INDIRECT DETERMINATION OF PARTICLE SHAPE OF FINE AGGREGATE

by

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Special Summer Undergraduate Trainee

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The following key is provided to identify for Virginia Department of Highways personnel the sources of the sands designated by number in the report.

Sand Number	Type	Producer and Location
1	Natural — silica	Massaponax Sand & Gravel Fredericksburg, Virginia
2	Natural — silica	Virginia Concrete #4 Alexandria, Virginia
3	Natural — silica	Potomac Sand & Gravel Washington, D. C.
4	Manufactured — limestone	Stuart M. Perry, Inc. Winchester, Virginia
5	Manufactured — limestone	M. J. Grove Lime, Co. Middletown, Virginia
6	Mixed	Grottoes Sand & Gravel Grottoes, Virginia
7	Natural — silica	Silica Products, Inc. Wytheville, Virginia
8	Natural — silica	Southern Materials, Co. Richmond, Virginia

SUMMARY

Three methods developed by various agencies for measuring indirectly the particle shapes of fine aggregates were used along with a visual classification procedure to study aggregates from eight commercial sources along with a reference sand. The methods were (1) measurement of void content of individual size fractions as originally developed by the National Crushed Stone Association and as currently used by the Virginia Department of Highways, (2) measurement of void content of a graded sample as more recently developed by Wills, and (3) determination of the rate of flow of aggregate through a standard orifice as suggested by Rex and Peck.

Based upon the application of these methods to the fine aggregates studied, the following conclusions were drawn:

(1) All methods, including visual classification, reflected the differences in particle shape among the sands.

(2) The correlation between the test methods was high.

(3) The high correlation among the three methods would permit utilization of data from either of the three methods.

(4) Many natural sands have poorer particle shapes than some manufactured sands.

(5) The variation in particle shape of fine aggregates used in Virginia, when compared with reported studies, was sufficient to indicate that this property would exercise a significant influence upon important properties of concrete such as water requirement, strength, slump, etc.

(6) The variation is sufficient to warrant consideration of particle shape as a variable in any broader study of fine aggregate.

(7) As far as time requirements are concerned, the Crushed Stone Method, which is currently used by the Virginia Department of Highways, appears to be not only the quickest but the easiest method.

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INTRODUCTION

For many years abundant supplies of high quality fine aggregate have existed throughout eastern Virginia. With increased urbanization and the depletion of existing sources, difficulties have been experienced in obtaining materials that meet some of the requirements established when supplies were more plentiful. The increasingly reduced supplies of fine aggregates suggest the need for a reevaluation of the requirements with the hope of relaxing for which lower standards will not adversely affect the quality of the concrete produced, and recognizing those which might adversely affect concrete quality but which are not now controlled. The study described in this report was undertaken to acquire background information about fine aggregate particle shape which would be useful in a projected, more comprehensive study of fine aggregate. Earlier studies by the Council have evaluated the influence on durability of a specific type of chert[1] and developed data on particle shapes of coarse aggregates.[2]

PURPOSE

The purpose of this study was:

(1) To develop, by several methods, particle shape data for several typical natural and manufactured fine aggregates.

(2) To determine if a correlation exists among the methods, and

(3) To suggest whether or not the variation of particle shape is sufficient to warrant its inclusion as a variable in any projected broader study of fine aggregate.

MATERIALS AND PROCEDURES

Eight sands from Virginia and Washington, D. C. were subjected to three methods used for measuring the particle shape of fine aggregate. The materials and procedures are described below.

Materials

The eight sands were selected to provide a wide range of particle shape. Five were natural sands, two manufactured, and one mixed. They are described in Table 1.

TABLE 1

Characteristics of Fine Aggregates Studied

Aggregate	Type	Specific Gravity Bulk (SSD)	Absorption %	Fineness Modulus
1	Natural - siliceous	2.59	0.71	2.81
2	Natural - siliceous	2.59	0.71	2.70
3	Natural - siliceous	2.59	0.70	2.90
4	Manufactured - limestone	2.71	0.80	2.79
5	Manufactured - limestone	2.70	0.68	2.77
6	Mixed - siliceous	2.62	0.80	2.52
7	Natural - siliceous	2.62	0.55	2.11
8	Natural - siliceous	2.59	0.60	2.68

For the purpose of comparison, a sample of Ottawa sand was tested by each of the methods with which testing of a one-sized material could be accomplished. Where this result occurs, it is listed as Sand No. 0. Enlarged photographs of the sands are shown in Figures 1-9. With the exception of Sand No. 7, which is not currently used for concrete, all the sands met the specification measurements.

These sands represented the following commercial sources*: Grottoes Sand and Gravel, Grottoes, Virginia; M. J. Grove Lime Company, Middleton, Virginia; Massaponax Sand and Gravel, Fredericksburg, Virginia; Stuart M. Perry, Inc., Winchester, Virginia; Potomac Sand and Gravel, Washington, D. C.; Silica Products, Inc., Wytheville, Virginia; Southern Materials Company, Richmond, Virginia; and Virginia Concrete #4, Alexandria, Virginia.

Procedures

Samples of the sands were gathered and oven dried. Sieve analyses (including the minus 200 material), absorption, and specific gravity determinations were then made. Some of the sample of each sand was graded to obtain the following sizes for tests:

Passing	Retained On
No. 8	No. 16
No. 16	No. 30
No. 30	No. 50

The three test methods used to examine particle shape were the following:

(1) The National Crushed Stone Association Method (NCSA), originally proposed by Gray,[3] which measures percent voids. This method has been used by the Virginia Department of Highways for many years in the acceptance of manufactured sands.

(2) The method used by Wills,[4] which measures the loose void content.

(3) The Orifice Flow Method used by Rex and Peck,[5] which measures the rate at which sand flows through a standard orifice.

*Note: The sources are listed in alphabetical order. This order does not coincide with the numerical order used elsewhere in this report.

