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DURABILITY OF AGGREGATES IN CONCRETE MIXES

(Final Report)

by

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INDUSTRIAL MINERALS DIVISION

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DURABILITY OF AGGREGATES IN CONCRETE MIXES

by

R. H. Picher*

GENERAL

This publication is the final report of a long-term investigation of concrete aggregates from rock deposits in eastern, southern and western Ontario. The investigation was originally planned to provide information for the selection of suitable local material for concrete aggregates in connection with the proposed waterway and power development on the St. Lawrence River. However, following the issue of the first progress report of the work in 1951, it was decided to include materials from southern and western Ontario, at the request of a number of commercial crushed-stone and gravel producers.

About one hundred and ten samples were taken from the larger rock and gravel deposits in these areas, of which twenty-six were gravel samples mostly from crushing and screening plants. Most of the rocks investigated consist of limestones, dolomites, and sandstones, the first two being by far the most common rocks in the areas covered

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by the survey. Outside of these areas, single samples of basalt, dolerite, anorthosite and serpentine were collected. The rock deposits lying closest to the site of the proposed work along the St. Lawrence River, that is, within 30 miles, consist of limestones of the Trenton, Black River and Chazy formations. Beyond the 30 miles but within 50 miles are found dolomites, magnesian limestones and calcareous sandstones of the Beekmantown formation. Nearly all samples of rock taken at a greater distance were from commercial crushing and screening plants, mostly in southern Ontario. About half of the gravel samples are also from commercial crushing and screening plants in eastern and southern Ontario.

Because of the large number of samples, the long duration of the tests with the available equipment, and because no such test had been carried out before on concrete specimens in our laboratory, it was decided to run through a limited number of samples to find whether some changes in the procedure might be advisable before going ahead with the balance of the samples. Therefore, the sampling, preparation and testing of materials fell into two series, each done separately.

Later it was decided to add a third series of samples. Most of these were from deposits of rocks that are presumably the best available for the proposed development work along the St. Lawrence. These had been intentionally left out in the original programme of sampling and testing because it was thought that more could be learned by proceeding first with the "doubtful" stones. Although these latter are apparently suitable for aggregate in ordinary concrete structures, they have slight defects, and it was the purpose of the first tests to find what influence these defects would have on the durability of concrete structures.

Two progress reports have already been published, one* while the specimens of the first series were under test, and the other** after the specimens of the second series had been through 125 cycles of freezing and thawing. The present and final report covers the whole investigation on the durability test from the time it was started on the samples of the first series until it was completed with the third and final series.

Since there is no standard procedure for the durability test on concrete, the methods followed in this investigation for the sampling of the deposits, the preparation of the test specimens and their testing are described in detail.

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* Report No. 101, Industrial Minerals Division, Progress Report on Road and Concrete Aggregate in Parts of Ontario and Quebec, by R. H. Picher, 1951.

** Report No. 102, Industrial Minerals Division, Durability Tests on Concrete Aggregates in Eastern and Southern Ontario, by R. H. Picher, 1952.

SAMPLING*

All the samples of the first and second series with the exception of a few were taken from stones of apparently good or fair quality, with only slight defects, which may or may not adversely affect the durability of concrete. These defects consist of unsound material (shale, chert, iron oxide, asbestos) mixed with the sound stone, or are due to the condition of the stone itself, such as partial weathering, loose texture, high absorption. The amount of unsound material varies between the different beds but is in all cases small, except in cherty limestones. The same may be said about partial weathering, since the more weathered stone, which in most cases occurs in the upper part of the deposit, is considered as overburden and is stripped off as waste in quarrying operations. Loose texture and high absorption also vary with the different beds but usually affect a large portion of the stone. Owing to the difficulty of taking a channel sample including the whole face of a rock exposure or quarry, chips were taken at more or less regular intervals across the deposits, the spacing of the intervals being slightly varied so as to obtain a sample that would be slightly below average in quality for the deposit, this to allow for any uncertainty or error in testing.

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* See also Table I - Location and Character of Materials Selected.

The samples of the third series, mostly from fresh and sound rocks, were collected so as to represent, as far as practicable, the average of the deposit. In quarries, they were taken from the stock pile or across the quarry face. In undeveloped deposits, pieces were broken from the rock at regular intervals in a line approximately at right angles to the strike. In the latter case, care was exercised in taking the pieces at sufficient depth to exclude any weathered surface material.

Shaly Limestone

Shale is mostly found in the Black River and Trenton limestones of eastern Ontario. It occurs in the form of thin films through the limestone which is otherwise fresh and sound. Although the proportion of shale to limestone is very small, probably below one per cent in the deposits sampled, it was thought advisable to test the stone to see if the widespread distribution of the shale films would impair the durability of the limestone as concrete aggregate, and also because these limestone deposits are closest to the proposed development work on the St. Lawrence.

Cherty Limestone

Chert occurs in only a few limestone deposits, mostly in the Onondaga limestone of southern Ontario. Several samples of the cherty limestone were taken from commercial quarries at the request of the operators. The samples included both weathered and fresh chert, or at least as fresh as could be found in the large quarries. They were tested to find whether or not the known poor behaviour of cherty limestone as aggregate in concrete was due to the weathered condition of the chert.

Rusty Sandstone

Iron oxide in the form of a rusty coating on the rock surface is found in a few deposits. Three samples were taken from a large quarry in Beekmantown calcareous sandstone and tested to determine what effect the rust would have on the durability of concrete in which this stone is used as coarse aggregate.

Serpentine

A sample of asbestos bearing rock (serpentine) was taken from a waste pile at the Beaver mine of the Asbestos Corporation, Limited, Thetford Mines, Eastern Townships, Quebec. The serpentine is a very fine-grained, dense, tough rock holding occasional veinlets of asbestos. The rock was tested to determine its durability in concrete structures, and also whether the small amount of asbestos that it holds would have an adverse effect.

Weathered Dolomite and Sandstone

Several samples were taken from partly weathered dolomite and calcareous sandstone of the Beekmantown formation. These rocks are quite sound and hard when fresh, and the purpose of the test was to find out to what extent partial weathering and high absorption resulting from weathering would lower the durability of the stone as concrete aggregate.

Basalt

The sample of basalt (No. 353) is from a large trap rock quarry east of Havelock and was tested at the request of the owner and operator, Building Products, Limited, and also because of the high quality of the rock as road aggregate; it being particularly suitable for non-skid pavements. The quarry is situated a long distance from the proposed work along the St. Lawrence but has good transportation facilities.

Dolerite

The sample of dolerite or trap rock (No. 355-356) is from George Island, off the northern coast of Prince Edward Island. The rock had been tested in the laboratory for road aggregate in connection with a road materials survey made in 1948, and the test results showed it to be a high grade rock for roads and pavements. With what was left from those tests, specimens were prepared for the present durability test. Dolerite also occurs at several places in New Brunswick.

