The Concept of Hardness As Applied to Mineral Aggregates

J. E. GRAY, Engineering Director, and
F. A. RENNINGER, Geologist, National Crushed Stone Association

A historical review is given of the soft particle requirements in specifications showing, with the development of the scratch hardness test, a broadening of the application of the test without sufficient supporting data to indicate that the test measures a property which actually affects performance. Originally softness was used to indicate the presence of unsound material which caused pop-outs in concrete. Softness as measured by the scratch hardness test is considered to be a measure of deleterious material in aggregate and is a specification requirement without association to any other property and without sufficient information to show that softness, per se, is in fact a deleterious property of aggregate. Data are presented that relate the scratch hardness test in terms of Mohs hardness scale which indicates that both procedures may classify minerals but not rocks of variable mineral composition. Finally, data are presented which demonstrate that aggregate which fails the scratch hardness test may make strong, sound, durable concrete. In light of the philosophy of materials testing, the historical review, and the test data submitted, it is suggested that the present concept of aggregate hardness be reconsidered and re-evaluated.

•A DICTIONARY might define the word hardness as "the state of being hard" or "the state of being firm or unyielding." That same dictionary, if it were scientifically oriented, might go even further and define hardness as "that quality of a mineral which resists scratching." Both definitions, that of being firm or unyielding and that of scratchability, relate to the concept of hardness as it is currently applied to mineral aggregates. When consideration is given to the hardness of an aggregate, one generally thinks in terms of (a) its resistance to abrasion as measured by the Los Angeles test (ASTM Designation C 131) or (b) the amount of soft or scratchable material present as determined by the scratch hardness test (ASTM Designation C 235). It is this second characteristic, that of aggregate softness or scratchability as a measure of quality, that is the basis for this report.

A soft particle limitation may be found in most concrete aggregate specifications, many of which are modeled after the ASTM C 33 specification which includes, as a quality requirement, the provision that not more than 5 percent of the coarse aggregate particles may be soft as determined following the procedure outlined in C 235, which is the determination of whether a piece of aggregate can or cannot be scratched by a brass rod. This discussion will be confined specifically to the ASTM scratch hardness test as a measure of quality and as an index of performance of aggregate in portland cement concrete.

Paper sponsored by Committee on Mineral Aggregates and presented at the 46th Annual Meeting.

HISTORY OF THE SOFT PARTICLE REQUIREMENT

The ASTM specification for concrete aggregates (Designation C 33) was first released in 1921 (1, 2). That portion relating to the coarse aggregate requirements was rather general, specifying little more than a suggested grading. With the expanding use of portland cement concrete and in recognition of the deleterious behavior observed in concretes containing certain constituents of natural aggregate deposits, it was soon realized that such a general, open type specification was of little real value. Soft, weathered chert particles, poorly bonded sandstone fragments, agglomerations of clay, shale, ochre, weathered schist, particles of coal, etc., had performed poorly as coarse aggregate particles in concrete. These fragments had one characteristic in common: they were all "soft" by comparison with the sound, durable particles comprising the majority of the deposit. By association, then, particle softness or hardness became connected with aggregate quality. The need to limit the tolerable amount of these deleteriously soft materials and to develop a test with which they might readily be recognized was felt desirable.

Douglass Test

In 1928, a provision limiting the soft particle content of coarse aggregate was placed in the ASTM concrete aggregate specification. At the same time a test with which to identify and measure these soft particles was proposed. A Method of Test for Determination of Soft Pieces in Gravel, commonly known as the Douglass test, was a simple compression test in which individual particles were subjected to a 75-lb load. Particles which yielded under this load were considered soft. The Douglass test, however, was not adopted by ASTM although the 5 percent limitation on soft pieces was placed in C 33.