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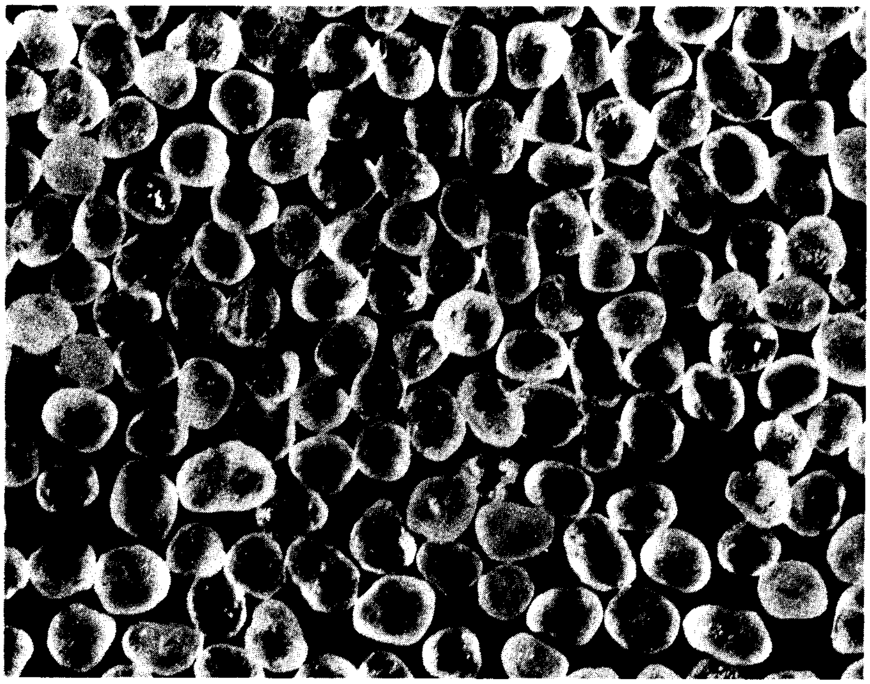

Figure 1. Sand 0 — Ottawa (10x).

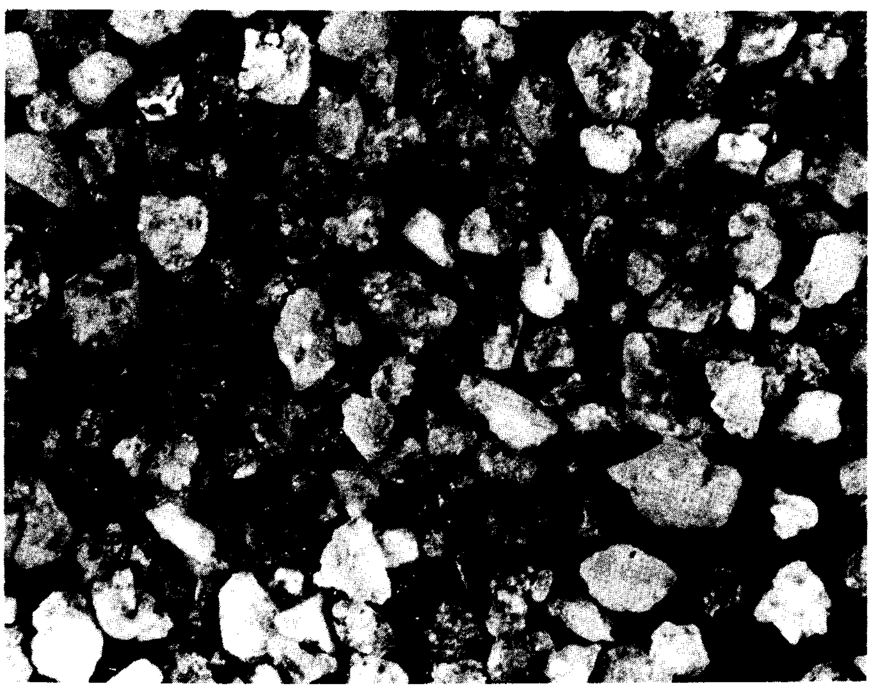

Figure 2. Sand 1 (10x).

Figure 3. Sand 2 (10x).

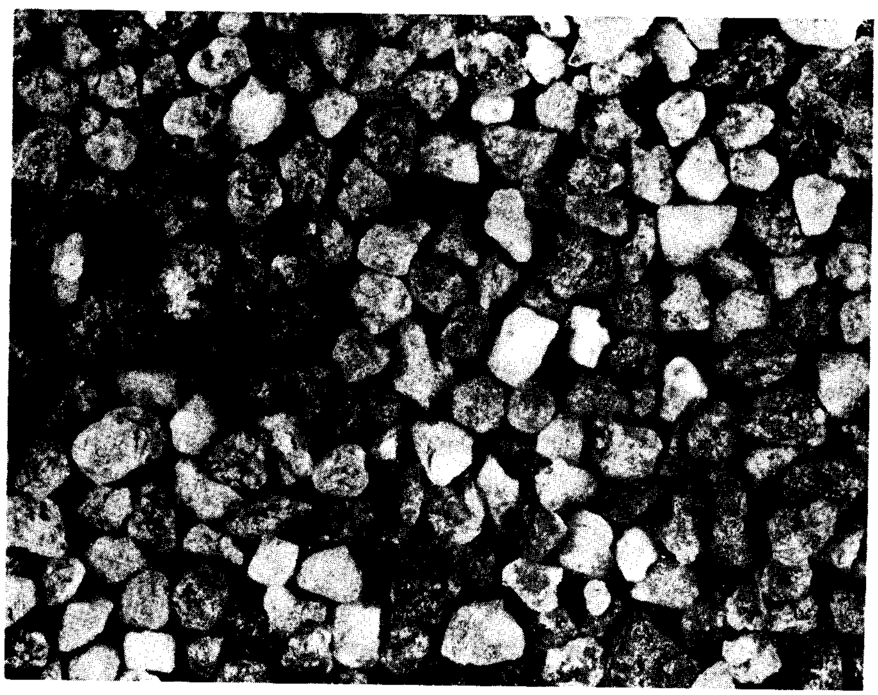

Figure 4. Sand 3 (10x).

