Influence of aggregate particle shape upon concrete strength
by Gary Alan Stensatter

A thesis submitted to the Graduate Faculty in partial fulfillment of the requirements for the degree of MASTER OF SCIENCE in Civil Engineering
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Abstract:

The influence of five coarse aggregate particle shapes upon the compressive strength of concrete were evaluated.

Three sizes of coarse aggregate of each different particle sphericity were hand cut from basalt, gneiss, and quartzite, rock materials. The particle shapes were called flat, elongated, flat and elongated, wedge, and equidimensional.

The elongated particles were three times longer than they were wide; and the flat particles were three times wider than they were thick. After the particles were cut, they were subjected to an attrition process until their roundness was classified as "subangular." The compressive test specimens consisted of concrete cylinders, two inches in diameter by four inches high. Each was made with ordinary sand, a constant 0.50 water-cement ratio, and a graded coarse aggregate of one particle shape and material. When tested at 28 days, the largest compressive strength difference was 10.7 per cent. Concrete made with equidimensional particles was the strongest, while that made with elongated particles was the weakest. Concrete made with flat and elongated type particles produced concrete that was zero, two, and six per cent weaker than with equidimensional particles for the three types of material. However, a statistical analysis of the data indicated that only concrete made with elongated particles was significantly weaker than concrete made with either flat or equidimensional particles.

INFLUENCE OF AGGREGATE PARTICLE SHAPE UPON CONCRETE STRENGTH

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ABSTRACT

The influence of five coarse aggregate particle shapes upon the compressive strength of concrete were evaluated. Three sizes of coarse aggregate of each different particle sphericity were hand cut from basalt, gneiss, and quartzite rock materials. The particle shapes were called flat, elongated, flat and elongated, wedge, and equidimensional. The elongated particles were three times longer than they were wide; and the flat particles were three times wider than they were thick. After the particles were cut, they were subjected to an attrition process until their roundness was classified as "subangular."

The compressive test specimens consisted of concrete cylinders, two inches in diameter by four inches high. Each was made with ordinary sand, a constant 0.50 water-cement ratio, and a graded coarse aggregate of one particle shape and material. When tested at 28 days, the largest compressive strength difference was 10.7 per cent. Concrete made with equidimensional particles was the strongest, while that made with elongated particles was the weakest. Concrete made with flat and elongated type particles produced concrete that was zero, two, and six per cent weaker than with equidimensional particles for the three types of material. However, a statistical analysis of the data indicated that only concrete made with elongated particles was significantly weaker than concrete made with either flat or equidimensional particles.

CHAPTER 1

INTRODUCTION

1.1 THE PROBLEM

For a long time aggregate was considered to be an inert filler which is added to cement paste simply for economic reasons. The properties of the resulting concrete were thought to be nearly independent of the properties of the aggregate. However, this concept of property independence has not gone without challenge.

Many studies have been made to determine the effect of the physical and chemical properties of aggregate on the behavior of concrete. They include investigations into the effects of particle strength, surface texture, shape, and alkali reactivity. Significant findings indicate that aggregate plays a more "active" role than was previously believed, and a better understanding will result from further research.

For this thesis, the broad problem concerning the influence of aggregate particle shape was delimited to a study of its effect on a single concrete property. This delimitation was necessary to permit a more detailed analysis.

1.2 PURPOSE OF STUDY

The primary purpose of this study was to evaluate the influence of different aggregate particle shapes upon the compressive strength of concrete. It was undertaken on the hypothesis that coarse aggregate particle shape has a definite effect on concrete strength. However, the degree of influence has not been fully determined by other investigators.

1.3 INVESTIGATIONAL PROCEDURE

This study was based on the use of coarse aggregate which was cut from natural stone material. The size, shape, and surface texture were carefully controlled to reduce the number of variables inherently involved with this type of research. The aggregate was made by cutting individual pieces from large rock boulders. These pieces were processed in an attrition machine until their edges and corners were slightly rounded. Concrete cylinders were then made with this aggregate and tested in compression to determine the relative strengths associated with the different coarse aggregate particle shapes.

1.4 IMPORTANCE OF STUDY

Several authors have indicated the need for more research to determine the effect of aggregate particle shape on the properties of concrete.[11,24,28] At present there is only a limited amount of information concerning the effect of aggregate particle shape on concrete proportioning, workability, and strength. This lack of information is reflected

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[11] These numbers refer to references on page 74. (LITERATURE CITED).

in specifications which place conservative limits on allowable amounts of particles of certain shapes. It is hoped that the results of this study will add to the general knowledge, and thereby aid in establishing a sound basis for the acceptance or rejection of concrete aggregates.

CHAPTER 2

REVIEW OF LITERATURE

2.1 HISTORICAL BACKGROUND

Studies into the effect of aggregate particle shape upon the properties of concrete have been conducted for many years. The peak volume of research was done in the early nineteen thirties. Sedimentary petrologists were among the first investigators to define and classify particle shape.[23,26]

In 1929 Lang[10] found there was very little information about the effect of particle shape on the properties of concrete. He stated that there was not enough data to warrant any conclusions. This lack of information was substantiated by Walker[24] in a review of the literature made in 1931. Mather[11] found in 1956 there was "almost no satisfactory data" available concerning the relations which may exist between the behavior of concrete and particle shape, surface texture, and coatings. He blamed this on a lack of standard definitions for these aggregate properties.

Many of the more recent studies have been conducted in Great Britain.[9,14,15,19] Also, references cited to work done in several other countries suggest a widespread interest in the effects of particle shape upon concrete properties.

2.2 FIELDS OF EXPERIMENTATION

Most investigators have dealt with the effect of aggregate particle shape on concrete proportions, workability, and strength. They found an inter-relationship among these three variables which was difficult to separate. This is because a change in one normally produces a change in the other two. Walker[24] speculates "as to whether or not flat and elongated particles affect the strength of concrete (if they affect it) because of the effect of their shape on the grading or because of the effect of their shape on the strength of the particle." He indicates that securing the proper aggregate for test studies is difficult.

2.3 TYPES OF COARSE AGGREGATE

Artificial and natural aggregate have both been used in investigations dealing with particle shape. Artificial aggregates were introduced in an attempt to obtain better control. Different aggregates consisting of steel punchings, glass beads, and crushed plate glass have been used with varying degrees of success.

Results obtained using glass beads were not significant because of extremely poor bond between the mortar and the beads. In comparison tests, the specimens containing glass beads yielded much lower strengths than those containing Ottawa sand. Also, the specimens made with beads did not increase in strength between 7 and 28 days.[2]

Gilkey[6] used broken plate glass of two thicknesses for experimental aggregate. Concrete made with the thinner plate glass carried much less load than the concrete made with the thicker glass. However, the artificialness of this "aggregate" presents a serious drawback when trying to correlate results with natural aggregate.

The main problem with natural aggregate in testing the effect of particle shape is a lack of consistency between particles. To overcome this, several methods of obtaining uniformily shaped natural aggregate have been used. Some investigators have simply hand-picked aggregate of the desired shape. Others have built machines for this purpose. An aggregate sorting device was built and used in the Engineering Experiment Station laboratory at Iowa State College.[5] It sorted particles according to their ability to remain on an inclined, moving belt.

Part of the difficulty associated with using natural aggregate in experimental investigations arises from a lack of standard definitions and classifications of particle shape. In the literature, different particle shapes are sometimes given the same name, or the same particle shapes are given different names. This makes it difficult to correlate data and results.

2.4 PARTICLE SHAPE

Aggregate particle shape is largely determined by the physical make-up and cleavage of the type of rock. Both internal layering and crystal structure are important. Slates and shales yield flat particles, while those from granites and limestones are generally more equidimensional.[18] However, the attrition or wear that these particles are subjected to also affects their shape.

It is quite obvious from an inspection of aggregate particles, that although a particle may be flat or elongated, its edges may either be rounded, or sharp and well defined. It is apparent then, that particle shape is a function of two relatively independent parameters, sphericity and roundness.

Although there have been many attempts to define particle shape, no standard definition has been established. Mather[11] states that roundness and sphericity are independent, and that both must be considered in defining particle shape. A distinction between these parameters must be made.