Gravel

Of the twenty-five gravel samples of the first and second series, eighteen are from eastern Ontario, six from southern Ontario and one from near Chicoutimi, Quebec. Thirteen samples are from commercial crushing and screening plants. For the other twelve the main consideration in sampling was not so much the size of the deposit or the scale of operations as the type of rock. The two gravel samples of the third series are from a very large deposit on Grenadier Island, in the Thousand Islands district. In composition and size grading it is somewhat different from local mainland gravels.

The anorthosite gravel sample (No. 145-146) from near Chicoutimi was tested to find how the anorthosite would affect the durability of concrete. In a previous investigation on the strength of mortar made with Quebec gravels in 1929, some of the gravels in the hills north of Montreal, which had a high proportion of anorthosite pebbles, showed a lower tensile strength at 28 days than at 7 days.

Absorption

High absorption is usually associated with weathering, but there are some fresh rocks which owe their high absorption to their open texture or cavities, such as certain sandstones and dolomites. High absorption in itself is not indicative of an unsound rock, unless associated with a very fine texture and microscopic pores or caused by weathering. The sampled rocks with high absorption include: in the finer grained - Onondaga and Black River cherty limestone, Black River magnesian limestone and Niagara shaly dolomite; and in the coarser grained - Potsdam sandstone, partly weathered Beekmantown dolomite and calcareous sandstone, Guelph dolomite and Onondaga sandy dolomite.

PREPARATION OF TEST SPECIMENS

The rock samples were run through a crusher with the jaws set at 7/16 inch maximum distance at the outlet end and the crushed material was passed over a 3/8-inch screen (mesh opening 0.371 inch) and a No. 6 screen (mesh opening 0.131 inch). The material retained on the 3/8-inch screen was discarded, that passing the 3/8-inch screen and retained on the No. 6 screen was used as coarse aggregate for test specimens, and that passing the No. 6 screen (screenings) was used as fine aggregate. A regular grade of concrete sand was also used as fine aggregate. Thus, two mixes were prepared from each sample, one with screenings and the other with concrete sand as fine aggregate, the coarse aggregate being the same in both.

In Tables II, III, and IV, the two mixes for each rock sample have different numbers; the odd numbers refer to mixes with concrete sand and the even numbers to mixes with stone screenings.

Five of the gravel samples were prepared in the same way as the rock samples. The balance of the gravel samples were screened over a 1/4-inch screen and only that part passing the screen was used for the test specimens, with the exception of two samples in which that part retained on the 1/4-inch screen was run through the crusher and screened in the same way as for the rock samples, and that part passing the 3/8-inch screen was used as coarse aggregate for the test specimens.

Moulding of Specimens

For the test specimens of the first two series of samples, cubical moulds 3 inches in size and cylindrical moulds 3 inches in diameter and 3.82 inches in height were used, both having the same volume. For the third series of samples, only 3-inch cubical moulds were used.

In the first two series, four specimens were prepared for each rock sample, as follows: One cylinder and one cube with concrete sand as fine aggregate; one cylinder and one cube with the sample screenings (minus No. 6) as fine aggregate. The minus 0.371 plus 0.131-inch stone was used as coarse aggregate in all four specimens.

For the samples of the third series, five cubes were made, three with concrete sand and two with the sample screenings as fine aggregate, the coarse aggregate being the same in the five specimens. The size grading of the screenings was improved only slightly, namely, by limiting the minus 100 mesh to 10 per cent and discarding the excess, so as to bring the screenings more in line with the concrete sand used, which had about 10 per cent of minus 100 mesh. No change was made in the samples holding less than 10 per cent of minus 100 mesh.

Specimens with Screenings used as Indicators

The purpose of preparing specimens with stone screenings was to use them as indicators in the durability test. Since the specimens usually weaken gradually under the test some time before there is any visible sign of deterioration, the failure of a specimen with screenings could serve as a signal to keep the corresponding specimen with concrete sand under close observation for possible signs of failure.

Proportions of Cement and Fine and Coarse Aggregate

The relative proportions of cement and fine and coarse aggregate used in the first series were 1: 2: 3.5 by weight, which were subsequently changed to 1: 2: 3. The proportions used for each sample are shown in Table II which gives the test results for the first series. All specimens of the second and third series were 1: 3: 3 mixes, with the exception of four trial mixes which were 1: 3: 4 mixes for specimens W and X and 1: 3: 5 for specimens Y and Z (Table III). The gravel specimens, in which no coarse aggregate was used, were 1: 5.5 mixes for the first series and 1: 6 mixes for the second series.

Water-Cement Ratio

The water absorbed by the coarse aggregate was determined for each sample, and allowance was made for this in gauging the amount of water to be used in mixing, with the exception of the more absorptive aggregates of the first two series, which were immersed in water 24 hours before mixing and surface dried just before using. The water absorption of the screenings was not determined and was assumed to be 1.5 times that of the coarse aggregate of the same sample, for the first and second series. For the third series, the water absorption of the screenings was taken as twice that of the coarse aggregate. The concrete sand used was a clean, hard sand for which a water absorption of

0.5 per cent by weight was assumed owing to the dry condition of the sand.

The water-cement ratio is based on the fineness modulus of the aggregates, the proportions in the mix, and the degree of consistency desired for the mix. For the specimens with concrete sand as fine aggregate, calculations gave 0.54 as the water-cement ratio by weight for the specimens of 1: 2: 3 mix of the first series for normal or dry consistency, and 0.57 for the specimens of 1: 3: 3 mix of the second and third series. The fineness modulus of the screenings was not calculated. For most samples it was smaller than that of the concrete sand.

The water-cement ratio by weight of all mixes is given in the tables. It was kept as close as possible to 0.55 for the rock mixes and 0.6 for the gravel mixes without coarse aggregate. The ratio of 0.55 was later changed to 0.6 for the rock mixes with screenings as fine aggregate. The water absorbed by the aggregate is not included in these ratios. The high ratio of 0.85 given for mix No. 138 was due to an error in mixing while the low ratio of 0.41 was intentionally used for mixes 127 and 128 because of the large amount of water absorbed by the aggregate (5.37 per cent by weight). The amount of water for specimens Nos. 301, 302, 341, 342, 357, and 358 of the third series was determined by using the flow table, but this did not work satisfactorily owing to the relatively high proportion of flat fragments in the crushed samples hindering the flow, so the same water-cement ratio was used as for the first and second series. More regularly shaped fragments would have been obtained with the samples of the third series if these had been crushed in two stages instead of one, since the samples consisted of larger rock chunks than those of the first two series.

Tamping Mix into Moulds

The mixes of the first series were packed in the moulds with a rectangular tamper having a cross-section of 1 by 0.5 inch, such as prescribed in the A. S. T. M. specifications for mortar mixes. This method of tamping worked satisfactorily with the specimens having concrete sand as fine aggregate but did not give as good results with the specimens having screenings. The material in the latter was not uniformly packed, so that these specimens had more voids and a rougher surface than those with concrete sand.

