Influence of Natural Sand Fine Aggregate on Some Properties of Hardened Concrete Mortar

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Most modern concrete specifications include requirements for quality of the fine aggregate portion to insure that it does not detract from the quality of the hardened concrete. The significance of many of the tests used to measure fine aggregate quality, however, is only poorly understood.

This paper reports a laboratory study of 25 New York natural sands and the effect that variations in their characteristics have on the freeze-thaw durability, drying shrinkage and water requirement of concrete mortar. The purpose of this study was to define significant aggregate properties and to suggest practical methods of measuring them.

It is concluded that except for varying amounts of surface damage in the form of small pits or "popouts," even extremely low quality fine aggregate, in itself, will cause no freeze-thaw deterioration of air-entrained concrete. The different fine aggregates, however, did cause variations in mortar shrinkage and water requirement. Modulus of elasticity was found to be the most significant aggregate property affecting shrinkage. Both aggregate elasticity and water requirement correlated empirically with results of the magnesium sulfate salt soundness test.

•FINE AGGREGATE is used in concrete principally to improve the properties of the plastic mix; that is, to provide workability, facilitate finishing, and promote uniformity by inhibiting segregation. The degree to which this is accomplished is determined largely by the grading, size, shape and surface texture of its component particles.

Most modern specifications include requirements for quality, as well, to insure that the sand selected for use does not detract from the properties desired in the hardened concrete. These requirements are usually based on mortar strength tests, sulfate soundness or freeze-thaw tests of unconfined aggregate, freeze-thaw tests of concrete containing the questionable aggregate, service records, or a combination of these. Unfortunately, the relationship between many of the tests available for judging quality and the properties imparted to concrete by the aggregate is poorly understood. The significance of these tests, therefore, is often difficult to interpret.

The increasing demand for aggregate of all types in the face of a decreasing supply resulting from depletion and zoning restrictions, has stimulated an increased interest in the influence of aggregate properties on the properties of concrete and in the search for simple tests to predict relative aggregate quality. The data reported here are part of the results of an investigation conducted in New York of natural sand concrete fine aggregate. This investigation was an attempt to contribute to an understanding of the influence of fine aggregate on the properties of hardened concrete, to define significantly related aggregate properties, and to suggest practical means of measuring them.

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HISTORY, SCOPE AND TEST PROCEDURES

Historical Review

In 1929, Gonnerman (1) summarized the principal considerations in selecting fine aggregate for concrete as:

> . . . (1) composition and structural characteristics of the particles, (2) cleanness of particles and freedom from injurious amounts of deleterious substances, and (3) size and grading of particles.

By and large, these same considerations are reflected in modern specifications (37). It was also recognized early that differences among fine aggregates cause variations in the properties of hardened concrete, principally, as they caused variations in the quantity of mixing water required to produce a given consistency (1). On the basis of these considerations, variations in the strength and durability of concrete and concrete mortar have frequently been explained by differences in their fine aggregate (2-9).

With the advent of air entrainment, however, it appeared that fine aggregate could be disregarded as a major contributing factor to concrete distress, at least from freezing and thawing (7, 8, 10). This view was supported by a growing understanding of the mechanism of frost damage in concrete, particularly of the effect of large numbers of small closely spaced air bubbles in the paste and of the significance of aggregate particle size (11). Accordingly, there have been only a few studies in recent years of the influence of fine aggregates on the properties of hardened concrete and mortar (12-15).

Scope and Test Procedures

Twenty-five sands were sampled from the stockpiles of New York producers operating from deposits of natural sand and gravel. An effort was made to include the wide compositional variations represented in the State as well as the extremes in quality. Laboratory studies of corresponding mortars were conducted between April 1964 and May 1965 in which measurements of freeze-thaw durability, drying shrinkage and water requirement were made. The laboratory studies were supplemented by field surveys of air-entrained concrete conducted during the summer of 1963 and outdoor exposure tests begun during the winter of 1964-1965.

Each sand was sampled in sufficient quantity to meet the needs of the entire testing program, broken down into individual size fractions, washed, and recombined for each series of tests to a predetermined gradation with a fineness modulus of 2.85 and with 2 percent by weight of unwashed material passing the No. 200 screen. The 24-hr absorption, bulk specific gravity and 5-cycle magnesium sulfate soundness of each sand were determined by the appropriate ASTM procedures (38). Specific gravity distributions were determined by separation in liquid media prepared to different densities, and sand equivalents were measured by Test Method No. Calif. 217-E (July 1963) of the California Division of Highways. The proportion of various lithologic types in each of the experimental sands was determined by examining 100 grains each of the $^3/_8$-in.-No. 4, No. 4-No. 8, No. 8-No.16, No. 16-No. 28, No. 28-No. 48, No. 48-No. 100 and No. 100-No. 200 sizes under the binocular microscope. The relative proportion of clay and silt size material in the minus No. 200 portion of each sand was determined by hydrometer analysis. The minerals comprising the clay-size portion (smaller than two microns) were determined by X-ray diffraction.

One hundred grains of the No. 14-No. 28 size of each sand were also examined for roundness and sphericity with a petrographic microscope and camera lucida. A qualitative roundness index was assigned to each sand which consisted of the average roundness value for the particles examined according to the following classification:

Classification	Roundness Value
Angular, all edges sharp	0
Subangular, < 50% of edges rounded	33
Subrounded, > 50% of edges rounded	66
Rounded, all edges rounded	100

The sphericity of each particle was computed from the lengths of its principal axes by the method of Krumbein (16) and the average value calculated for each sand. Specific surface areas were also estimated from the lengths of principal axes by the following formula:

$$\text{Specific surface area, } cm^2/cm^3 = 2/b\,(1/x + y + 1)$$

TABLE 1

LITHOLOGIC AND SHAPE CHARACTERISTICS OF EXPERIMENTAL SANDS

Sand	Rock Types, in Order of Decreasing Amount[a]		Particle Shape[b]				Relative Specific Surface Area
	Major	Minor	B/A	C/B	Sphericity[c]	Roundness	
1	Q, G	M	0.80	0.70	0.75	33.7	8.18
2	Q	L, S	0.76	0.79	0.77	35.7	7.36
3	Q, G	—	0.74	0.73	0.73	44.3	7.27
4	S, Q	L, Sh, C	0.76	0.66	0.72	46.0	7.68
5	Q, L	S, Sh	0.76	0.71	0.73	41.3	7.45
6	Q	S, Sh	0.76	0.72	0.74	53.6	7.41
7	S, Q, L	C, Sh	0.78	0.68	0.74	55.7	7.67
8	Q, S	L, Sh	0.80	0.73	0.77	55.3	7.36
9	Q, S, Sh	C	0.78	0.69	0.74	45.3	7.57
10	S, Q, L	C, Sh	0.73	0.63	0.69	36.7	7.86
11	Q, L, S, Sh	C	0.76	0.67	0.72	38.4	7.66
12	S, L, Q	Sh, C	0.74	0.72	0.73	38.7	7.32
13	Q, S, Sh	—	0.76	0.74	0.74	43.6	7.28
14	S, Q, C	Sh	0.77	0.66	0.72	35.7	7.71
15	S, Q, Sh, C	L	0.77	0.71	0.74	47.0	7.47
16	S, Q, L	Sh	0.73	0.66	0.70	47.6	7.63
17	Sh, Q, S	—	0.75	0.66	0.71	43.6	7.72
18	S, Q	L, Sh	0.73	0.73	0.72	51.7	7.14
19	S, Q, Sh, L	—	0.74	0.64	0.70	49.3	7.81
20	S, Q	Sh, C, L	0.76	0.71	0.73	42.0	7.44
21	S, Sh, Q	L, C	0.76	0.69	0.73	47.3	7.52
22	S, Q	L, Sh	0.74	0.66	0.70	46.3	7.79
23	Sh, Q, S	—	0.75	0.65	0.71	44.6	7.74
24	Sh, S, Q	—	0.72	0.55	0.68	49.7	8.59
25	S, Sh, Q	L	0.73	0.62	0.78	33.1	8.16

[a] "Major" > 10 percent of total; "Minor" 2-10 percent of total; according to the following notation, Q = quartz and feldspar including quartzite, G = granite and gneiss, S = sandstone, L = limestone and dolomite, Sh = shale and siltstone, C = chert, M = mica.

[b] Average values for 100 grains examined in the No. 14-No. 28 size range.

[c] As defined by Krumbein (16) in which A, B and C are the major, intermediate and minor axes, respectively, of the enclosing rectangular prism.