2.41 SPHERICITY

Sphericity, as the term implies, is the measure of a particle's similarity to a spherical shape. However, there is disagreement among investigators as to which basis should be used in defining this property. Suggested definitions include relative volumes or maximum particle dimensions. Sphericity has been described as the cube root of the ratio of the volume of the particle to the volume of the circumscribing sphere, and by the relative surface area of the particle to its volume.[23] Other definitions define sphericity by the ratios of the lengths of the particle's principal axes (or those of its circumscribing rectangular prism).[3,11]

2.42 ROUNDNESS

Mather[11] states that roundness is "that property measured by the relative sharpness or angularity of the edges and corners of the particle." It has been defined as the ratio of the average radius of curvature of the corners and edges of the particle to the radius of the maximum inscribed circle.[23] In this definition, the maximum inscribed circle is the largest circle which can be inscribed in the projected image of the particle.

Roundness is primarily a function of the toughness or durability of the particle and the abrasion to which it has been subjected. Descriptive terms of roundness range from angular (little evidence of wear) to well rounded (no original particle faces).[17]

The general term angularity is often used to describe particle shape. It is not a third parameter, but merely another means of describing roundness.

2.5 PARTICLE CLASSIFICATION

Methods of classifying the shape of natural aggregate particles may be divided into two groups. One group classifies particles on an individual piece basis, while the other group is based on a means of bulk classification. Individual pieces have often been classified by visual inspection. This turns out to be a tedious process, and is entirely dependent on the judgment of the investigator. Some refinement in classification is gained by measuring either lineal dimensions or radii of curvature with the aid of special instruments. The shapometer and the convexity gage are two of the instruments which have been developed for this purpose.[21,26]

Many methods of classifying aggregate in bulk have been suggested and used. Shergold[19] outlined the following means of classification: (1) rate of fall of particles in water, (2) rate of flow of water through gravel, (3) behavior of particles on an inclined plane, (4) number of particles in a given volume or weight, (5) surface area of particles, (6) percentage differences passed by square and round-holed sieves of the same nominal aperature size, and (7) percentage of voids in the aggregate when compacted in a standard manner. None of these methods have been standardized by any society, nor has any been widely accepted by different investigators.

The American Society for Testing and Materials does give partial definitions of two particle shapes, but it does not specify a method of analyzing a quantity of aggregate to determine the amount of these particles.

2.51 ELONGATED PARTICLE

Elongated particles are usually defined by a length to width ratio. ASTM Designation: C 125-58 defines an elongated piece as "one in which the ratio of the length to width of its circumscribing rectangular prism is greater than a specified value."[3] This is only a partial definition until a "specified value" is given. Suggested values of this ratio of length to width range from one and one half to five. Three is a value often used.

2.52 FLAT PARTICLE

ASTM defines a flat piece as "one in which the ratio of the width to thickness of its circumscribing rectangular prism is greater than a specified value."[3] Values used for this ratio also range from one and one half to five.

Although the ASTM standards do not state this, the definitions just given can be used singly or in combination. A flat and elongated particle is simply one which meets the requirements of both definitions.

2.6 CONCRETE STRENGTH STUDIES

The effect of flat or elongated particles upon concrete strength is not fully known. To be conservative, specifications frequently limit allowable amounts of these types of particles. Mercer[13], Woolf[28], and Walker[24] found that specification limits concerning particle shape were unduly restrictive. Walker also found there has been a tendency to confuse "flat and elongated" particles with "soft, friable, and laminated" pieces. He concludes that if they are of such non-durable rock types, they should be judged on that basis rather than on the basis of shape.

Allen[1] states that particle shape has little or no effect on the compressive strength of concrete, provided: the proportioning takes into account the percentage of voids in the coarse aggregate, and the percentage of flat and elongated particles is not excessive. He did not elaborate on what percentage of particles would be considered excessive.

2.61 FLAT PARTICLES

Tests of concrete strength with up to 14% of flat particles (length five or more times thickness) were conducted by Walker and Proudley.[25] They found there was no decrease in the compressive or flexural strength. Walker[24] concluded that for the quantities of flat particles likely to be encountered in commercial aggregates, their presence would not reduce compressive or flexural strength.

There is some indication that the effect of particle shape is more pronounced in tension and flexure than in compression. Kaplan[9] calculated correlation coefficients for flakiness (flatness) versus concrete strength, and found they were statistically non-significant for compressive strength, but significant for flexural strength. Others have also found this to be true.[10,22]

Mercer[12] found that orientation of flat particles can materially change the compressive strength of concrete. He hand packed two cylinders with flat particles and then grouted them. In one cylinder the particles were packed upright; in the other cylinder they were placed horizontally. The compressive strength of the cylinder with vertical particle orientation was 60 per cent of the other. His conclusion was that low strengths result from particle orientation along the plane of shear, and relatively high strengths result when particles project through the natural shear planes.

2.62 ELONGATED PARTICLES

Elongated particles are often considered to have the same adverse effects as flat particles on the properties of concrete.[1,22] Blanks[4] states that more sand is required with these types of particles, and a lower compressive strength is likely. However, this author could find no reference in the literature to any concrete strength tests where only elongated (rod-shaped) particles were used.

2.63 FLAT AND ELONGATED PARTICLES

Aggregate of this particle shape is generally considered to be the least desirable for making concrete. Allen[1] found specifications limiting particles of this shape to approximately 5 per cent by weight. The basis for such limitation was not revealed in a study of the literature made by Walker.[24] He believes that such limitations express a desire for the ideal rather than an economic consideration.

There is some evidence that reduced strengths are associated with this type of particle because of poor bond. Blanks[4] and others believe that poor bond is produced by bleed water which is entrapped under flat particle faces when they are oriented horizontally. The actual amount of strength reduction has not been determined.

CHAPTER 3

LABORATORY RESEARCH

3.1 PREPARATION OF MATERIALS

Carefully controlled aggregate of different particle shapes was the major item in this study. Consistent particle shapes were obtained by hand-cutting all of the coarse aggregate particles from large boulders to prescribed dimensions. As far as can be determined, this is a unique approach to the problem of aggregate analysis.

Stanton Walker[24], in discussing the influence of aggregate particle shape on the properties of concrete, said:

> "Probably one of the most difficult features of conducting an investigation of the effect of flat and elongated particles...is presented by the problem of securing the proper aggregates. It appears, therefore, that laboratory investigations will yield most value and can be carried out most conveniently by the utilization of artificial aggregates."

Mortar, terra-cotta, glass, and metal were suggested for experimental use. Although no mention was made of cut stone, it is certainly an ideal form of "artificial" aggregate.

3.11 COARSE AGGREGATE

The coarse aggregate was cut from three different types of rock so that the test results would be a function of particle shape rather than material composition. Variations in the composition were restricted by cutting all of the particles of a particular material from a single boulder. The rock material, in the form of large boulders, was obtained at the mouth of the Gallatin River Canyon, twenty miles southwest of Bozeman, Montana. The following types of rock were selected:

(1) fine-grained basalt with scattered phenocrysts and some weathered fractures

(2) fine-grained granite gneiss with mild foliation

(3) very fine-grained quartzite.

These identifications and descriptions were made by Dr. W. J. McMannis of the Montana State College Earth Sciences Department.

3.111 CUTTING AGGREGATE PARTICLES

Preliminary slicing of these boulders into slabs two inches thick was done at the Livingston Marble and Granite Works, Livingston, Montana. This was found to be an important step as it greatly facilitated the final aggregate cutting in the laboratory. The pieces were not only smaller, and therefore easier to handle, but the flat surfaces provided a base to work from and thereby increased cutting efficiency. Typical slab sections of the three different materials can be seen in Figure 1.

All of the cutting in the laboratory was done with the diamond blade cut-off machine shown in Figure 2. The one half

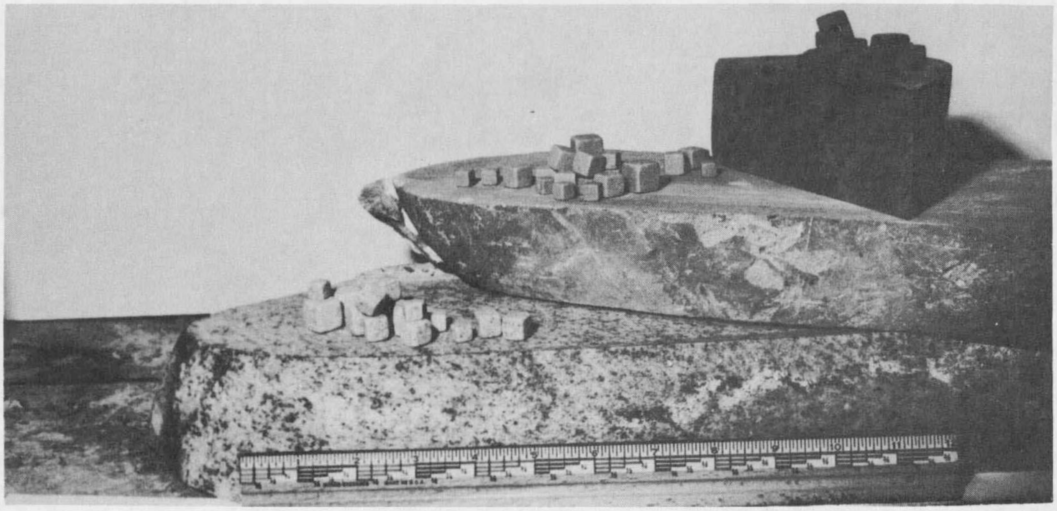

Fig. 1. Coarse aggregate materials: basalt, quartzite, and gneiss (top to bottom).