For the second series, a round rod with a blunt point was used in rodding the mix. This gave better results than the tamper used in the first series in the sense that there was much less difference in appearance and voids-content between the specimens with sand and those with screenings. None of them, however, were packed as densely or had as smooth a surface as the specimens of the first series having sand as fine aggregate, but this may have been partly due to the leaner mix used in the second series.

For the third series, more vigorous tamping was done than in the other two series, using a rod with a flat circular end slightly less than one-half square inch in area. The change in manner of tamping was made because the crushed aggregates held a relatively high percentage of flat fragments, and more effective packing was deemed necessary in order to obtain specimens of uniform density. This method of tamping gave uniformly dense and smooth specimens with sand, and although those with screenings were not quite as good they were on the whole in better condition than the specimens with screenings of the first two series.

Preliminary Air Curing

All specimens were cured in water for 30 days and then stored in air at room temperature and humidity for several months, that is, five months for the first series, eleven months for the second series and one month for the third one. The air curing was not part of the original plan, but owing to other more urgent work, the durability test had to be postponed several months. The testing of the second series was also postponed for the same reason. The test on the third series could have been started right after the 30 day curing in water, but it was thought desirable to give the specimens at least one month air curing so that their condition prior to testing would not be too different from those of the first two series.

TEST PROCEDURE

Durability Test

The testing for durability consists in immersing the specimens in water at room temperature for about 5 hours and then taking them out of the water and putting them in the freezing room at 0° to -5 °F for about 19 hours. So one complete cycle of freezing and thawing takes 24 hours. The cycle is repeated daily until the specimen fails. To speed the handling during the second and third series, the specimens were not completely taken out of the water but were placed in pans, the latter in water so as to completely immerse the specimens. After the 5-hour period, the pans were taken out of the water, partly drained so as to leave one-half or three-quarters inch of water, and then placed in the freezing room for the 19-hour period.

In the first series, the 116 specimens (58 mixes), were run through 149 cycles of freezing and thawing. In the second series, consisting of 186 specimens (93 mixes), one half of the number of specimens, one of each mix, were submitted to a compressive strength test before the start of the durability test, and the other half were run through 164 cycles of freezing and thawing. In the third series of 152 specimens (61 mixes), about 100 specimens were run through 149 cycles of freezing and thawing, while the remainder were tested for compressive strength 15 months after moulding.

Soniscope Test

In the second and third series, the gradual deterioration of the specimens could be followed with the Soniscope, which was not available until the durability test on the first series of samples was completed. With the additional data given by the Soniscope apparatus, the indicator specimens could, it would seem, have been dispensed with. However, specimens with screenings as fine aggregates were also prepared with the samples of the third series, because the information obtained with the Soniscope on both types of specimens while the second series was undergoing the durability test proved helpful in interpreting the test results and threw more light on the probable cause of failure of the specimens with concrete sand as fine aggregate. They are also useful in determining the suitability of the rock for the making of artificial concrete sand.

The Soniscope apparatus was designed by the Hydro-Electric Power Commission of Ontario for testing the soundness of concrete structures. It is an instrument which transmits an ultra-sonic wave impulse through the concrete. Any crack, lack of homogeneity or other defect is indicated on the instrument by a reduction in velocity of the wave impulse.

Method of Using the Soniscope

The Soniscope apparatus proved very useful in observing the gradual deterioration of the specimens undergoing the freezing and thawing test. The instrument was designed primarily for testing the soundness of field structures up to 50 feet in thickness (dams, etc.). Although in testing small laboratory specimens such as three-inch cubes the same order of accuracy cannot be expected as in testing field structures, good results can be obtained with proper care in conducting the test.

In testing the condition of field concrete structures a formula is provided wherewith the modulus of elasticity of the concrete can be calculated from the reading of the apparatus. A table giving directly in general terms the condition of the concrete corresponding to different wave impulse velocities as calculated from the Soniscope readings is also provided for concrete of normal density, so that the conversion of the velocity into the modulus of elasticity can be dispensed with. A reproduction of the table follows:

Soniscope Indications of the Condition of Concrete in Relation to Wave Velocity

Wave Impulse Velocity		Condition
feet/ sec.	metres/ sec.	
Above 15000	Above 4500	Excellent
12000 - 15000	3600 - 4500	Generally good
10000 - 12000	3000 - 3600	Questionable
7000 - 10000	2100 - 3000	Generally poor
Below 7000	Below 2100	Very poor

The table is to be interpreted in a general way, since it is found that the velocity is influenced not only by the quality of the concrete but also to some extent by the character of the aggregate. In order to interpret accurately the Soniscope indications, it is essential to know as much as possible about the concrete being tested. In most cases two or more readings are taken at different intervals, so that the condition of the concrete can be ascertained by comparing the readings.

In the present investigation the Soniscope was used with the purpose of following the gradual deterioration of laboratory specimens undergoing the durability test. Readings were taken at different intervals as the freeze-thaw test progressed. The important point in this test was not so much the absolute velocity of the wave impulse as the amount of rate of reduction in the velocity after so many cycles of freezing and thawing. For instance, some specimens which the Soniscope indicated as being in "excellent" condition at the start of the durability test, according to the above table, deteriorated rapidly in the test, whereas others, indicated as "generally good" or even "questionable" at the start, deteriorated at a much slower rate. In general the rate of deterioration, if not too fast, was fairly constant after a certain number of cycles. It has already been said that for specimens made of materials of average soundness the wave impulse velocity increased during the first part of the test, then decreased rather rapidly for a period to become slower and then remain constant. The point of failure was determined also from the percentage of decrease in the velocity of the wave impulse rather than from a limiting value in the absolute velocity.

Definition of Specimen Failure

At every ten or fifteen cycles, the specimens were given a visual inspection. A specimen was deemed to have failed when a whole face had chipped or spalled off, when the specimen had split through, or when the velocity of the wave impulse as indicated by the Soniscope had been reduced a certain percentage.

The spalling off in nearly all cases starts at the corners or edges of the lower part of the specimen which receives more severe treatment in the freeze-thaw test than the upper part. Throughout the test the specimen sits in the same position as when moulded, that is, on the bottom face. A specimen was considered as having failed in the test on the first series when none of the original surface remained on the bottom face.

The splitting across occurred only in the specimens of the first series having screenings as fine aggregate and was apparently due to uneven packing of the mix, since the splitting in nearly all cases occurred at a line about one inch above the bottom face of the specimens, or at the line of separation between the first and the second layer (in all specimens the mix was poured in three layers and each layer tamped separately). In the other two series a different method used in packing the mix eliminated this cause of failure.