TABLE 2

ABSORPTION AND SPECIFIC GRAVITY OF EXPERIMENTAL SANDS

Sand	24-Hr Absorption (%)[a]	Bulk Specific Gravity (dry)[a]	Specific Gravity Distribution (% by wt lighter than)				
			2.00	2.20	2.40	2.60	2.80
1	0.78	2.62	0.0	0.1	0.5	8.3	97.6
2	0.40	2.63	0.0	0.0	0.3	33.8	97.5
3	0.66	2.66	0.0	0.0	0.1	18.1	88.3
4	1.56	2.57	0.0	0.1	0.8	13.3	95.8
5	1.05	2.63	0.0	0.1	0.2	9.4	96.5
6	0.99	2.59	0.2	1.1	3.5	16.8	97.4
7	1.50	2.58	0.0	0.0	0.9	11.0	98.7
8	1.39	2.59	0.0	0.2	2.0	22.7	96.8
9	2.04	2.53	0.1	0.2	4.4	52.5	98.6
10	1.86	2.58	0.0	0.1	0.4	11.4	96.8
11	1.65	2.62	0.0	0.0	0.2	7.8	76.6
12	1.41	2.60	0.0	0.0	0.4	6.1	90.7
13	1.97	2.55	0.1	1.2	2.9	10.7	99.6
14	2.66	2.49	0.0	0.5	3.1	34.3	98.5
15	1.98	2.54	0.0	0.1	1.1	24.0	98.8
16	1.89	2.57	0.0	0.1	0.8	15.0	90.4
17	2.70	2.52	0.2	1.2	3.7	31.7	97.3
18	1.58	2.57	0.0	0.0	0.7	12.7	96.4
19	2.09	2.59	0.0	0.2	0.8	15.7	87.0
20	2.28	2.51	0.0	0.1	1.1	31.0	98.6
21	2.18	2.56	0.0	0.0	0.4	5.0	94.6
22	1.90	2.54	0.0	0.2	0.7	16.8	98.3
23	2.30	2.58	0.2	0.2	0.9	13.8	97.4
24	2.49	2.53	0.3	0.8	2.5	19.5	99.4
25	3.02	2.52	0.0	0.1	0.4	10.7	97.4

[a] Average of a minimum of two tests on each sand, ASTM Designation C 127-59.

in which x equals the length ratio of the longest to the intermediate axis (reciprocal of flatness), y equals the length ratio of the intermediate to the shortest axis (reciprocal of elongation), and b equals the length of the intermediate axis in centimeters.

Measurement was also made of the quantity of water required to bring a standard mortar to a predetermined consistency. These mortars were mixed to a constant volumetric proportion between cement and saturated surface dry sand and the consistency determined by measuring the penetration of a standard cone similar in construction to that reported by Cordon (17).

The results of all decriptive tests on the experimental aggregates are given in Tables 1 through 4.

The mortars for the freeze-thaw study were proportioned for a 1:2.75 ratio of cement to sand by absolute volume and a net water cement ratio of 0.43 by weight. The cement used in this and the drying shrinkage study was from a blend of five cements from different local mills. A fixed amount of liquid neutralized vinsol resin was added to each batch in sufficient quantity to insure the development of a minimum air content of 10.0 percent. Mixing was in 0.21-cu-ft batches in a 24-qt Hobart food mixer. Each batch was tested for air content with a 200-cc pressure-type mortar air meter and for consistency with the cone penetrometer previously described. Each sand was stored for 24 hr before mixing with enough water to bring it to a saturated surface dry state.

TABLE 3

QUALITATIVE MINERAL ANALYSIS OF MINUS 2-MICRON PORTION[a]

Sand	Calcite	Dolomite	Chlorite	Illite	Kaolinite
1				X	X
2	X			X	
3				X	
4	X		X	X	
5	X	X	X	X	
6			X	X	
7	X		X	X	
8	X			X	
9			X	X	
10	X	X	X	X	
11	X	X	X	X	
12	X		X	X	
13			X	X	
14				X	
15			X	X	
16	X	X		X	
17			X	X	
18	X		X	X	
19	X	X	X	X	
20			X	X	
21			X	X	
22			X	X	
23			X	X	
24			X	X	
25			X	X	

[a] Determined by X-ray diffraction.

TABLE 4

MISCELLANEOUS DATA RELATING TO EXPERIMENTAL SANDS

Sand	Five-Cycle Magnesium Sulfate Soundness	Clay Size in Minus No. 200 Portion[a] (%)	Sand Equivalent	Water Requirement (ml)
1	4.0	5.9	87	198
2	5.9	2.0	92	189
3	12.8	0.9	94	201
4	13.2	1.2	89	195
5	14.0	1.1	93	194
6	14.1	1.1	91	203
7	15.0	1.8	87	191
8	15.4	1.3	92	191
9	17.5	1.7	87	199
10	17.6	5.5	81	205
11	18.3	1.6	93	194
12	18.8	2.0	84	201
13	20.0	2.2	80	202
14	21.6	2.2	81	210
15	22.0	2.0	84	205
16	22.6	5.2	83	198
17	24.2	4.0	80	207
18	25.6	2.9	86	201
19	26.7	3.8	84	198
20	28.1	1.5	80	211
21	29.1	3.6	74	213
22	33.5	2.2	80	210
23	34.2	2.2	74	202
24	40.3	6.4	69	215
25	43.1	6.8	78	233

[a] Smaller than an effective diameter of 2μ as determined by hydrometer analysis.

TABLE 5

SUMMARY OF MORTAR MIXING DATA AND DURABILITY STUDIES

Sand	Mortar Mixing Data			Durability Factors		Surface Condition Rating (lab tests)[d]
	Consistency (mm of pen.)[a]	Unit Wt[a] (gm/cu-cm)	Air Content (%)[a]	@ 300 Cycles (lab tests)[b]	@ 70 Cycles (natural exposure)[c]	
1	65.5	2.08	11.8	99.5	111.3	6
2	74.0	2.06	12.6	98.8	116.3	16
3	69.3	2.07	12.8	93.0	106.3	12
4	72.3	2.03	12.8	100.2	110.8	22
5	72.7	2.05	12.6	100.6	108.8	10
6	65.7	2.01	13.0	96.1	112.4	66
7	74.0	2.05	12.0	99.0	110.3	29
8	73.7	2.03	12.4	97.9	120.2	22
9	68.8	2.05	11.8	102.6	119.3	54
10	65.5	2.07	10.7	97.3	111.8	28
11	72.5	2.08	12.8	100.8	113.7	30
12	67.0	2.05	12.5	100.7	109.0	22
13	70.8	2.02	12.4	103.7	118.5	120
14	65.7	2.02	11.6	99.5	117.3	61
15	66.2	2.06	10.6	100.2	111.4	22
16	74.2	2.05	12.0	98.8	118.4	40
17	71.5	2.07	10.0	97.5	115.9	132
18	69.3	2.05	11.9	97.5	111.8	38
19	73.2	2.06	12.1	96.6	115.8	34
20	64.0	2.05	10.4	95.1	111.9	39
21	67.5	2.05	10.0	95.0	110.2	30
22	62.4	2.01	13.0	97.2	114.8	24
23	69.6	2.06	11.2	95.5	112.0	64
24	63.2	2.07	10.1	98.7	109.2	142
25	61.2	2.07	10.2	98.9	116.5	150

[a] Average of one determination on each of two batches mixed on different days.

[b] Average of values for six prisms, three from each of two batches.

[c] Estimated from daily max. and min. temperatures recorded at Albany Co. Airport, in accordance with the method outlined in reference (18).

[d] Number of "popouts" exceeding 1 mm in any dimension.

Note: Water-cement ratio, by weight, 0.42; cement-sand ratio, by volume, 1:2.75.

Eight 2- by 2- by 11-in. prisms were molded from each mortar, four from each of two batches mixed on different days. All prisms were cured for 14 days at 100 percent relative humidity and 73.4 ± 3 F. After curing, three prisms from each batch were subjected to rapid freezing in air and thawing in water at the approximate rate of 8 cycles per day. The relative performance of each prism was evaluated by the resonance frequency technique and durability factors were calculated after 300 cycles or at 60 percent relative dynamic modulus of elasticity, whichever occurred first (39). The fourth prism from each batch was resonated initially and then placed in an outdoor exposure area for long-term observation. Results of the freeze-thaw study are given in Table 5.

The mortars for the drying shrinkage study were also proportioned for a net water-cement ratio of 0.43 but with no artificial air entrainment. The fractional volume of sand was adjusted slightly from batch to batch to compensate for variations in the water requirement of the different aggregates and to produce a cone penetration of 67 to 71 mm. Mixing was in 0.25-cu-ft batches but otherwise followed the same procedures used for the freeze-thaw specimens. Three series of mortar were prepared, each consisting of one batch from each of the experimental sands. The mixing and molding of each series was completed before another was begun.

