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

by

GARY A. STENSATTER

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TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

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."

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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

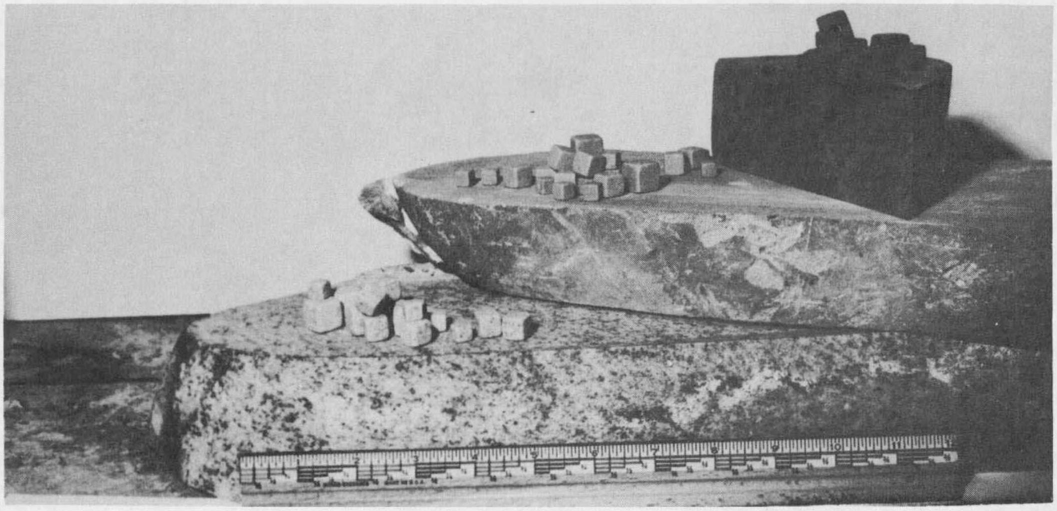

Fig. 1. Coarse aggregate materials: basalt, quartzite, and gneiss (top to bottom).

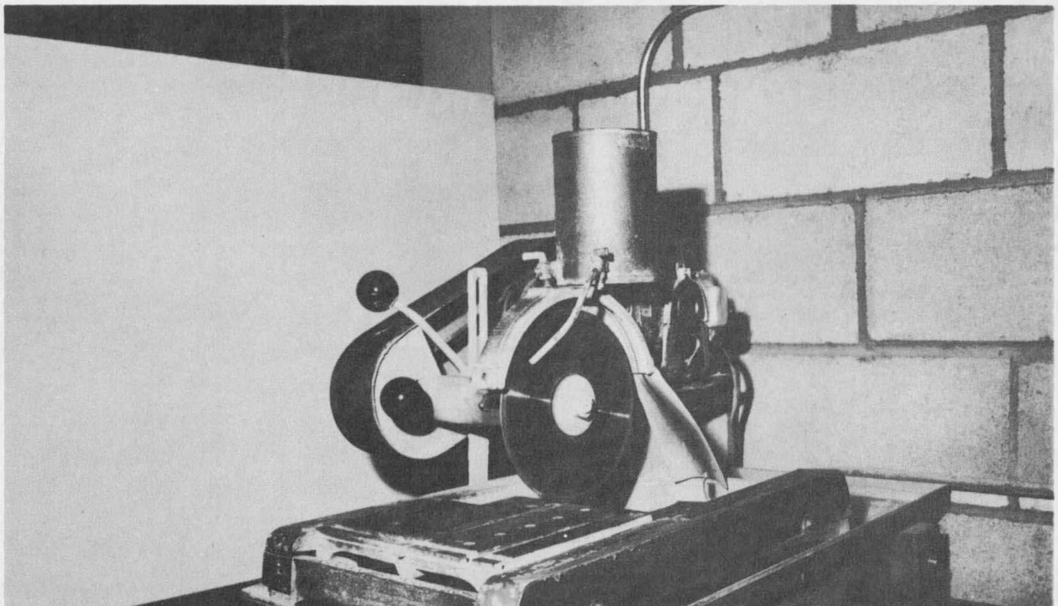

Fig. 2. Diamond blade cut-off machine used to prepare coarse aggregate materials.