The gradual deterioration of the specimens of the second and third series in the durability test could be observed with the Soniscope. In the test on the second series, a specimen was considered as having failed either when the original surface of the bottom face of the specimen had disappeared through gradual spalling off or when the Soniscope indicated a 13 per cent reduction in the speed of the wave travel up to the 125th cycle, which ever occurred first. The limiting of the permissible reduction in speed of the wave impulse to 13 per cent is arbitrary and was arrived at after consideration of the quality of the aggregate and the results of the compression test run just before starting the durability test. A line had to be drawn somewhere in order to separate the suitable from the less suitable aggregates, and 13 per cent at 125 cycles appeared to give the more satisfactory line of demarcation. A lower percentage would have left out some of the better aggregates, while a higher percentage would not have eliminated some of the more doubtful or even poor aggregates.

The specimens of the third series suffered less spalling in the freezing and thawing test and appeared in better condition than those of the first two series after the same number of freeze-thaw cycles. As the test progressed, however, the velocity of the wave impulse as indicated by the Soniscope decreased at a faster rate than for the specimens of the second series. For these reasons the specimens of the third series were deemed to have failed when the reduction in velocity of the wave impulse reached 20 per cent. Another reason for drawing the line at that point is that the Soniscope readings became more erratic beyond the 20 per cent reduction.

Compressive Strength Test

For compressive strength, all specimens were tested after being dried for various periods in air at room temperature and humidity with the exception of a number of specimens of the third series, which, after two month's storage in air, were immersed in water for 24 hours and tested immediately after. The test results look unusually high for specimens that have been through 150 cycles of freezing and thawing. Except for the specimens tested before the start of freeze-thaw test of the second series, all were tested without capping. Since all the specimens that had been through the durability test were in a more or less damaged condition, the plates of the testing machine were in contact with only part of the end areas of the specimens, so an allowance had to be made for that in calculating the unit strength. Most of the surface damage done to the specimens by the durability test occurred at or near the bottom as moulded, since they were kept in that position throughout the freeze-thaw test. For the compression test, however, they were laid on their side so that the pressure of the machine would be applied on the faces that were in contact with the walls of the mould when moulding the specimens. They were tested for compression in that position because the side faces of the specimens were truer planes than their top faces, and also to avoid the constraining effect of that part of the specimen not under the direct pressure of the machine. In this position whatever constraining effect took place was done by the most damaged part of the specimen.

Curing Periods During and After Durability Test

The freeze-thaw test on the first series was interrupted for 12 days after cycle 105 for repairs to the freezing plant. During that time the specimens were left in the water. After 149 cycles (end of freeze-thaw test) the specimens were stored in the air at room temperature and humidity for 22 days and then immersed in water for three days prior to the Soniscope readings. After the Soniscope determinations they were left to dry in the air for 10 days and then tested for compressive strength.

The second series went through the freeze-thaw test without interruption up to the 157th cycle. The specimens were left in the water for 27 days prior to making a Soniscope determination. The unexpectedly high results obtained on the Soniscope indicated a healing effect caused by the 27-day water immersion. The specimens were then run another seven cycles (164 cycles in all) with the expectation that the Soniscope indications would be more in line with those obtained before the 27-day immersion, but the Soniscope readings taken immediately after thawing the specimens at the end of cycle 164 were only slightly different from the ones taken after the 27-day immersion in water. The specimens were then put back in the water and another Soniscope determination made after a 25-day immersion. The Soniscope readings were again higher than the ones taken before the 25-day immersion, in fact for most of the specimens with concrete sand as fine aggregate the readings were as high as those taken before the start of the freezing and thawing test. The healing effect was more marked with the stronger specimens than with the weaker ones. For the purpose of interpreting the test results in relation to the durability of the different specimens, the freezing and thawing test may be considered as having ended at the Soniscope determination made immediately after cycle 125, since no other Soniscope readings were taken until after cycle 157.

While running the durability test on the third series of specimens, trouble was experienced with the freezing apparatus resulting in several interruptions on the test between cycles 50 and 100. The specimens were left in the freezer during short interruptions and in the air at room temperature if the interruption lasted more than two days. As judged by the Soniscope indications, the air storage of the specimens during the longer interruptions seemed to have also a healing effect on the specimens although the effect was not so pronounced as with water immersion of the same duration. At no time during the entire test, which was run 149 cycles, were the specimens more than a few hours in water between freezings. Although the interruption did not affect all the specimens to the same extent, that is, the stronger ones probably recuperated more during the periods of rest than the weaker ones, the effect was not marked enough to render the interpretation of the test results more doubtful than for the first two series.

TEST RESULTS

General

Comparison of the Three Series

Comparisons between the three series as regards the test results can only be made in a general way, because of the different mixes used, the different methods of packing the mixes in the moulds and different conditions under which they were tested. A comparison of the first series with the second and third ones is also difficult to make because no compressive strength and Soniscope tests were made on the first series until after the durability test. The unusually high results obtained in the compressive strength and Soniscope tests made at the end of the durability test on the first series may be the cumulative effect of several causes, such as the richer mixes used, the amount of healing taking place during the 35-day interval between the end of the freeze-thaw test and the compressive strength test, and finally the constraining action of the capping which had to be made thicker because of the more or less damaged condition of the specimens. Other possible causes will be mentioned below when comparing the second and third series.

Effect of Varying Mix Proportions

The effect of varying the proportions in the mix on the test results is well shown in the trial mixes U to Z at the head of Table III, all made with the same stone as aggregate, a fine grained limestone holding but little shale. The proportions in the mix were 1: 3: 3 for U and V, 1: 3: 4 for W and X, and 1: 3: 5 for Y and Z. The difference in the test results on these trial specimens, however, was made even greater because of the difficulty of tamping the mixes with the large proportions of coarse aggregate and the higher percentage of voids in the specimens, particularly those with stone screenings as fine aggregate, such as X and Z.

In comparing the second and third series, in which the proportions in the mix are the same (leaving out the trial specimens U to Z) and which were tested under about the same conditions, at least as far as cycle 125 for the second series, it is found that the effect of following different methods of packing the mixes for the two series is reflected in the test results. The more vigorous tamping adopted in the third series produced denser specimens, which had the effect of increasing their strength as shown by the compressive strength and the Soniscope tests made before starting the freeze-thaw test. However, they weakened at a slightly higher rate in the durability test than those of the second series, although the proportion of specimens that failed was smaller.

Effect of Packing Methods

The method of packing adopted in the second series, which consisted of rodding the mixes into the moulds, was probably the more satisfactory, mainly because the difference in density and surface smoothness between the specimens with concrete sand and the ones with stone screenings was smaller than between the corresponding specimens of the first and third series. Furthermore, this difference between the specimens with concrete sand and those with screenings was greater in the first than in the third series. In the latter there was a larger proportion of flat particles in the crushed and screened samples, and because of this it was deemed advisable to use a more vigorous method of packing the mixes than in the first two series.