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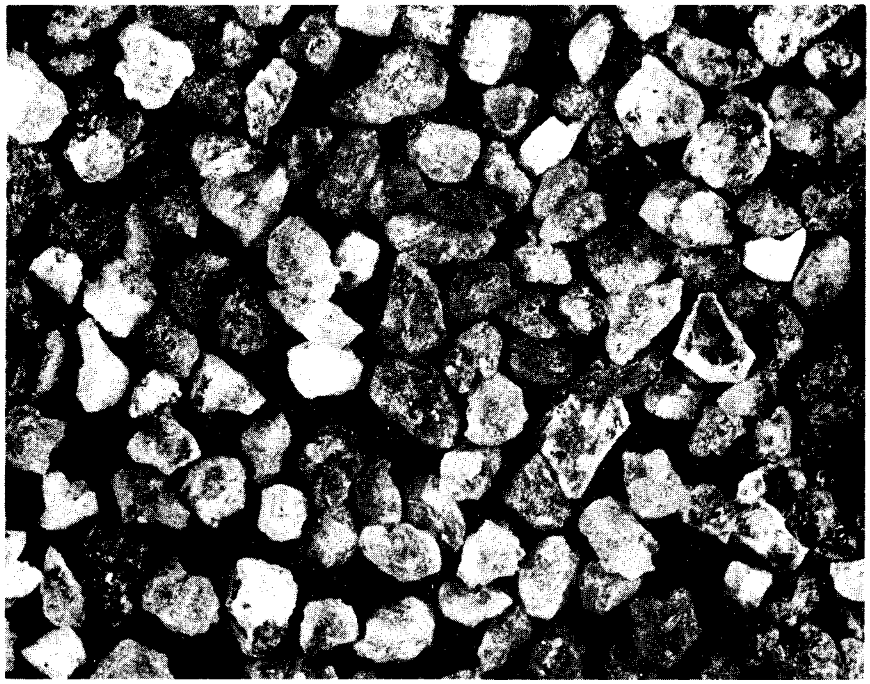

Figure 5. Sand 4 (10x).

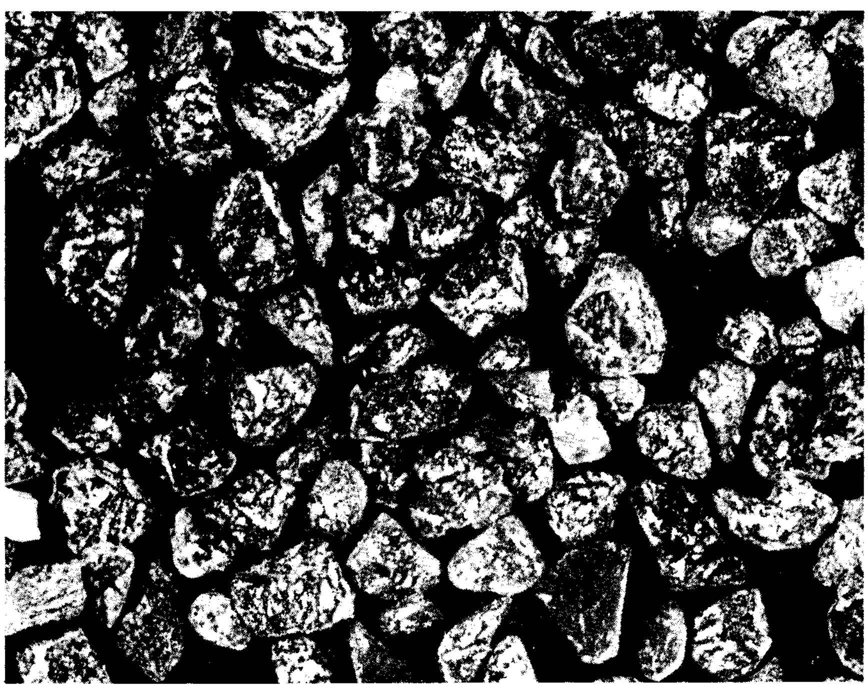

Figure 6. Sand 5 (10x).

Figure 7. Sand 6 (10x).

Figure 8. Sand 7 (10x).

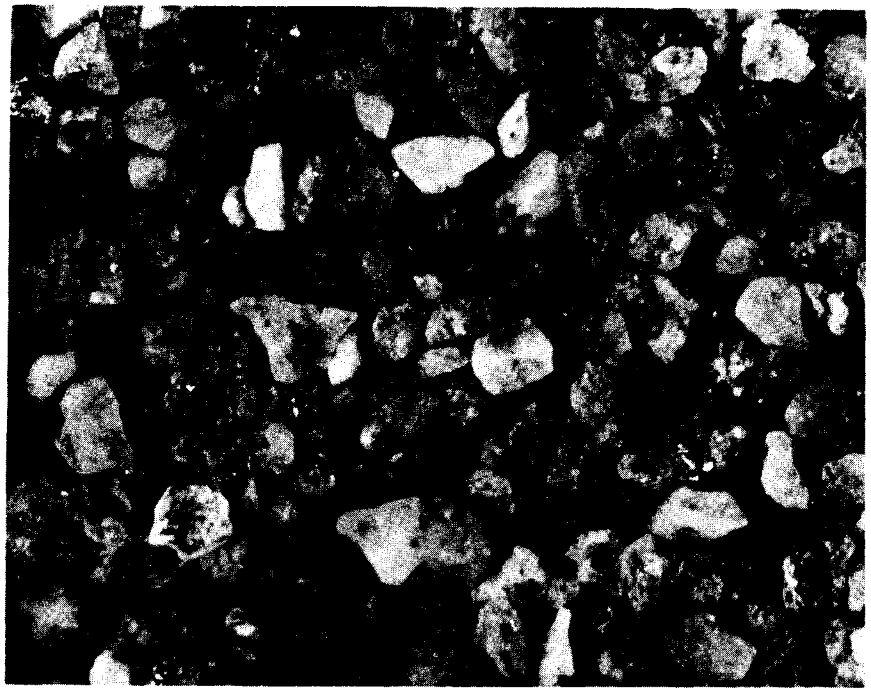

Figure 9. Sand 8 (10x).