The 1930 version of C 33 cited, as the method for soft particle determination, the Douglass test as adopted by AASHO. The 1936 revision cited this same test as then identified as AASHO Designation T-8. The Douglass test last appeared as an AASHO method in their 1938 printing. In 1940 action was taken to delete T-8 and the procedure was not published in the 1942 edition of the AASHO test methods. The 1949 version of C 33 contained the same five percent limitation on soft pieces, but referenced no method by which to make the determination. It was during this same period that research work relative to soft particle determination was conducted by the Bureau of Public Roads (then the Public Roads Administration). In 1941, Subcommittee IX of ASTM C-9 on Concrete and Concrete Aggregates had requested such an investigation. The results of BPR's investigations were reported by Woolf (3) in 1947. It was this work which ultimately led to the standardization of the current ASTM scratch hardness test (Designation C 235), first adopted by the society in 1949.

The 1952 revision of C 33 corrected the deficiency present in the 1949 version by again providing a method by which to determine the soft particle content. The correction approved was simply to reference the scratch hardness test; the 5 percent limitation on soft pieces was left unchanged. Since 1952 the status of C 33 with respect to the scratch test has remained unchanged, the test has gained wide usage, and softness, per se, as determined by the scratch test, has become firmly entrenched as being a deleterious quality. Even though the AASHO specification for concrete aggregate, M 80, does not explicitly refer to the scratch hardness test, it does have a recommended limit of 2 percent and a maximum limit of 5 percent on soft fragments and the only AASHO method of test for soft particles is T 189 (ASTM C 235).

From the above, it is apparent that since the inception of the soft particle limitation in 1928, the significance or interpretation of that limitation has undergone a gradual metamorphosis. The net result of these changes has been to apply the 1928 "consensus" limitations under a dramatically different and drastically enlarged set of circumstances—different with reference to the strict enforcement and literal compliance of specification provisions currently advocated and enlarged with the present interpretation of softness, per se, as a deleterious characteristic of aggregates in general. The changes offered and enacted through the years have also been made without sound research data supporting the validity of a general overall soft particle limitation, and the applicability of the various soft particle tests employed. The 5 percent limitation established in 1928

TABLE 1

ROSIWAL EQUIVALENT FOR MOHS SCALE MINERALS

Mineral	Mohs Value	Rosiwal Value[a]
Talc	1	0.04
Gypsum	2	2.0
Calcite	3	5.6
Fluorite	4	6.4
Apatite	5	8.0
Orthoclase	6	50.2
Quartz	7	175.0
Topaz	8	194.0
Corundum	9	1,000.0
Diamond	10	140,000.0

[a]Abrasive loss with corundum numbering 1,000.0.

was to be enforced by the Douglass test, designed and developed to detect softness in gravel aggregates. No mention of its applicability to other materials was cited. Woolf's data (3) relative to the development of the scratch hardness test were also limited to gravel aggregates and also gave no indication as to applicability to other materials. Woolf did point out, however, that the scratch test was more selective than the Douglass test, that is, the scratch test gave results greater by a factor of two or more. The 5 percent limitation originally based on the Douglass test remained unchanged, however, with the adoption of the scratch hardness test.

Scratch Hardness vs Mohs Hardness

The rather arbitrary Mohs scale, in which hardness values are assigned with respect to the ease or difficulty with which a given substance may be scratched by a set of certain scale minerals, has proven extremely satisfactory in the science of mineralogy. It performs admirably when uniform substances, pure crystals, materials composed of a single mineral, or in essence, materials having a uniform hardness characteristic, are subjected to test. Geologists are reluctant to apply the Mohs hardness scale to rocks due to their heterogeneous mineral composition, yet it has been felt by certain materials engineers that a modification of this same test (i.e., using as the scratching medium a certain size and type brass rod) is universally applicable to all aggregate materials.

Hardness, or conversely softness, has not been satisfactorily defined as there are a number of different physical concepts associated with the term. Compressive hardness, impact hardness, abrasive hardness, and indentation hardness are the major measures of hardness applicable to materials. Each measures hardness from a different point of view depending upon the nature of the stress applied and each might be expected to evaluate the "relative hardness" of a group of materials in a somewhat different order.

The indentation type hardness tests most generally find applicability in the field of metallurgy although values may be found for certain of the common rock forming minerals.

