



COMMONWEALTH OF KENTUCKY
DEPARTMENT OF HIGHWAYS
FRANKFORT

April 8, 1959

Ward J. Oates
COMMISSIONER OF HIGHWAYS

ADDRESS REPLY TO
DEPARTMENT OF HIGHWAYS
MATERIALS RESEARCH LABORATORY
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D. 1. 7.

MEMO TO: D. V. Terrell
Director of Research

SUBJECT: Interim Reports
1. Discussion of Manufactured Stone Sand
2. Dense Graded Aggregate Base

The two attached reports were prepared and presented for the 16th Annual Meeting of the Kentucky Crushed Stone Association, Kentucky Hotel in Louisville, on April 4, 1959. They have been reproduced for inclusion in the Bound Volume records of the Research Division.

Respectfully submitted,

A handwritten signature in cursive script that reads "W. B. Drake".

W. B. Drake
Associate Director of Research

WBD:dl
Att: Reports

Commonwealth of Kentucky
Department of Highways

DISCUSSION OF MANUFACTURED STONE SAND

by

James H. Havens
Assistant Director of Research

(Prepared for the 16th Annual Meeting of the Kentucky Crushed
Stone Association, Kentucky Hotel, Louisville, Kentucky, on
April 4, 1959)

Highway Materials Research Laboratory
Lexington, Kentucky

April, 1959

DISCUSSION OF MANUFACTURED STONE SAND

Our research on the use of stone sand in portland cement and bituminous concretes is still in the preliminary stages. Actually, we have been trying to crystallize our thinking as to the pertinent issues involved and as to the specific properties of the sands that might require investigation. Generally speaking, the thinking of people more experienced in the use of stone sands has been rather favorable provided that due precautions are observed. For instance, Blanks and Kennedy (1) have

(1) Blanks, R. F. and Kennedy, H. L. The Technology of Cement and Concrete, Vol. 1, p. 396; John Wiley & Sons, 1955.

said this about manufactured sand in portland cement concrete:

"The effect of particle shape and uniformity of gradation is most important in stone sand. It is well known that gyratory or cone crushers are not suitable types of equipment for producing stone sand because of the flabby particle shapes. On the other hand, impact crushers such as hammermills and rod mills yield excellent cubical shapes. The added costs, if any, for the mills will be far more than offset by the reduced water and cement requirements and improved quality of the resulting concrete.

The first crushed stone sand to be used as fine aggregate in concrete was nothing more than ordinary "screenings," i.e., the -1/4-in. waste product from secondary crushers. Such material is poorly suited for concrete because of poor grading, harsh angular character and large excess of stone dust. Screenings should not be confused with stone sand which is a carefully prepared product, and when manufactured according to the best practices is an excellent concrete-making material.

The classifying, sizing, and blending of stone sand to obtain a uniformly graded finished product is not greatly different from those same operations with natural sand. The high percentage of rock dust in the fine fraction causes some complications which can be overcome by special design and adjustment of the plant."

The PCA Manual on Design and Control of Concrete Mixtures, 10th Ed., 1952, p. 11 says:

"Natural sands are usually made up of rounded particles. Stone sands, made by crushing stone consists of more angular particles and when used for fine aggregate in concrete, it is essential that those materials having an abundance of thin, sharp and slivery particles be avoided."

The Bureau of Reclamation's Concrete Manual, 6th Ed., 1955, p. 165, similarly says:

"Use of sand manufactured by crushing or grinding rock or gravel may result in a harsh mix and should be resorted to only when it is impracticable to obtain suitable natural sand at reasonable cost. Since the angular shape of crushed sand is its only inherent disadvantage, it is important that crushing equipment be used which will produce the best practicable shape of particles from the material to be crushed. Sand produced by crushing in rolls is generally unsatisfactory because of the high percentage of thin and elongated particles. Much better, in this respect, is the product of a rod mill. If the material is not too hard, as in the case of limestone, good results may be obtained with equipment of the impact type, more commonly known as the hammer mill, which excels in producing particles that approach a cubical shape."

Thus, in portland cement concrete the major problems seem to be:

1. Control of particle shape
2. Control of gradation (dust and intermediate fines)

Unless these factors are precisely controlled, it seems to be rather difficult to obtain strengths and workability (slump) comparable to those obtained with natural sands. In other words, poorly manufactured sands may require more water to obtain comparable workability and a higher cement factor to obtain comparable strengths. Thus, it would appear, also, that concrete with good strength and durability can

be made with properly manufactured stone sand.

