Freeze-Thaw Durability of Michigan Concrete Coarse Aggregates

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The Michigan Highway Department is currently called upon to approve, each year, coarse aggregate for approximately one million cubic yards of concrete. These aggregates are furnished from deposits ranging in size from roadside pits up to large well-established commercial sources and are distributed over an area exceeding 600 miles between extremities. There is every indication that the rate of aggregate consumption will increase with the accelerated highway construction program. This will surely require evaluation of the freeze-thaw durability, both of deposits now considered of marginal quality and of entirely new sources as proven aggregate reserves become depleted.

The present paper presents laboratory freeze-thaw results as well as field observations on the major Michigan aggregate sources and is considered a first step in formulation of a policy regarding acceptance of future aggregates of unknown service behavior.

Brief description is made of automatic freeze-thaw equipment wherein considerable cost was saved by utilizing an existing large cold room as the source of freezing medium. Six cycles per day are obtained using either rapid freezing in air and thawing in water, or rapid freezing in water and thawing in water. Both types of cycle can be obtained simultaneously if desired. Every effort has been made to provide a rugged trouble-free design. The equipment has now operated continuously for two years with a minimum of attention.

Laboratory evaluation of coarse aggregate durability is achieved by following a rigidly standardized procedure wherein the aggregates are graded and placed in air-entrained concrete in a vacuum saturated condition. The ASTM rapid cycle of freezing in air to 0 F and thawing in 40 F water is used. Failure is considered to have occurred when the sonic modulus of 3- by 4- by 16-in. specimens has decreased 30 percent. Durability factors at 300 cycles of freezing and thawing appear to adequately describe the behavior of the aggregates. Data are presented giving durability factors of the major aggregate sources, and also from three plants using heavy media methods of gravel improvement. Results of a special series of tests are presented wherein the effect of chert still remaining in the heavy media improved gravel is evaluated. The results indicate that this high gravity chert is far less harmful than low gravity chert. Correlation with the magnesium sulfate soundness test was found to be doubtful.

The laboratory durability results correlate reasonably well with known service behavior and it now seems possible to provide the highway administrator with reliable factual data for proper decision.

● THE Michigan Highway Department is currently called upon to approve coarse aggregates for roughly one million cubic yards of concrete annually. These aggregates are incorporated in concrete whose use and importance range from a few yards for a small culvert, up to thousands of cubic yards necessary for paving an expressway. In addition, high quality aggregates are required for the many bridges and grade separation structures incident to an increasing construction program. The aggregate sources likewise range from small roadside pits producing from glacial deposits up to large well-established gravel plants. The upper Great Lakes region also has limestone sources which furnish coarse aggregate crushed from ledge rock. This is usually brought down by boat to the Detroit area on the eastern side of the state or to ports on the western shore. In addition, some limestone aggregates are furnished Michigan from nearby deposits in Ohio, Indiana, and Illinois. The geography of the state itself poses a problem in coordination since the deposits are distributed over an area exceeding 600 miles between extremities.

The southern part of the state is more densely populated with consequent greater mileage of highways. Simultaneous with this is the observation that this portion experiences more cycles of freezing and thawing in the winter in the presence of moisture from melting snow, sleet, or rain and provides a challenging proving ground for genuinely frost resistant concrete. Chloride salts for ice removal are also used in abundance.

Selection of concrete aggregates for this severe exposure has been accomplished in the past by knowledge gained over the years as to sources which are definitely unsuitable, by careful indoctrination of aggregate inspectors, and by what may well prove to be injudicious reliance on the magnesium sulfate soundness test.

Some aggregate deposits have become depleted from use over the years and new sources are continually being investigated. Proven service record is naturally not available on the latter and there is every indication that this sequence of events will accelerate with an increasing highway construction program as well as by increasing demand by other users of concrete. Proper evaluation of these unproven sources as to suitability for use in highly durable concrete is becoming more and more urgent.

If the literature be examined for suitable methods for conducting freeze-thaw tests beginning with, for instance, Scholer's paper published in 1928 (1) up to the work of the early 40's, there is insufficient unanimity to permit drawing firm conclusions. Development of air entrainment with its consequent remarkable improvement in durability of concrete gave impetus to many excellent studies. At present, the underlying reasons for this increase in durability of air-entrained concrete are pretty definitely established and are well summarized by Woods (2).

Briefly, the work of Powers (3) and others has shown that a system of well-distributed, discrete air bubbles in the cement paste fraction of hardened concrete provides reservoirs which relieve the stresses caused by expansive action accompanying formation of ice when water, if present, freezes. Destructive action may well be due to hydraulic pressures developed ahead of the advancing ice front. Since the role of the fine aggregate appears to be of subordinate significance in the over-all freeze-thaw durability of concrete, this paste, well-protected by entrained air, can be considered to be surrounding the fine aggregate particles, thus providing a well-protected mortar. It will be, in part, the object of the present study to show that when coarse aggregate is embedded in this protected mortar, the over-all concrete freeze-thaw durability may be profoundly influenced.

The implications of the above, as a method of studying aggregate durability as distinguished from mortar or paste durability, have been investigated by Woods and by Sweet (4), Lewis and Venters (5) and associates at Purdue, and form a basis for the present study. Their studies indicated considerable promise for a scheme of studying concrete aggregate freeze-thaw durability wherein the aggregate to be investigated is placed, usually in a vacuum-saturated condition to increase its vulnerability to frost attack, in air-entrained concrete and the concrete is then repeatedly frozen in air and thawed in water. The latter freezing cycle does not promote saturation of the mortar and appears to successfully isolate possible destructive effects of the aggregates themselves. It is a common observation that if even well-protected air-entrained concrete containing excellent coarse aggregate be repeatedly frozen and thawed when completely immersed, disintegration will start at the surface and progress inward as saturation builds up toward the interior. If, simultaneously, interior destructive action is occurring due to inferior coarse aggregates, measurement of the mortar durability separately from the coarse aggregate durability then becomes very difficult.

Michigan has now used the freeze-in-air, thaw-in-water cycle for studying aggregates sufficiently to gain considerable confidence in the results obtained. Perhaps the most compelling evidence for success, using the method, has been the observation that for those specimens which deteriorate rapidly, destructive action is centered, in most cases, around those types of deleterious particles for which the department has imposed specification limits for the past 25 years and has trained its aggregate inspectors to watch for diligently. On the other hand, aggregates of unquestioned durability in service have sustained a very high number of cycles with very little sign of deterioration when using the same technique.