There have been many test methods and many sclerometers described over the years as being applicable to the measurement of "soft pieces" in aggregates. Several impact tests have been proposed. Woolf (3) described one that was AASHO Standard T-6 but never an ASTM method. The Douglass test measured compressive hardness. The present scratch hardness test may be considered a particularly arbitrary measure of abrasive hardness.

The Mohs scale of scratch hardness (the concept on which the scratch hardness test is based) was developed in 1812 as a simple guide to aid in the identification of minerals. The scale chosen was a qualitative measure of abrasive hardness intended solely to relatively evaluate the normal rock forming minerals. This simple scale of 1 to 10 takes on a very different aspect, however, when abrasive hardness is determined quantitatively by the method outlined by Rosiwal (data obtained through private correspondence with Dr. Ralf Villwock, Wiesbaden, Germany). Table 1 gives the quantitative Rosiwal equivalent for each of the Mohs scale minerals.

Since approximately 70 percent of the 780,000,000 tons of crushed stone produced in this country in 1965 is in the 3 to 4 Mohs hardness range; since the quantitative range in abrasive hardness between calcite (Mohs 3) and fluorite (Mohs 4) is the least of the entire hardness scale; and since the "relative hardness" of brass varies appreciably, the scratch hardness test would appear to be without any established reliability or precision. Consequently, its general acceptance can only lead to trouble for the industry as it is applied by way of a specification item. The main point of this discussion is that no difficulty is encountered with established methods of test in separating very good from very bad materials, but that it is always difficult to separate borderline materials. The above is true of the present scratch hardness method, but by the very nature of the test a tremendous "borderline" category, based on an arbitrary characteristic and including the majority of the crushed stone produced, is created. Strict enforcement of its provisions can only result in many ill-founded arbitrary decisions.

PHILOSOPHY OF MATERIALS TESTING

Indeed the entire philosophy behind the soft particle tests and the specification limitation is open to question in light of an article by Plum et al (4) published recently in the Rilem Bulletin. Plum and his co-workers in reviewing the basic philosophy underlying the science of materials testing state:

> The object of testing materials is to obtain a prediction of its serviceability. If an indication of the performance in service can be expressed quantitatively, comparison has been made possible and the information can be used as a basis for choice between alternatives. The testing of materials is, therefore, connected with the definition of serviceability, or the requirements to the performance on the one hand and with the criteria for making the choice, or the economic consequences on the other.

The development and adoption of the present soft particle limitation and its associated scratch hardness test without the benefit of supporting data appears to be in conflict with this basic philosophy. The literature search for making the historical review did not uncover a single attempt to correlate the scratch hardness test with performance of aggregate.

RESEARCH STUDIES OF SCRATCH HARDNESS TEST

In the past the soft particle test and limitation have taken on the guise of a "sleeper clause" in specifications, seldom enforced. However, the present trend toward rigorous specification enforcement and contract compliance from the legal standpoint is heralding the day of strict enforcement of both this test and its compliance requirements. As an example of just such an instance, a commercially quarried serpentine aggregate has recently been rejected for noncompliance with the scratch hardness requirements despite the fact that the stone meets all other physical and chemical requirements and has a long-standing satisfactory service record.

A rather comprehensive laboratory investigation was made on the physical characteristics and the concrete making properties of this rock. The results of this study were most revealing.

Description of Testing Program

The quarry was examined, ledge samples chosen, and separated in the field into "hard" and "soft" fractions using a brass rod mounted as a pencil meeting the requirements of the scratch hardness test. On being returned to the laboratory, the two fractions (hard and soft) of ledge rock were re-examined, using the standard scratch hardness device, and re-classified. Any doubtful pieces which could not readily be termed hard or soft on the basis of the scratch test were not used in further analysis. This laboratory selection procedure was followed by two individuals independently, its purpose being simply to insure that the separation into hard and soft was the best that could be expected. Each sample was crushed to 2-in. maximum size aggregate in a laboratory jaw crusher and tested again, this time in strict accordance with the scratch hardness test. The test was performed on the same samples by different individuals. The results, shown in Tables 2 and 3, demonstrate the variability of the test. That portion classified as soft in the field had 64 percent soft when tested in the laboratory. This 64 percent when crushed and re-tested had 65 percent soft. Likewise, the portion classified as hard in the field had 70 percent hard when tested in the laboratory. This 70 percent, when crushed and re-tested, had 92 percent hard.