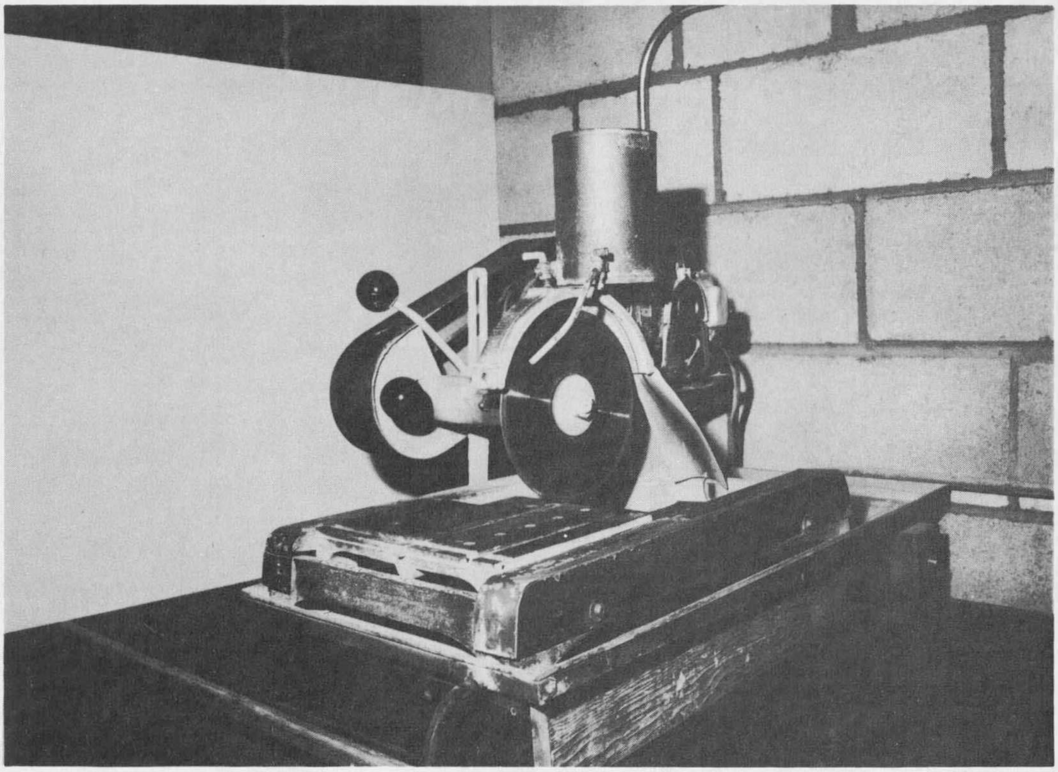

Fig. 2. Diamond blade cut-off machine used to prepare coarse aggregate materials.

horsepower Model 11B machine was manufactured by the Felker Manufacturing Company of Torrance, California, and operates with a blade speed of 3450 rpm. Blades 8 inches in diameter by 0.05 inches thick were used for all cutting operations.

A water coolant was selected for cutting, rather than a solvent or oil-base type coolant, to avoid contaminating the aggregate. However, this resulted in faster wear of the diamond blades. Ten blades were worn out in the one hundred eighty hours required to cut the aggregate.

As the rock materials were relatively hard to cut, it was occasionally necessary to "sharpen" the blades by cutting into bricks. The type of brick was found to be very important for this purpose. For example, one cut through a slab of rock was timed at forty-four minutes when a common red brick was used for the sharpening agent. The time to make an identical cut through the slab took only six minutes when the blade had been sharpened by cutting into a yellow, granular type brick. Small cuts into this type of brick were found to be sufficient, as over "sharpening" only resulted in faster wear of the blades.

Several definite steps were employed to minimize the amount of time required to cut the aggregate. The first step was to slice the large slabs of rock into smaller slabs of the desired particle thickness. These smaller slabs were then cut into rods, and finally, the rods were cut into individual pieces. Following this procedure, one dimension of the particle was controlled in each step.

Three sizes of five different shapes of coarse aggregate were cut from basalt material. The shapes are commonly called: flat and elongated, equidimensional, flat, wedge, and elongated. Only particles of the first two shapes mentioned were cut from the quartzite and gneiss materials. The five particle shapes are shown in Figure 3.

The properties of flatness and elongation were determined by arbitrarily letting the "specified values" in the ASTM definitions equal three. Therefore, the elongated particles had a length three times their width, and the flat particles had a width three times their thickness. Particles of the flat and elongated shape met both these length to width, and width to thickness, dimension requirements. The equidimensional particles were simply cubes, while the wedge-shaped particles were not of any particular classification. The dimensions of all five particle shapes are expressed as ratios in Table I.

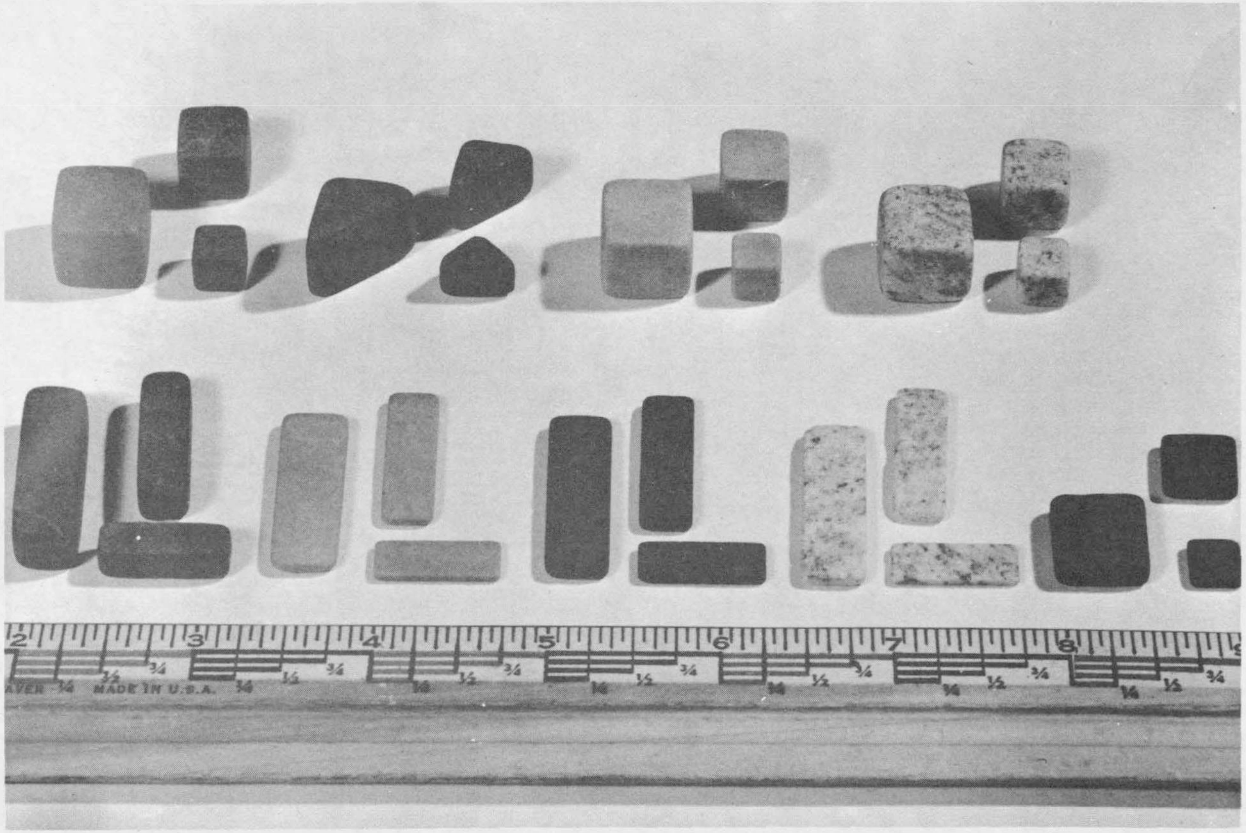

Fig. 3. Hand cut coarse aggregate particles of three rock materials and five particle shapes.