Equipment

Automatic Freeze-Thaw Apparatus. Figure 1 shows a schematic diagram of automatic freeze-thaw equipment which has been used in this work and is much the same in principle as reported by Walker and Bloem (6), with one important exception. At the time of designing the equipment, the laboratory had just completed renovation of its 13- by 10½-ft cold room with installation of a modern 6-ton refrigeration unit utilizing hot vapor automatic defrosting. Calculation indicated this refrigeration would provide adequate cooling capacity for freeze-thaw work aside from other uses of the room. Consequently, the specimen chamber is located in this room and is exposed to cooling at all times, regardless of whether in the freezing or thawing portion of the cycle. This differs from the usual equipment which provides an individual refrigeration unit for the freeze-thaw system. It has been found that heat loss from the surface of the 40 F water during the thawing period is inconsequential and the controls are simplified by not requiring that the cooling fans be turned off during this period. Defrosting of the unit coolers occurs approximately every six hours, depending upon the cold room load, at which time the air temperature rises to 14 F for about three minutes. This has been found to have little influence on the temperature of the specimen centers when it occurs during the freezing period. The thermal capacity of the specimen chamber was kept as low as possible to conserve heat with metallic connections through to the supporting framework reduced to a minimum. The metal tank rests on wood saddles and except for the open top, the whole is surrounded by 4 in. of cellular glass rigid insulation. The thawing water storage tank is in a pit to one side and below the freezing chamber and is surrounded by air at room temperature. The storage tank itself is similarly enclosed by 4 in. of cellular glass insulation.

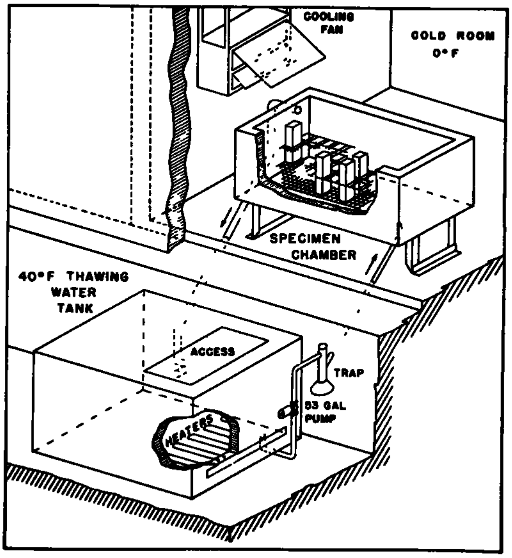

Figure 1. Schematic diagram of automatic freeze-thaw equipment using existing cold room.

The equipment furnishes a cycle which complies with the requirement of ASTM Method C-291, "Resistance of Concrete Specimens to Rapid Freezing in Air and Thawing in Water." In the freezing and thawing cycle used for evaluation of aggregates, 3- by 4- by 16-in. concrete specimens are placed in the specimen chamber on a rack which keeps them accurately positioned for uniform exposure to both the freezing air and thawing water. Freezing is accomplished by circulating the cold room air at 0 F to -5 F around the specimens. The temperature of the center of the specimens is brought from 40 F to 0 F in 2½ hours and remains at this temperature or slightly lower (temperatures of -2.5 F have been observed) for 30 minutes, at which time a switch turns on the centrifugal pump and rapidly circulates water at 42 F around the specimens to thaw them. The water continues to recirculate by means of the overflow and the specimen centers rise to 40 F in 45 minutes and thawing continues for an additional 15 minutes at which time the pump automatically stops, and the water in the specimen chamber drains back through the pump into the thawing water storage tank. The equipment thus provides six cycles per day. Temperature loss of the thawing water (about 3 F per cycle) is made up by five 1,000-watt thermostatically controlled immersion heaters in the thawing tank. The test chamber accomodates 36 freeze-in-air specimens and 12 freeze-in-water specimens. With a full load of test beams, approximately 140 gallons of thawing water surrounds the specimens. Since the capacity of the lower thawing water tank is relatively large (370 gallons), severe temperature changes of the thawing water are not encountered at any time.

This freeze-thaw equipment has no interconnection, either mechanical or electrical, between the refrigeration system and freeze-thaw equipment, consequently maintenance has proven relatively simple and the equipment has now operated continuously for two years with very little trouble.

Vacuum Saturation Apparatus. Figure 2 shows a photograph of the vacuum saturation apparatus used to saturate the coarse aggregates under test. Vacuum is obtained by the high-capacity water jet pump shown and brings the pressure down to very close to the vapor pressure of the water (12-15 mm of Hg). The chamber accomodates four

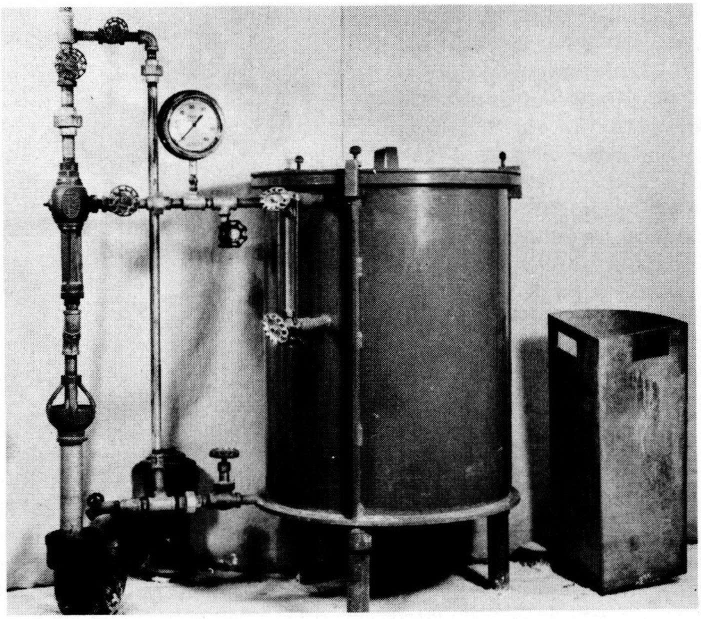

Figure 2. Vacuum saturation apparatus used to saturate coarse aggregate.

quarter-circle segmental shaped containers for simultaneously saturating four different aggregates. The watter valves shown are so arranged as to permit flooding the samples while still under vacuum. The gage glass permits observation that inundation is accomplished and after which saturation is completed at atmospheric pressure.

Concrete Mixer. A rotating drum mixer with inclined axis is used. This mixer is capable of handling a batch slightly larger than one cubic foot. Rotational speed is 22 rpm.

Preparation of Aggregates and Concrete

Effort has been made to establish a highly standardized procedure both for preparation of the aggregates for test and for making the concrete. Insofar as applicable, all procedures for fabricating and proportioning the specimens correspond with ASTM C-233, "Method of Test for Air-Entraining Admixtures for Concrete." This method specifies use of 5½ sacks air-entrained concrete with fixed sand-total aggregate ratios.