The first method involves determinations on each size fraction separately while the other two require a single determination on a combination of the three sizes. These methods are discussed in detail below. In addition to the measurements by the three methods, the shapes of the sands were also estimated from enlarged photographs of the intermediate size fraction (16-30).

Crushed Stone (Gray) Method

This method is based upon the fact that the more irregular the shape, the less dense will be the packing of the particles in a given volume. The volume of the voids in a given volume of material is thus an indirect measure of the particle shape.

The method requires a truncated metal cone having an overall height of four inches and inside diameters of $5\frac{1}{2}$ inches for the large opening and 1 inch for the small opening. It is mounted with the small diameter downward, exactly 1 inch above a cylindrical tube. This tube has an inside diameter of 2 7/8 inches and a height of $5\frac{1}{2}$ inches, and it is mounted on a metal base. The apparatus is shown in Figure 10.

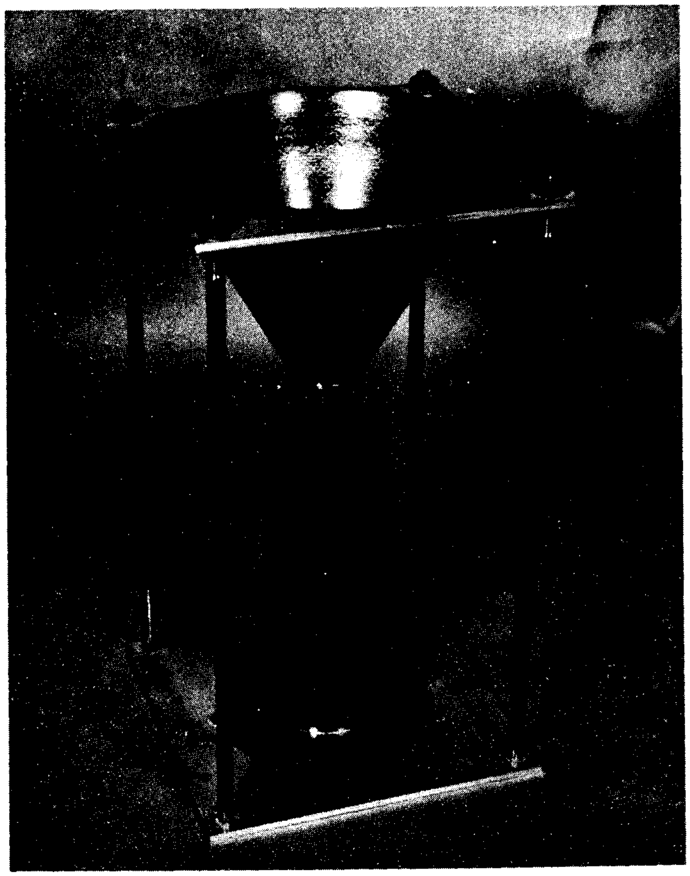

Figure 10. Apparatus used in NCSA method.

One of the three size fractions of fine aggregate to be tested is poured into the cone while a stiff piece of metal is held against the bottom aperture. The piece of metal is quickly withdrawn in a horizontal movement and the sand permitted to flow freely into the cylinder until it overfills. The sand is then struck off with a straight edge at the top of the cylinder. Care is taken to avoid any downward pressure on the sand or jarring of the cylinder. The weight of the contents is determined to the nearest 0.1 g. An average of three determinations having a maximum range of 4.0 g. constitutes a valid test result.

The percentages of voids for each size are determined by the following formula:

$$\text{Percent voids} = 100\left(1 - \frac{W}{VG}\right)$$

where,

W = weight of sand in cylinder

V = volume of cylinder (280 cc.)

G = bulk specific gravity of sand

The percentages of voids are determined for each of the three size fractions separately and the arithmetical average of the three values is reported.

Wills Method

This method is based upon the same principle as the NCSA (Gray) method. However, tests are made on several size fractions combined to a standard gradation rather than on the individual size fractions.

A pint Mason jar with an aluminum cap containing a 3/8 inch orifice fitted with a stopper is used. This assembly, which is shown in Figure 11, is inverted and placed in a ring stand over a cylindrical tube with a volume of 200 cc.

The percent voids is determined by the following formula:

$$\text{Percent voids} = 100\left(1 - \frac{W}{VG}\right) \%$$

where,

W = weight of sand in cylinder

V = volume of cylinder (200 cc.)

G = bulk specific gravity

The percentage of voids is reported as the arithmetical average of three determinations.

Rate of Flow (Rex and Peck) Method

This method is based upon the fact that irregular particles offer more interference to flow than do regular particles.

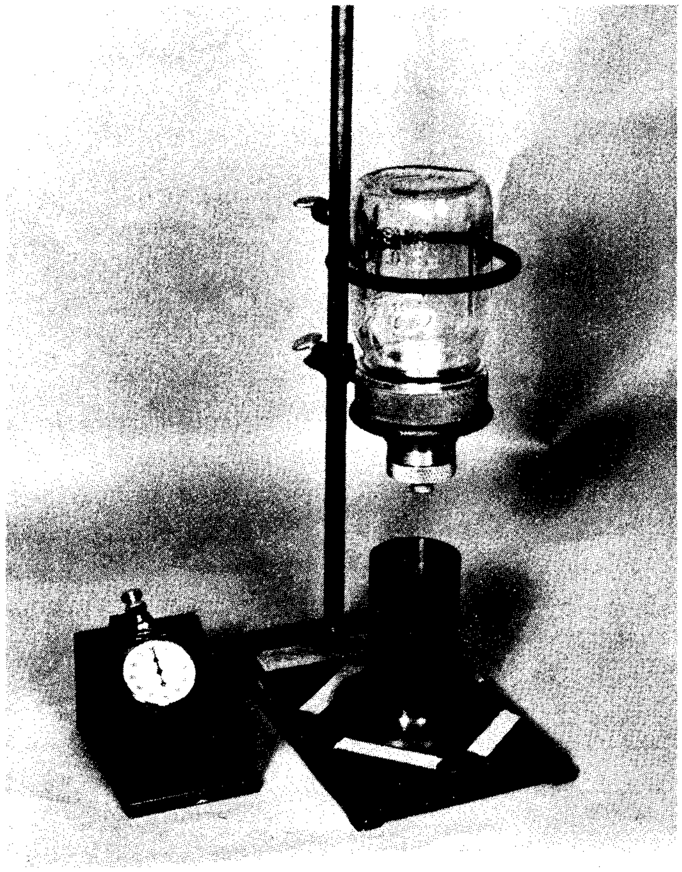

Figure 11. Apparatus used in Wills and Orifice Flow methods.