TABLE 2

SUMMARY OF SCRATCH HARDNESS TEST RESULTS[a]
(No. 6823—Soft Sample)

Part A. Selection, by Geologist, of "Soft" Rocks in the Field
Total weight—1503 lb

Part B. Examination and Classification of Field Sample in the Laboratory
Soft—956 lb (64 percent of original)
Hard—547 lb (36 percent of original)

Part C. Results of Scratch Hardness Test Performed on Crushed Aggregate Prepared From That Identified as Soft in Part B Above

Operator	Percent by Weight Soft Pieces				
	2-1½ In.	1½-1 In.	1-¾ In.	¾-½ In.	½-⅜ In.
A	63	52	47	61	55
B	60	78	77	82	83
C	60	65	66	80	75
Average	61	65	63	74	71

[a]Method of Test—ASTM Designation C 235.

The same samples subjected to the scratch hardness procedure were also subjected to the Mohs test. The last separations into hard and soft fractions made on the laboratory prepared samples were left intact and each fraction of each size of each sample was tested to determine its range in Mohs hardness. The results obtained are given in Tables 4 and 5. Representative results are shown in Figure 1.

The $^{1}/_{16}$-in. diameter brass rod specified for use in the ASTM scratch hardness test is described as being capable of scratching a Lincoln penny but unable to scratch a Jefferson nickel. Translated into the Mohs scale of index minerals, it should then be capable of scratching the mineral calcite but not the mineral fluorite. In effect, then, the brass rod might be described as having a Mohs hardness between 3 and 4. According to the present test method, those materials which are scratched or have fragments dislodged by the brass rod are considered soft and hence unsatisfactory for use as concrete aggregates. As has been indicated, the rock tested was a serpentine, that is, a rock composed essentially of the serpentine minerals. It was, therefore, somewhat easier to apply the Mohs and scratch hardness tests to these samples than it would be to a granite or some other rock with a more heterogeneous mineral composition.

The serpentine minerals are described as having a Mohs hardness varying from 2 to 5 depending on type. The massive serpentines, generally, fall above 3 on this hardness scale. Tables 4 and 5 and Figures 1 through 3 indicate that the samples all

TABLE 3

SUMMARY OF SCRATCH HARDNESS TEST RESULTS[a]
(No. 6824—Hard Samples)

Part A. Selection, by Geologist, of "Hard" Rocks in the Field
Total weight—1385 lb

Part B. Examination and Classification of Field Sample in the Laboratory
Soft—423 lb (30 percent of original)
Hard—962 lb (70 percent of original)

Part C. Results of Scratch Hardness Test Performed on Crushed Aggregate Prepared From That Identified as Hard in Part B Above

Operator	Percent by Weight of Soft Pieces				
	2-1½ In.	1½-1 In.	1-¾ In.	¾-½ In.	½-⅜ In.
A	2	5	6	4	7
B	15	10	5	10	17
Average	8	8	6	7	12

[a]Method of Test—ASTM Designation C 235.

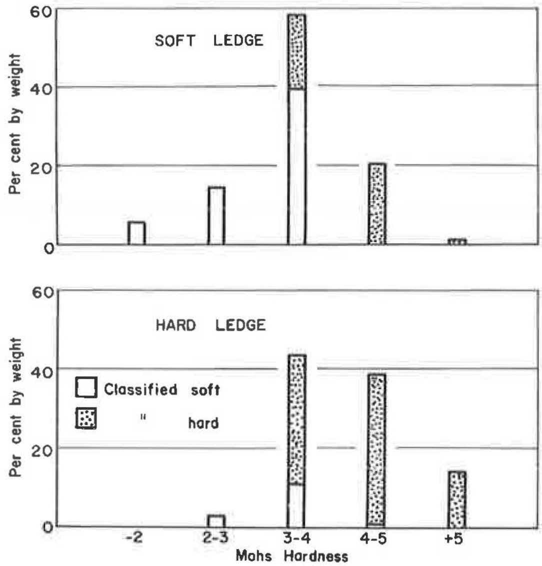

Figure 1. Mohs hardness vs scratch hardness (+1½ inch sieve size).