Test Coarse Aggregates. The air-dried aggregate is first separated into four sizes as follows:

1 to ¾ in.	½ to ⅜ in.
¾ to ½ in.	⅜ to No. 4

Two 5,000-gram samples (1,250 grams of each size) are then prepared, one for specific gravity and usual 24-hour absorption and the other for vacuum saturation absorption.

Vacuum saturation is accomplished by placing the coarse aggregate under vacuum for one hour after which water is admitted to flood the sample while still under vacuum. The vacuum is then released and the aggregate allowed to absorb water for 23 hours. After absorption and specific gravity tests are completed, these same samples are used to determine deleterious particles content by visual examination.

Fine Aggregate. The fine aggregate is not vacuum saturated and is placed in the mix in a dry condition. All sand used so far has come from a single glacial deposit in southern Michigan. The sand is separated into four size fractions and recombined immediately before placing in the mix in the following proportions:

Pass No. 4, retained No. 16	30 percent
Pass No. 16, retained No. 50	53 percent
Pass No. 50, retained No. 100	15 percent
Pass No. 100	2 percent

TABLE 1

PROPERTIES OF CEMENTS USED

	Lot 1	Lot 2	Lot 3
Physical Tests			
Air in mortar, percent	12.0	9.0	11.9
Specific surface, air permeability, sq cm per gram	3133	3128	3111
Autoclave expansion, percent	0.08	0.09	0 09
Time of setting (Gillmore)			
Initial, hours, minutes	4.00	3.15	3.55
Final, hours, minutes	6.00	5.00	5.55
Tensile strength, psi			
7 days	358	340	-
28 days	462	422	-
Compressive strength, psi			
7 days	3117	-	3258
28 days	4460	-	4663
Chemical Tests, Percent			
SiO_2	21.0	21.0	21.3
Al_2O_3	5.9	5 9	5 8
Fe_2O_3	3 0	2.9	3 0
CaO	61 9	64.6	64.6
MgO	2 3	2.3	2 4
SO_3	2.2	2.3	2.1
Loss on ignition	1 5	1.1	1.2
Na_2O	0.49	0.25	0 32
K_2O	0.68	0.67	0.65
Alkali as Na_2O	0.94	0 69	0.75
3CS	42	53	52
2CS	29	20	22
3CA	11	11	10
4CAF	9	9	9

Cement. Type I portland cement, consisting of a blend of three brands readily available in the Detroit area has been used. Properties of three lots of this blend which have been used are shown in Table 1.

Air-Entraining Admixture. Neutralized vinsol resin (NVX) in water solution has been used in all mixes.

Mixing Concrete. Twenty-four hours before mixing the concrete, the test coarse aggregate is weighed into one of the segmental shaped containers in an amount sufficient for 0.8 cu ft batch of concrete (usually about 60 lb). Equal amounts of the four sizes are used, and the aggregate is given the same vacuum saturation treatment as indicated for the absorption test. Immediately before placing in the previously "buttered" mixer, most of the water which has been used to inundate the aggregate is poured off and the container and contents weighed. From this, the free and absorbed water contributed by the moist aggregate can be accurately determined for eventual calculation of the water-

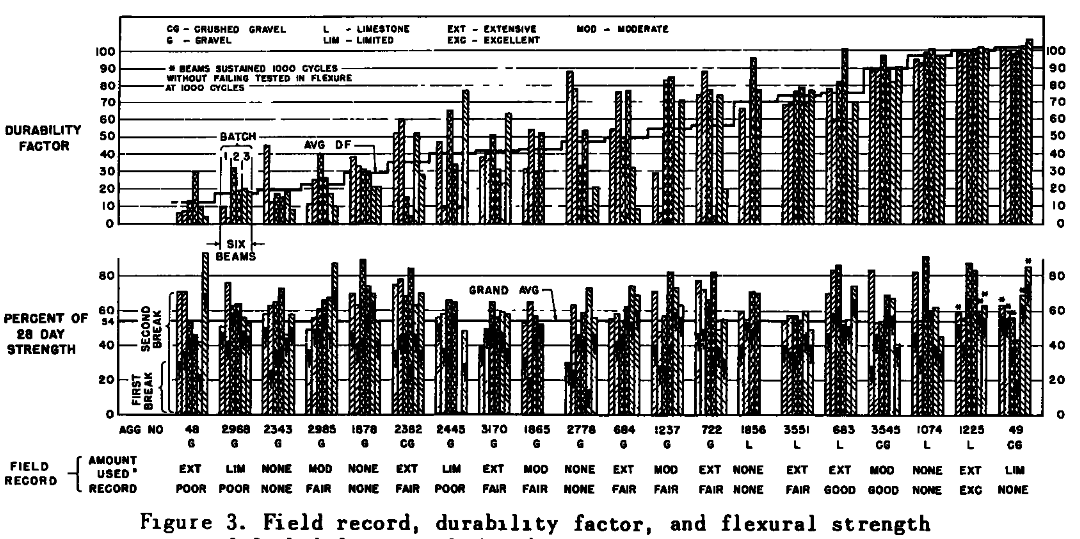

Figure 3. Field record, durability factor, and flexural strength of failed freeze and thaw beams of twenty aggregates.

cement ratio. The dry sand and cement are then placed in the mixer and the air-entraining admixture and most of the water introduced at the instant of starting the mixer. A two-minute mix is first given during which time small increments of water may be added to adjust the estimated slump. This is followed by a three-minute rest period with the mixer stopped and the batch is then given a final one-minute mixing. The batch is then dumped into a moistened pan and slump, pressure air content, and unit weight of the fresh concrete immediately determined, after which the following specimens are cast: (1) four 3- by 4- by 16-in. beams, one each for 7- and 28-day flexural strength and two for freeze-thaw durability; (2) four 4- by 8-in. compression test cylinders, two each for 7- and 28-day test.

A complete test on a single aggregate source consists of three such batches each made on a different day.

The molds are stripped the following day and all specimens cured in a constant temperature (74 ± 1 F) moist cabinet. After 14 days moist curing, the durability specimens are cooled in water to 40 F, weighed, the initial transverse sonic modulus determined, and then placed in the freeze-thaw chamber. Sonic modulus measurements are made at intervals thereafter to trace the progress of deterioration of each specimen. The beams are vibrated in the direction of both the 3-in. and 4-in. dimensions and the average loss of modulus determined.

Freeze-Thaw Durability Results

Included herein are durability results on 20 aggregate sources having service performance from poor to excellent. The field service ratings shown in Figure 3 are the results of general observation and are not intended to represent precise evaluations. Long acquaintance with some of these aggregates, particularly those where the amount used is shown as "extensive," permits a reasonably satisfactory estimate of field performance which is sufficient for the present purpose.