Hubbard (2) likewise states:

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- (2) Hubbard, Fred. "Workability and Plasticity," Significance of Tests and Properties of Concrete and Concrete Aggregates, ASTM Special Technical Publication No. 169, 1956.
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"It is well established that the shape of sand grains has a marked effect on the workability and plasticity of mortar and concrete. Natural sand made up of rounded grains produces much more workable concrete than does crushed sand made up of sharply angular and sometimes flat or elongated pieces. One of the major problems in the production of crushed sand is to secure a material that is well shaped and free from flat or elongated pieces. Sand with poorly shaped grains usually has a high percentage of voids, and when used as concrete aggregate it not only results in poor workability but also may cause excessive bleeding, or water gain, in the concrete."

Elsewhere, Mr. Blanks (3) compared similar projects in which well

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- (3) Blanks, R. F. "Good Concrete Depends on Good Aggregate," Civil Engineering, Vol. 122, No. 9, Sept. 1952, pp. 651-655.
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rounded sand was used in one case while harsh and angular sand was used in the other:

"For concrete with 1-1/2-in. maximum size and a water-cement ratio of 0.50, by weight, using the angular material, 300 lb. of water and 6.39 sacks of cement per cu. yd. of concrete were required. Using the rounded aggregate the same factors were 220 lb. of water and 4.69 sacks of cement per cu. yd. of concrete... The latter concrete, in addition to being of higher quality by reason of its lower water requirement, saved 1.7 sacks of cement per cu. yd. which would more than pay for an effective abrading operation to improve the characteristics of the angular aggregate."

Price (4) confirms further the general ideas proposed by Blanks and

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- (4) Price, Walter H. "Grading and Surface Area," Significance of Tests and Properties of Concrete and Concrete Aggregate, ASTM STP No. 169, 1956.
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Hubbard. In one place he says:

"...Experience has shown that usually very coarse sand or very fine sand is unsatisfactory for concrete mixes. The coarse sand results in harshness, bleeding, and segregation; and the fine sand requires a comparatively large amount of water to produce the necessary fluidity and also tends to cause segregation. Fine aggregate gradings falling within the specification limits of ASTM Specification C33 (See note below)... should be satisfactory for most concretes.

Under these specifications the minimum percentage of material passing the No. 50 and No. 100 sieves may be reduced to 5 and 0, respectively, if the aggregate is to be used in air-entrained concrete containing more than 4-1/2 bags of cement per cu. yd., or in non-air-entrained concrete containing more than 5-1/2 bags of cement per cu. yd., or if an approved mineral admixture is used to supply the deficiency in fines passing these sieves. Specification C33 also requires that fine aggregate shall have not more than 45 percent retained between any two consecutive sieves..., and that the fineness modulus shall be not less than 2.3 nor more than 3.1."

Note: The grading requirements given in ASTM C33 are as follows:

<u>Sieve</u>	<u>% Passing</u>
3/8"	100
No. 4	95-100
No. 8	80-100
No. 16	50-85
No. 30	25-60
No. 50	10-30
No. 100	2-10

Mr. Price points out further (loc-cit.) that:

"...In the construction of Norris Dam in which manufactured fine and coarse aggregates were used, it was found that a deficiency between the No. 100 and No. 200 sieves could not be made up at a reasonable cost. It was determined that the effect of this deficiency - that is, poor workability and excessive "water gains" - could be minimized by using additional material finer than No. 100 from which particles finer than No. 325 had been removed..."

It is sometimes difficult to finish a floor because of the grading of the sand which causes "chattering" or waves to form under the trowel. In one case this "chattering" was eliminated by increasing the amount of material passing the No. 50 sieve from 12 percent to 18 percent and the amount passing the No. 200 sieve from 1 percent to 4 percent."

Summarizing the above discourses, it appears that "harsh" sands whether manufactured or natural, if deficient in extreme fines, may be improved either by increasing the fines or by air-entrainment. In other words, it appears that entrained air bubbles take the place of very fine, fine aggregate particles. Thus, air-entrainment may greatly improve the workability of concrete containing a harsh sand deficient in fines, and increasing the fines may improve a non-air-entrained mix. Actually, this suggests different gradings of fine aggregates for air-entrained and non-air-entrained concretes. The most surprising point, however, is the idea proposed by Blanks that it might prove economical in concrete design to improve harsh or angular fine aggregate particles by some kind of an abrading process and that the savings in cement requirements could more than offset the cost of the additional processing. Presumably, however, it might not prove to be as practical to grind and "round" a quartz sand as it would a limestone or dolomite. Presumably, too, Mr. Blanks was probably thinking of processing these sands through a ball mill or a rod mill. Alternatively to this, fly ash, by virtue of its roundness and fineness, is known to enhance workability when used to replace as much as 25 percent of the fine aggregate. Likewise, fly ash may compensate for harshness in sands.