TABLE I

RATIOS OF PARTICLE DIMENSIONS

Particle shape	Thickness:width:length ratios
flat	1 : 3 : 3
elongated	1 : 1 : 3
flat & elongated	1 : 3 : 9
equidimensional	1 : 1 : 1
wedge	1 : 1 : 1 : (1.4 slope)

Some clarification of the wedge-shaped particles can be gained from a description of the manner in which they were cut. They were made by cutting along a square rod diagonally; thus producing two rods of wedge-shaped cross section. The individual particles were formed by making right-angled transverse cuts through these rods. This cutting procedure was followed because it was quite fast. These particles could also have been produced by making single diagonal cuts through cubical particles.

The amount of aggregate required for this study was 1½ lbs. of each particle size, shape, and material. This amounted to a total of 40 lbs. of finished cut aggregate, most of which is shown in Figure 4.

3.112 PARTICLE SIZE

Three sizes of aggregate particles were cut of each shape

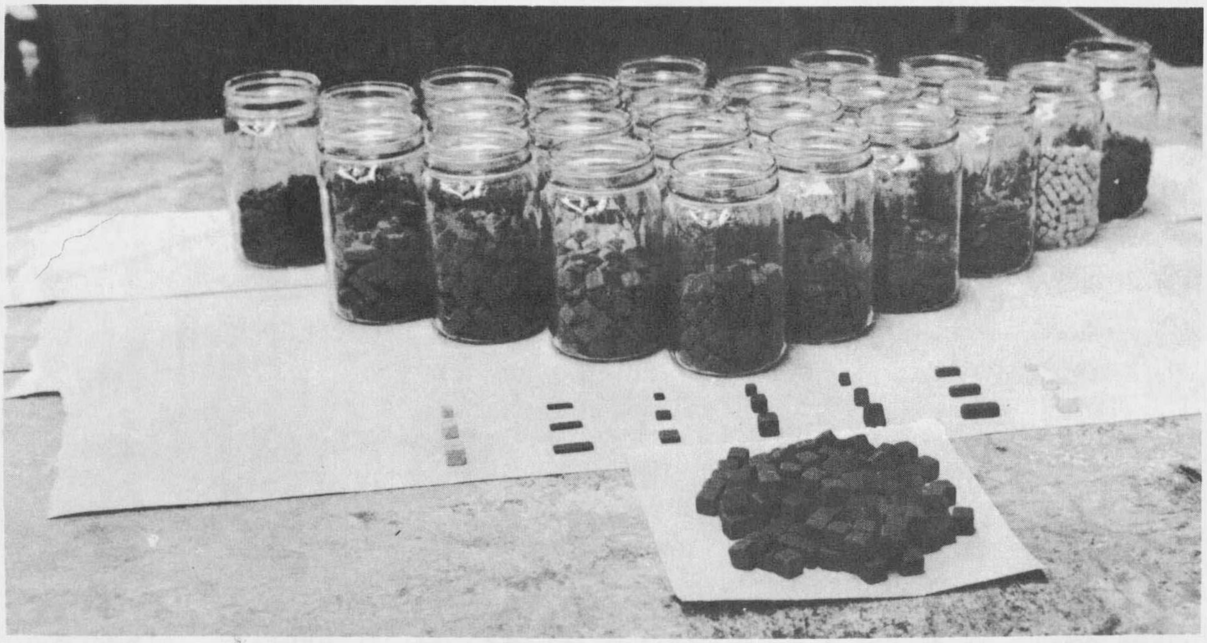

Fig. 4. Quantity of coarse aggregate that was hand cut.

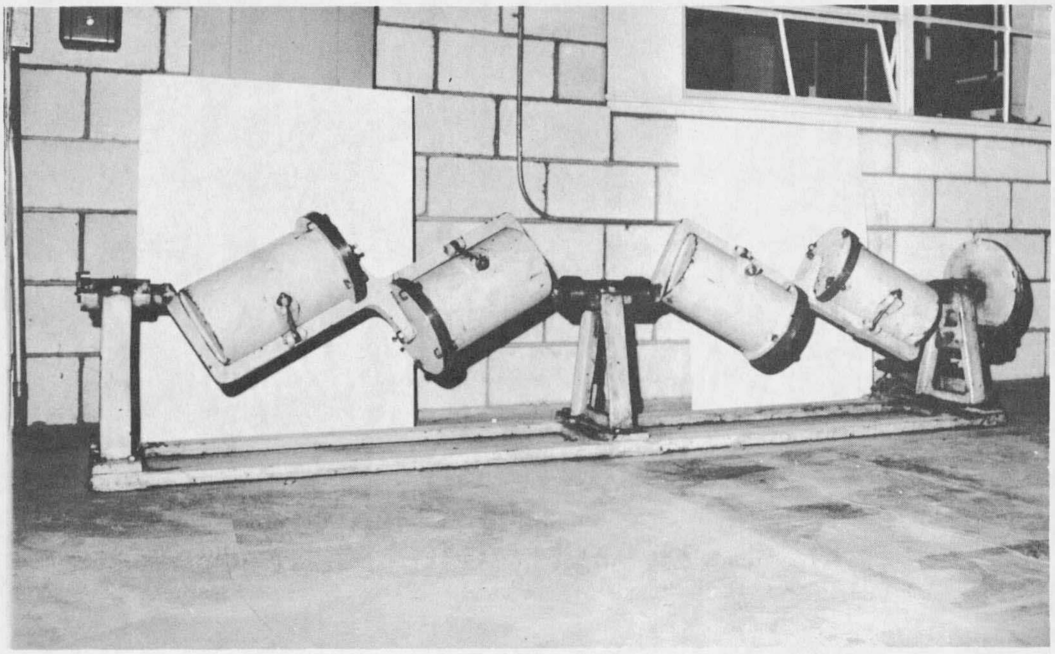

Fig. 5. Deval abrasion machine which was used for coarse aggregate attrition.

to establish a gradation. The dimensions of a random sample of 30 particles per shape were measured with a scale to within ± 0.01 in. and were found to vary from predetermined dimensions by approximately ± 0.02 in. Averages of the dimensions are given in Table II.

The nominal particle dimensions of the flat, wedge, and equidimensional shaped particles were determined so that the particles would be retained on standard 1/2 in., 3/8 in., and No. 4 sieves. The controlling dimensions of the large, medium, and small particle sizes of these shapes were respectively 9/16, 7/16, and 5/16 of an inch. A deviation from this sieve size basis for the other two shapes was chosen to avoid excessively large particles. Their controlling dimensions are 3/8, 5/16, and 1/4 of an inch.

3.113 PARTICLE ATTRITION

The particles were subjected to an attrition, or wearing down process, after they were cut. This was done so the particles would more nearly approach the shapes found in naturally weathered aggregates. The attrition was accomplished in the Deval abrasion machine shown in Figure 5. The particles, together with some No. 36 coarse grit and water, were tumbled until the loss of weight was about 11 per cent. This required approximately 50,000 revolutions which took 25 hours. The process rounded the edges and corners of the particles, and

TABLE II

DIMENSIONS OF COARSE AGGREGATE PARTICLES

Aggregate material	Particle shape	Average dimensions of a random sample of 10 particles per size
		inches
basalt	equidimensional	0.57 x 0.57 x 0.57
		0.45 x 0.45 x 0.45
		0.32 x 0.32 x 0.32
basalt	flat & elongated	0.13 x 0.39 x 1.13
		0.11 x 0.31 x 0.94
		0.08 x 0.25 x 0.75
basalt	flat	0.19 x 0.57 x 0.57
		0.14 x 0.44 x 0.44
		0.10 x 0.31 x 0.31
basalt	wedge	0.59 x 0.59 x 0.59
		0.44 x 0.47 x 0.47
		0.32 x 0.34 x 0.35
basalt	elongated	0.39 x 0.39 x 1.13
		0.30 x 0.30 x 0.95
		0.24 x 0.25 x 0.75
quartzite	equidimensional	0.57 x 0.57 x 0.57
		0.44 x 0.44 x 0.44
		0.32 x 0.32 x 0.32
quartzite	flat & elongated	0.13 x 0.38 x 1.12
		0.11 x 0.32 x 0.94
		0.08 x 0.25 x 0.75
gneiss	equidimensional	0.57 x 0.57 x 0.58
		0.44 x 0.44 x 0.45
		0.32 x 0.32 x 0.32
gneiss	flat & elongated	0.13 x 0.38 x 1.13
		0.11 x 0.31 x 0.94
		0.08 x 0.26 x 0.76

produced a uniform, moderately rough surface texture devoid of all saw blade marks. However, it did not materially reduce the actual particle dimensions. According to Pettijohn's descriptive terms of roundness, the finished particles would be classified as "subangular."