TABLE 6

SUMMARY OF MORTAR MIXING DATA AND LENGTH CHANGE MEASUREMENTS

	Mortar Mixing Data			Length Changes[b]	
Sand	Sand-Cement Ratio (by vol)	Consistency (mm of pen.)[a]	Unit Weight (gm/cu-cm)[a]	Expansion 27-Day Moist Cure (%)	Shrinkage 2 Months Drying (%)
1	2.68	70.0	2.25	0.009	0.0913
2	3.10	67.7	2.25	0.007	0.0847
3	2.80	69.0	2.24	0.010	0.0862
4	2.99	69.5	2.25	0.005	0.1089
5	2.98	67.7	2.24	0.008	0.0923
6	2.82	65.2	2.22	0.009	0.0961
7	3.07	68.7	2.25	0.004	0.1099
8	3.09	68.3	2.22	0.009	0.1057
9	2.90	69.5	2.21	0.008	0.1187
10	2.78	66.5	2.25	0.007	0.1239
11	2.95	69.7	2.26	0.009	0.0985
12	2.70	69.2	2.19	0.007	0.1152
13	2.83	69.2	2.22	0.007	0.1221
14	2.70	72.2	2.19	0.007	0.1180
15	2.75	67.7	2.23	0.011	0.1237
16	2.98	69.0	2.25	0.009	0.1118
17	2.81	70.2	2.23	0.009	0.1377
18	2.82	71.8	2.23	0.007	0.1141
19	3.06	67.0	2.25	0.007	0.1176
20	2.75	67.5	2.21	0.011	0.1239
21	2.82	68.8	2.25	0.007	0.1367
22	2.69	69.5	2.21	0.007	0.1238
23	3.05	68.0	2.26	0.007	0.1519
24	2.78	67.8	2.24	0.005	0.1812
25	2.61	69.0	2.21	0.008	0.1602

[a] Average of one determination on each of three batches mixed on different days.

[b] Average of values for nine prisms, three from each of three batches.

Note: Water-cement ratio, by weight, 0.43.

Six 3- by 4-in. high cylinders and three 1- by 1- by 11-in. prisms fitted with gage plugs were molded from each batch of mortar. Three each of the cylinders were tested for compressive and split cylinder tensile strength after 28 days of moist curing under the conditions previously described. The results of the strength tests were inconclusive and are, therefore, not included. The length of each 11-in. prism was measured when the molds were stripped after 24 hr of moist curing and again after 27 days of additional curing. They were then allowed to dry in the laboratory during which time periodic measurements were made of their length up to two months. During this time, the temperature in the area where the shrinkage specimens were stored was maintained at 73.4 ± 2 F but the relative humidity dropped from 50 percent at the beginning of the drying period to about 20 percent where it remained until testing was completed. Nevertheless, all mortars from the same series were subjected to nearly the same humidity conditioning because they were mixed within a relatively short period of time. This is confirmed by the near perfect correlation among the results from the three series of tests. The variation in relative humidity, therefore, is reflected principally by a high among-batch variance in shrinkage. Results of the shrinkage study are given in Table 6.

DURABILITY STUDIES

Any consideration of the influence of variations in fine aggregate, per se, on variations in the freeze-thaw durability of concrete or mortar must recognize, above all, the significance of aggregate particle size. The hydraulic pressure theory set forth by

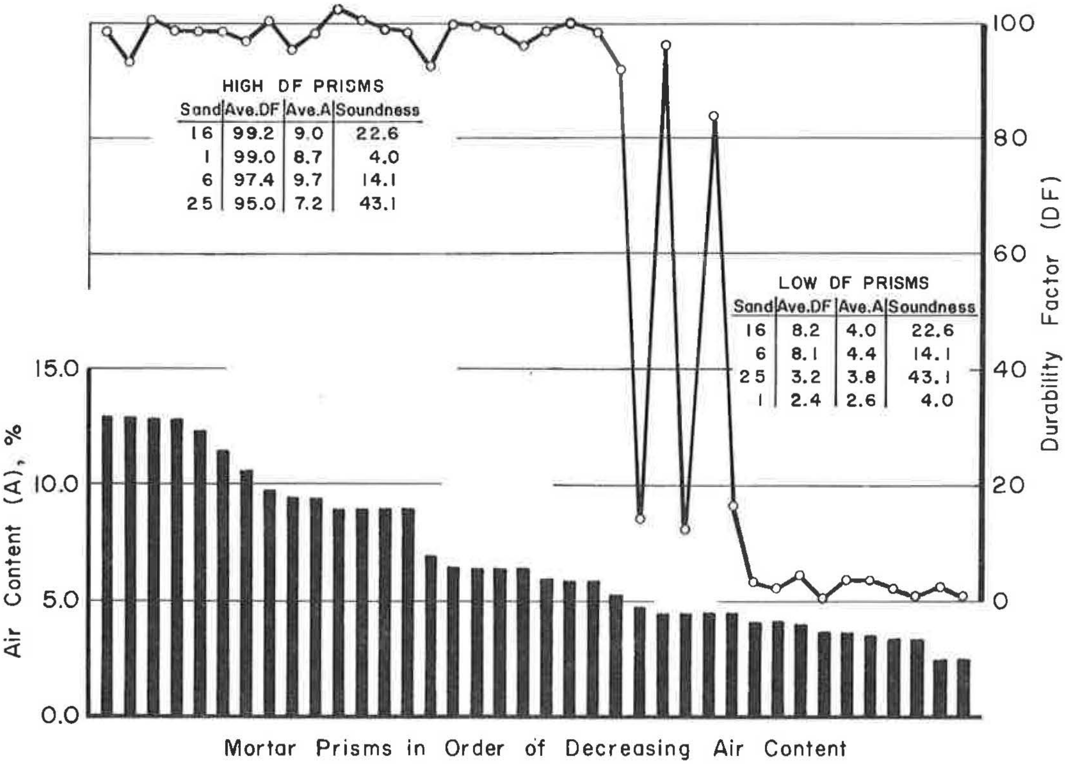
Powers (11) and expanded on by Verbeck and Landgren (19) explains the effect of the physical properties of aggregate on the frost resistance of concrete. The theory argues that the potential for disruption decreases with decreasing aggregate size when other factors remain unchanged.

In order for disruptive hydraulic pressure to develop in a saturated aggregate when water escapes from a zone of freezing, the particle must contain sufficiently long flow paths. Even with stone of high porosity and low permeability, critical sizes are on the order of 0.5 in. (19). It may be shown analytically that any mechanism causing a given percentage increase in the volume of an aggregate embedded in concrete will stress the surrounding paste in direct proportion to its own effective diameter. Likewise, if failure is to occur by expulsion of water into the surrounding paste, it is the size of the particle (i.e., volume-surface area ratio) that determines the critical parameter, volume of water expelled per unit surface area per unit time. Further, the small volume of water expelled by small particles is more readily accommodated by entrained air voids in the paste than the larger volumes expelled by larger particles.

The literature abounds with examples of the effect of particle size on the resistance to frost damage of saturated aggregates both unconfined and in concrete. These are reviewed by Schuster and McLaughlin (20). There are fewer, but equally convincing studies that demonstrate the innocuous character of fine aggregate, as such, in air-entrained concrete and mortar subject to freezing (7, 8).

Freeze-Thaw Tests of Mortar

Statistical analysis of durability factors obtained from the freeze-thaw studies of mortar prisms (Table 5) indicated that their performance was unrelated to the sand used in their preparation. All performed at an acceptably high level. The variation



HIGH DF PRISMS

Sand	Ave.DF	Ave.A	Soundness
16	99.2	9.0	22.6
1	99.0	8.7	4.0
6	97.4	9.7	14.1
25	95.0	7.2	43.1

LOW DF PRISMS

Sand	Ave.DF	Ave.A	Soundness
16	8.2	4.0	22.6
6	8.1	4.4	14.1
25	3.2	3.8	43.1
1	2.4	2.6	4.0

Figure 1. Results of supplemental freeze-thaw tests.

in average durability factor among the different mortars was of the same magnitude as the experimental error. These results are, therefore, consistent with the theoretical considerations and the experience of others, cited above.

The conditions of the freeze-thaw test were considerably more severe than what would normally be experienced under natural exposure. The freezing rate, the degree of aggregate and paste saturation, the proportion of sand in the mix, and the number of cycles administered were all excessive. It seems probable, therefore, that even sands of exceptionally low quality can be used in air-entrained concrete without causing deep-seated distress as a result of freezing and thawing. Where magnesium sulfate soundness is the frame of reference, exceptionally low quality would mean approximately 40 percent loss (Table 4).