Actually, we had occasion to study the strength and durability of such concretes in 1948 and 1949 (5). At that time, the comparative

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- (5) Young, J. L., Jr.; Havens, J. H.; and Gregg L. E. "A Laboratory Investigation of the Mineralogical, Chemical and Physical Properties of Limestone Aggregates," HRB Abstracts, Vol. 19, June, 1949.
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durabilities of different qualities of limestone coarse aggregates were under study; and, in order to eliminate any stray influences that might arise from using natural sand fine aggregates, stone sands were manufactured in the laboratory from the same stone used for coarse aggregate. We were unable to obtain as great a differentiation among the concretes in 200 cycles of freeze-thaw as was expected from the performance histories of these aggregates in pavements. The specimens were cured 28 days before beginning freeze-thaw testing; whereas, now it is standard practice to cure only 14 days and to terminate them at 300 cycles (ASTM C 291). The tests described above, however, were terminated after 200 cycles (of 24-hrs. duration), and while we might surmise that the tests were terminated prematurely or that the concrete was cured too long before beginning the tests, all of the concretes performed very well. Since those data might have some bearing on the present problem, they have been tabulated and appended to this report.

Manufactured limestone sand was used in the construction of Wolf Creek Dam, but we do not have the specific design details. The Norris Dam fine aggregate was a crushed dolomite and satisfactory workability was obtained without air-entrainment (11% passing No. 100, FM 3.10).

In more specific regard to limestone fine aggregates in portland cement concrete, we can cite results from a rather cursory

series of tests made in June and July, 1953, comparing concrete made with Ohio River sand and limestone fine aggregate manufactured in the laboratory from Tyrone and Oregon limestones, and a tabulation of them is appended hereto.

Although the problem at present is presumably concerned only with sands produced from limestone, it is foreseeable that similar questions may arise ultimately with regard to sands produced from sandstones. With this possibility in mind, we might cite some pertinent references also. For instance, the "Kentucky Department of Highways' Report of Portland Cement Concrete Pavement Condition Study, 1945" calls specific attention to the poor performance of crushed sandstone fine aggregate used with crushed sandstone coarse aggregate (1 case, Harlan-Bell Co., FA 151, BC, 1927); but calls similar attention to a slightly superior performance of crushed sandstone coarse aggregate over gravels when not used with sandstone fine aggregate (1 case, Jenkins-Whitesburg, SP 6F, 1927).

There are several instances, however, where sandstone aggregates were used in concrete culverts and bridges. In 1949, L. C. Pendley, D. K. Blythe and D. V. Terrell began a study of the performance of these concretes; and, while it is believed that the study was not completed, correspondence in our files indicate that the following projects were under construction:

FA 121, Jackson-Compton
FR 80-A, Hazard-Jackson
SR 28-A, SR 28B, Hazard-Hyden
SP 28A, SP 28B, Dwarf-Hindman
FA 128-D, FA 128-E, Hazard-Whitesburg-Cody
FA 151-A, FA 151-B, Harlan-Pineville
SP 6F, Jenkins-Seco

In bituminous mixes the desired shape of the particles is also cubical, or at least angular as opposed to rounded. Both flat and slivery and rounded particles are rather objectionable. Higher percentages of dust are usually permissible and desirable. Whereas, rounded aggregates, all sizes, are favorable to workability in portland cement concretes; it is difficult to achieve stability with such aggregates in bituminous concretes. Stabilities in bituminous mixes may be improved somewhat by using angular fine aggregate in conjunction with the rounded coarse aggregate, and vice versa, and by the judicious use of mineral fillers. The use of harder grades of asphalt cement will improve stability at temperatures well below the softening point of the asphalt but will not prevent such mixtures from becoming critically unstable at summer temperatures.

It has been our experience also that flat, slivery particles in bituminous surface courses tend to orient horizontally under traffic and to cause flushing of asphalt to the surface. This is due, of course, to densification of the aggregate structure under traffic in a manner not achievable by initial compaction.