Compressive Strength Test

The high strength of the specimens may be explained by assuming that the upperpart of the specimens suffered but little deterioration in the durability test. Another explantion is that the fine material derived from the gradual deterioration of the specimens acted in the manner of a clay binder, i. e., exercised a strong cementing action only when in a dry condition. The fact that the 24 hours immersion in the third series reduced the strength by an average of 27 per cent would tend to confirm the latter view. The Soniscope determinations, which are always made on saturated or at least thoroughly wet specimens, are also more in line with the compressive strength of the wet specimens. In any case it would have been preferable to make all the compressive strength tests on the specimens in the wet condition.

Soniscope Test

In testing the second and third series it was observed that the Soniscope readings showed increases in the velocity of the wave impulse from the start of the freeze-thaw test up to about cycle 35, tending to indicate an increase in soundness of the specimens. After that the velocity decreased at a rather rapid rate, sothat at about cycle 50 the velocity was slightly less than at the start of the freezing and thawing test. Past the 50th cycle the velocity decreased but at a slower rate. Since this early increase affected all specimens made of rocks or gravels of average soundness, and since the specimens which did not register any increase in the first part of the durability test were among the earlier failures, the increase in the first part of the freeze-thaw test is apparently not abnormal.

Effect of Weathering

An interesting fact was brought out on investigatingthe cause of failure of the specimens with stone screening as fine aggregate. It was observed that specimens made of freshly quarried rock or rock that has not been exposed to the weather for more than one or two years failed earlier in the test than the ones made of the same kind of stone exposed to the weather for years, say 15 or more. Examples of this occurred in all three series.

There is a possible explanation to account for this behaviour, at least in the case of the limestones with shale films. The usual effect of long exposure is to split the rock along the films or to weaken the cohesion of the rock along that direction without altering or otherwise affecting the limestone between the films, which usually remains fresh even after ages of exposure. A sample of rock long exposed to the weather, when run through a crusher, would break much more easily along the films than would a freshly quarried rock. This would materially reduce the chances of further breaking or splitting of the aggregate when later exposed to adverse conditions, such as freezing and thawing. It is probable also that the shale gradually loses all its reactivity or sensitivity on long exposure.

In large-scale quarrying for concrete aggregate to be used in field structures, long exposure to the weather would be out of the question and the rock would break in any direction in the crusher, so that many fragments would have films of unweathered and reactive shale running through them. For field structures also the coarse aggregate would be of larger sizes than those used in preparing laboratory specimens, probably several inches as compared with the 0.371 inch maximum used in the laboratory. In the coarser field crushing there would be less concentration of the shale in the screenings than in the finer laboratory crushing, so that more of the shale would remain in the coarse aggregate, thus increasing the risk of the aggregate splitting and disrupting the concrete structure, since the splitting of the aggregate is probably brought about by the swelling or increase in volume of the shale.

Specimens with Screenings as Fine Aggregate

The assumption that specimens with screenings as fine aggregate have a lower durability was shown to be valid by the test results, except in the case of the rocks holding little, if any, objectionable material, such as the sandstones and most of the dolomites. For most of the limestones the difference between the specimens with concrete sand

and the ones with screenings was even greater than had been assumed at the outset, which suggested that the cause of failure of the specimen with limestone screenings was due more to the fine (screenings) than to the coarse aggregate. The failure is probably due to a concentration of shale particles in the screenings in the process of crushing and screening the samples. The large amount of fines (minus 100 mesh) may have been a contributing factor in the failure of some specimens, although the composition of the screenings has a greater influence on the durability than their size gradings.

In examining the specimens with limestone aggregate after failure it was observed that some of the large limestone fragments had split in two, generally along shale films. This, however, could not be considered as the main cause of failure, since the corresponding specimens with concrete sand went through the test without too much deterioration. The splitting of the coarse aggregate was almost exclusively confined to the very fine-grained limestone of the Black River.

The specimens with stone screenings as fine aggregate proved their usefulness in more than one way. They are more sensitive than the specimens with concrete sand to the effects of slight defects or objectionable materials in the stone, which in some cases are difficult to detect on visual inspection alone. Their greater usefulness probably is in connection with the making of artificial sand by rock crushing and screening.

Reasons for Failure of Specimens with Screenings

It is thought that the specimens with stone screenings as fine aggregate failed earlier in the test than the corresponding specimens with concrete sand for the following reasons:

With the proportions of coarse to fine aggregate used in preparing the specimens, those with screenings hold about twice as much rock as those with concrete sand.

The objectionable material likely to cause failure is more friable, crumbling more easily than the sounder part of the sample, so that the crushing and screening of the sample leaves more of this objectionable material in the screenings than in the coarser aggregate.

The screenings are more dusty and less regular in size grading than the concrete sand. This cause of failure was partly eliminated in the specimens of the third series by limiting the amount of minus 100 mesh to 10 per cent or less.

In preparing the specimens, slightly more mixing water had to be used for those with screenings than for those with concrete sand to obtain the same consistency.

Although prepared in exactly the same manner, the specimens with concrete sand have a smoother surface and hold less voids than those with screenings.

By Series

First Series

The test results and other data on the specimens of this series are shown in Table II. All specimens were run 149 cycles of freezing and thawing, except those that failed before the end of the test and trial specimen U which was run 82 cycles with this series and 164 cycles in the test on the second series. The gradual deterioration of the specimens under alternate freezing and thawing was not observed as the test progressed because the Soniscope was not available at that time.

In the course of the test, 18 specimens failed, of which one was prepared from a gravel sample and 17 from rock samples. All 17 specimens from rock samples had screenings as fine aggregate. The following comments are limited to a discussion of these since no failure occurred among the specimens with concrete sand.

Specimens Nos. 112, 134 and 136, made from two picked samples of presumably shale-free Black River limestone, failed much earlier in the test than expected; in fact they lasted hardly longer than other limestone containing some shale. The two picked samples may have held a high proportion of fines (minus 100 mesh) after crushing and screening, or more probably held some shaly or argillaceous matter in very thin films more or less uniformly distributed throughout the limestone and not so easily detected by visual inspection as the thicker films or partings in other limestone samples. The fact that in most samples of Black River limestone both limestone and shale are dark in colour and fine in grain would make the detection of thin films difficult. Another possible cause of early failure may be that both samples had been taken from rocks exposed only a short time to the weather, so that what little shaly or argillaceous matter was present still retained much of its sensitivity. Other cases will be mentioned where recently quarried rocks holding a small amount of shale deteriorated at a faster rate in the durability test than similar rocks exposed to the weather for years.

The failure of magnesian limestone No. 128 is probably due to a combination of fineness of grain and very high water absorption.