fell within this 2 to 5 range and are concentrated in the 3 to 4 hardness group. Taken as a whole, the only difference between the hard and soft samples was the amount of material having a hardness of 4 or more or 3 or less, respectively. In other words, the tails of the skewed distribution histograms were simply reversed from one sample to another (Figs. 2 and 3).

In each instance the brass rod classified a portion of that material in the 3 to 4 Mohs hardness range as hard and a portion as soft. Apparently the separation of this hardness group is largely arbitrary and extremely difficult to make. This would account for the rather significant differences noted between operators conducting the scratch test on the same samples (Tables 2 and 3). There is, apparently, little difficulty in classifying, with the brass rod, that material having a Mohs

TABLE 4

MOHS HARDNESS CLASSIFICATION
(No. 6823—Soft Sample)

Mohs Hardness	-2	2-3	3-4	4-5	+5
	Percent by Weight				
Sieve Size					
+1½ in.	5.5	14.7	58.4	20.4	1.0
1½-1 in.	1.3	8.3	64.4	17.8	8.2
1-¾ in.	3.5	10.9	73.9	6.5	5.2
¾-½ in.	1.7	30.2	53.6	7.6	6.9
½-⅜ in.	2.2	42.9	44.0	8.4	2.5
Arithmetic Avg.	2.8	21.4	58.9	12.1	4.8

NOTE: The brass rod in the NCSA scratch hardness apparatus has a Mohs hardness between 3 and 4. This range coincides with that of a majority of the sample, making separation extremely difficult and largely arbitrary. This is evidenced by the appreciable overlap of the brass rod classified hard and soft fractions in the Mohs hardness range of 3 to 4 (see Fig. 1).

TABLE 5

MOHS HARDNESS CLASSIFICATION
(No. 6824—Hard Sample)

Mohs Hardness	-2	2-3	3-4	4-5	+5
	Percent by Weight				
Sieve Size					
+1½ in.	0.0	3.0	43.9	39.0	14.1
1½-1 in.	0.0	2.5	53.3	38.4	5.8
1-¾ in.	0.0	0.9	55.4	41.6	2.1
¾-½ in.	0.0	0.0	69.9	18.7	11.4
½-⅜ in.	0.0	4.2	60.2	20.3	15.3
Arithmetic Avg.	0.0	2.1	56.5	31.6	9.8

NOTE: The brass rod in the NCSA scratch hardness apparatus has a Mohs hardness between 3 and 4. This range coincides with that of a majority of the sample, making separation extremely difficult and largely arbitrary. This is evidenced by the appreciable overlap of the brass rod classified hard and soft fractions in the Mohs hardness range of 3 to 4 (see Fig. 1).