As we understand it, there is a tendency for the crushing process to produce excesses of coarse particles and very fine dust from limestone. Thus, in order to obtain mid-range sizes, it is usually necessary to use mills in parallel (fed through variable splitters) and to re-cycle at least part of the coarse fractions. This, again, contributes to an excess of dust. Consequently, since a large quantity of dust is altogether undesirable in sand for air-entrained portland cement concrete and since small quantities are usually desirable in

non-air-entrained mixes, air-separation of the dust at the crushing plant is usually quite necessary. Similarly, since the major difference between concrete sand and Class I sand for bituminous mixes is in the percentages of material permitted to pass the No. 100 and No. 200 screens, we would suspect that some of the problems associated with collecting and returning appreciable quantities of dust in hot-mix plants and the problem of segregation in concrete plants might be avoided by requiring separation of the extreme fines (as Mineral Filler, Art. 7.3.6. 1956 Std. Spec.) at the crushing plant and re-introducing the desired amount direct to the pug-mill or mixer. In effect, this would permit the production of a dual purpose sand and mineral filler.

However, the problem of slipperiness overshadows the use of limestone fine aggregates in both portland cement and bituminous concrete pavement surfaces. Current thinking is unfavorable to the use of limestone fine aggregate in pavement surfaces (6). We mention

(6) Stutzenberger, W. J., and Havens, J. H. "A Study of the Polishing Characteristics of Limestone and Sandstone Aggregates in Regard to Pavement Slipperiness," Bulletin No. 186, HRB, Jan., 1958.

this here simply to avoid any possibility of it being overlooked as one of the more important considerations in the over-all problem. Thus far, studies related to this problem have created a demand for selected, angular, silica sands whether they be river sands, bank sands or sands manufactured from sandstones.

In regard to the manufacture of fine aggregates (and coarse aggregates) from sandstones for use in bituminous concretes, and possibly sand asphalt surface mixes; experiences from the Salyersville-

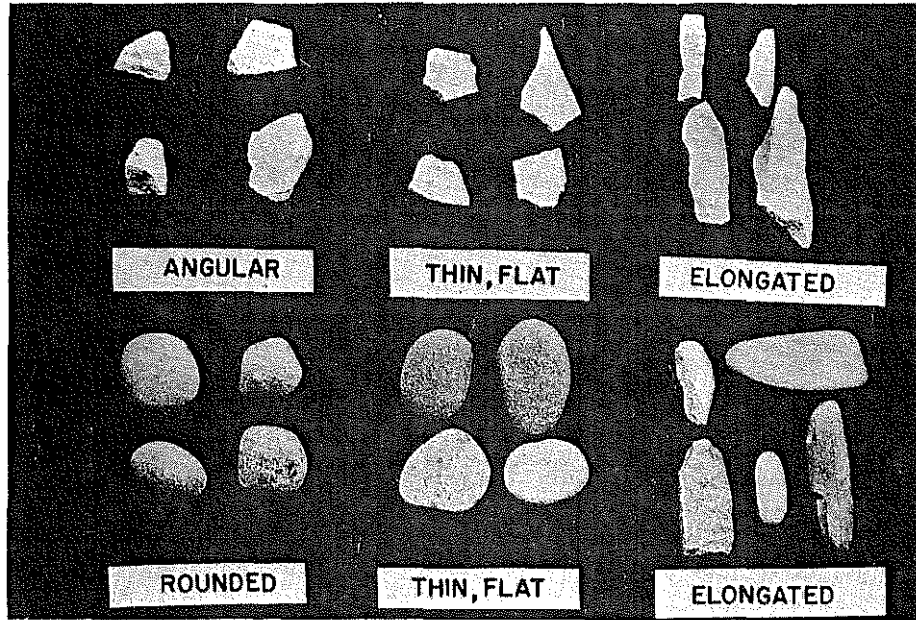
Jackson test road (7) indicated that it is feasible to produce aggre-