3.114 TESTS

Specific gravity and absorption tests were made on graded samples of each type and shape of coarse aggregate. Standard ASTM methods and procedures (C 127) were employed with the exception that only 4 lb. samples were tested. The results are given in Table III.

TABLE III

SPECIFIC GRAVITY AND ABSORPTION OF COARSE AGGREGATE

Aggregate material	Particle shape	Bulk specific gravity (SSD basis)	Absorption (24 hr.), %
basalt	equidimensional	2.85	0.66
	flat & elongated	2.85	0.72
	wedge	2.85	0.58
	elongated	2.85	0.59
	flat	2.84	0.72
quartzite	equidimensional	2.68	0.44
	flat & elongated	2.69	0.39
gneiss	equidimensional	2.62	0.23
	flat & elongated	2.63	0.24

Thirty minute aggregate absorption tests were also made as there is some evidence this might be nearer the effective absorption. This was brought into consideration because the aggregate was used in an oven-dry condition to make the concrete samples. Newman[16] made a series of tests to determine the effect of aggregate absorption on the water-cement ratio. He concluded that when air-dry or oven-dry aggregates are used, a 30 minute absorption is the "effective" one. For the aggregate used in this study, the absorption on this 30 minute basis was found to be approximately 40 per cent of the 24 hour absorption. Its effect on the water-cement ratio of the mixes will be considered later in this thesis.

3.12 FINE AGGREGATE

The same fine aggregate, obtained locally, was used in all concrete mixes. It consisted of a good quality, washed mixture of crushed stone and natural river sand. To carefully control the gradation, it was separated into standard sieve sizes and then later recombined to the gradation shown in Appendix A at the time the concrete was mixed.

Standard ASTM specific gravity and absorption tests (C 128) were made on samples of the proper gradation. The bulk specific gravity (SSD basis) was found to be 2.62, and the absorption to be 1.77 per cent. As with the coarse aggregate, 30 minute absorption tests were also made. The 30 minute sand absorption was 93 per cent of the 24 hour value.

3.13 CEMENT

The cement used in this study was a mixture of several bags of high quality Type I portland cement. It was thoroughly mixed and then stored in a covered metal container during the testing sequence. The cement was manufactured by the Ideal Cement Company at the local Trident plant. A chemical analysis furnished by the company is found in Appendix B.

3.2 CONCRETE PROPORTIONING

It was difficult to select a suitable criterion for concrete proportioning, as aggregate particle shape is known to have an influence on the proportions. For example, flat and elongated particles cause a higher percentage of voids than do more equidimensional particles.[8,19,27] Therefore, mixtures with particles of this shape require a higher percentage of sand to fill the voids and to separate the coarse aggregate particles. With this in mind, an attempt was made to proportion the concrete aggregates so that particle spacing or interference would be the same for all shapes of particles.

The criterion which was selected for determining the aggregate combinations was a maximum combined aggregate density. The proper aggregate combinations were obtained from a series of aggregate density tests which were made with the different particle shapes and varying percentages of sand.

Once the percentages of sand by weight were established, the solid volume basis of proportioning was used.

Constant aggregate gradings, following the requirements outlined in ASTM Designation: C 33, were used throughout these tests for both the fine and coarse aggregate. These same gradings were used in the concrete mixes, and are given in Appendix B.

3.21 PERCENTAGE OF FINE AGGREGATE

The combined aggregate density tests were made in a one thirtieth cubic foot proctor mold. Starting with low percentages of sand, three or four density tests were made with each combination of fine and coarse aggregate. The fine and coarse aggregates had a tendency to become segregated so it was necessary to use the method of quartering when obtaining portions to be placed in the mold. The mold was filled in 1/3 lifts and compacted with 25 drops per lift on a mortar flow table. The percentage of sand in the total aggregate which gave maximum density was used in proportioning the concrete. The unit density curves are given in Appendix C, and the percentages of sand used in proportioning are listed in Table IV.

TABLE IV

PERCENTAGE OF SAND IN TOTAL AGGREGATE

Particle shape	Percentage of sand by weight
elongated	42
wedge	42
equidimensional	48
flat	48
flat & elongated	68

3.22 CONSISTENCY

The individual batches of concrete were too small for standard consistency tests. However, the maximum size of aggregate was small enough to permit the use of a mortar flow table (ASTM Designation: C 230). A relatively constant consistency, as measured by this modified flow table test, was obtained through preliminary testing. Increasing amounts of water-cement slurry were added to the mixes in the trial tests until the desired flow was obtained. The chosen flow of 5½ in. (from a mold diameter of 4 in.) was measured after the table was raised and dropped 12 times in 7 seconds.

3.3 CASTING CYLINDERS

The general cylinder casting procedure outlined in ASTM Designation: C 192 was followed. The aggregate used in making the concrete was in an oven-dry rather than a saturated, surface-dry condition to permit a faster batching process. Adjustments for the oven-dry condition were made by adding sufficient water to each batch for aggregate absorption.

All of the cylinders were made in open-end bronze gang molds. Each mold produced three cylinders 2 inches in diameter by 4 inches high. The molds were placed on plate glass during the casting and initial hardening of the concrete. A vaseline seal around the base of each mold prevented water leakage from the cylinders. The tamping rod used in compacting the cylinders was scaled down from standard specifications to be more consistent with the cylinder size. It was a steel rod ¼ inch in diameter by 8 inches long, with a hemispherical tip.

Prior to mixing the concrete, the aggregates were dried in an oven for 24 hours and then cooled to room temperature in sealed containers. The separate sand sizes were then recombined by weight to the proper grading and thoroughly mixed with the cement before adding the coarse aggregate and water. A rubber glove was used when mixing the concrete by hand in a small metal container. When the concrete was well mixed (approximately two minutes), a single consistency test per batch was made. The results of these tests indicated the consistency of the batches was good; and therefore, no adjustments in the proportions were required. The concrete was then remixed before casting two cylinders from each batch. They were cast by filling the mold in 1/3 lifts, and rodding each lift 25 times. Shortly after the cylinders were cast, they were placed in a moist room where they remained in the molds for 24 hours.

Thirty-one batches of concrete were required to make the sixty-two cylinders for the main compressive strength tests. Cylinders with different shaped aggregate particles were cast in random order so that any variations caused by changes in temperature, humidity, or mixing procedure would tend to be compensating. Fifty-four cylinders were cast the same day to minimize the variations, while the remaining eight were cast the following morning.

Six cylinders from three different batches of concrete were made with particles of each shape and material. Thirty-four of the cylinders were made with basalt coarse aggregate material, while fourteen were made with gneiss, and fourteen were made with quartzite. An additional thirty cylinders were made at a later date to check mortar strength and the effect of particle orientation.

All of the cylinders for the main strength comparison tests were cured for a standard 28 days in a laboratory moist room where a temperature of 71 ± 5 F, and a humidity of 100 per cent were maintained. The remaining cylinders were cured in the moist room for a seven day period.

3.4 CAPPING CYLINDERS

It was necessary to design and build a special capping device for small cylinders to prepare them for compressive testing. This was accomplished in cooperation with the Instrument Laboratory at Montana State College. Their ingenious conversion of a microscope frame produced a very accurate and workable device. It is shown in Figure 6.

The conversion was made by replacing the microscope tube with a larger hinged tube to hold the cylinders. This permitted the use of the original microscope movement to raise and lower the cylinders. The conversion was completed by fastening a capping compound mold to the base plate of the microscope frame. The aluminum mold had a tapered top and an optically flat plate glass bottom. This construction assured cylinder caps that were well within the required tolerances. The optically flat plate glass provided smooth ends, while the fixed position of the cylinder to the microscope movement produced ends that were parallel.