Four of the experimental sands were mixed into mortar of the same proportions as before but with successively smaller doses of air-entraining agent. The durability factors for these mortars calculated after 300 cycles of freezing and thawing (Fig. 1) demonstrate that the durability of the mortar was not affected by the soundness of the sand even at low levels of air content.

Surface Condition Evaluation

The effect of aggregate on the appearance and surface smoothness of concrete is frequently of equal importance as its effect on deep-seated durability. Some distress resulting from unsound aggregate was noted on the surface of nearly all prisms after 300 cycles of freezing and thawing (Table 5). This appeared as either true popouts in which conical spalls of mortar were removed over affected particles or as simple failures of thin paste covers. Distress of this type was not restricted to any one particle size or size range but seemed to depend on a combination of size and proximity to the surface, with the smaller particles requiring greater proximity to the surface to cause disruption.

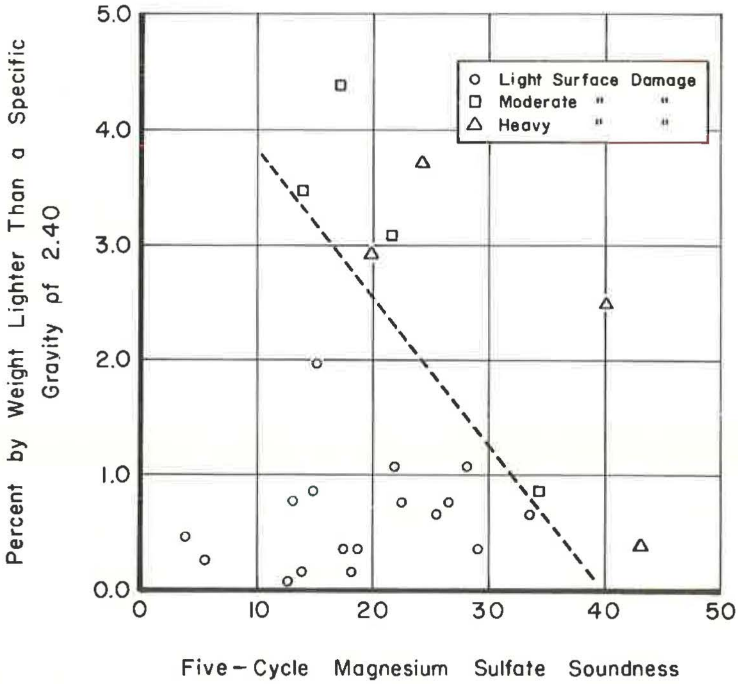


Figure 2. Relationship between sand soundness and proportion of lightweight particles.

TABLE 7

DELETERIOUS PARTICLES IDENTIFIED ON THE SURFACE OF MORTAR PRISMS

Rock Type	Estimated Frequency of Occurrence (%)	Mortars in Which Observed	Description
Shale	45	4, 6, 7, 13, 15, 16, 17, 20, 21, 22, 23, 25	Typically containing minor amounts of detrital quartz and carbonate; frequently porous and fractured; moderately to extensively weathered.
Siltstone	30	6, 9, 10, 13, 14, 15, 16, 17, 18, 20, 25	10-45% clay or hydromica typically finely dispersed but occasionally as discrete accumulations; smaller quantities of sand-sized quartz, feldspar and carbonate; usually weathered.
Dolomite	5	7, 8, 11, 19, 23, 24	Fine-grained; usually impure with some weathering of impurities; frequently porous and/or fractured.
Calcareous shale	5	24, 25	Typically weathered and porous.
Slate	5	24	Typically dense with slight weathering.
Chert	5	10, 17, 18, 20, 22	Typically impure (clay or hydromica and dolomite); weathered.
Sandstone	< 5	17, 22	Fine-grained, detrital quartz and feldspar in a weathered clay (or hydromica) or iron oxide matrix.
Limestone	< 5	18, 25	Impure, weathered and porous.
Hydrous iron oxide	< 5	1, 4	Intensely weathered and porous.
Hematite	< 5	9	Individual crystal; fresh.

It is difficult to evaluate the significance of distress of this type by scanning 528 sq in. of mortar surface distributed among six small beams. Even in the worst instances (i.e., with sands 13, 17, 24 and 25) damage was not nearly severe enough to result in even moderate attrition of the mortar surface, and it seems unlikely that its depth and areal extent would be sufficient to detract, say, from the riding quality of a concrete pavement.

Concerning appearance, again the significance of this type of distress was difficult to evaluate. The number of particle failures which, in the opinion of the observer, detracted from the appearance of the surface either because of their size or because of high color contrast with the cement paste was counted for each mortar. Ratings by

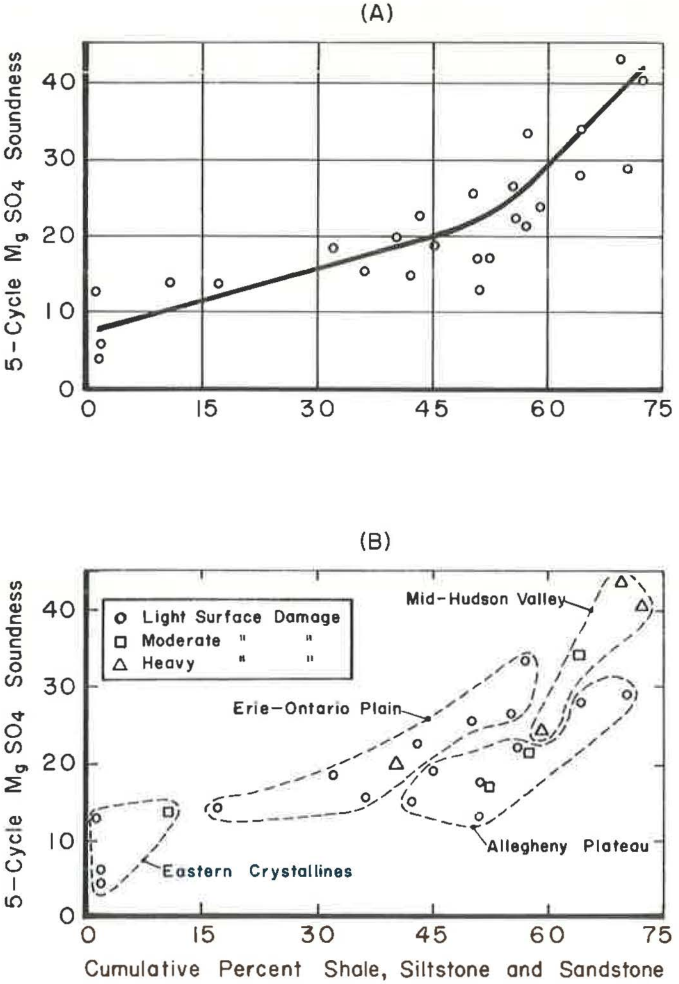


Figure 3. Relationship between sand soundness and its lithologic constituents.

this method correlated well with the surface condition ratings (Table 5). It is probable that the worst cases would detract in an application where appearance was particularly important.

Figure 2 shows the relationship among the surface condition rating of the mortar prisms and the magnesium sulfate soundness and specific gravity distribution of the sands. Mortars exhibiting relatively moderate (rating of 50-100) or heavy (rating of 100-150) surface damage contain sands with magnesium sulfate soundness greater than 34 percent loss or, more commonly, with more than 2.0 percent by weight of material lighter than a specific gravity of 2.40. These data illustrate the well-recognized fact that a gross test such as the one using sodium or magnesium sulfate will frequently not warn the user of the presence of small quantities of material of a deleterious nature.

All individual particles causing "popouts" that were judged to be visually offensive because of size or color contrast were examined in place under a binocular microscope. Representative grains were selected from those examined in each mortar for further examination in thin section under the petrographic microscope. The various materials so identified are described in Table 7 with an estimate of their relative frequency of occurrence. Two characteristics noted to be common to most of these particles were a relatively high content of clay or hydromica and substantial weathering, both of which would increase the propensity for porosity, softness, lack of strength and, thereby, the observed instability.