- (7) Williams, E. G. and Gregg, L. E. "Evaluation of Sandstones as an Aggregate in Plant Mix Bituminous Pavements," Proceedings, AAPT, Vol 22, 1953.
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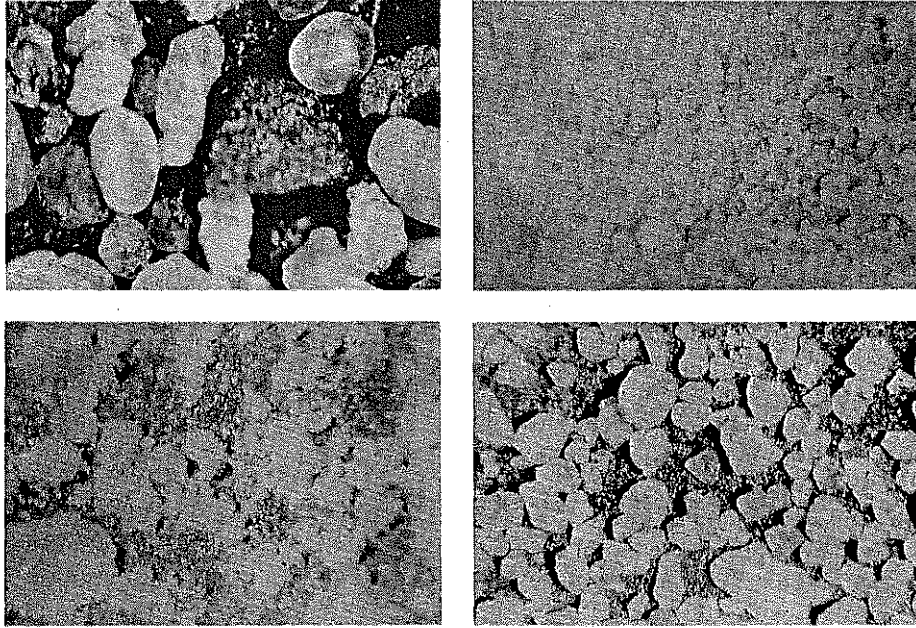
gate from such stone; and, when used for surface courses, they exhibit excellent skid resistance (8).

- (8) Havens, J. H. "Skid Prevention Studies in Kentucky," Proceedings, First International Skid Prevention Conference, University of Va., Sept., 1958.
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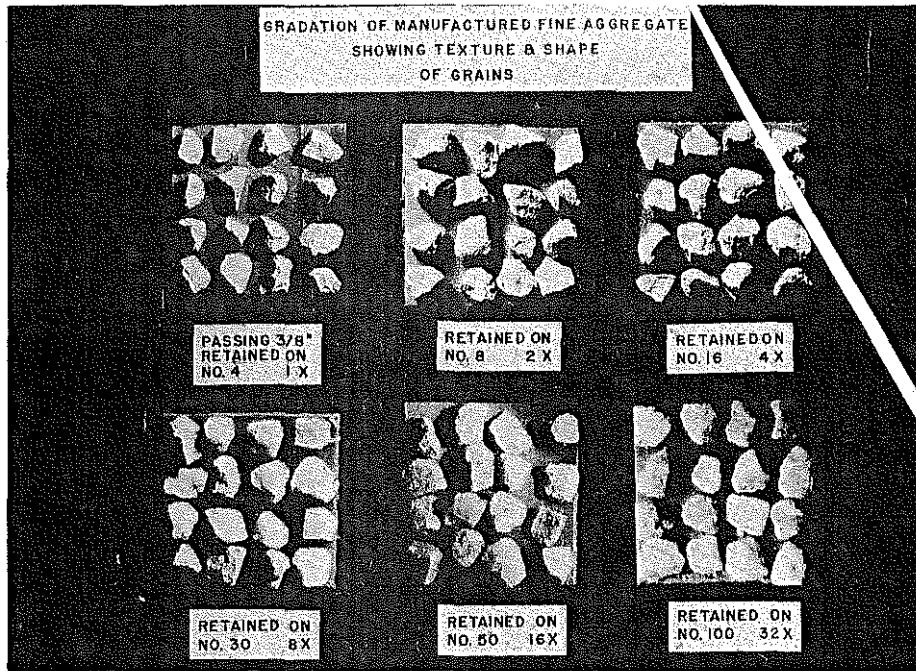
Although we have interpreted the term "stone sand" to be literally unrestricted to limestone sand, the report reflects the status of our work on the subject in general as well as the status of our thinking in regard to it. We are, of course, receptive to, and invite, suggestions as to specific avenues of study. Several significant features of this discussion are illustrated on the following pages.