The same apparatus and procedure used in the Wills Method are used in this test. The two tests are actually run simultaneously. The time required for the 450 g. sample to run through the 3/8 inch orifice is determined. Three determinations constitute a test.

The flow rate is determined by the following formula:

$$\text{Flow Rate} = \frac{TG}{W} \times 100 \quad (\text{sec.}/100\ \text{cc})$$

where,

T = total time of flow

W = weight of sample (450 g.)

G = specific gravity

The flow rate obtained from the arithmetical average of the three determinations is reported.

Visual Classification

Photographs of -16+30 fraction of the sands were taken and enlarged to the same scale. These were shown as Figures 1-9. From these photographs the sands were ranked visually according to particle shape from "best" to "worst" (0-8) by seven people. Because the ranking was subjective, individuals were influenced in their rankings by different characteristics. Probably the most influencing factor was the departure of the particle from sphericity or roundness.[6] It should be noted that the result from this visual classification is a relative ranking of the nine sands used in this project whereas the results of the other methods are intended to be generally applicable.

RESULTS

Shape Measurements and Comparison of Methods

The numerical values obtained from the tests and the visual classification are reported in Table 2. Considering these results it should be recalled that the higher the void content, the less spherical or cubical the particle. Several interesting points are evident from these test values. As can be seen, all values obtained by the Crushed Stone Method are approximately 4 percentage points higher than those obtained with the Wills Method for the same aggregate. This can be explained by the use in the Wills Method of a combined grading containing several sizes as opposed to the use of the different single size fractions for the Crushed Stone Method. The combined grading would be expected to give the denser packing. Also, there was a tendency for the values from the Crushed Stone Method to increase as the size decreased. This pattern is consistent with the fact that the smaller particles undergo more breakage and hence present more irregular surfaces. A similar trend was noted in earlier studies of coarse aggregates.[2] Two of the sands showed no trend of void content with size. One showed a decrease in percent voids with a decrease in size. This was Sand 6, which

TABLE 2

PARTICLE SHAPE RESULTS

Values reported are results of three determinations on each sand. Averages ($\bar{X}$) and standard deviations (SD) are given. Unless otherwise noted, each value is the average of three determinations.

Fine Aggregate Number	1		2		3		4		5		6		7		8		0
	$\bar{X}$	SD	$\bar{X}$	SD	$\bar{X}$	SD	$\bar{X}$	SD	$\bar{X}$	SD	$\bar{X}$	SD	$\bar{X}$	SD	$\bar{X}$	SD	
<u>Crushed Stone Method</u>																	
Percent Voids:																	
Size 8 to 16	49.87±	0.06	49.30	0.20	46.27±	0.12	49.33±	0.12	47.00±	0.00	52.87±	0.03	47.77±	0.06	47.63±	0.21	—
Size 16 to 30	51.20±	0.00	48.23	0.29	47.17±	0.06	50.03±	0.06	47.17±	0.23	50.70±	0.10	47.17±	0.06	48.67±	0.12	41.97*
Size 30 to 50	52.63±	0.06	49.00	0.27	47.93±	0.06	51.67±	0.06	48.77±	0.06	50.57±	0.06	48.60±	0.10	49.50±	0.20	—
Average	51.23	0.04	48.84		47.12		50.34		47.65		51.38		47.85		48.60		—
<u>Wills Method</u>																	
Percent Voids:																	
Combined Size	47.95±	0.15	44.60±	0.10	43.13±	0.15	46.63±	0.21	43.60±	0.17	46.67±	0.06	43.97±	0.31	44.50±	0.00	—
<u>Rate of Flow</u>																	
Sec./100 cc.	22.60±	0.53	20.90±	0.20	19.63±	0.12	22.17±	0.38	20.40±	0.27	23.53±	0.38	19.70±	0.10	21.30±	0.53	15.53**
Visual Classification***	6.29		3.86		1.86		6.29		5.43		5.00		1.86		5.43		0.00

* Only size available

** Done with 500 gm. of 16 to 30 size

*** Average of rankings by 7 observers

was a mixture of natural and manufactured material. The smaller sizes are naturally occurring material whereas the larger sizes are from a crushing operation. The observed trend for Sand 6 would thus be expected. All average values obtained from the Crushed Stone Method, which is the method used by the Virginia Department of Highways, were below the currently specified maximum void content of 51.5%, although Sands 1 and 6 were quite close to this upper limit.

The correlation between methods is given in Figures 12-14. The analyses for the correlations among the three methods were made by computer for the following types of relationships:

$$Y = Ax + B$$

$$Y = Ax^2 + Bx + C$$

$$Y = Ax^3 + Bx^2 + C$$

$$Y = Ax^3 + Bx^2 + Cx + D$$

From these analyses the straight line was found to be better than any curved lines studied. The line of best fit is given on each graph along with the individual data points. The correlation between methods was very good, as evidenced by the following correlation coefficients obtained:

Crushed Stone Method — Wills Method:	0.971
Crushed Stone Method — Rate Flow Method:	0.965
Wills Method — Rate Flow Method:	0.895

The correlations are of the same order as those reported by Wills.[4] As shown by these figures, the two tests which were run simultaneously had the poorest correlation. Because there is no possibility that the difference is from sampling or operator variation, one can only speculate that the two methods were not measuring exactly the same characteristic.

With slight variations, the three test methods gave the same general ranking of the sands from "best" to "worst", as shown in Table 3. The NCSA and Wills Methods appear to give the closest agreement. The results of the test methods were supported in a general trend by the visual classification.