The top line of bars shows the durability factor of each beam, together with the average of the six beams (in two cases, four beams) for each aggregate. The aggregates have been arbitrarily ranked in order of increasing average durability factor. The durability factor shown is based upon discontinuing the test at 300 cycles or at a 30 percent reduction in sonic modulus whichever occurs first. Discussion of this durability factor, as properly representing the resistance to freezing and thawing will be made later. The line of bars directly below, in the figure, represents the corresponding flexural strength of the failed beams (or after 1,000 cycles of freezing and thawing if they have not yet failed) expressed as percent of strength of the 28-day beams. The very substantial loss in strength caused by disruptive action of bad aggregate is apparent. Two strengths are obtained on each beam, using center point loading on an 8½-in. span with the load applied in the direction of the 3-in. dimension. It will be observed that considerable variation occurs in these strengths and does not appear to be related to the durability factor ranking. The average flexural strength of the failed beams is 54 percent of the 28-day strength which provides a highly convincing criterion of failure to the highway engineer who is conscious of the necessity for maintaining a high flexural strength in paving concrete. It should be pointed out that the durability beams are cured only 14 days and presumably attain about 85 percent of the 28-day strength before freezing and thawing started.

The rather large variations in durability factor and in flexural strength following failure for a given aggregate, both within batch and from batch to batch, are now regarded not as the result of an inherently faulty test method but as the normal consequence of a random distribution of deleterious particles in the specimens. The sonic modulus test appears to give an average value of the disintegration of the specimen and does not foretell that certain portions of the beam may have suffered severe internal breakdown.

In the case of specimens which failed in a relatively few number of cycles, it was observed that this failure centered around the types of deleterious particles which, with one exception, are already well-known in Michigan; namely, iron clay stones, chert, shale, soft sandstone and the like. Examination of the beams following failure in freezing and thawing frequently permits accurate prediction that one or the other flexural breaks will be unusually low due to a concentration of cracks near one end of the beam. The crack pattern will frequently be radial, fanning out from an underlying particularly expansive particle. The fracture, after breaking, is often highly irregular, following a random path greatly weakened by disruptive action of bad aggregate and the fractured face usually exposes the offending particle. A type of particle which had not heretofore been considered deleterious in Michigan practice has been observed in these tests in several Michigan deposits, namely, a limestone pebble which ordinary techniques have been unable to identify. Work to date which is only suggestive, using differential thermal analysis, indicates these to be calcium carbonate rock pebbles containing small amounts (less than 10 percent) of clay minerals, probably kaolinite.

Inference might be drawn from the above that the freezing and thawing tests constitute

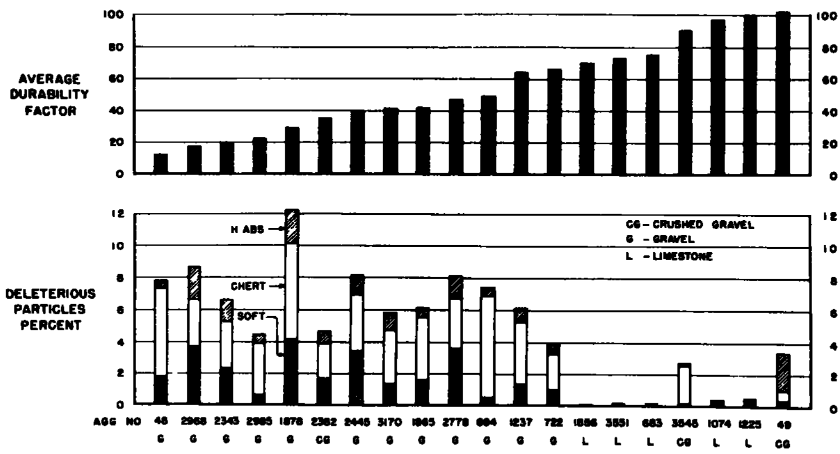

Figure 4. Deleterious particles content and durability factor of twenty aggregates.

primarily a confirmation of knowledge already gained from field observations as to the types of particles which are deleterious. To some extent, this is true for aggregates showing low durability. However, for the aggregates which exhibit intermediate durabilities, the freeze-thaw tests provide a continuous scale of measured values obtained by a method not subject to personal judgment, and extend knowledge beyond that gained by visual examination of the aggregates. Figure 4 presents the results of hand-picking these same aggregates for the three classes of deleterious particles as presently defined by the Michigan specifications; namely, (1) "soft particles" which include "shale, soft sandstone, ochre, coal, iron bearing clay, weathered schist, shells, floaters, partially disintegrated particles, cemented gravel and any other particles which are structurally weak or which fail to meet the soundness test," (2) "chert," and (3) "hard absorbent particles." Hard absorbent particles are less-easily defined but cover, in general, an intermediate class of particles, less objectionable than the soft particles, which experience over the years, have proven deleterious. It is observed from Figure 4 that although, generally, durability increases with diminishing amounts of deleterious particles, the relation is not a satisfactory one. The ranking of the aggregates obviously would be quite different if the deleterious particles content was used as the sole criterion.

It seems possible to consider the over-all aggregate durability as consisting of two parts: (1) breakdown due to identifiable deleterious particles and (2) ultimate breakdown due to "basic" durability of the aggregate. For instance, the poor durability of aggregate reference No. 2985, as evidenced by an average durability factor of only 22 — contrasted with some of the other aggregates having comparable, or more amounts of recognizable deleterious particles, may indicate a lower "basic" durability for this particular aggregate or, of course, it may also mean that the deleterious particles found in this aggregate are unusually destructive. Consideration had been made as to whether more useful data could be acquired by removing the recognizable deleterious particles prior to conducting the freeze-thaw tests to enable a better estimate of this basic durability. The present opinion is that removal of the deleterious particles prior to the test infers a degree of knowledge of their relative destructiveness which is not now justified. Data presented later, on the durability of chert in connection with heavy media separation plants, confirms the wisdom of this decision.