The capping process was quite simple. A cylinder was clamped in the hinged tube and then lowered to a thickness gage which was placed in the end mold. A pointer on the side of the microscope frame was then adjusted to a mark on the movable tube. The cylinder was then raised and the thickness

Fig. 6. Cylinder capping device for 2 by 4 in. cylinders. Made from a microscope frame.

gage removed before the heated capping compound was poured into the mold. Finally, the cylinder was lowered until the pointer and mark were again aligned. The other end of the cylinder was similarly capped after the compound had cooled and solidified. To do this, it was not necessary to remove the cylinder from its clamped position in the hinged tube. The tube was simply raised and removed from the microscope frame, then inverted and lowered again. The other end was capped by repeating the entire process, including a re-setting of the pointer which controls the cap thickness.

The cylinders were removed from the moist room 48 hours prior to compressive testing and allowed to become surface dry. The cylinders were then capped with a sulfur compound in the manner described, and placed in a water bath for 24 hours. This soaking was done to assure that any moisture lost during the capping process was restored. They were removed from the water 12 hours before they were tested, but kept in the moist room.

3.5 COMPRESSIVE TESTING

A 300,000 lb. hydraulically operated Riehle machine was used in full compliance with ASTM Designation: C 39 in testing the molded concrete cylinders. The ultimate loads of the small cylinders permitted the use of the lower load indicator scale which has 100 lb. divisions.

The initial loading of the cylinders was done at a rate of 50 psi per second. This was reduced to a load rate of 35 psi per second during application of the second half of the ultimate load. Shortly after the maximum loads were reached (as indicated by definite, rather sharp drops in the amount of loads sustained by the cylinders), the loading was stopped and the cylinders were removed from the machine and stored. Two thirds of the cylinders were reloaded in the machine the following day and crushed to indicate the types of fracture. The remaining cylinders were sliced vertically with the cut-off machine to check particle spacing and orientation.

The ultimate compressive strengths of the cylinders were computed in the standard manner by dividing the maximum load by the cross sectional area. A check on the dimensions of the cylinders prior to testing indicated that a constant cross sectional area could be used in all computations, and that no height corrections were necessary. A random sample of twelve cylinders were measured with these results: length = 4.13 ± 0.03 in., diameter = 2.00 ± 0.01 in. The strength differences caused by these variations were less than 1 per cent, and therefore were not considered. Averages of the ultimate compressive strengths associated with the different coarse aggregate particle shapes and materials are given in Table V, and are shown graphically in Figure 7. The compressive strengths of individual specimens are listed in Appendix D.

TABLE V

CONCRETE COMPRESSIVE STRENGTHS ASSOCIATED WITH DIFFERENT PARTICLE SHAPES

Coarse aggregate material	Particle shape	Average compressive strength 6 specimens, psi
basalt	equidimensional	4,190
	flat	4,150
	wedge	4,020
	flat & elongated	3,950
	elongated	3,740
quartzite	equidimensional	4,360
	flat & elongated	4,270
gneiss	equidimensional	4,410
	flat & elongated	4,410

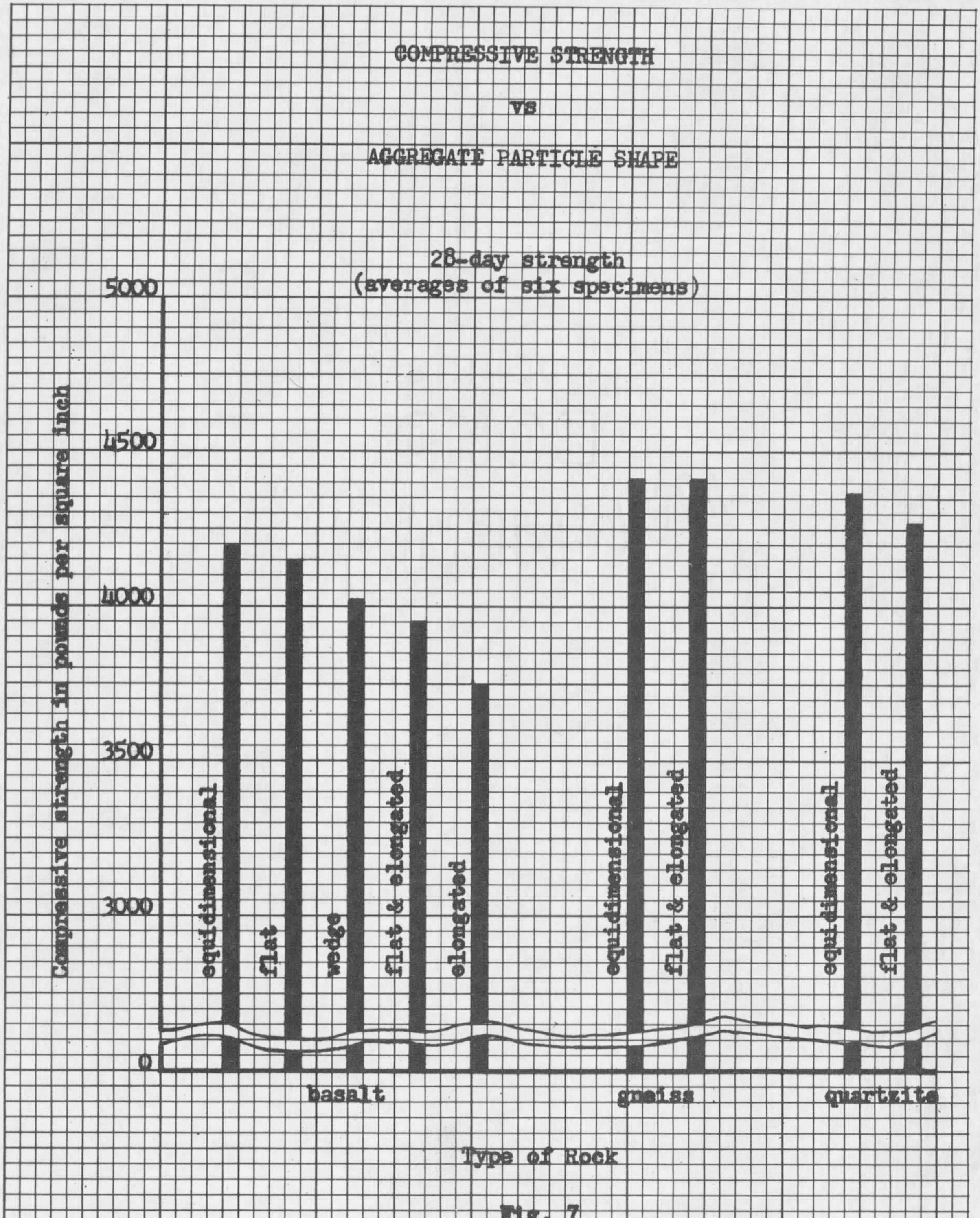
COMPRESSIVE STRENGTH
vs
AGGREGATE PARTICLE SHAPE
28-day strength
(averages of six specimens)
Compressive strength in pounds per square inch
5000
4500
4000
3500
3000
0
equidimensional
flat
wedge
flat & elongated
elongated
equidimensional
flat & elongated
equidimensional
flat & elongated
basalt
gneiss
quartzite
Type of Rock

Fig. 7

CHAPTER 4

ANALYSIS OF DATA

4.1 STATISTICAL ANALYSIS

A statistical analysis of the data in this study was made to determine the variability of the test results and the significance of the differences among the means. The concrete compressive strength data consisted of nine different coarse aggregate treatments with six replicates or observations per treatment. Both pair and group analyses were made to test for significant differences between the means, which was the main purpose of this study.

4.11 COEFFICIENTS OF VARIATION

The coefficient of variation (variability) is to some extent a measure of experimental control. It is defined as the sample standard deviation expressed as a percentage of the sample mean.[20] The coefficients for the nine treatments range from 3.14 to 10.75 per cent, and average 7.37 per cent. They are listed in Table VI. Although this amount of variation in concrete cylinder strengths is not considered excellent (less than 5 per cent would be), it is a sign of good control.

4.12 CONFIDENCE LIMITS ON MEANS

Confidence limits for the compressive strength means were calculated using a common variance for each aggregate material calculated in accordance with standard statistical procedures.

In determining the limits, a probability level of 95 per cent was chosen. Thus, on the average, the probability is 0.95 that the true means will lie between the confidence limits given in Table VI.

TABLE VI

COEFFICIENTS OF VARIATION AND CONFIDENCE LIMITS

Coarse aggregate material	Particle shape	Coefficient variation, %	Confidence limits on means, psi
basalt	equidimensional	8.8	4,190 ± 260
	flat	7.1	4,150 ± 260
	wedge	3.1	4,020 ± 260
	flat & elongated	7.8	3,950 ± 260
	elongated	9.7	3,740 ± 260
quartzite	equidimensional	10.8	4,360 ± 370
	flat & elongated	7.4	4,270 ± 370
gneiss	equidimensional	5.5	4,410 ± 220
	flat & elongated	5.6	4,410 ± 220

4.13 SIGNIFICANCE OF MEANS

Three different group tests were made to determine the significance of differences between coarse aggregate treatment means. Duncan's new multiple-range test and Tukey's w-procedure were used to make a one-way classification of the means associated with the basalt particles.[20] The third test was made by considering two of the particle shapes and the three types of rock material as a factorial. The results of these group tests were checked by testing the differences between pairs of means.

