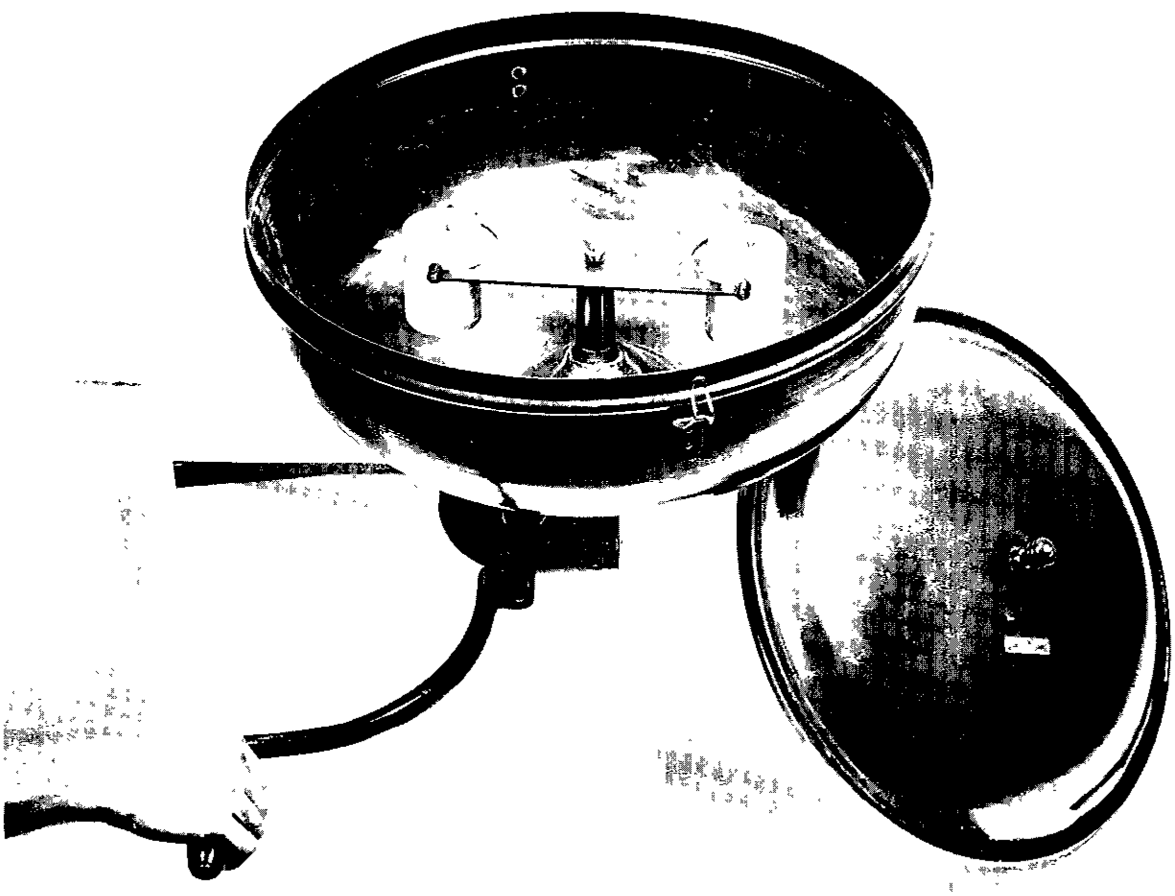
GRADING CHART FOR BITUMINOUS MIXTURES




% By Weight
Sp.Gr. 2.00
Sp.Gr. 2.65
+ 4 Matl. 47%
Sp.Gr. 2.65
− 4 Matl. 47%
Filler 6%
Sp.Gr. 2.67
Sp.Gr. 1.57
+ 4 Matl. 47%
Sp.Gr. 2.65
− 4 Matl. 47%
Filler 6%
Sp.Gr. 2.65
+ 4 Matl. 47%
Sp.Gr. 2.00
− 4 Matl. 47%
Sp.Gr. 2.67