Durability Factor versus Total Cycles for Failure

Consideration has been given as how best to express the numerical rating of the durability of a particular aggregate. For those aggregates whose beams all fail at less than, for instance, 300 cycles of freezing and thawing, the average number of cycles for failure would appear to be an entirely satisfactory method. However, some aggregates have beams which do not fail at even several hundred more cycles. This, inci-

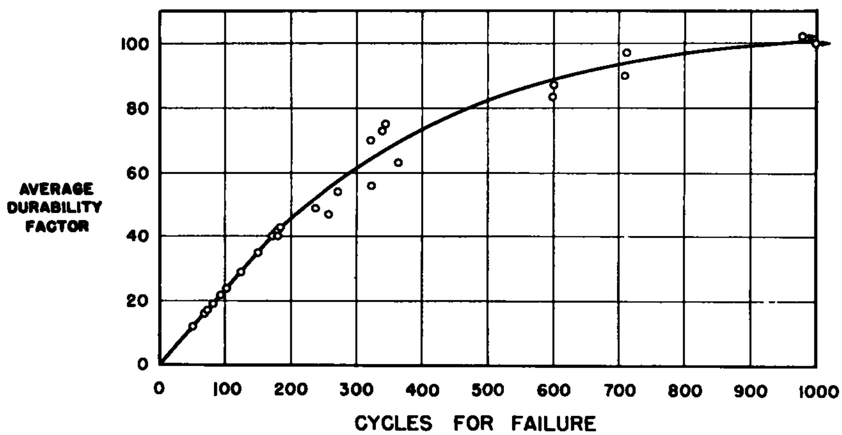

Figure 5. Average durability factor of vacuum saturated coarse aggregate versus number of cycles for failure.

dentally, ties up freezer space. It is desirable in the latter case to make recourse to the durability factor to express the rating of such an aggregate so as to permit removal of the beams from the freezer at a specified time. Durability factors shown are based upon terminating the test at 300 cycles, or at a 30 percent reduction in sonic modulus, whichever occurs first. It should be emphasized that such a choice of 300 cycles and 30 percent reduction in modulus provides a unique scale of durability rating and is, so to speak, an irrevocable choice. The values cannot usually be transferred to a durability factor of another base, nor can they be compared with, for instance, published data unless that likewise was based upon 300 cycles and 30 percent reduction. For beams which fail at greater than 300 cycles, the durability factor can be likened to taking a snapshot of the beam's condition at 300 cycles and then predicting from this at what number of cycles it actually will fail. The extent to which this prediction is successful is shown in Figure 5 where number of cycles for failure is plotted against average durability factor. It is observed that the durability factor, once its peculiarities are learned, reasonably successfully predicts the total number of cycles for failure and it is concluded that almost as much useful information is obtained by terminating the test at 300 cycles as by continuing on to failure. Terminating the test at 300 cycles certainly simplifies the procedure greatly by permitting orderly scheduling of freezer space.

In this series of tests, the durability factor does not bear a linear relationship to the total cycles for failure except at the low end of the scale. For instance, aggregate having an average durability factor of 45 sustained about 190 cycles, whereas the curve indicates that aggregate having twice this durability factor would fail at much more than twice this number of cycles, actually at about 630 cycles. To state it differently, for very durable aggregates, the number of cycles at which failure occurs is underestimated by the durability factor.