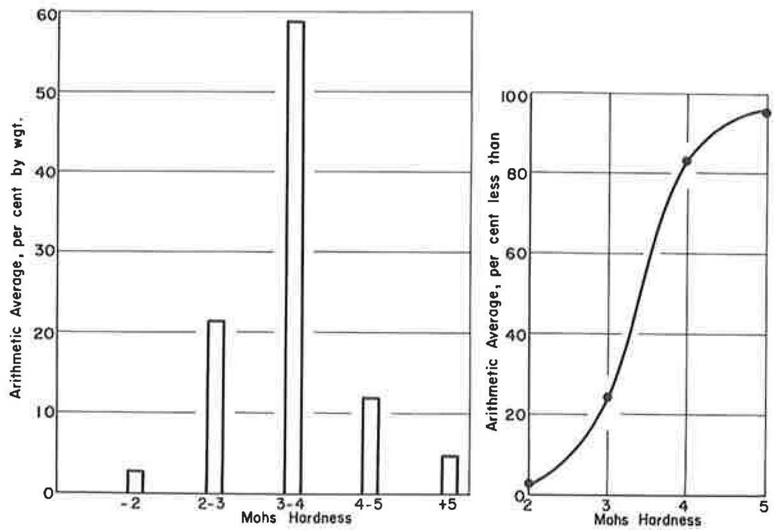

Figure 2. Mohs hardness distribution (No. 6823—soft ledge).

hardness of less than 3 or greater than 4, that is, in the separation of obviously soft from obviously hard. This statement gains support when Woolf's (3) data are re-examined. He synthesized samples by mixing a quartz gravel (Mohs hardness of 7) with obviously soft material and experienced no difficulty in making a rather precise separation with the scratch hardness test. The separation difficulty arises with the 3 to 4 hardness group, a range quite common to the majority of crushed stone aggregates, and the range which comprised roughly 60 percent of the materials involved in this investigation. Pursuing this line of reasoning, an individual working with the brass rod and the soft sample might classify anywhere from 24.2 to 83.1 percent of the sample as soft. Likewise, with the hard sample it might be reasonable to expect a classification of soft particles to fall within a range from 2.1 to 58.6 percent (Tables 4 and 5). If, therefore, a sample were chosen at random from the commercially produced aggregate, one might expect a soft particle classification anywhere from 2.1 to 83.1 percent. Although it is true that some of the variation might, in fact, reflect a true difference, the greatest

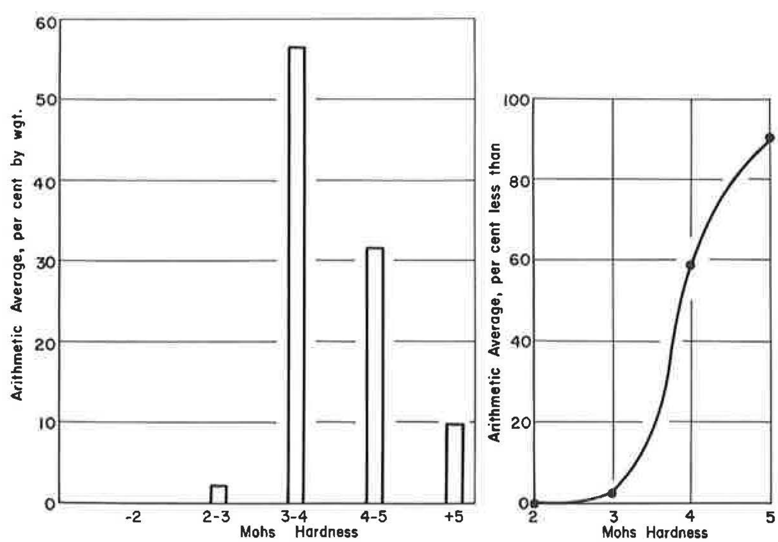

Figure 3. Mohs hardness distribution (No. 6824—hard ledge).

TABLE 6

RESULTS OF PHYSICAL TESTS PERFORMED ON CONCRETE AGGREGATES

Laboratory No. / Identification	6824 Hard	6793 & 6794 Commercial	6823 Soft
Gradation (ASTM C 136)			
Total percent passing 2½ in.	100	100	100
2 in.	96	96	96
1½ in.	72	72	72
1 in.	50	50	50
¾ in.	38	38	38
½ in.	20	20	20
⅜ in.	10	10	10
No. 4	—	1	—
Specific gravity (ASTM C 127) bulk dry	2.71	2.70	2.66
Absorption, percent (ASTM C 127)	0.6	1.1	1.6
Dry rodded unit weight, pcf (ASTM C 29)	96.7	103.7	96.4
b/b_o	0.57	0.61	0.58
Soft particles (ASTM C 235) weighted average, %	8	17	65
Los Angeles abrasion, grading "A" (ASTM C 131) % loss in 500 revolutions	17	17	24
Sodium sulfate soundness (ASTM C 88) weighted % loss in 5 cycles	0.6	0.3	9.9
California durability index (Calif. 229-C)[a] durability factor, D_c	66	—	53
Water-alcohol test (HRB Bull. 201)[b] % loss in 16 cycles	0.1	1.5	11.2

[a]See text for description and interpretation.
[b]See text and Ref. (6) for interpretation.

majority of it would be the result of the difficulty in adequately classifying the 3 to 4 Mohs hardness group with the brass rod.