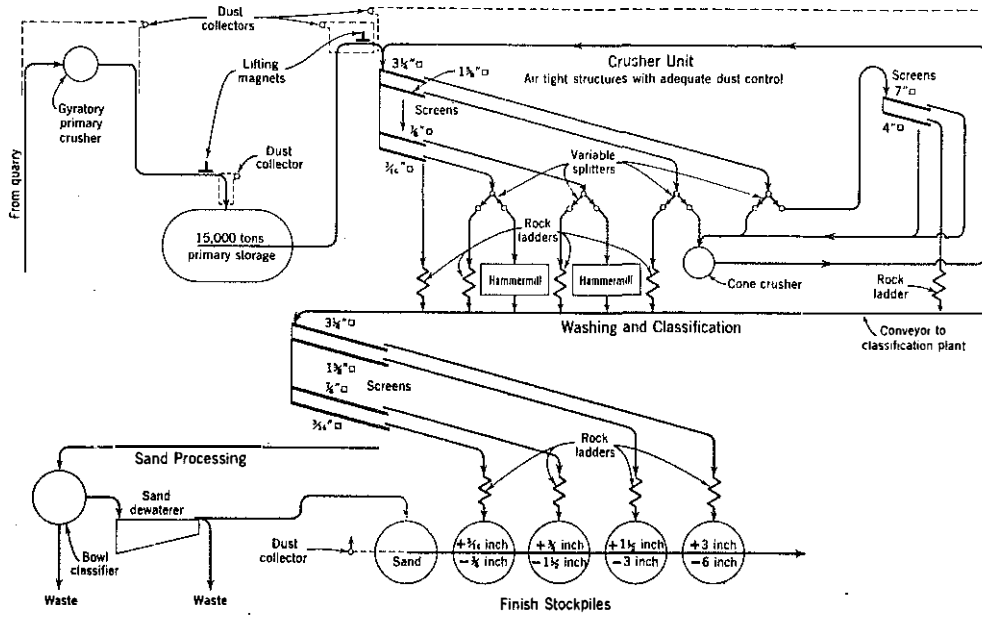
Photograph Illustrating Comparatively Three Dominate Shapes of Gravels and Crushed Aggregate Particles. Flat and elongated particles are most objectionable.



Photomicrographs Illustrating Comparatively the Sizes and Shapes of River Sands, Bank Sands and Sandstone Sands. Upper left: Ohio River Sand; note - tendency toward roughness and the absence of very fine particles. Upper right: Louisville Bank Sand; note - fineness and uniformity in sizes. Lower left: Webbville Sandstone Sand; note - abundance of fine dust. Lower right: Kyrock Sand (crushed sandstone); note - absence of fines.



Photomicrograph Showing the Different Size-Fractions (-No. 4 Sieve) from a Hammer-Mill, Enlarged to the Same Size; and Illustrating Comparatively the Particle Shapes in the Different Size-Fractions.



Flow-Diagram (Schematic) Illustrating a Plant-Layout for Production of Crushed Coarse and Fine Aggregates.

Mix-Design Data (Project C-22)
Limestone Coarse and Fine Aggregates
1949

Series	Unit Wt. Fresh Conc. lbs./c.f.	Slump ins.	Calc. Wt. Fresh Conc. lbs./c.f.	C.F. bbls. per c.y.	W/C gals per sk.	% Air Grav.	Workability
1-1	149.6	2-1/2	151.6	1.45	6.39	1.3	Fair
1-3	149.2	2-3/8	152.4	1.45	6.18	2.1	-
1-4	150.0	2-1/4	152.6	1.46	6.30	1.7	Good
1-5	149.0	2+	152.5	1.45	6.18	2.3	Fair
(95'L)							
2-1	149.6	2	153.0	1.48	5.75	2.2	Good
2-4	148.4	2-5/8	151.0	1.45	6.03	2.4	Good
2-5	148.0	3-	151.6	1.45	5.96	2.4	Good
2-8	148.4	2-1/2	151.4	1.45	6.16	2.0	Fair
(95'L)							
3-2	147.6	2-3/4	151.1	1.45	6.18	2.3	Good
3-3	149.0	2-1/4	152.4	1.45	6.18	2.2	Fair
3-9	146.0	2-1/4	149.2	1.45	6.18	2.1	Fair
3-10	146.8	2-1/2	151.1	1.43	6.40	2.0	Good
(95'L)							
4-1	150.6	2-1/4	154.3	1.44	6.39	2.4	-
4-4	151.6	2	153.5	1.47	6.00	1.3	Fair
4-7A	150.0	2-1/4	153.6	1.45	6.18	2.3	Fair
4-7	148.8	2	152.6	1.44	6.31	2.5	Fair
JQ-16	151.4	2	154.9	1.48	6.18	2.3	Fair
4-1s	150.4	2-1/2	154.0	1.44	5.75	2.3	Good
3-3s	150.2	2	151.8	1.48	5.96	1.1	Good

Note 1: Mixes non-air entrained (to accelerate effects of F. & T.)