Duncan's test determined which of the ten differences between the means relating to the five particle shapes were significantly different, and which were not. In this test "special protection levels" are used in place of significance levels to guard against finding false significant differences. The results of this test for a 95 per cent probability level are given in part a of Table VII. In this table any two means not underscored by the same dashed line are significantly different. Therefore, the strengths of the cylinders made with the elongated versus the flat particle shape are significantly different, as are the strengths of the cylinders made with the elongated versus the equidimensional particle shape. Based on this test, the differences between the other eight combinations of means are considered to be non-significant.

A more conservative one-way classification test was proposed by Tukey.[20] The results of this test are shown in part b of Table VII. All means are underscored by the same dashed line which indicates there are no significant differences at the 95 per cent probability level.

TABLE VII

ONE-WAY CLASSIFICATION OF MEANS
(cylinders made with basalt coarse aggregate)

elongated	flat and elongated	wedge	flat	equidimensional
		Part a: Duncan's test		
3,740	3,950	4,020	4,150	4,190
	- - - -	- - - -	- - - -	- - - -
- - - -	- - - -	- - - -		
		Part b: Tukey's test		
3,740	3,950	4,020	4,150	4,190
- - - -	- - - -	- - - -	- - - -	- - - -

A two by three factorial experiment was obtained by considering two particle shapes and the three types of rock material. The two particle shapes were the flat and elongated and the equidimensional. The results of this analysis indicate there is no significant effect of type or shape of aggregate upon cylinder strength. Or stated another way, none of the types of material produced significantly stronger or weaker concrete than the other two; and concrete made with equidimensional particles was not found to be significantly stronger or weaker than concrete made with the flat and elongated particles for any of the materials. Thus, the results of this test for the two particle shapes support those obtained from Duncan's test.

4.2 QUALITATIVE CYLINDER ANALYSIS

After the cylinders were tested in compression they were saved for visual inspection and study. This was done in an attempt to correlate concrete strength with the type of cylinder fracture, and with aggregate particle spacing and orientation. In a general observation of the crushed cylinders, a very small percentage of the coarse aggregate was found to be broken, thus indicating bond and mortar failure in all cases. This is evident in Figures 8 and 9.

4.21 TYPE OF FRACTURE

The types of cylinder fractures ranged from long slanting fractures common to cylinders made with flat and elongated particles to stubby irregular breaks associated with wedge or equidimensional particles. However, most of the fractures were of a conical shape with an almost complete lack of vertical splitting or columnar types of fracture. The cylinder caps were sound in all cases. In a study of the caps after ultimate loads were applied, only a few small edge cracks were found.

Bond failures between the mortar and the flat and elongated type of coarse aggregate particles can be seen in Figure 8. Orientation appeared to be critical with particles of this shape whenever the particles were located along what would be the normal "shear cone" surface of fracture. When this

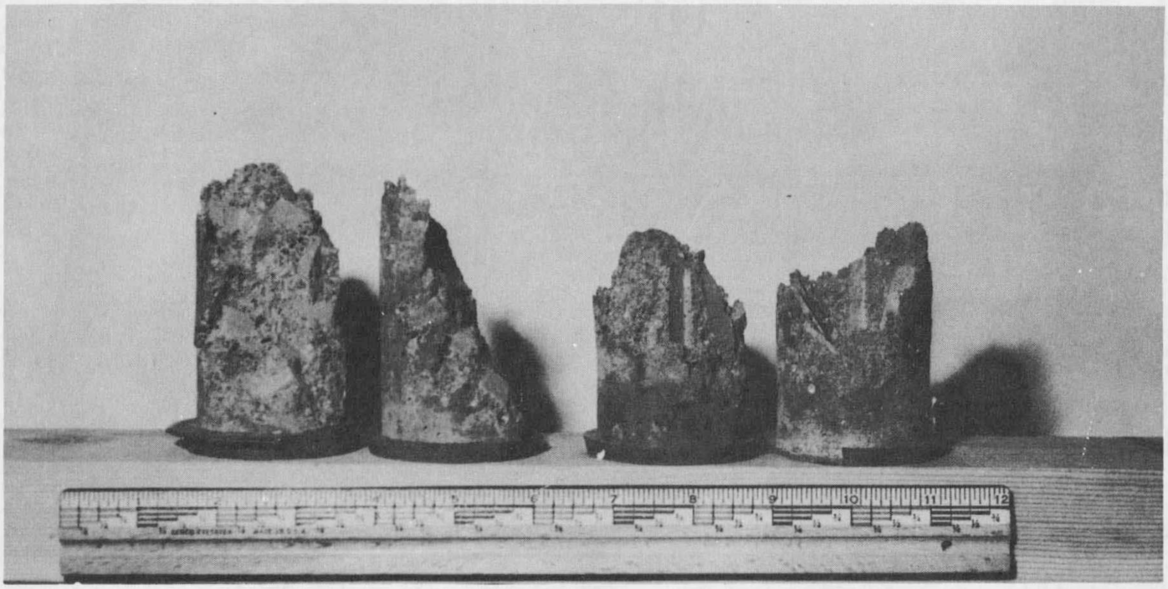

Fig. 8. Cylinders made with flat and elongated type particles showing bond failure.

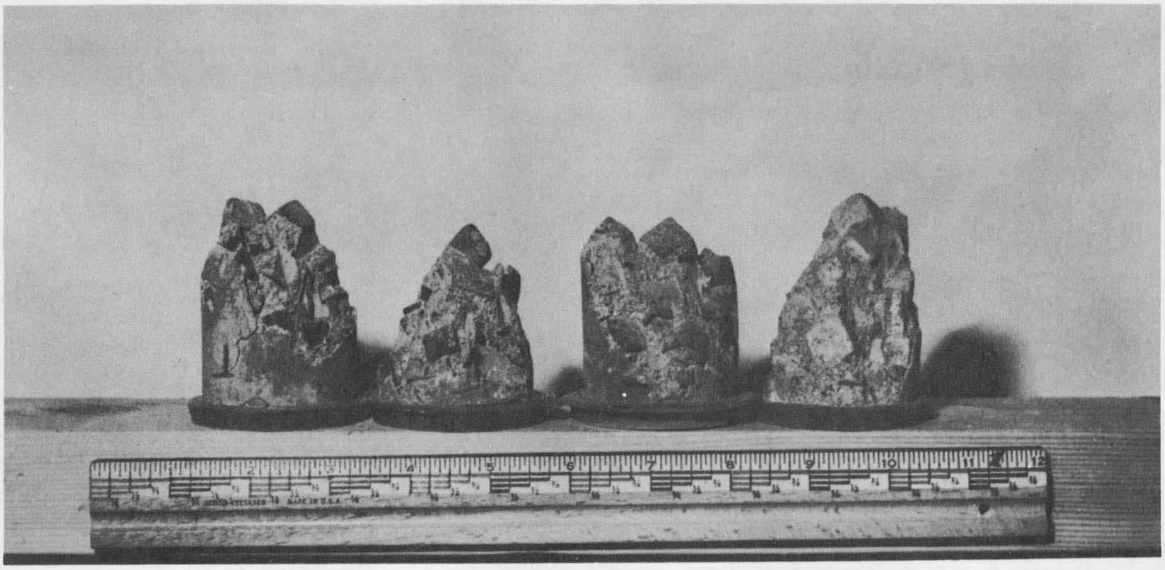

Fig. 9. Corners and edges of protruding "key" aggregate apparently initiated failure in these cylinders.

orientation occurred the cylinder strength was relatively low. However, if a sufficient number of these particles were oriented so they formed a plane partially across the cylinder, with an angle between 50 and 70 degrees with the horizontal, then the failure would be along this plane extending across the entire cylinder. The left specimen in Figure 8 shows this type of failure. Although not so pronounced, this type of failure was also evident in cylinders made with the elongated type of aggregate.