Performance in Concrete

The second phase of the laboratory investigation was the determination of the physical properties of the hard and soft fractions and a study of the performance of these materials as coarse aggregate in portland cement concrete. In addition to the prepared samples, a sample of the commercially produced concrete aggregate was secured and included in these tests. These three samples of aggregate had, respectively, 8 percent soft particles in the laboratory hard stone, 17 percent in the commercial stone, and 65 percent in the laboratory soft stone. The laboratory crushed samples were graded the same as the commercial aggregate and the physical properties of each determined (Table 6).

The air-entrained concretes were designed to have a cement factor of 6.25 sacks/cu yd, a slump of 1 to 2 in., and an air content of 4.0 ±0.5 percent, in accordance with NCSA Bulletin No. 11 (5). Each mix was repeated at least once and specimens prepared and tested for compressive and flexural strength, as well as for the effect of freezing in air and thawing in water. The use of the small specimens (3 by 3 by 12 in.) for the determination of freezing and thawing resistance necessitated wet screening the fresh concrete over a 1-in. sieve prior to casting the prisms. As a check against the effect of the abnormally high cement factors thus produced, 3 by 3-in. beams were also cut from the 6 by 6-in. beams used in the flexural strength test and these, too, subjected to the freezing and thawing procedure. The results of the tests performed on both the plastic and hardened concretes are summarized in Table 7.

The performance of the three aggregates in the various physical tests is summarized in Table 6. Even the hard ledge (No. 6824) had 8 percent soft particles, and thus would not be acceptable under the C 33 provision. The water absorption increased in direct

TABLE 7

RESULTS OF TESTS ON PLASTIC AND HARDENED CONCRETE

Mix No.	A	B	C
Coarse aggregate laboratory No.	6824	6793 & 6794	6823
Coarse aggregate identification	Hard	Commercial	Soft
Soft particle content, %	8	17	65
Actual batch proportions, per cu yd of concrete			
Cement, lb	595	600	596
Water, lb	240	238	241
Fine aggregate, lb[a]	1040	830	1000
Coarse aggregate, lb	2150	2330	2160
Vinsol resin solution, oz	5.8	5.9	5.9
Actual cement factor, bags/cu yd	6.3	6.4	6.3
Actual water content, gal/cu yd[b]	28.8	28.6	28.9
Actual water-cement ratio, gal/bag[b]	4.57	4.47	4.59
Slump, in.	1.0	1.6	1.1
Air content, %	3.8	4.3	3.6
Unit weight, pcf	149.8	149.2	149.2
Compressive strength, psi (28 day)	5230	4740	4510
Flexural strength, psi (28 day)	790	735	730
Freezing and thawing resistance (ASTM C 291)	Durability Factor at 300 Cycles		
Wet screened over 1 in.	101	102	101
Cut beams[c]	98	97	96

[a] Laboratory stock–natural sand; bulk dry specific gravity = 2.62; absorption = 0.6 percent.
[b] Net water content; does not include water for absorption of aggregates.
[c] 6 by 6-in. flexural strength beams cut to 3 by 3 by 12-in. prisms for F & T Tests.

proportion with the soft particle content but even with a soft particle content as high as 65 percent, did not exceed 1.6 percent, certainly not a level for concern. The Los Angeles abrasion test results indicate that even that sample containing 65 percent soft particles would be well within any specification set forth for concrete aggregate. The sulfate soundness results, although a measurable difference was recorded between that sample having 8 percent soft fragments and that containing 65 percent, indicate that each of the materials was sound and should perform satisfactorily in concretes subjected to a freezing and thawing environment.