Note 2: Data from Project C-22 (HRB Abstract, Vol. 19, 1949; also Reports of the Highway Materials Research Laboratory, Vol. III, 1948)

Note 3: Sources of Aggregate

1. Lexington, Kentucky; Jessamine & Benson Formations
 2. Mt. Vernon, Kentucky; St. Genevieve, Gasper, and Ohara Formations
 3. Avoca, Kentucky; Laurel Dolomite
- JQ: Avoca, Kentucky; Laurel Dolomite

Durability Data (Project C-22)
Limestone Coarse and Fine Aggregate
1949

Series	28-Day Flex. Str.	Flex. Str. (200 cycles F & T)	% Loss Flex. Str.	% Change Sonic "E"	28-Day Comp. Str. (Mod. Cube)
1-1	780	753	-3.4	-1	3685
1-3	920	900	-2.1	-9	3960
1-4	900	960	+6.7	-0.2	4095
1-5	860	900	+4.8	-7	3900
(95'L)					
2-1	928	907	-2.2	+3	4820
2-4	800	773	-3.3	+5.5	3830
2-5	945	967	+2.3	0.0	4140
2-8	1026	940	-8.2	-2.5	4300
(95'L)					
3-2	960	876	-6.9	+8.5	4120
3-3	872	780	-10.6	-7	3840
3-9	955	880	-7.7	-0.2	3150
3-10	944	920	-2.4	+9	4340
(95'L)					
4-1	806	667	-18.7	-11	3640
4-4	1006	920	-8.5	+1	4800
4-7A	920	1026	+11.6	+3.5	4285
4-7	806	900	+11.8	+4.5	4290
JQ-16	943	633	-32.8	+1.5	4665
4-1s	920	893	-2.9	+3	4485
3-3s	1013	553	-27.4	-20.8	4860

Note 1: Flexural tests made on 3" x 5" x 20" specimens

Note 2: 28-day comp. str. tests made on end of 3" x 5" x 20" beam after broken in flexure (ASTM C-116)

DATA (INCOMPLETE) FROM COMPARISON OF CONCRETES
MADE WITH OHIO RIVER SAND AND LIMESTONE SAND
1953

Type Cement	F. A.	Mix Date	7-Day	7-Day	28-Day	% Air	Slump	W/C gal. /bag	Unit Weight		%F. A. to Total
			Compr. Str.	Flex. Str.	Flex. Str.				Actual	Calc.	
I	O.R. Sand	6-8-53	1866	-	633	2.0	3-1/2"	8.08	148.0	151.0	45.8
I	Ls. Sand	6-22-53	3048	545	-	1.4	3-1/2"	7.98	149.6	153.1	46.3
I-A	Ls. Sand	6-11-53	2067	-	680	2.7	2-1/2"	8.3	150.6	152.3	42.7
I-A	Ls. Sand	6-18-53	3009	560	-	2.1	3-1/2"	7.39	149.8	154.1	42.7
II-A	O.R. Sand	6-3-53	1481	467	-	6.1	2-1/2"	8.62	-	151.5	47.9
II-A	O.R. Sand	6-5-53	2123	493	-	6.0	2-1/4"	7.12	144.0	152.4	45.8

Note 1: Strength data represents average of 3 specimens.

Note 2: Data taken from an incomplete series of tests.

Note 3: No freeze-thaw data available.

Note 4: Limestone sand crushed in laboratory (Tyrone and Oregon limestones), fineness modulus 2.74.

ADDENDUM

MEASUREMENTS OF PARTICLE SHAPE

The foregoing discussions merely emphasize the importance of particle shape and of precise control of gradations of sands manufactured for particular uses. Effective use of this knowledge is contingent upon practical means of defining and measuring shape in terms of a specification or method of test. While even an unexperienced observer may recognize extremes in particle shapes from word descriptions such as rounded or spherical, thin or flat, slivery, cubical, angular and elongated; limits in acceptable shapes should be defined either directly or indirectly by quantitative measurements. Mr. Mather (9) of the Corps of Engineers Waterway Experiment Station, Jackson,

(9) Mather, Bryant. "Shape, Surface, Texture and Coatings", Significance of Tests and Properties of Concrete and Concrete Aggregates, ASTM Special Technical Publication No. 169, 1956.