The Beekmantown dolomites survived the test without registering any failure, even though all samples were taken from partly weathered material. The calcareous sandstone of the same formation did not fare so well, although the first failure occurred only when the test had reached the 74th cycle. This stone shows more variation in texture and water absorption between the different beds than the other stones sampled. The failure of calcareous sandstone No. 126 was apparently due to the rusty condition of the stone and the concentration of the more rusty and friable part in the screenings. Two other specimens, Nos. 350 and 352, of less rusty stone from the same quarry were tested in the third series but gave no better results. In fact the specimen from the fresher of the two samples failed first. No. 118 failed earlier than expected. The stone used in this specimen had weathered to a rusty brown colour but the thickness of weathered material was generally not more than a small fraction of an inch.

Mixes Nos. 145 and 146 were made with a gravel holding 60 per cent of anorthosite pebbles. All but the anorthosite pebbles were discarded, and these were crushed and screened. The specimens were prepared in the same way as rock samples, except that in mix No. 145 that part of the sample passing the No. 6 sieve was used as the fine aggregate instead of concrete sand. At the completion of the test, specimen 146 was in poor condition but had not yet deteriorated to the point of failure, as erroneously stated in the progress report of May, 1951.

As judged by the results of the durability test on the specimens with screenings as fine aggregate (indicator specimens) the Beekmantown dolomite stands out as the more durable stone, with the calcareous sandstone of the same formation ranking next. The test results put both Trenton and Black River limestones on about the same level as regards durability. However, the early failure of two presumably shale-free Black River limestones, and the splitting of some of the coarse aggregate in a few of the very fine-grained stones of the Black River formation would indicate a greater durability for the Trenton. The Trenton specimens with concrete sand gave better results also in the compressive strength and Soniscope tests than those of the Black River.

The twelve gravel specimens prepared from the material passing the No. 4 sieve gave somewhat poorer results in the durability test than the rock specimens with concrete sand as fine aggregate. In Table II, gravel specimen No. 154 is marked as having failed at 12 cycles. This applied to the cylindrical specimen. The cubical specimen had not disintegrated to the point of failure at the end of the test. The specimens prepared from samples collected in the pit banks gave better results in the test than those made from samples collected from stockpiles of crusher run material. The difference in the results is more apparent in the compressive strength test than in the Soniscope reading. For example, Nos. 148 and 149 are two specimens from the same deposit, the first one from a stockpile of crusher run material and the second one from the pit bank. Nos. 154 and 285 (the latter in the second series, Table III) are also from the same deposit, the first from the pit bank and the second from crusher run material. The reason for the difference in results is that for the pit run gravels the coarser part (pebbles) is largely composed of limestone with shale films while in the part passing the No. 4 sieve (sand) quartz and hard rock grains predominate. In the crusher run material, however, a large proportion of the limestone pebbles are crushed to the size of the finer part (minus No. 4 sieve) with probably a concentration of the more friable shaly material in the screenings.

Second Series

The freezing and thawing test was run 164 cycles, but the run from cycle 157 to 164 was in the nature of an experiment to study the healing effect of long immersion in water. After 157 cycles the specimens were left in water for 27 days after which Soniscope determinations were made. The specimens were then run another 7 cycles (164 cycles in all) and Soniscope readings taken immediately after thawing the specimens (Table III). From these readings it is seen that the 7 cycles of freezing and thawing did not completely nullify the effect of the 27-day immersion.

A leaner mix than the ones used in the first series was adopted with the idea of shortening the duration of the freezing and thawing test. Trial mixes U to A at the head of Table III were made to find out which would be the more suitable of the three mixes 1: 3: 3, 1: 3: 4 and 1: 3: 5. The 1: 3: 3 mix was selected mainly on the appearance of the specimens after removal from the mould.

As seen from Table III, thirty-seven specimens failed in the course of this durability test, nine of them having concrete sand as fine aggregate. Two of the latter are trial specimens W and Y which are made of leaner mix than the regular specimens. A few specimens which failed by spalling between cycles 100 and 109 had registered on the Soniscope at cycle 100 only a slight reduction (3 to 5 per cent) in the velocity of 13 per cent or more at cycle 125.

Most of the limestones behaved in about the same manner as those of the first series, that is, the specimens with screenings deteriorated at a much faster rate than the corresponding specimens with concrete sand, except three of them, Nos. 212, 230 and 262, which deteriorated at the same rate as the corresponding specimens with concrete sand and lasted to the end without failing. Trenton limestones 212 and 230 were taken from old quarries that had been idle for many years and the stone apparently held as much shale as most other limestones of the series. No. 262 is a mixture of shale-free limestone and magnesian limestone of the Detroit River. The sample was taken from the conveyor belt in a commercial quarry located in southwestern Ontario.

The four samples of magnesian limestone gave better results than the limestones notwithstanding their much higher porosity. Of the specimens with screenings, two went through the test with no more deterioration than the specimens with concrete sand, one lasted until cycle 109 and the fourth one, which was more shaly than any of the limestones, failed at about cycle 40.

All cherty limestone weakened at a fast rate and went down early in the test with the exception of No. 245 which lasted until cycle 100. No. 245 is from a picked sample of fresh cherty limestone, or as fresh as could be found in the quarry face.

Some of the soft and friable rocks, such as the Potsdam sandstones and the Guelph dolomites gave better results and deterioration was much less than expected of such soft rocks. In this connection it may be of interest to mention that many concrete sidewalks built in Ottawa in the years 1903 to 1907 with Nepean (Potsdam) sandstone as coarse aggregate, which is a rather soft and porous stone, are still in good condition with comparatively little cracking. They do not show signs of disintegration or even pitting, even though the sandstone aggregate is now much exposed in the surface after many years of wear.

All shale-free dolomites stood up well under the test with the exception of Nos. 243, 244 and 260. The two specimens 243 and 244 were from a sample of Bertie-Akron dolomite holding a small amount of chert, and their failure can be imputed to the chert. The failure of No. 260 of Guelph dolomite, however, cannot be easily accounted for. Nos. 257, 258, 259 and 260 were prepared from two samples taken from the same quarry. Nos. 257 and 258 are from buff, soft, porous dolomite, and Nos. 259 and 260 are from dark brown, hard, slightly porous dolomite which occurs only in the lower 7 feet of the quarry. Both specimens of the softer buff stone and specimen 259 of the much harder brown stone weakened but little in the test, while No. 260 of the brown stone failed at cycle 34. It could not have been damaged on removal from the mould or in handling, judging from the Soniscope reading of 15, 500 feet per second before the beginning of the durability test. The reading of 13, 900 at cycle 19, however, showed that it had weakened more than the other three specimens. In fact, Nos. 257 and 258 registered an increase of 500 feet per second at cycle 19. The Niagara dolomites, although much harder than the Guelph dolomites, deteriorated slightly more than the latter in the durability test.

The shale-bearing dolomites behave much the same as the limestone with shale films, in that the specimens with screenings weakened at a faster rate than the ones with concrete sand. In one of them, Nos. 241-242, holding more shale than the others, both specimens failed, although the one with concrete sand lasted much longer than the other.