Although the magnesium sulfate soundness of the various sands was influenced strongly by the cumulative percent of shale, siltstone and sandstone that they contained (Fig. 3A), popouts on the surface of mortar prisms were associated with shale in about 45 percent of the cases, with siltstone in about 30 percent of the cases but only rarely with sandstone. It is reasonable to infer that this has resulted from the relative preponderance of clay normally found in these rocks. This observation also partially explains why the eight sands which caused the highest incidences of popouts on mortar surfaces were not always the ones with the highest losses in the soundness test. As might be expected, six of the eight were included among the seven sands having together the highest proportion of shale, siltstone and sandstone (greater than 40 percent) and the highest ratios of shale and siltstone to total shale, siltstone and sandstone (greater than 30 percent).

A regional grouping of these same data (Fig. 3B) suggests that although the generality regarding the influence of cumulative percent of shale, siltstone and sandstone on magnesium sulfate soundness may hold true, the exact functional relationship varies somewhat among regions having different geologic histories. This variation apparently results from differences in the character of the particles themselves from region to region as well as from the influence of other materials. The only inconsistency within these groupings is the point represented by the triangle in the zone occupied by sands from the Erie-Ontario Plain. This point represents a sand from the lower Hudson Valley near the Pennsylvania border.

Figure 3B shows that although sands from the Erie-Ontario Plain include about the same range of soundness as sands from the Allegheny Plateau, the former do not cause an appreciable frequency of popouts, whereas the latter, in some instances, do. Should further sampling and testing establish this trend as fact, the knowledge gained could be quite useful in judging acceptability (on the basis of sulfate soundness) in regions such as these where natural sands with low losses in the soundness test are rare.

Outdoor Exposure Tests

After one winter of exposure to natural weathering in which approximately 70 cycles of freezing and thawing were experienced, prisms similar to those used in the laboratory freeze-thaw test have experienced no loss in dynamic modulus of elasticity (Table 5) and no popouts. The lack of deep-seated deterioration is consistent with results of the laboratory freeze-thaw tests. The absence of surface deterioration undoubtedly reflects the less severe weathering conditions. Annual observation of these specimens will continue.

Field Performance Surveys

During the summer of 1963, reconnaissance-type surveys were conducted over 1,160 lane-miles of air-entrained concrete pavement and 264 structures incorporating fine aggregate from 37 different sources including 14 from which samples were taken for this study. The sources have produced sand with losses in the magnesium sulfate soundness test of up to about 25 percent. More than half of the concrete examined used sand with soundness losses in excess of 15 percent. The surveys included a detailed inspection of all structures. Pavements were examined while driving the shoulder between 10 and 20 mph with periodic stops for closer observation.

Most of the concrete was in excellent condition. No significant distress was observed that could be related to fine aggregate. Popouts or pits caused by the largest fine aggregate sizes or by smaller sizes where they were close to the surface were observed in some concrete, however, in no instance did they detract noticeably from the appearance of the concrete or from the riding quality of pavements or bridge decks. These field observations are consistent with the laboratory studies. No observations were made of concrete in an application where the effect of deleterious particles on appearance might be more obvious.

DRYING SHRINKAGE STUDIES

Portland cement paste, which in many respects functions essentially as a hydro-gel, adjusts its bulk volume to changes in the relative humidity of its atmosphere. These adjustments are most apparent when the paste dries from its initially saturated state after mixing and setting, but continue to occur whenever the paste is not in equilibrium with its environment. The unit linear shrinkage of portland cement concrete or mortar during this early period is commonly used as an index of moisture-volume stability. For most applications, high volume stability is a desirable attribute.

The drying shrinkage of concrete or mortar is affected by many factors, chief among which is the unit volume of water (21). The principal effect of aggregate is to provide a rigid internal structure and, thus, to restrain the shrinkage of the paste. It has been shown, however, that aggregates vary in their ability to provide this restraint (15, 21-24). Carlson (21) concluded that their relative compressibility is the most important property in this respect, a view which was later expressed by Pickett (25) in an equation relating shrinkage to the fractional volume and elastic constants of the aggregate.

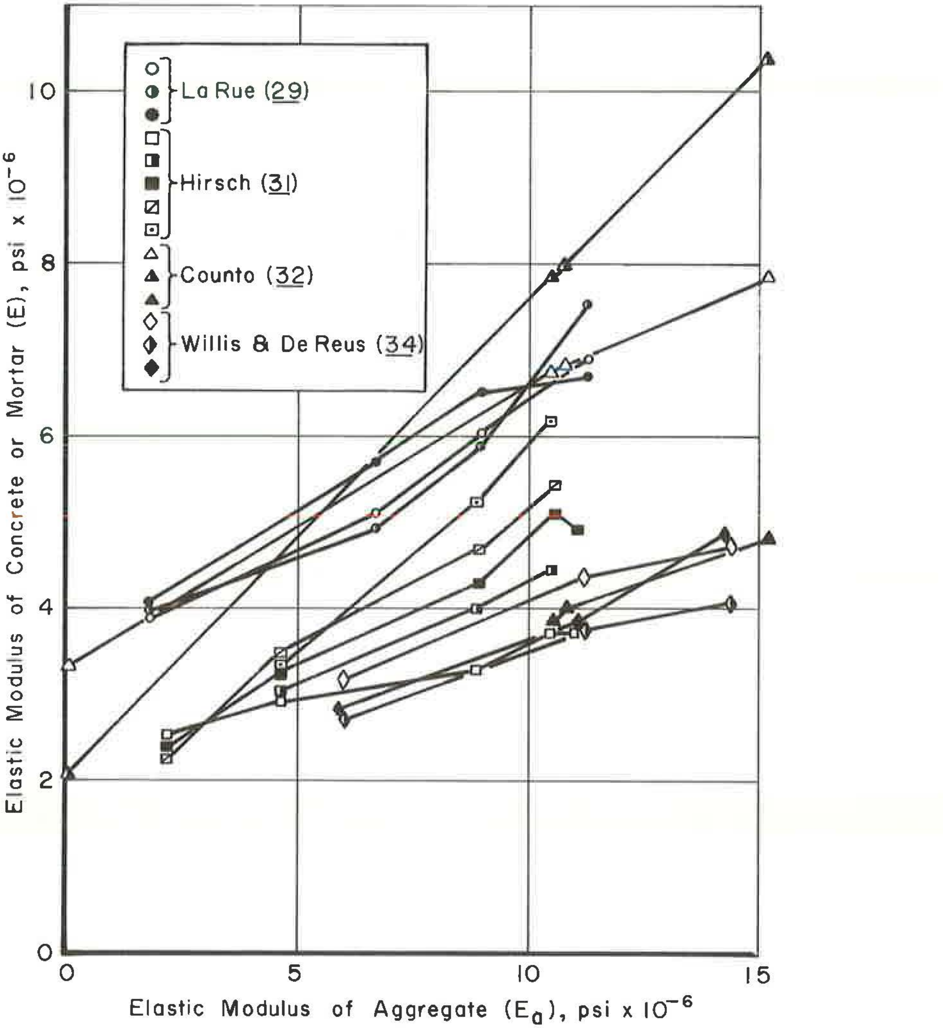


Figure 4. Effect of variations in elastic modulus of aggregate on variations in elastic modulus of concrete or mortar when E_m and V_a are constant.

Carlson also suggested that the moisture-volume stability of the aggregate itself is a significant factor. This point was demonstrated by Roper (15) and by Snowdon and Edward (22) in studies of shrinking aggregates and their effect on volume changes in concrete and mortar. Roper, Cox and Erlin (26) stated that ". . . the moisture-volume instability of the aggregate per se can be significantly more important than the effects of measured elasticity . . . ." This view was supported by Hansen and Nielsen (27) as a result of their extension of Pickett's theory to include, among other things, the effect of aggregate shrinkage.

Hveem and Tremper (12) have concluded that the presence of clay particles in concrete sand, as measured by the sand equivalent test, is a major contributing factor to shrinkage. The results of drying shrinkage tests of mortars made from 248 samples of commercially produced concrete sand yielded a correlation coefficient* of 0.66 when compared with corresponding measures of sand equivalent. Recognizing the influence of the elastic modulus of the aggregate and its partial dependence on porosity, Hveem and Tremper introduced absorption into their correlation and, thereby raised the coefficient to 0.86. Powers (28) speculated that clay particles associated with aggregate increase shrinkage because they function like cement gel instead of offering restraint, thereby decreasing the effective fractional volume of aggregate.

There is general agrement that aggregate size and gradation affect shrinkage only incidentally as they affect the volumetric proportions of the mix (21, 23, 27).

Effect of Elastic Moduli of Sands

The 25 natural sand fine aggregates studied were associated with varying degrees of mortar shrinkage. Some of the mortars shrank more than twice as much as others. As part of the effort to establish the significantly related aggregate properties, elastic moduli of the sands were estimated from the average initial dynamic elastic modulus (E_o) of the prisms used in the freeze-thaw test.