CENTRIFUGE KEROSENE EQUIVALENT APPARATUS



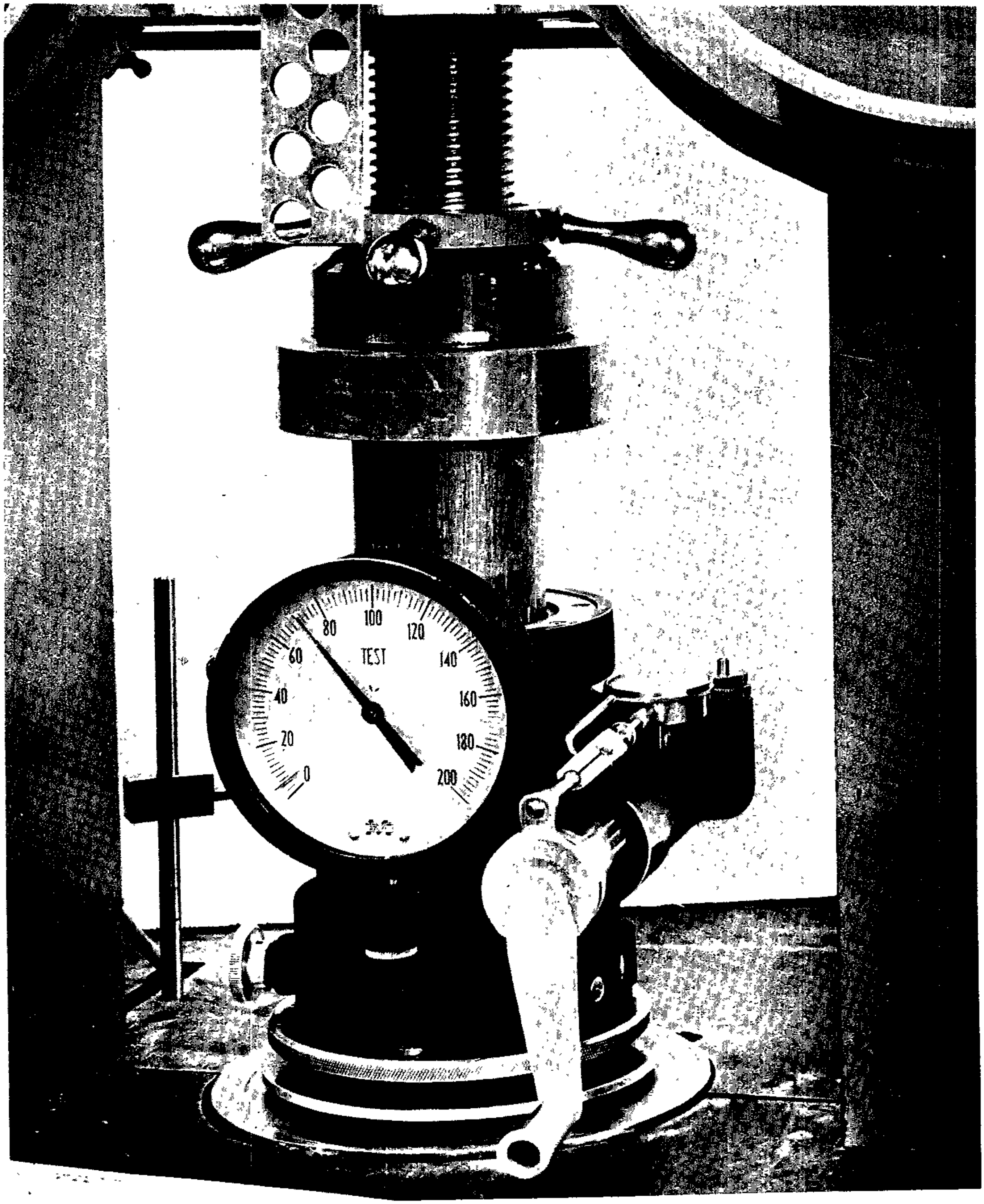

100
80
120
60
TEST
140
40
160
20
180
0
200

Figure 16