The orientation of certain particles also appeared to be critical in cylinders made with both the wedge and equidimensional shaped particles. Failures seemed to originate at points of edges of these "key" particles even though they were located near one edge of the cylinder. Figure 10 shows the result of wedge action caused by an equidimensional particle located near the cylinder's edge. Failure apparently initiated by the points of other critically oriented particles are shown in Figure 9. In one case the corner of a flat piece was the apparent locus of failure. This edge or corner effect would be diminished with a more rounded aggregate, or possibly with larger cylinders.

4.22 PARTICLE SPACING AND ORIENTATION

Coarse aggregate particle spacing and orientation can be seen in the sliced cylinders shown in Figures 11 and 12. All

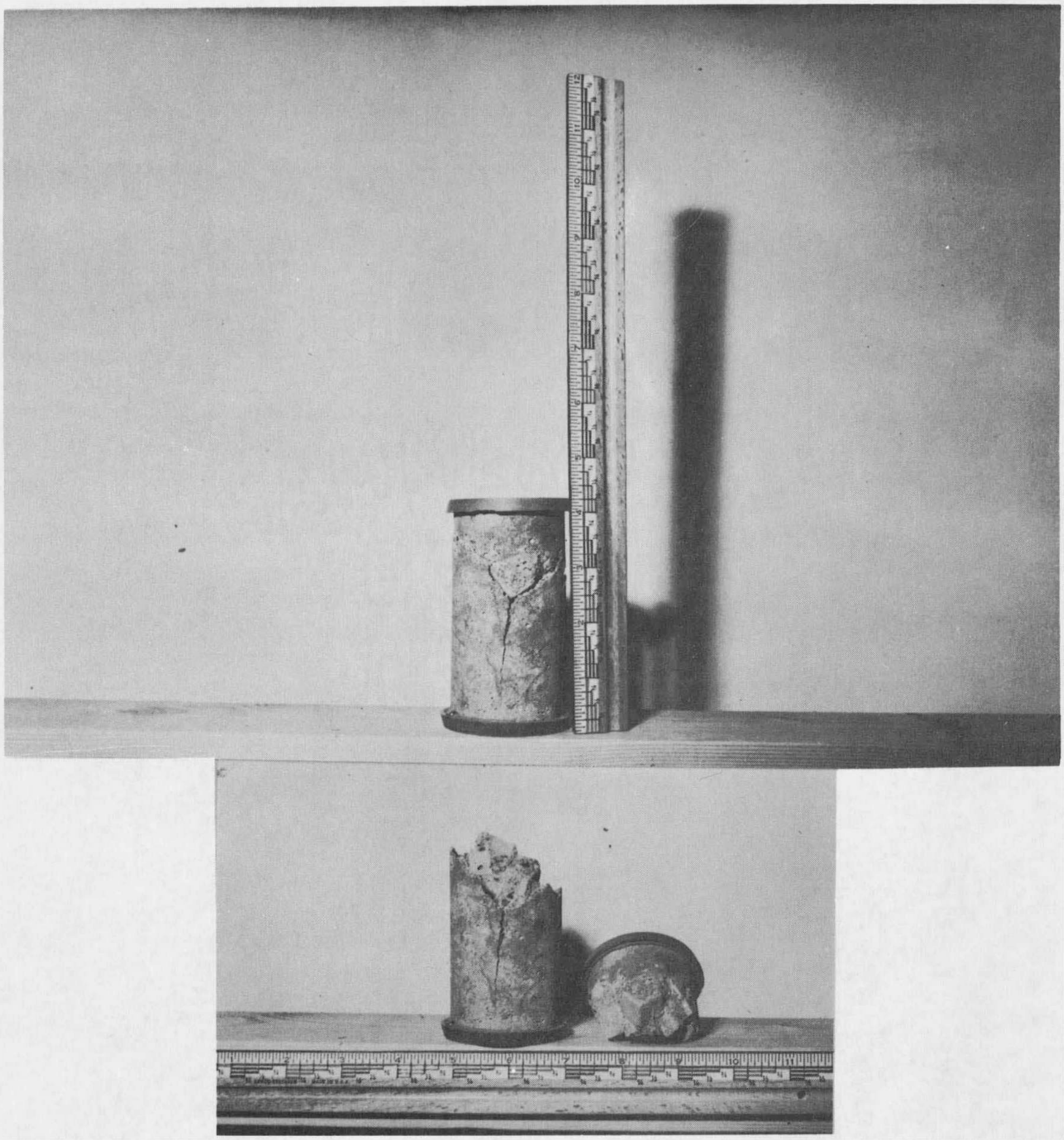

Fig. 10. Splitting wedge action caused by critically oriented equidimensional particle.

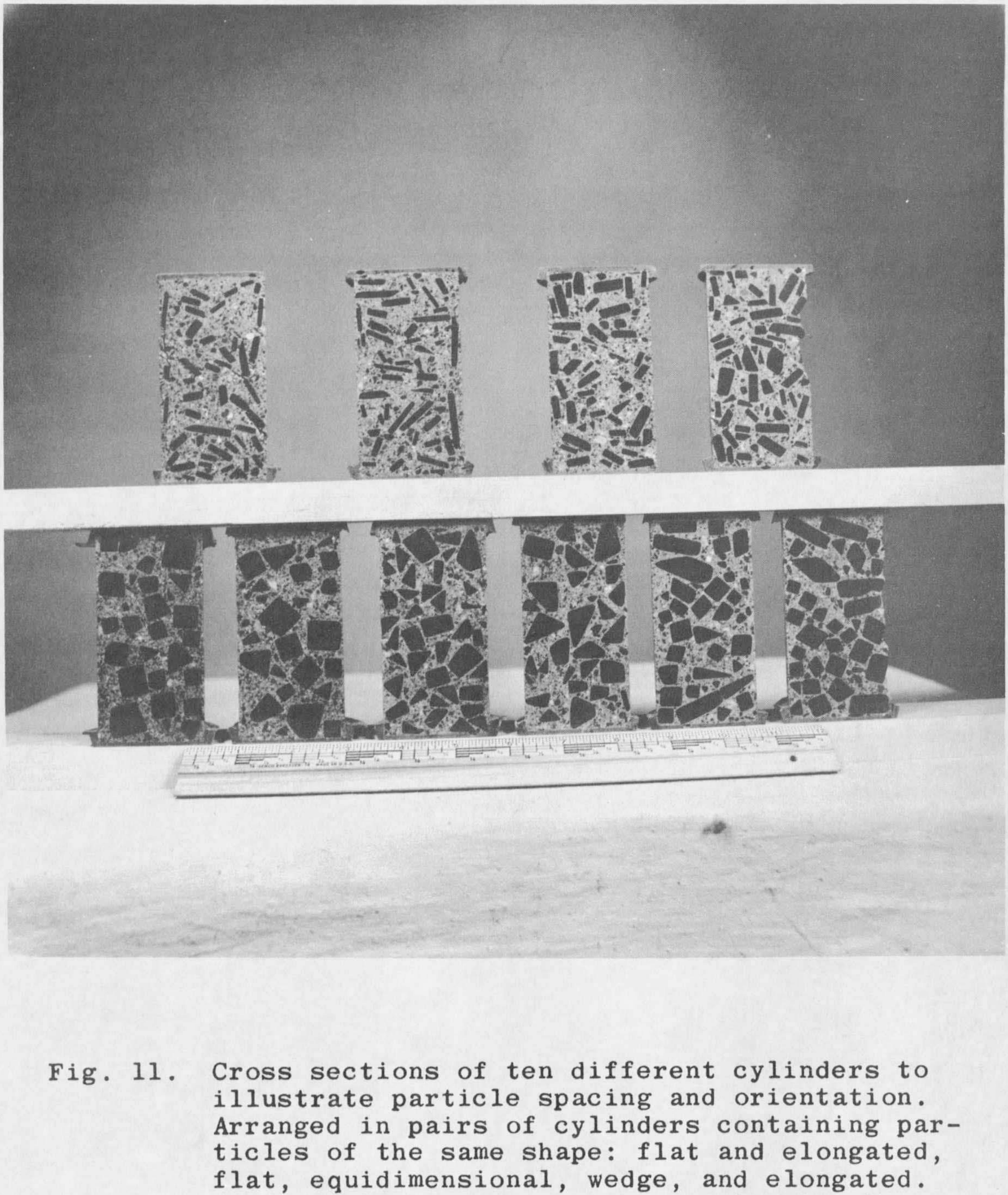

Fig. 11. Cross sections of ten different cylinders to illustrate particle spacing and orientation. Arranged in pairs of cylinders containing particles of the same shape: flat and elongated, flat, equidimensional, wedge, and elongated. (left to right and top to bottom). Basalt coarse aggregate material.