TABLE 2

COARSE AGGREGATE ABSORPTION AND SPECIFIC GRAVITY AND CONCRETE DATA FOR DURABILITY MIXES

Coarse Aggregate					Concrete Mix Data							Strength, psi				
Aggregate No.	Bulk Sp Gr (dry basis)	Absorption, % 24-hour	Absorption, % Vacuum	Absorption, % Ratio	Batch No	Sand, % of total Agg	Slump in	Wt per cu ft, lb	Actual Cement sk/cyd	Net Water gps	Air, %	Compressive [a] 7-days	Compressive [a] 28-days	Flexural [b] 7-days	Flexural [b] 28-days	Durability Factor
48 Gravel	2.61	1 73	2 14	0.81	1	36	2½	145 8	5 51	4 78	6.4	2750	3320	625	705	12
					2	36	3⅝	144 7	5 45	4 93	6.4	2395	3330	515	650	
					3	36	3¾	147.5	5.56	5 02	5.5	2475	3260	500	625	
					Avg	36	3¼	146 0	5 51	4 91	6.1	2540	3305	545	660	
2968 Gravel	2.53	2.63	3.14	0.84	1	36	3¼	145 7	5 56	4 81	4 9	2415	3305	645	755	17
					2	36	3	146 1	5.57	4.78	4 8	2825	3500	595	735	
					3	36	4½	144 1	5 48	5.06	6 0	2150	3085	580	760	
					Avg	36	3½	145.3	5 54	4 88	5 2	2465	3295	605	750	
2343 Gravel	2 58	2.12	2.54	0 83	1	38	4¾	142 8	5 40	4 91	7.3	2700	3320	660	765	19
					2	38	2⅝	147.5	5.58	4 96	5 2	2910	3720	665	820	
					3	38	3¼	145 6	5.50	5 02	6.3	2390	3530	720	710	
					Avg	38	3½	145.3	5 49	4 96	6.3	2665	3525	680	765	
2985 Gravel	2 64	1.45	1 60	0.91	1	36	2¼	148.4	5 58	4 89	5 8	2540	3300	685	780	22
					2	36	2	149 3	5.61	4 97	5 1	2900	3640	615	785	
					3	36	2¼	148.9	5.60	4 89	5 5	2780	3860	790	800	
					Avg	36	2⅛	148 9	5.60	4 92	5 5	2740	3600	695	790	
1878 Gravel	2.56	2.66	2 81	0.95	1	36	4¾	144.7	5.48	5 17	6.0	2460	3260	590	720	29
					2	36	3⅛	144.7	5 49	4 98	6.1	2410	3380	585	710	
					3	36	4	145.8	5.53	5 01	5.2	2310	2935	545	640	
					Avg	36	4	145.1	5.50	5 05	5.8	2395	3190	575	690	
2382 Crushed Gravel	2 67	1.25	1 48	0 84	1	38	1½	149.2	5.59	4 80	4.9	2660	3815	740	845	35
					2	38	1⅞	149.0	5.56	5 06	5.0	2280	3090	645	670	
					3	38	3	147.5	5 50	5 10	7 0	2490	3210	615	700	
					Avg	38	2⅛	148.6	5.55	5 00	5.6	2475	3370	665	740	
2445 Gravel	2 65	1.33	1.70	0.78	1	36	3½	148 0	5 54	4 94	4.7	2735	3115	745	825	40
					2	36	2⅞	146 3	5.47	5 25	4.9	2360	2995	720	840	
					3	36	3⅛	146.7	5.49	5.02	5.6	2445	3235	570	660	
					Avg	36	3⅛	147 0	5.50	5.07	5.1	2515	3115	680	775	
3170 Gravel	2 64	1 19	1 61	0 74	1	36	2⅜	147 0	5.52	4.99	6.3	2430	3420	690	850	41
					2	36	1⅞	149 9	5 66	4 47	4.3	3310	3720	705	835	
					3	36	2	148.5	5 59	4.75	6.2	2760	4080	660	825	
					Avg	36	2⅛	148 5	5 59	4 74	5.6	2835	3740	685	835	
1865 Gravel	2 64	1.20	1.65	0.73	1	36	3½	146.5	5 54	4 99	5.6	2925	3540	750	785	42
					2	36	3¼	147 7	5.59	5 00	5.2	2625	3315	665	755	
					Avg	36	3⅜	147 1	5 57	5 00	5.4	2775	3430	710	770	
2778 Gravel	2.62	1.62	2 00	0.81	1	36	5	144 9	5.44	5 27	6.6	2205	2915	705	730	47
					2	36	1¾	149.7	5.65	4 66	4.0	2490	3555	755	855	
					3	36	1¾	149 1	5 49	4 70	4.4	2860	3765	635	730	
					Avg	36	2⅞	147 9	5.53	4 88	5.0	2520	3410	700	770	
684 Gravel	2 61	1 73	1 96	0.88	1	36	3⅜	146 0	5.51	5 04	6 3	2505	3320	625	715	49
					2	36	3½	146 3	5 51	5.02	6.3	2655	3270	635	720	
					3	36	1	149.7	5 65	4 94	4.1	2825	3800	585	645	
					Avg	36	2⅝	147 3	5 56	5 00	5.6	2660	3465	615	695	
1237 Gravel	2 63	1.60	2 03	0.79	1	36	2⅞	147 7	5 55	4 94	6.4	3005	4070	575	715	54
					2	36	3	147 3	5 54	4 92	6.0	2840	3750	705	790	
					3	36	5⅜	147.1	5.54	4 75	6 4	2685	3395	715	790	
					Avg	36	3¾	147 4	5.54	4 87	6.3	2845	3740	665	765	
722 Gravel	2 67	1 53	1 70	0 90	1	36	4¼	147.0	5.51	4 65	6.8	2455	3250	590	665	56
					2	36	5¾	146.3	5.46	5 01	7.1	2660	3425	610	665	
					3	36	1¼	151.5	5.66	4 91	4.5	2825	3880	565	625	
					Avg	36	3¾	148 3	5.54	4 86	6 1	2645	3520	590	650	
1856 Limestone	2 57	3.25	3.79	0.86	1	41	1⅜	146 7	5 55	5.69	5.2	3410	4615	795	950	70
					2	41	1⅜	145.7	5.49	6 02	5.0	3190	4385	755	880	
					Avg	41	1⅜	146.2	5.52	5 86	5.1	3300	4500	775	915	
3551 Limestone	2 61	1.28	1 42	0.90	1	41	1⅝	146.5	5 54	5 04	5 9	2710	3200	725	835	73
					2	41	1⅜	146 2	5 52	5 02	5 1	2900	3420	690	920	
					3	41	1	147 2	5 55	5 30	4 5	2535	3435	660	765	
					Avg	41	1⅜	146 6	5 54	5 12	5.2	2715	3350	690	840	
683 Limestone	2 71	1 45	1 78	0 81	1	41	¾	152 2	5 63	5 16	4.5	3135	3820	655	660	75
					2	41	4¼	147 5	5 44	5 40	6 3	2700	3255	655	690	
					3	41	2	149 2	5 50	5 41	5.1	2600	3535	605	625	
					Avg	41	2⅜	149 6	5 52	5 32	5 3	2810	3535	640	660	
3545 Crushed Gravel	2 60	1 53	2.39	0.64	1	38 5	1¾	147 4	5 56	5 01	4 9	3165	4240	695	880	90
					2	38 5	3	147 1	5 54	5 05	4 9	3125	4405	745	895	
					3	38 5	2¾	148 1	5 60	4 77	5 1	2960	4190	720	890	
					Avg	38 5	2½	147 5	5.57	4 94	5.0	3085	4280	720	890	
1074 Limestone	2 62	2.14	2 94	0 73	1	41	¾	149 2	5 57	5 24	5.1	3030	4215	790	865	97
					2	41	3	146 5	5 45	5 51	5.7	2960	3915	725	975	
					3	41	2⅝	146.8	5.47	5 54	5 6	2855	3885	710	925	
					Avg	41	2⅛	147.5	5 50	5 43	5 5	2950	4005	740	920	
1225 Limestone	2 64	0.76	1 10	0.69	1	41	1½	146 8	5.50	5 41	5.3	2880	3780	690	810	100
					2	41	3⅞	144 1	5 40	5 42	6.7	2645	3360	735	870	
					3	41	3¼	144 5	5.41	5 54	7.6	2625	3210	800	885	
					Avg	41	2⅞	145.1	5.44	5 46	6 5	2715	3450	740	855	
49 Crushed Gravel	2 68	1.45	1.71	0.85	1	38.5	2⅜	146 6	5 45	5 15	6.6	2420	3290	535	725	102
					2	38 5	3¼	146 0	5 44	5 03	7 0	2485	3070	615	730	
					3	38 5	1¼	148.9	5.55	4 92	4 8	2810	3670	580	725	
					Avg	38 5	2¼	147 2	5 48	5 03	6 1	2570	3345	575	725	

[a] Each value shown is average strength of two 4 x 8 in cylinders
[b] Each value shown is average of two breaks on one 3 x 4 x 16 in. beam.

Table 2 shows certain characteristics of the coarse aggregates together with usual concrete mix data. The 24-hour cold water immersion absorption is shown for the aggregates and also the vacuum saturation absorption together with the ratio of the two. No useful relation between these values and durability factor has been discovered, nor does specific gravity appear to have particular significance for these twenty aggregates.

Close scrutiny of the proportioning and strength data in Table 2 reveals occasional anomalous values which seem unavoidable in making such a series of batches of concrete, but generally the averages appear satisfactory. Average compression strengths appear related fairly well to water-cement ratio whereas flexural strengths presumably reflect different structural qualities and surface texture of the aggregates. Neither

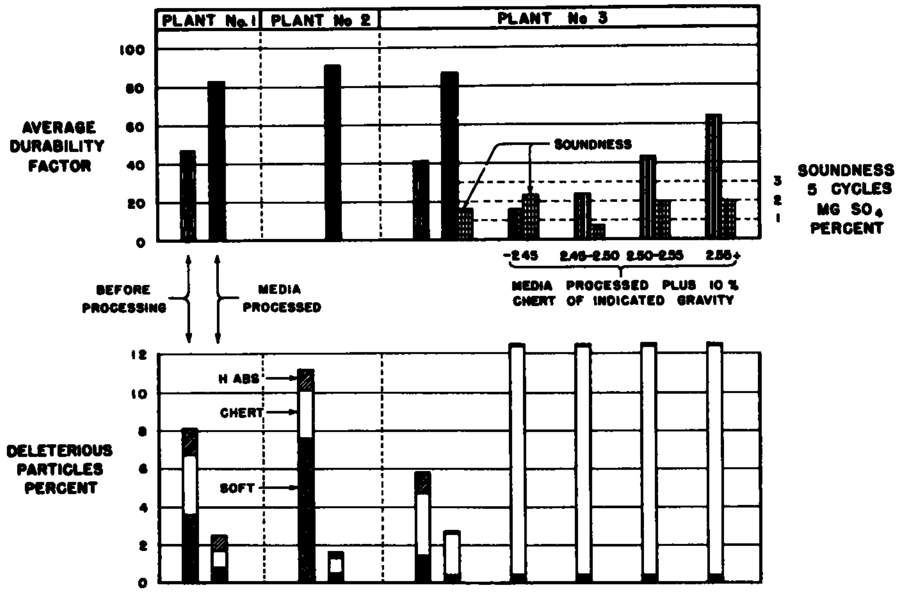

Figure 6. Durability and deleterious particles content before and after processing in three commercial heavy media plants. Also durability and accelerated soundness when diluted with chert of different specific gravities.

type of strength appears related to freeze-thaw durability.