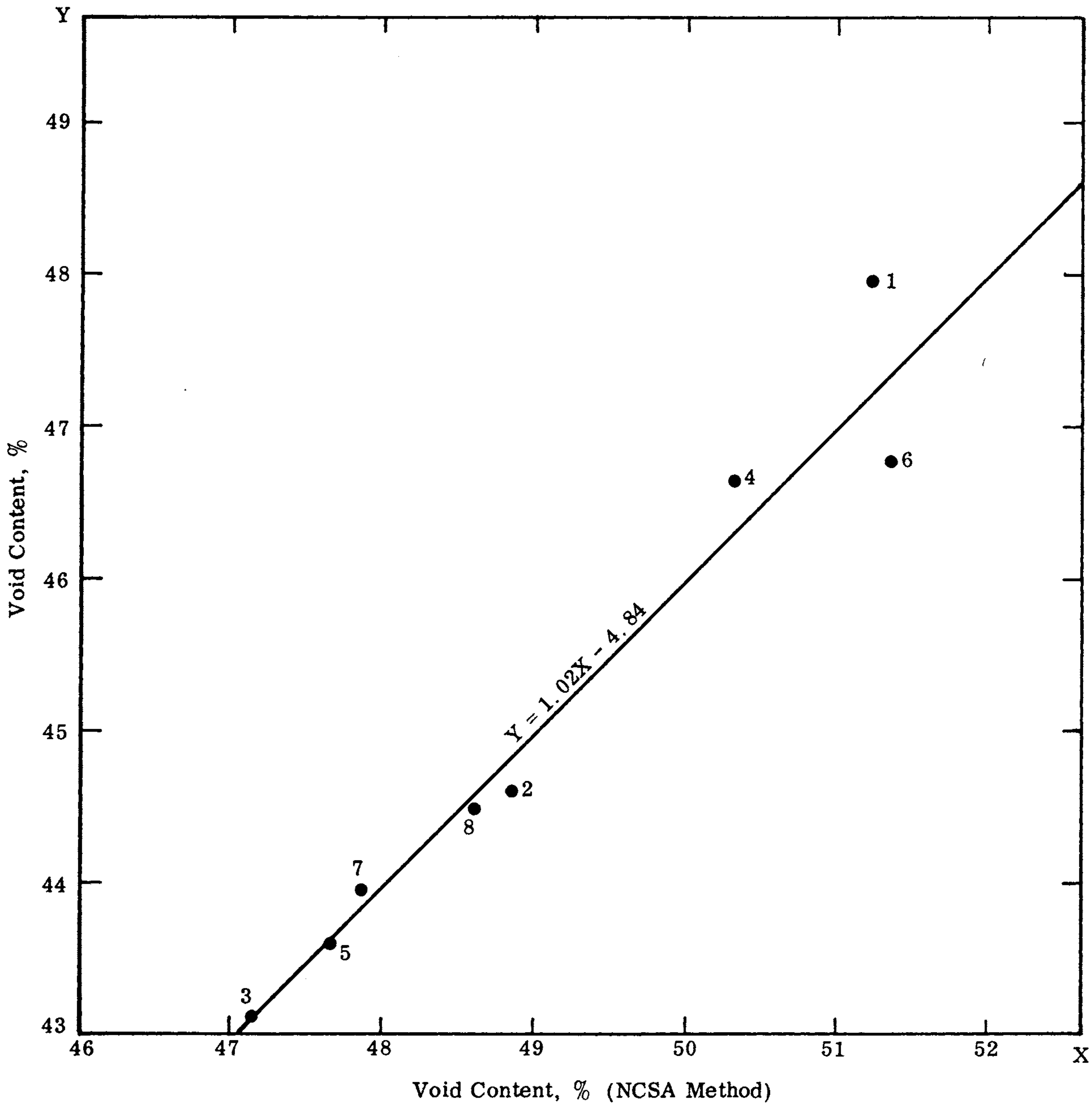

Figure 12. Correlation and relationship between the results from the Wills and NCSA methods.