Two non-standard physical testing procedures were also employed in an effort to develop as much information relative to the three aggregate materials as was possible. The California durability index test (California Division of Highways Method 229-C) is a test designed to detect those base course aggregates which, when subjected to traffic, might be expected to degrade excessively and produce plastic fines. In a sense it might be considered a form of "hardness" test more akin, possibly, to the abrasion tests. The results are evaluated on an empirical scale ranging from 0 to 100, the harder, more resistant materials yielding higher numerical results. Certainly the difference recorded for the hard and soft ledges would not be considered critical in light of the California specification which permits materials having an index as low as 35. The final physical test performed, the water-alcohol test as described by Brink (6), is the one test whose results might suggest that all is not as it should be. The loss (11.2 percent) recorded for the soft ledge would, under the interpretation of the test as advanced by Brink, be suggestive of a material which might not yield frost resistant concrete. The results of the freezing and thawing tests on the concrete specimens (Table 7) contradict such a conclusion in this instance.

Analysis of Test Data

The performance of the three aggregates in portland cement concrete is given in Table 7, as well as the proportions and properties of the fresh concrete. Both the compressive and flexural strength results tend to decrease somewhat as the soft particle content increases. The increase from 8 to 17 percent soft particles resulted in approximately a 500-psi decrease in the recorded compressive strength and a 50-psi decrease in the measured flexural strength. A further increase in soft particle content to 65 percent resulted in an additional change of roughly 250 psi in compressive strength but little if any additional change in flexural strength. The effect on strength, therefore, is not uniform and in light of these results and the fact that even with a soft particle content as high as 65 percent, both the compressive and flexural strengths were well in excess of those normal to 6.25 bag concrete; the 5 percent soft particle limitation present in many concrete aggregate specifications is without practical significance.

The durability factors recorded following the procedure set forth in ASTM Designation C 291 likewise lend no support to the validity of limiting soft particles, per se, to a maximum of 5 percent. All the concretes, regardless of soft particle content or initial treatment, performed satisfactorily when subjected to a freezing and thawing environment.

SUMMARY

To summarize the results of all the laboratory tests performed, the following statements seem to be in order:

1. Difficulty was encountered when subjecting the serpentine samples to the scratch hardness test. Results had poor reproducibility and when compared with those of the Mohs hardness test indicated that the scratch hardness results were largely arbitrary and of little significance in the 3 to 4 Mohs hardness range.
2. The coarse aggregate samples performed well in all the physical tests except the ASTM scratch hardness test. None of the aggregate samples prepared would meet the 5 percent soft particle limitation set forth in ASTM C 33.
3. Despite the nonconformance to C 33, each of the materials produced strong, durable concretes, thus casting doubt on the strict interpretation of the soft particle limitation, and on the significance of the scratch test. When the difference between 8 and 65 percent soft fragments fails to make a critical difference in performance, the 5 percent limitation is without validity.

More comprehensive research is needed to re-evaluate the present concept of aggregate hardness.

REFERENCES

1. ASTM. Book of Standards. Philadelphia, 1921-1965.
2. ASTM Proc. Philadelphia, 1921-1965.
3. Woolf, D. O. Methods for the Determination of Soft Pieces in Aggregate. ASTM Proc. Vol. 47, 1947.
4. Plum, N. M., Jessig, J., Bredsdorff, P., and Spohr, H. A New Approach to Testing of Building Materials, Fragmentary Contribution to the Philosophy of Testing. Rilem Bulletin, No. 30, March 1966.
5. Goldbeck, A. T., and Gray, J. E. A Method of Proportioning Concrete for Strength, Workability, and Durability. NCSA, Bull. No. 11 (Revised) 1953, 6th Printing, Feb. 1965.
6. Brink, R. H. Rapid Freezing and Thawing Test for Aggregate. HRB Bull. 201, pp. 15-23, 1958.