Sand content of the mixes was proportioned by interpolation between 36 and 41 percent for gravel aggregates containing appreciable amounts of crushed particles.

Consideration has been given as to whether the inadvertent changes in air content for the individual batches were affecting durability. For an aggregate on which three batches were made, the average durability of the two beams from each batch has been calculated and three observations made as to whether the durability increased or decreased with an increased air content. For the twenty aggregates, 56 such observations can be made (only two batches each were made on two aggregates). In 25 cases durability increased with increased air content and in 26 cases durability decreased. In five cases, observation could not be made since the air content was the same. It is concluded that within the range used (average 5-7 percent), air content was not significantly affecting the aggregate durability. Field observations amply support the viewpoint that air-entrainment has not alleviated the problem of deleterious aggregates.

Service Record versus Durability Factor

Establishment of a rating of these aggregates in actual services poses numerous problems. The environment of the concrete certainly influences the behavior of the aggregates, — moist conditions favor pop-outs from deleterious particles. On the other hand, the nature of the environment may well influence the desired performance. For instance, almost complete absence of unsightly pop-outs is desired on the exposed architectural concrete of a bridge or grade separation structure. It is not considered that too much reliance should be placed on behavior of these aggregates in concrete prior to the days of air-entrainment. Mortar disintegration of non-air-entrained concrete may well not be distinguished from distress due to aggregates. Insofar as our present knowledge extends, the durabilities reported herein correlate reasonably well with service performance of air-entrained concrete, particularly in distinguishing the aggregates which show excessive surface pop-outs in paving concrete as well as those of unquestioned durability. The department now has a service performance program underway for determining the extent of surface defacement caused by deleterious particles in pavements constructed since 1945, — approximately the time when reliable, extensive air-entrainment construction records became available. The work to date in this program shows promise of confirming the laboratory data.

The aggregate samples on which tests are shown herein, represent current production. It is common knowledge that the character of glacial deposits as well as limestone ledges may vary greatly within a distance of a few feet, consequently, rigorous correlation of laboratory tests of present production with field performance of past production presents a serious obstacle.

Heavy Media Separation Plants

Three commercial heavy media separation plants have now been operating in Michigan sufficiently long to gain some knowledge of their performance in improving gravel aggregates. In the case of two of these plants, freeze-thaw studies have been made of the gravel both before and after heavy media separation. The product of the third plant, before processing, had such a high content of deleterious particles that freeze-thaw tests were not conducted.

Figure 6 summarizes the durability tests on these three commercial plants and demonstrates the substantial decrease in deleterious particles content and corresponding

TABLE 3

MISCELLANEOUS TESTS OF DURABILITY CONCRETE MIXES MADE WITH GRAVEL BEFORE AND AFTER COMMERCIAL HEAVY MEDIA PROCESSING ALSO MEDIA PROCESSED GRAVEL CONTAINING CHERT OF VARIOUS GRAVITIES

Coarse Aggregate						Concrete Mix Data							Strength, psi				Durability Factor	
	Source	Bulk sp gr	Absorption, %			Batch	Sand	Slump	Wt per cu ft,	Actual Cement	Net water	Air	Compressive[a]		Flexural[b]			
		(dry basis)	24-hour	Vacuum	Ratio	No	%	in	lb	sk/cyd	gps	%	7-day	28-day	7-day	28-day	Beam 1	Beam 2
Plant No 1	Before Processing	2 62	1 62	2 00	0 81	1	36	5	144 9	5 44	5 27	6 6	2205	2915	705	730	88	78
						2	36	1¾	149 7	5 65	4 66	4 0	2490	3555	755	855	33	53
						3	36	1¾	149 1	5 49	4 70	4 4	2860	3765	635	730	7	21
						Avg	36	2⅞	147 9	5 53	4 88	5 0	2520	3410	700	770	47	
	Media Processed	2. 70	0 91	1 09	0 83	1	36	3¼	148 6	5 51	5 08	4 8	2255	3175	665	765	56	89
						2	36	2½	149 4	5 56	4 99	4 8	2435	3230	695	795	96	79
						3	36	2¼	149 7	5 58	4 81	4 8	2490	3180	730	815	91	88
						Avg	36	2⅝	149 2	5 55	4 96	4 8	2395	3195	695	790	83	
Plant No 2	Media Processed	2 69	1 06	1 08	0 98	1	36	2¾	149 4	5 58	4 87	6 3	2775	3645	655	890	98	92
						2	36	¾	152 1	5 69	4 69	4 2	3215	3895	815	970	93	77
						3	36	2¾	149 6	5 57	5 03	5 7	2975	3740	725	790	92	95
						Avg	36	2⅛	150 4	5 61	4 86	5 4	2990	3760	730	885	91	
Plant No 3	Before Processing	2 64	1 19	1 61	0 74	1	36	2⅜	147 0	5 52	4 99	6 3	2430	3420	690	850	38	40
						2	36	1⅞	149 9	5 66	4 47	4 3	3310	3720	705	835	51	31
						3	36	2	148 5	5 59	4 75	6 2	2760	4080	660	825	23	63
						Avg	36	2⅛	148 5	5 59	4 74	5 6	2835	3740	685	835	41	
	Media Processed	2 68	1 00	1 17	0 85	1	36	2¾	149 8	5 63	4 38	4 8	3330	4415	755	860	87	88
						2	36	4¾	146 8	5 49	4 86	6 9	2700	3805	625	845	70	90
						3	36	4	147 7	5 54	4 61	6 6	2780	3720	715	865	94	90
						Avg	36	3⅞	148 1	5 55	4 62	6 1	2935	3980	700	855	87	
	Media Processed +10% chert sp gr -2 45	2 63	1 40	1 80	0 78	1	36	3¼	146 3	5 52	4 66	5 4	2890	3835	690	730	14	14
						2	36	2¾	147 7	5 56	4 77	5 5	3380	4100	690	840	32	9
						3	36	1¾	147 4	5 53	4 66	5 3	3345	4165	665	800	24	4
						Avg	36	2⅝	147 1	5 54	4 70	5 4	3205	4035	680	790	16	
	Media Processed +10% chert sp gr 2 45 - 2 50	2 65	1 21	1 36	0 89	1	36	3	147 9	5 57	4 60	5 3	3165	3670	750	760	21	34
						2	36	3½	146 8	5 52	4 82	6 4	2955	3835	640	810	22	24
						3	36	2¼	149 5	5 64	4 50	4 8	3535	4580	770	830	12	32
						Avg	36	2⅞	148 1	5 58	4 64	5 5	3220	4030	720	800	24	
	Media Processed +10% chert sp gr 2 50 - 2 55	2 66	1. 13	1 38	0 82	1	36	3	147 8	5 53	4 76	5 8	3080	3840	670	825	71	41
						2	36	3¼	147 9	5 56	4. 70	5 5	2760	3900	715	865	12	35
						3	36	2½	149 5	5 62	4 74	5 3	2785	3460	615	745	24	72
						Avg	36	2⅞	148 4	5 57	4 73	5 5	2875	3735	665	810	43	
	Media Processed +10% chert sp gr 2 55+	2 68	0. 97	1 10	0 88	1	36	3⅛	147 5	5 52	4 82	5 6	2805	3915	635	725	28	89
						2	36	4⅝	147 6	5 52	4 88	6 0	2985	3955	650	870	77	61
						3	36	2¾	147 5	5 54	4 48	6 0	2980	3455	675	710	40	86
						Avg	36	3½	147 5	5 53	4 73	5 9	2925	3775	655	770	64	