The Beekmantown dolomite (Nos. 215-216), represented by one single sample in this series, stood up fairly well under the test, taking into consideration that the sample was of slightly poorer rock than the samples of similar rock tested in the first series. The single sample of Chazy limestone (Nos. 201-202) was not much different in texture and shale content from the Black River limestone and gave about the same results in the durability test, although the specimens with screenings lasted till the 124th cycle.

The sample of asbestos-bearing serpentine (No. 271-272) behaved somewhat differently from the other rocks. The specimen with screenings, which was weak from the start, failed at cycle 18, due to the concentration of asbestos in the screenings. The specimen with concrete sand stood up quite well until cycle 125, with a reduction of the wave velocity of only 6 per cent, but from cycle 125 to cycle 164, the wave velocity was reduced another 6 per cent, notwithstanding the healing action of the 25-day immersion after cycle 157. The compressive strength of 1,100 lb. psi. for one of the specimens with concrete sand (No. 271) was undoubtedly too low. The specimen must have been damaged on removal from the mould or in subsequent handling, since the other specimen with concrete sand registered 2,400 lb. psi. in the compression test after going through 164 cycles of freezing and thawing. The five samples of gravel pebbles, composed mainly of shale-free dolomites and limestones, registered no failure in the freeze-thaw test. In the seven samples of gravel and sand, four failures occurred, three of them due to shale, and the fourth one, No. 286, due to much weathered material in the minus 4 mesh. Specimen No. 281 which was prepared from a shaly and dusty crusher-run gravel, never hardened and never dried properly.

Specimens Nos. 282 and 283 are from two different samples collected from a large pit, in which the material is processed for concrete and road aggregate. Close to 95 per cent of the gravel pebbles are limestone, and about 50 per cent of the limestone pebbles have thin shale partings. No. 283 was taken from the pitbank and had very little shale after the plus 4 mesh pebbles were screened off. No. 282, which failed at cycle 125 in the durability test, was taken from a stockpile of crusher run gravel and held some shale in the minus 4 mesh derived from the crushing of the pebbles. All the four gravels that failed in the test are used exclusively for road purposes.

Third Series

The durability test was run 149 cycles on three of the five specimens of the third series prepared from each sample, the other two specimens being kept in reserve for the compressive strength test and stored in air at room temperature and humidity. All specimens that did not suffer too much damage in the freeze-thaw test were stored in air after the completion of the test at 149 cycles, and two months later they were tested for compressive strength together with the specimens that had been kept in reserve. All specimens were tested dry, except a certain number that were put in water 24 hours before testing.

The same proportions in the mix, i. e. 1: 3: 3, were used in this series as in the second series, but the method of packing was done with a tamper having a flat, circular end, 0. 5 square inch in area. Because of the larger proportion of flat fragments in the crushed sample, the mixes were packed more vigorously than in the other two series. For specimens Nos. 301, 302, 341, 342, 357 and 358, which were prepared on the first day of mixing, the water-cement ratio was determined with the flow table, but this did not work satisfactorily, as already explained, so the same W/C ratio was used as in the second series, that is, 0. 55 for the specimens with concrete sand and 0. 60 for the one with stone screenings, both ratios being on a weight basis.

The results of the compressive strength and Soniscope tests made both before and after the durability test are given in Table IV.

Other Soniscope determinations were made at intervals as the freezing and thawing test progressed.

Table IV shows that thirteen failures occurred in the course of the freezing and thawing test, all of them among the specimens with stone screenings as fine aggregate. Eight of the failures involved stones with shale films; six limestones and two dolomites. The stones with shale films behaved in much the same manner as in the other two series, in that the specimens with stone screenings deteriorated at a much faster rate than the ones with concrete sand. Among these eight failures attention may be drawn to specimen No. 306, prepared from the same sample as specimen No. 110 of the first series. No. 306 just failed at the end of the durability test (cycle 149), while No. 110, made of a richer mix, failed at cycle 50 in the first series. It is possible that No. 110 held more shale than No. 306, since only part of the sample was crushed and screened in the preparation of mixes Nos. 109 and 110, and later on another part of the same sample was processed for mixes Nos. 305 and 306. In the average deposit of limestone with shale films, the films are irregularly distributed throughout the limestone and, in taking a sample, the shale content of the different rock fragments making up the sample may vary within fairly wide limits. In the deposit where the sample was taken, however, the shale films are very thin and regularly distributed at one-half to one inch intervals. It is more likely that the difference in durability of the two specimens was due to the different methods used in the two series for packing the mix. Specimen No. 306 was denser and had a smoother surface than No. 110.

All three calcareous sandstones included in Table IV failed, at least as far as the specimens with screenings are concerned. Calcareous sandstone samples specimens Nos. 349-350 and 351-352 were taken from the same quarry as the sample for specimens Nos. 125-126 of the first series. The stone in the quarry is fairly fresh, except at the numerous joints and some bedding planes where it is more or less weathered and quite rusty. Specimens Nos. 125-126 included mostly weathered and rusty stone, Nos. 349-350 represented the quarry average, and Nos. 351-352 included only fresh stone, or as fresh as could be obtained, yet the specimen using screenings No. 352 failed much earlier in the test than the same type of specimen in the other two sets. In examining the fresh stone, it is seen that there are numerous black lines, like pencil marks, running through it. The composition of the material making up the lines was not determined, but the behaviour of the rock in the test suggests that they are composed of iron-bearing shale, and that this shale possessed more sensitivity in the fresh than in the weathered and rusty rock.

Of the other two failures, one occurred in silty and partly weathered dolomite, Nos. 317-318, and the other in the dolerite (trap rock), Nos. 355-356. The latter were made from a sample taken in

Prince Edward Island in 1948 and tested for road purposes. The left-over part of the sample was used in preparing specimens for the durability test. The cause of these two failures is not known, but the dolomite is very impure and for this reason would not be expected to give good results in the durability test.

Specimen Nos. 311-312 were made of material from the same deposit as Nos. 111-112 of the first series, but not from the same bed. Nos. 111-112 were from recently quarried rock and Nos. 311-312 from outcrops, 200 yards from the quarry. Both rocks are very fine in grain but are not otherwise similar; the first being a medium soft, pure or presumably pure limestone, and the second a hard magnesian limestone. There is no shale visible in either rock. The test results on specimen Nos. 311-312 are about what would be expected, but 112 stood up very poorly for a pure limestone. It is probable that the rock of specimen Nos. 111-112 holds some shaly or argillaceous matter either in very thin films or more or less evenly disseminated throughout the lime stone, conditions difficult to detect by visual inspection alone. This would account for the failure of specimen No. 112 in the durability test. Since the rock from which specimen Nos. 111-112 were taken has been quarried only recently, the objectionable matter in the rock would still retain much of its sensitivity.