Various investigators (29-33) have proposed equations expressing the relationship among the elastic modulus of concrete or mortar (E), the elastic modulus (E_a) and fractional volume (V_a) of the aggregate, and the elastic modulus of the matrix (E_m), be it cement paste or mortar. The relationship between E and E_a has usually been expressed as a nonlinear function. However, when E_m and V_a are constant, as they were in the freeze-thaw prisms, the functional relationship between the two can, for practical purposes, be approximated by a straight line for the range of E_a normally encountered in concrete aggregate ($2 - 15 \times 10^6$ psi) without introducing any great error. This is illustrated in Figure 4 by data taken from the literature.

Accordingly, E_o of each freeze-thaw prism was corrected for the variations in air content (A) existing among the different mortars, and the average of the eight resulting values for each mortar was used as an estimate of the relative effective elastic modulus (REEM) of the corresponding sand (Table 8). The corrections were based on equations expressing the average relationship between E_o and A derived by the method of least squares from the same data used to calculate the values plotted in Figure 1. Figure 5 shows the derivation of the correction factor.

The high degree of correlation found between REEM and mortar shrinkage is best expressed empirically by a second degree polynomial (Fig. 6). This form is consistent with the nonlinear relationship between the two described by Hansen and Nielson (27). Thus, 83 percent of the variation observed in the drying shrinkage of mortar can be explained by variations among the elastic moduli of the sands. This value corresponds to a correlation coefficient of 0.91. (Strictly speaking, the correlation coefficient has no meaning for a nonlinear fit; it is used here for comparison with other data only.) When the small variations which occurred in the fractional volume of aggregate are taken into consideration, the coefficient of regression is virtually unaffected.

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*Coefficient of sample linear regression, unless otherwise noted.

TABLE 8

RELATIVE EFFECTIVE ELASTIC MODULI (REEM) OF EXPERIMENTAL SANDS

Sand	Average E_o (psi)[a]	Correction (psi)[b]	REEM (psi)
1	4.581×10^6	-0.099×10^6	4.482×10^6
2	4.562	-0.043	4.519
3	4.412	+0.083	4.495
4	4.036	+0.087	4.123
5	4.215	+0.057	4.272
6	4.180	+0.098	4.278
7	4.143	-0.004	4.139
8	4.185	+0.045	4.230
9	3.816	-0.057	3.759
10	4.080	-0.136	3.944
11	4.051	-0.056	3.995
12	4.043	+0.074	4.117
13	3.921	+0.041	3.962
14	3.723	-0.036	3.687
15	3.917	-0.139	3.778
16	4.068	-0.004	4.064
17	3.897	-0.209	3.688
18	3.975	-0.012	3.963
19	3.919	+0.012	3.931
20	3.974	-0.168	3.806
21	3.939	-0.209	3.730
22	3.874	+0.046	3.920
23	3.814	-0.083	3.731
24	3.678	-0.191	3.487
25	3.662	-0.181	3.481

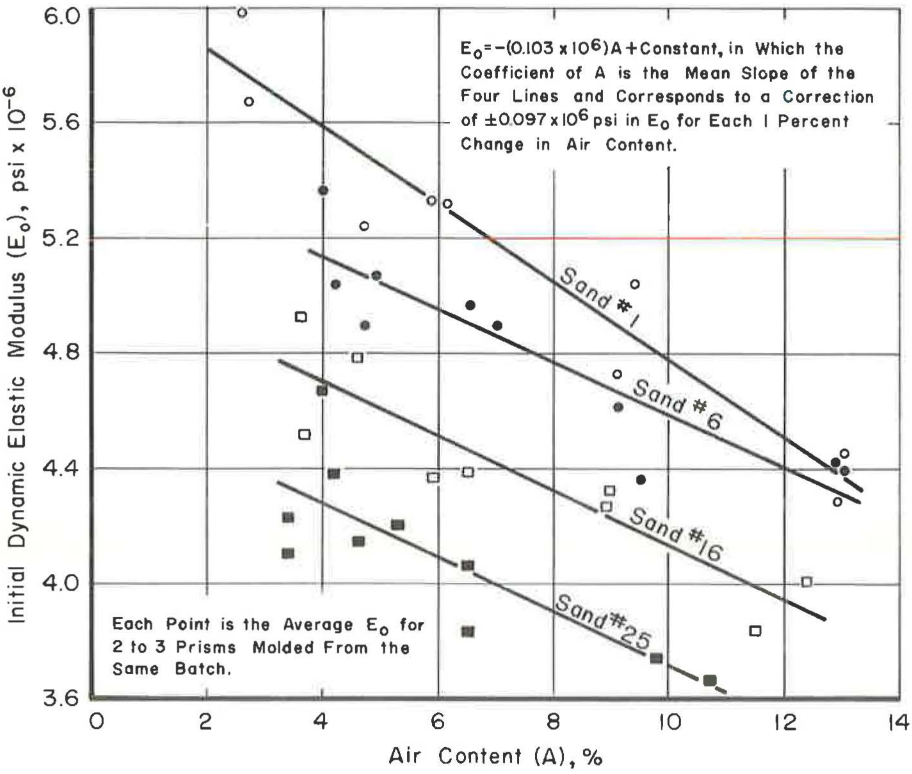
[a] Average of values for 8 prisms.

[b] All mortars adjusted to 12.0 percent air.

Effect of Clay

As already noted, other aggregate properties have also been identified with drying shrinkage, specifically, the moisture-volume characteristics of the aggregate themselves and the quantity and type of clay as indicated by the sand equivalent. Interestingly, sand equivalents of the experimental aggregates also correlate with drying shrinkage and to a rather high degree. A coefficient of 0.91 was obtained which is somewhat higher than that reported by Hveem and Tremper (12) for approximately the same range of sand equivalents.

Powers' speculative explanation (28) of the Hveem and Tremper data is a reasonable hypothesis. However, it hardly seems adequate to account for any but minor variations in the shrinkage observed in this investigation when it is recalled that each sand contained only 2 percent by weight of material passing the No. 200 mesh screen, that the proportion of this amount which was of clay size was small and did not vary



$E_o = -(0.103 \times 10^6)A + \text{Constant}$, in Which the Coefficient of A is the Mean Slope of the Four Lines and Corresponds to a Correction of $\pm 0.097 \times 10^6$ psi in E_o for Each 1 Percent Change in Air Content.

Each Point is the Average E_o for 2 to 3 Prisms Molded From the Same Batch.

Figure 5. Derivation of the correction factor for variations in air content.

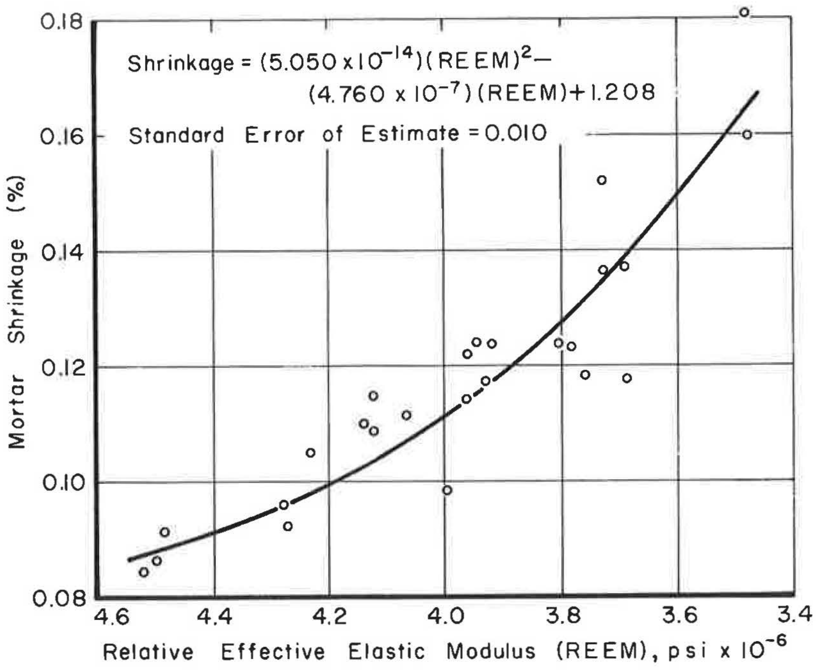


Figure 6. Effect of aggregate elasticity on mortar shrinkage.