[a] Each value shown is average strength of two 4 x 8 in cylinders
[b] Each value shown is average of two breaks on one 3 x 4 x 16 in beam

increase in durability of the processed material. Table 3 gives the concrete mix data for these batches together with specific gravity and absorption data. It is gratifying to observe from the table that 17 of the 18 test beams made with the media processed gravel from the three plants had durabilities of 70 or greater, demonstrating that the nondurable particles have been quite successfully removed by the processing.

Routine daily tests on the processed gravel from plant No. 3 indicated that the small amount of deleterious particles which were not removed by the heavy media processing was predominantly chert. Question naturally arose as to how deleterious this small amount of relatively high gravity chert actually is, particularly in view of the work of Wuerpal and Rexford (7) who concluded that the unsound chert was confined largely to that having a bulk specific gravity of less than 2.40. In order to investigate this conclusion using Michigan aggregates, approximately one ton of the gravel rejected and wasted by the flotation process was brought to the laboratory and the chert removed by hand picking. The chert was then graded into the four size groups used in the previous durability studies, namely, 1 to ¾ in., ¾ to ½ in., ½ to ⅜ in., and ⅜ in. to No. 4, and then separated into four specific gravity ranges in a saturated condition by laboratory separation processes using acetylene tetrabromide-carbon tetrachloride mixtures, as follows: minus 2.45, 2.45 to 2.50, 2.50 to 2.55 and 2.55 plus.

The choice of values for specific gravity ranges was arbitrary. It seemed probable, however, from previous work (5) that commercial operations would usually float off objectionable material somewhere between 2.50 and 2.60 gravity. As a consequence, this range was split in the middle at 2.55 to provide more detailed information. The two lower gravity groups, minus 2.45 and 2.45 to 2.50, would provide chert to substantiate trends in aggregate durability reported elsewhere.

In the chert series of durability tests, decision was made to replace the flotation-improved gravel by 10 percent chert of each gravity group and to distribute it in equal amounts down through the four coarse aggregate sizes. For example, one sample of gravel for durability study was prepared using 90 percent flotation-improved gravel plus 10 percent chert of minus 2.45 specific gravity. The choice of 10 percent chert with which to dilute the gravel in each case was based on the premise that if the chert were actually deleterious there would surely be enough to be readily detected.

Figure 6 includes the results of the chert durability studies from plant No. 3. The data indicates the flotation processed material to be most frost resistant. Marked reduction in durability occurs when this flotation-improved gravel is diluted with 10 percent chert of minus 2.45 gravity but the durability successively improves as higher and higher gravity chert is introduced, leading to the conclusion that the high-gravity chert remaining in the media-processed gravel should be less harmful than "average" chert of variable specific gravity.

The results of the accelerated soundness test (5 cycles of $MgSO_4$) are also shown. It is there observed that the soundness test is entirely unsatisfactory for predicting freeze-thaw durability of the aggregate diluted with chert. For instance, the aggregate containing 10 percent of the lowest gravity chert exhibits poor freeze-thaw durability but shows a magnesium sulfate soundness loss of only 2.4 percent. Since much higher soundness losses have been observed in the past on samples from other sources at this laboratory, it seems proper to regard the soundness test as a highly selective one which is destructive to some types of particles but not to chert.

Summary

Included herein is a review of the efforts of one organization to solve the long perplexing problem of laboratory evaluation of the freeze-thaw durability of concrete coarse aggregates. Considerable promise is shown for a method using automatic equipment to provide a freeze-thaw cycle wherein the aggregates under test are placed in concrete in a vacuum saturated condition to make them more vulnerable to frost attack. The mortar fraction of the concrete is made highly resistant to frost action by using dry sand and by incorporation of entrained air. The cured concrete is then alternately subjected to freezing in air to 0 F and rapid thawing is water to 40 F. This cycle does not promote saturation of the concrete and destructive action appears to be centered around

deleterious particles in the aggregate, thus indicating considerable success for isolating the effect of aggregate durability from possible lack of mortar durability. Sonic modulus measurements are used to detect internal breakdown of the concrete.

The field surveys necessary for more positive proof, than reported here, of precise correlation of the laboratory durabilities with service performance may be time consuming. Surface defacement studies of existing air-entrained concrete using many of the aggregates reported are now underway. A desirable supplement to this would be acquisition of field data aimed at measuring the internal distress of the concrete from freezing and thawing action.

Three types of evidence make it appear that the laboratory data is consistent within itself and that the method is indeed measuring the characteristics for which it was designed:

1. Early breakdown of the laboratory concrete is associated with types of deleterious particles which Michigan has long recognized as being necessary to limit in frost resistant concrete.
2. The method has successfully measured the improvement in freeze-thaw resistance of commercially produced heavy media processed gravel over the unprocessed gravel such as was predicted by others.
3. The method has successfully measured the loss in durability when aggregate is diluted with low gravity chert so as to confirm work done some 15 years ago, and extends that work to show there to be a definite scale of chert durability.

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