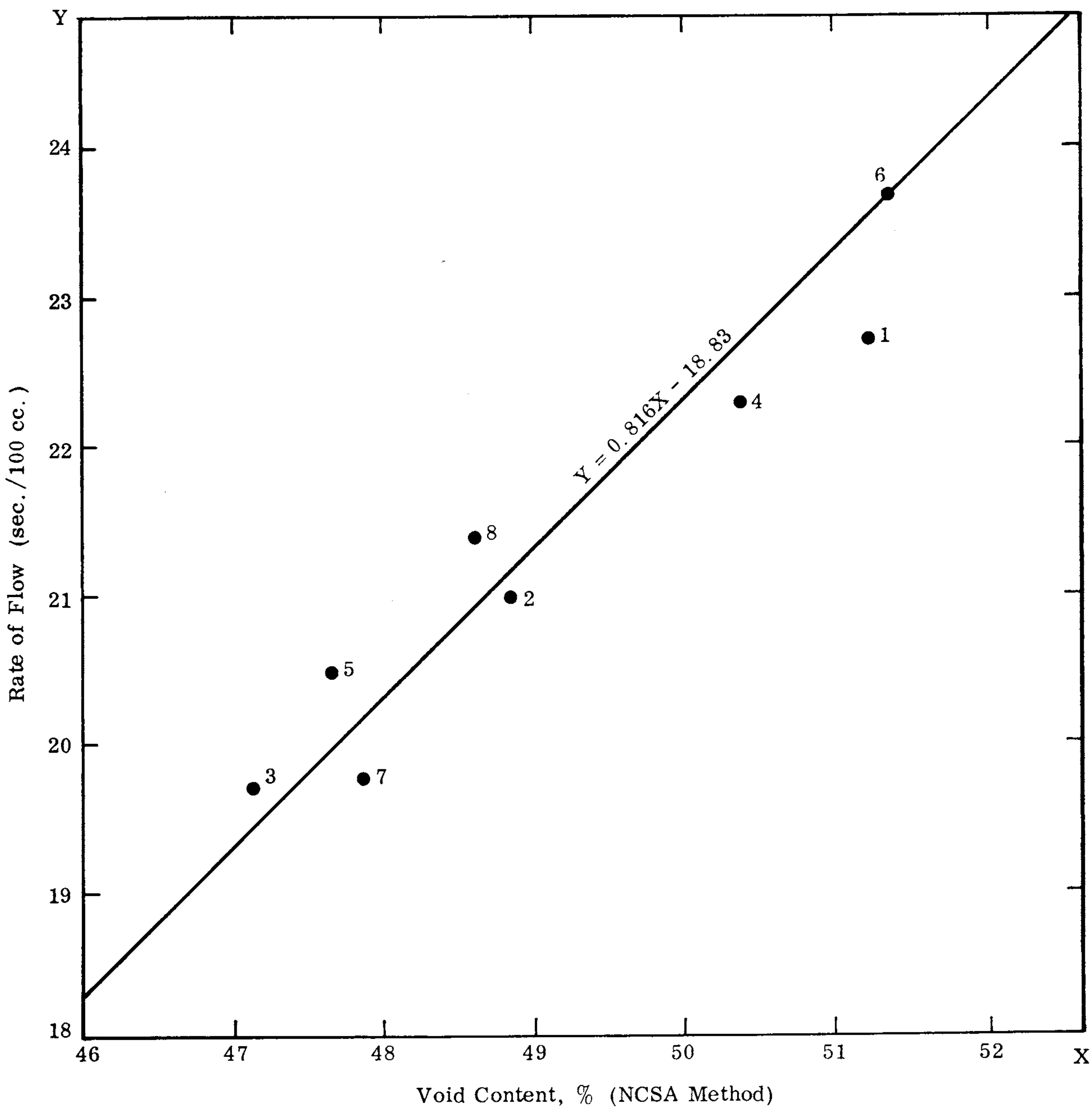

Figure 13. Correlation and relationship between the Orifice Flow and NCSA methods.

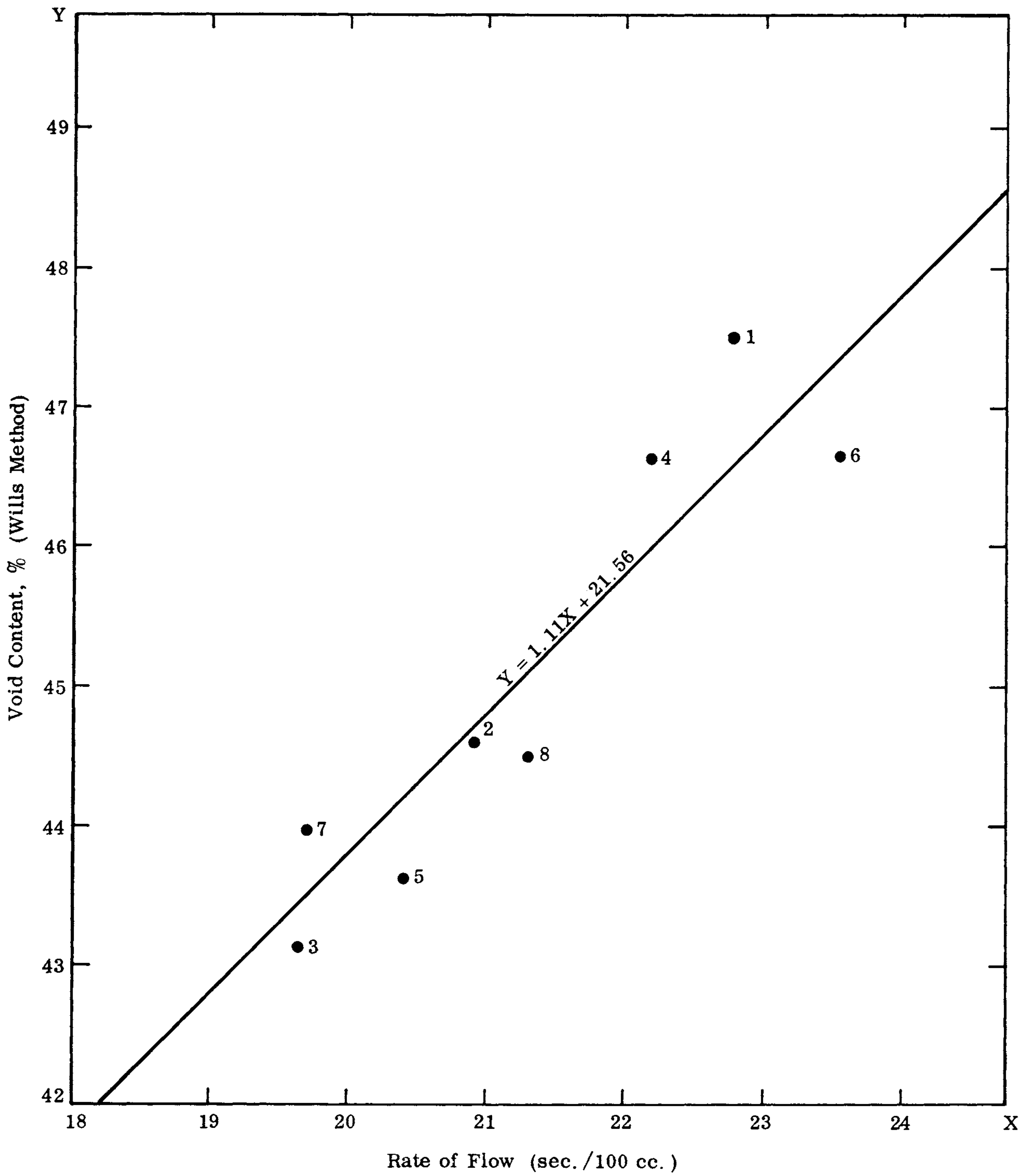

Figure 14. Correlation and relationship between Wills and Orifice Flow methods.

TABLE 3

Relative Ranking of Sands by Four Methods

Ranking	Crushed Stone Method	Wills Method	Flow Rate Method	Classification
"Best"	0	0	0	0
	3	3	3	7
	5	5	7	3
	7	7	5	2
	8	8	2	6
	2	2	8	8
	4	4	4	5
	1	6	1	4
"Worst"	6	1	6	1

Time Requirements

After drying and grading of the sand, a task which is common to all methods, the time requirements for the tests varied slightly. The Crushed Stone Method requires approximately 30 minutes from start of test to the time values are obtained. The Wills Method and Rate of Flow Method take about 45 minutes because of the time required to combine the different sizes of sand. Two results can be obtained, however, instead of one.