Mississippi, reviewed the status of this problem from the standpoint of the effects of aggregate shape in portland cement concrete and from the standpoint of methods of measurement also. He points out, however, that no ASTM method exists by which quantitative determinations of particle shape may be made. AASHTO, M80, which pertains to coarse aggregates simply requires that length be less than 5 times the average thickness. The Corps of Engineers uses proportional, or ratio, calipers which apparently are used as "go" or "no go" gages to measure individual pieces of aggregate. If the width-to-thickness (W/T) ratio or the length-to-width (L/W) ratio is greater than 3 ($L > W > T$), pieces are classed as flat and elongated, respectively. Mather

(ibid) makes no mention of any application of this method or criterion to the measurement of fine aggregate particles although it is conceivable that similar measurements might be made on fine particles by the use of a microscope.

ASTM C 125, Definition of Terms, says:

"Flat Piece - One in which the ratio of the width to thickness of its circumscribing rectangular prism is greater than a specified value."

"Elongated Piece - One in which the ratio of the length to width of its circumscribing rectangular prism is greater than a specified value."

Mather (ibid) points out that these are only descriptions of the basis for definitions because no "specified values" are given. British Standard 812 classifies flat pieces as those having thicknesses less than 0.6 times the mean size of the sieve and elongated pieces as those having lengths greater than 1.8 times the mean size of the sieve.

The Kentucky Department of Highway's Standard Specifications for Road and Bridge Construction, Article 7.4. limits the number of flat and elongated pieces in coarse aggregates to not more than 15% and defines such pieces as those having lengths greater than 5 times their thicknesses. Articles 7.3.2, 7.3.4 and 7.3.5 on fine aggregate limit the combined amount of deleterious substances including shale, alkali, mica, coated grains, soft and flaky particles to 1% but provide no specific method of test for the latter.

Academically, the problem of shape, its measurement and description, assumes a more complicated role. Sphericity and roundness though seemingly similar, are presumably independent expressions of shape. Sphericity has been described as the cube root of the ratio of the volume of the particle to the volume of a circumscribed sphere. Roundness has been described 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. According to Mather (ibid), sphericity alone fails to reveal the nature of any departure from spherical shape, and there is no direct correlation between roundness as defined above and empirical methods of measuring roundness (or angularity).

An example of the empirical approach is a method proposed by Goldbeck (10) in which the sand is separated into sieve fractions, No. 8

(10) Goldbeck, A. T. "Stone Sand for Use as Fine Aggregate", Concrete, Vol. 59, 1951.

to No. 16, No. 16 to No. 30, and No. 30 to No. 50, and then each fraction is poured, without vibration or compaction, into a right cylinder of known volume. After carefully striking off the sample at the top of the cylinder, it is weighed; and, from its bulk specific gravity, the volume of solids is computed. Mr. Goldbeck proposes that 53% voids (100-percent solids) be taken as the maximum permissible limit and presents data showing that samples having objectionable shapes exceed this value slightly. The method requires extreme care in its performance since the range in values seems to be from about 48% to 60%.

Although other empirical-type tests, involving compaction of the aggregate or specific surface measurements have been proposed; the Goldbeck method seems to offer the most practical advantages from the standpoint of simplicity and interpretation.

It is of interest to note theoretically that a sphere inscribed within a cube occupies 52.3% of the cubical volume ($100 - 52.3 = 47.6\%$ void volume). Thus, the loosest systematic packing (cubical) of

uniform spheres yields 47.6% voids. In contrast, 30- to 50-mesh glass beads poured into a graduated cylinder, without compaction or vibration, gave only 38% voids, and this value agrees closely with the theoretical average value between loosest (47.6%) and closest (26%) packing of uniform spheres.

According to Gray (11), the Virginia Highway Department

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- (11) J. E. Gray's Discussion of a paper by John G. Dempsey on "The Effects of Fine Aggregate Characteristics other than Grading on Strength and Durability of Portland Cement Mortar", Proceedings, ASTM, Vol. 58, 1958.
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controls shape by specifying a maximum percentage voids as proposed by Goldbeck.