TABLE 9

EFFECT OF MINUS NO. 200 PORTION ON MORTAR SHRINKAGE

Sand	Minus No. 200	Sand Equiv.	S at 56 Days (%)	Average S (%)
3	From Sand 3	94	0.077	
			0.080	
			0.079	
			0.081	0.079
3	From Sand 24	91	0.085	
			0.081	
			0.081	
			0.080	0.082
24	From Sand 24	69	0.161	
			0.160	
			0.163	
			0.162	0.162
24	From Sand 3	68	0.157	
			0.159	
			0.156	
			0.162	0.158

greatly (Table 4), and that the clay minerals identified by X-ray diffraction were nearly all of the same type, illites (Table 3).

The relative contribution of aggregate elasticity and clay content (as measured by sand equivalent) to the observed shrinkage cannot be distinguished by statistical methods alone. This is because the two factors correlate significantly with one another (coefficient of 0.80), that is, sands with low elastic moduli tend also to have low sand equivalents and both, therefore, would be expected to influence shrinkage in the same direction and in unison.

That the observed shrinkage of mortar specimens has been influenced to only a minor degree by variations in clay content is illustrated by the results of supplemental drying shrinkage tests in which sands 3 and 24 were prepared with their minus No. 200 portions interchanged. These sands are those which, respectively, produced the least and the greatest shrinkage and the highest and lowest sand equivalents. The results are given in Table 9.

The changes in shrinkage accompanying the switching of these fine sizes, if indeed they are significant at all, are in the proper direction and are of the same order of magnitude as might be expected from small adjustments in aggregate volume associated with the probable differences in clay content between the two sands (Table 4), as suggested by Powers (28). Accordingly, it may be concluded that the difference in drying shrinkage between mortars made with sands 3 and 24, and probably the observed variation in shrinkage among all of the mortars, has not been greatly affected by variations in the type or quantity of clay present in the minus No. 200 size fraction. This is in spite of a considerable variation in sand equivalent among the experimental aggregates.

Table 9 is of interest also because it shows that the sand equivalents of sands 3 and 24 were also virtually unaffected by the interchange of fines. A similar exchange between sands 3 and 25 and between sands 2 and 25, likewise, had no significant effect on sand equivalent. It appears, therefore, that while the observed variations in the sand equivalent of the experimental sands do reflect variations in shrinkage of the corresponding mortars, they do not represent significant variations in the type or amount of clay present in the sands at the time the mortars were mixed. Rather, they reflect some other characteristic of the sands which coincides to a high degree with elastic modulus.

A limited number of tests with sands 24 and 25 prepared without the minus No. 200 portion show that fines generated during the shaking portion of the sand equivalent test produce a value of sand equivalent that is only slightly greater than that produced when the minus No. 200 material is included, and that the sand equivalent is higher or lower than this value when the shaking action is continued for a fewer or a greater number of strokes (i.e., for 5 strokes and for 180 strokes). A similar experiment with sands 2 and 3 produced only a small variation in sand equivalent for the same variation in the number of strokes. These results suggest that the variation observed in sand equivalent for the experimental aggregates was caused principally by the tendency of the different aggregates to generate varying amounts of fines during the sand equivalent test and that this tendency generally increases as the elastic modulus of the sand decreases, thus, accounting for the high correlation observed between sand equivalent and drying shrinkage.

Effect of Aggregate Shrinkage

While no direct measurements were made of the moisture volume characteristics of the experimental sands, an indirect indication of this effect should be obtainable from the shrinkage data by using the equations of Hansen and Nielsen (27), and the estimates of REEM previously described. If the unrestrained linear shrinkage of the paste, S_p, the linear shrinkage of the aggregate, S_a, and E_a are known, the dimensionless parameter E_a/E_m can be calculated. If S_a/S_p is assumed to be zero, E_a/E_m thus determined, is an apparent relative elastic modulus reflecting the combined effect of both the elastic modulus and the shrinkage of the aggregate and, in fact, any other aggregate-related factor affecting shrinkage.

In connection with the mortar shrinkage tests, no measurements were made of the unrestrained shrinkage of the paste. Hansen and Nielsen (27) have shown that the shrinkage of cement mortar and concrete made with different quantities and types of high-quality aggregate is reasonably well accounted for by assuming $S_a/S_p = 0$ and $E_a/E_m = 10$. Their equations also show that as E_a/E_m exceeds 10, the additional restraint offered by aggregate particles diminishes rapidly. Accordingly, S_p was estimated by assuming a value of $E_a/E_m = 10$ for the mortar exhibiting the least shrinkage and the resulting value was used to calculate the parameter E_a/E_m for the remaining sands under the assumption that $S_a = 0$ for all sands.

In Figure 7, the resulting apparent relative elastic moduli, E_a/E_m, are plotted against REEM estimated previously from values of E_o. These parameters represent