SIGNIFICANCE OF RESULTS

The correlation of the particle shape data with properties of mortars or concretes containing the fine aggregates tested was beyond the scope of this study. From the results of published research, however, some insight can be gained as to the significance of these results in terms of the probable contributions of variables such as those measured on important properties of concrete. In a recent nationwide survey of sand properties by the National Sand and Gravel Association,[7] loose void contents of 130 sands measured by the Wills procedure ranged between 37.8% and 49.8% with an average of 43.0% as compared with the range from 43.1% to 48.0% for the eight sands studied here. Thus, the sands studied in Virginia all gave average values above those for the larger sample. This suggests that Virginia is faced with the need to use sands of poorer than average particle shape.

Wills concluded from his study[4] that the fine aggregate had more influence on the properties of concrete than did the coarse aggregate. He developed the relationships between loose void content, water content, and strength shown in Figure 15. Thus, one would infer from a comparison of the data from the Council's study with those developed by Wills that other things being equal, concrete made with Sand 6 would require an increase in water content of 6 gal./cy. over that made with Sand 3. The corresponding reduction in compressive strength would be approximately 1,000 psi.

In a recent survey by the Materials Division of the Virginia Department of Highways, void contents measured for 28 sands by the NCSA Method ranged between 46.8% and 54.8%. Assuming that the void contents measured by the Wills procedure would have ranged from 43.0% to 50.0%, the potential difference in water content would be 8 gal./cy. and that for compressive strength almost 2,000 psi between the best and worst shaped sands.

Thus, the variations measured are significant in terms of their potential influence on significant concrete properties. It is also significant to note that many of the natural sands have poorer particle shapes than some manufactured sands.

CONCLUSIONS

This investigation was intended to provide typical information about the particle shape of fine aggregate as indicated by several methods of tests. Because of time limitations, it was necessarily limited in scope. Sufficient data were obtained, however, to provide information on fine aggregate particle shapes in terms of percent voids, rate of flow, and visual classification, as well as to determine a correlation between the methods. The data support the following observations and conclusions:

(1) All methods, including visual classification, reflected the differences in particle shape among the sands.

(2) The correlation between the test methods was high.

(3) The high correlation among the three methods would permit utilization of data from either of the three methods.

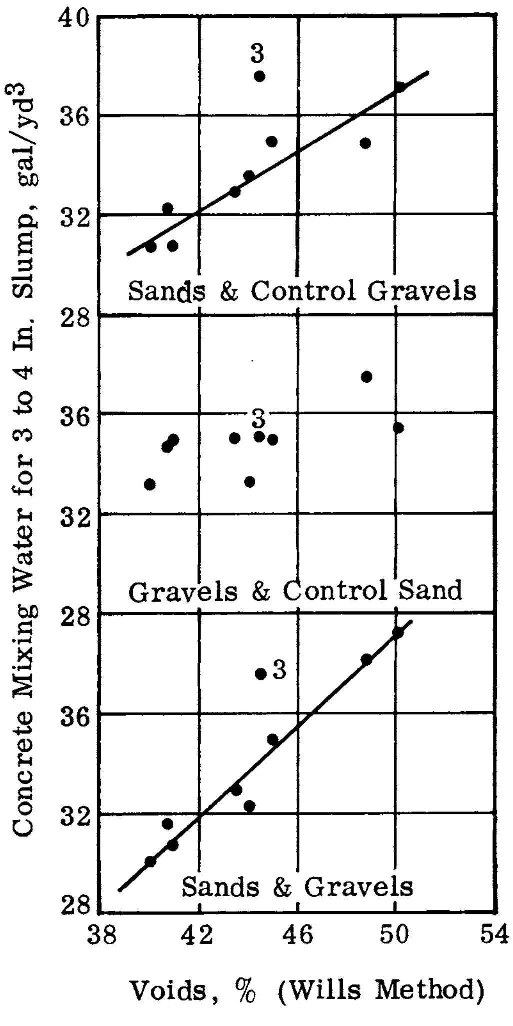

Figure 15. Effect of aggregate shape on concrete mixing water demand. (From Ref. 4.)

(4) Many natural sands have poorer particle shapes than some manufactured sands.

(5) The variation in particle shape of fine aggregates used in Virginia, when compared with reported studies, was sufficient to indicate that this property would exercise a significant influence upon important properties of concrete such as water requirement, strength, slump, etc.

(6) The variation is sufficient to warrant consideration of particle shape as a variable in any broader study of fine aggregate.

(7) As far as time requirements are concerned, the Crushed Stone Method, which is currently used by the Virginia Department of Highways, appears to be not only the quickest but the easiest method.

REFERENCES

1. Newlon, Howard H., Jr., Michael A. Ozol, Kenneth H. McGhee, and Hollis N. Walker, "Concrete Case Study No. 17, Freezing and Thawing Resistance and Petrographic Examination of Sand with High Sulfate Loss," Virginia Highway Research Council, March 1969.

2. Conway, C. D., "Measurement of Shape Characteristics of Coarse Aggregates," Virginia Highway Research Council, March 1968.

3. Gray, J. E., "The Effect of Shape of Particle on Properties of Air Entrained Stone Sand Mortar," Crushed Stone Journal, September 1961.

4. Wills, M. H., Jr., "How Aggregate Particle Shape Influences Concrete Mixing Water Requirement and Strength," Journal of Materials, Volume 2, No. 4, December 1967.

5. Peck, Robert A., and Harry M. Rex, "A Laboratory Test to Evaluate the Shape and Surface Texture of Fine Aggregate Particles," Public Roads, December 1956.

6. Mather, Bryant, "Shape, Surface Texture, and Coatings," STP 169-A, Significance of Tests and Properties of Concrete and Concrete-Making Materials, ASTM 1966.

7. Gaynor, R. D., "Exploratory Tests of Concrete Sands," National Sand and Gravel Association.