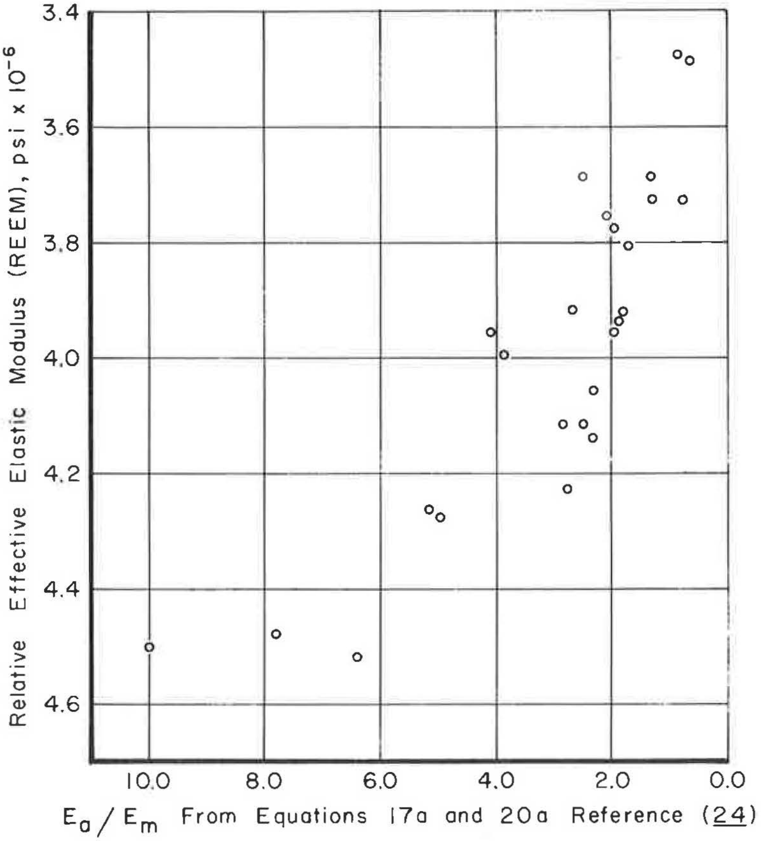


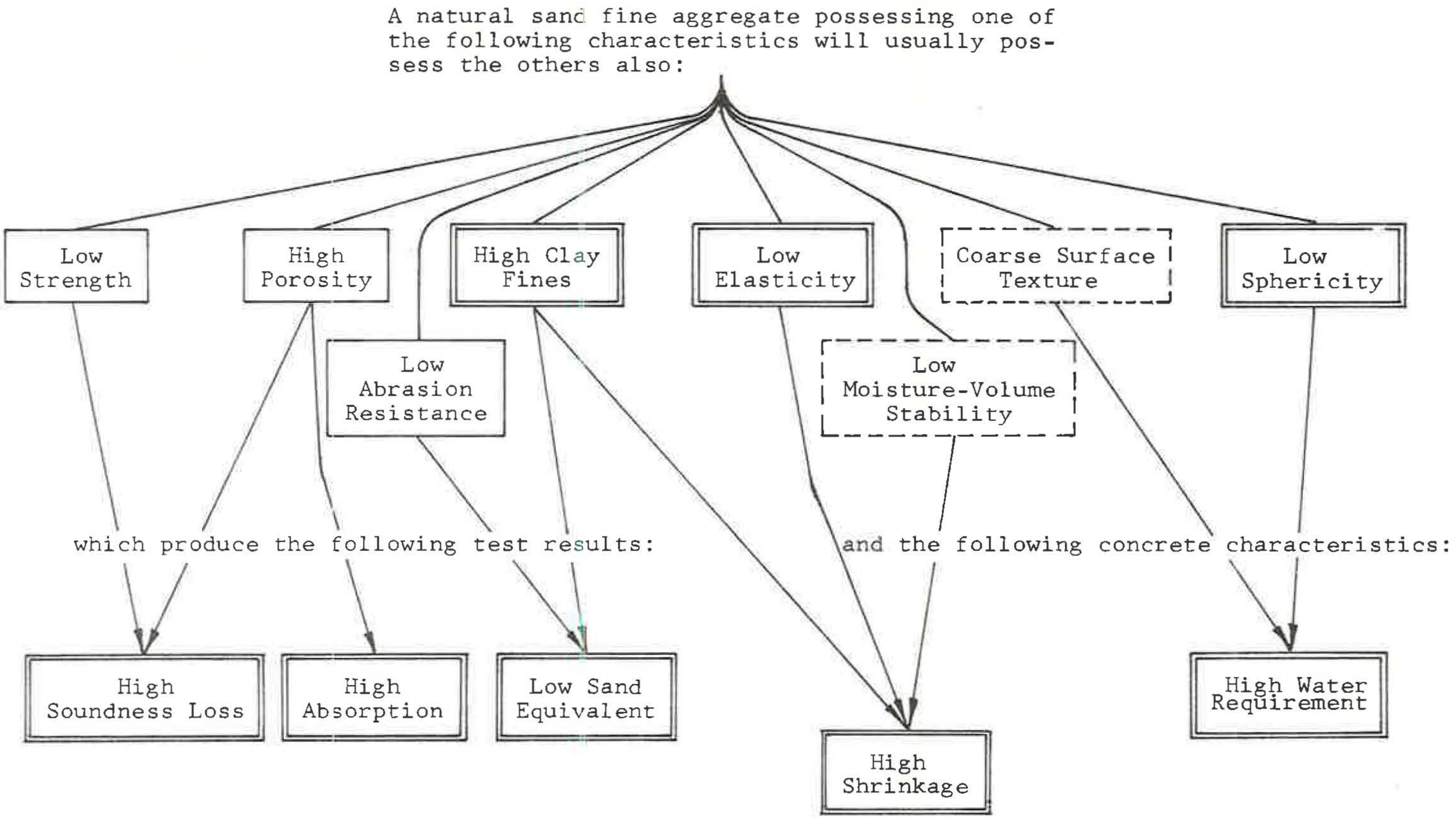
Figure 7. Relative effective elastic modulus (REEM) vs E_a/E_m.

two sets of independent estimates of the elastic moduli of the experimental sands, and in the absence of other aggregate-related factors affecting shrinkage, would be expected to be linearly related. The correlation between the two is only slightly less (coefficient of 0.84) than that obtained between REEM and mortar shrinkage itself which suggests that if shrinkage of the sands has been a significant contributory factor, variations in aggregate shrinkage have probably coincided in large measure with variations in elastic modulus. If E_a/E_m of the low shrinkage mortar is assumed to be less than 10, which it may be because of the low water-cement ratio paste, the linearity of the relationship is improved over that shown in Figure 7.

WATER REQUIREMENT

It has been shown (14, 35) that when concrete is proportioned to a predetermined fineness modulus of combined aggregate by adjusting the relative volumes of fine and coarse aggregate according to the fineness modulus of the sand (the fineness modulus method), the grading of the sand has no consistent effect on the water requirement of the mix. Under these conditions, water requirement is influenced largely by variations in most of the important concrete properties.

The variations in water requirement observed in this study are only partially predicted by the estimates of specific surface area and sphericity (correlation coefficients of 0.49 and 0.63, respectively). The introduction of roundness index improved the correlation with sphericity by only a small amount. Even allowing for substantial error in the estimates of surface area and sphericity, it would seem that variations in surface texture among the different sands exercise a considerable influence on variations in water requirement, probably equal to that of particle shape.



Double-line box indicates properties measured in this study.
Dashed-line box indicates properties for which inclusion in the generality is quite speculative.

Figure 8. Interrelationship among measured factors.

INTERRELATIONSHIP AMONG VARIOUS FINE AGGREGATE CHARACTERISTICS

The high degree of mutual correlation among sand equivalent, REEM and mortar shrinkage has already been noted. If the experimental sands are arranged in order of increasing elastic moduli, they are also arranged in approximate order of increasing sand equivalent and decreasing mortar shrinkage. Many of the other measured characteristics of the experimental sands and their corresponding mortars also produce nearly this same array. This observation led to the generality stated in Figure 8, the validity of which, for the experimental sands, is supported by the following coefficients of linear correlation with magnesium sulfate salt soundness:

Percent clay-sized material in minus No. 200	0.59
Elastic modulus of sand	0.85
Sphericity	0.74
Flatness	0.66
Elongation	0.59
Absorption	0.82
Sand equivalent	0.82
Mortar shrinkage	0.92
Water requirement (mortar penetration)	0.78

The foregoing discussion leads immediately to at least one significant conclusion. Results of the magnesium sulfate soundness test are a meaningful index to the relative quality of these particular experimental sands. This is not because the test simulates the growth of ice crystals in aggregate pores (which is not the proper mechanism anyway) or, in fact, has anything to do with freezing at all, but because it is a degradation test which empirically correlates to a high degree with two significant properties of the aggregate—modulus of elasticity and water requirement. Apparently, rock materials which abrade to flat and elongated particles with rough surfaces usually have low elastic moduli, and, by virtue of a high porosity and low strength, break down readily in the salt soundness test.

A sand with a high loss in the sulfate soundness test may contribute to low volume stability in concrete or mortar because of the combined effect of a lower elastic modulus, higher water requirement, more clay in the fine size range, and possibly lower moisture volume stability than a sand with a lower loss in the test (Fig. 8).

Criticism which has properly been leveled against the sulfate soundness test, on theoretical grounds (19, 36), derives from the fact that the test does not measure or reflect those physical characteristics of aggregates involved in the mechanisms of freezing in concrete. That these mechanisms do not completely apply to fine aggregates because of their small particle size partially nullifies this criticism for these materials.

CONCLUSIONS AND PRACTICAL IMPLICATIONS

The more important conclusions arising from the study of New York natural sand fine aggregates are the following.

1. Extreme variations in the quality of fine aggregate, per se, have an undetectable influence on variations in the freeze-thaw durability of air-entrained concrete or mortar. Where five-cycle magnesium sulfate soundness is the frame of reference, "extreme" includes sands with losses of approximately 40 percent.
2. Different fine aggregates cause varying numbers of popouts on the surface of air-entrained mortar prisms subjected to laboratory freezing and thawing, the worst of which probably detract from the appearance of concrete in some applications. This form of distress was consistently associated with sands having a magnesium sulfate soundness in excess of 34 percent and/or with more than 2.0 percent by weight of material lighter than a specific gravity of 2.40.
3. Most deleterious particles identified on the suface of mortar prisms contained a high proportion of clay or hydromica and were substantially weathered. Seventy-five percent of them were either shale or siltstone.

4. Variations in the drying shrinkage of mortars coincided to a high degree with variations in the effective elastic moduli of the experimental sands.

5. Variations in the clay content of the experimental sands had only a very minor effect on mortar shrinkage in spite of a large variation in their sand equivalent. The sand equivalent test was found to measure, primarily, the tendency of the different sands to generate varying amounts of fines during the sand equivalent test itself. This tendency appears to coincide with a decrease in effective elastic modulus, thus accounting for the high correlation between sand equivalent and mortar shrinkage.

6. The magnesium sulfate soundness of the experimental sands correlates to a high degree with many of the other measured aggregate and mortar factors. In order of decreasing correlation, they are mortar shrinkage, sand elasticity, absorption, sand equivalent, water requirement, sphericity, and percent clay-sized material in the minus No. 200 portion. It probably also correlates well with the abrasion resistance of the sand.

There are several practical implications of these conclusions.

1. Results of the magnesium sulfate soundness test correlate well with several significant properties of some natural sand fine aggregates: modulus of elasticity and water requirement. In geographic regions where these correlations exist, results of the test provide a meaningful index of relative quality.

2. Results of the magnesium sulfate soundness test bear little or no relationship to the effect of fine aggregate, itself, on the frost resistance of concrete. This is because variations in fine aggregates, themselves, have little effect in this respect. Paragraph 5(c) of ASTM Designation: C 33, "Standard Specifications for Concrete Aggregates," which allows acceptance of a fine aggregate which fails the salt soundness test if it gives satisfactory results in concrete subject to freezing and thawing tests, may be misleading because it seeks an effect which probably does not exist (lack of freeze-thaw durability) and overlooks one that may (lowered volume stability with changes in moisture content).

3. A fine aggregate acceptance test based on the resonance frequency of a standard mortar prism expressed as a percent of the resonance frequency of a similar mortar prism mixed to the same volumetric proportions with the same cement but with a standard sand (graded Ottawa, perhaps), would provide a more direct method of testing for the significant property of elastic modulus and may be less time-consuming than the sulfate soundness test.

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