Specimen Nos. 315-316 are from a coarse-grained, rather soft limestone of the Chazy formation and quite different from Nos.

201-202 of the second series which are also from the same formation. The rock behaved in the durability test somewhat like some of the dolomites, in that the specimen with stone screenings deteriorated less than the one with concrete sand.

Precambrian basalt (No. 353) weakened little in the freezing and thawing test, judging from the compressive strength test before and after the durability test, eventhough the Soniscope readings indicated a rather fast rate of deterioration for such a hard and tough rock.

The Beekmantown dolomite stood up quite well in the test, leaving out of consideration a few impure or shaly stones. So did the Grenadier Island gravel, represented by the last four specimen Nos. 357 to 360 (Table IV). The slightly lower results from Nos. 357-358 as compared with Nos. 359-360 were undoubtedly due to the high-water-cement ratio in the mix. The effect of a high W/C ratio was also reflected in the test results on limestone Nos. 301-302 and dolomite Nos. 341-342.

The high results obtained on Beekmantown dolomite Nos. 319-320 may be due in part to the fact that the sample was taken from a shallow quarry that had apparently been idle for many years. It lies in low ground and is partly under water in the early part of the year. Under these trying conditions any shale and other reactive matter in the rock of the quarry face and bottom must long ago have lost their "punch".

CONCLUSION

With the type of freezing apparatus available for the test, it was not convenient to run more than one cycle of freezing and thawing in 24 hours. This made the tests last a long time, with the attendant risk of temporary interruptions for defrosting or repairs. The time lost during these interruptions is not only that of the interruptions themselves, but also of the extra cycles that must be run to counteract the 'curing' effect the interruptions have on the specimens under test. The slow freezing apparatus may reproduce more closely the conditions affecting structures in the field, but this is a small advantage when put against the efficiency and time saving of quicker freezing and thawing system.

As already mentioned at the beginning of the report, the third series included mostly sound stones and the other two series included, besides crushed aggregate from commercial producers, mostly stones that are considered good but hold small amounts of presumably harmful matter, such as shale, weathered or rusty material, etc. A few samples of stone which because of their slightly higher content of harmful material were of more doubtful quality were also included in the three series. However, no samples were taken of stones that were either of poor or much doubtful quality.

In looking over the test results of the three series, the number of specimens with concrete sand as fine aggregate that failed in the test appears surprisingly small. Leaving out the experimental specimens U to Z and the gravels, only seven failures were recorded, all in the second series. Four of the failures were limestones holding large amounts of chert (Nos. 233, 245, 247, 249). These were investigated because of the stone's poor reputation as concrete aggregate. However, the stone is harder and tougher than the orinary chert-free limestone, has been extensively used with good results for railway ballast, and has been satisfactory as bituminous paving aggregate.

The wide difference in durability in the limestones, between the specimens with concrete sand and the ones with screenings, may be explained by the fact that the shale in the coarse aggregate is more or less locked up, whereas in the screenings, which are much finer and have a much larger surface area, the shale has more chance to exert its harmful effect. Even in the comparatively pure limestones composed of 95 per cent or more of calcium carbonate, if the remaining 5 per cent is mostly reactive shale it would be more than enough to explain the early failure of the specimens using screenings prepared from these pure limestones.

Magnesia seems to have a beneficial effect on durability even when present in a relatively small amount. For instance, the magnesian limestones of the Black River formation stood up better in test than the limestones, although they are soft and porous and on visual inspection alone would be judged as rather poor stones. Most of the stones high in magnesia, such as the Beekmantown magnesian limestones and dolomites (both designated as dolomites in this report), the Niagara dolomites, and the soft and porous Guelph dolomites deteriorated little in the freezing and thawing test.

The rocks that are closest to the site of the proposed St. Lawrence River development and that are available in large amounts comprise the Black River limestone and, farther inland, the Trenton limestone. Fairly pure Black River limestone is exposed east of Eamer's Corners and lies close to the surface as far west as Mill Roches. The nearest large exposure of Trenton limestone is at Strathmore but the stone is rather shaly, that is, holds many shale partings, and for this reason was not included in the investigation.

Chazy limestone underlies a fairly large strip of land near the St. Lawrence but is not exposed anywhere except in two old quarries, one near Summerstown Station and the other at the water's edge on Sheek Island.

Beekmantown dolomite underlies part of the town of Cornwall, Cornwall Island, and a large area south of the St. Lawrence River, including a large section of Huntingdon county and the northern part of Beauharnois county in Quebec. There are no known outcrops near Cornwall but in Beauharnois county several large exposures of hard and rough dolomite are found at several places. Beekmantown and Potsdam sandstones are also available in this county and the latter also in Ile

Perrot. These sandstones are harder and not so porous as the two sandstones included in the second series, and which stood up well in the durability test.

Another large area of Beekmantown dolomite starts at Iroquois, occupies nearly all Grenville county and large portions of Leeds, Lanark and Carleton counties. The rock is available in large amounts at several places close to the shore of the St. Lawrence River between Iroquois and Brockville and at numerous places farther inland. Near Iroquois and Cardinal the stone is more impure and more variable in texture than farther west. The two Iroquois samples of Table IV include only the upper 2 to 3 feet, and the two Cardinal samples only the upper 6 to 7 feet of the deposits. There may be purer and better stone deeper in the deposits. One of the Iroquois samples and the ones taken near Johnstown, Ventnor, Spencerville, Prescott and Maitland all gave very good results in the durability test. The poorer results of specimens Nos. 341-342 north of Maitland were undoubtedly due to the high water-cement ratio of the two mixes. The failure of No. 346 was unexpected as there is no shale or other harmful matter visible in the stone. The stone is similar to dolomite Nos. 343-344 which stood up well under the test. Specimen Nos. 345-346 were made from freshly quarried material, while Nos. 343-344 were made from chips and fragments that had been exposed to the weather for many years.

The dark, very fine-grained Black River limestone available near Cornwall (No. 313) gave good results in the test as far as the coarse aggregate is concerned but not quite as good as most of the dolomites occurring farther west. For fine aggregate, the limestone appears to be much inferior to the dolomite, not to say unsafe to use. Specimen Nos. 313-314 were made from chips and larger fragments that may not have been as free of shale as the average of the deposit. Since, however, the material had been exposed to the weather for many years, what little shale there might have been would have lost a great deal of its sensitivity. In preparing specimen No. 314 no attempt was made to improve the size grading of the screenings, apart from limiting the amount of minus 100 mesh to 10 per cent. In the manufacture of artificial sand, size grading is strictly controlled, which may make some difference.

The Beekmantown dolomite from Beauharnois county was not included in the present investigation but, from the appearance of the stone and from tests made years ago in our laboratory to determine the suitability of the stone for road aggregate, there is hardly any doubt about its durability. Besides being harder and tougher than the Iroquois or Cardinal dolomites it is also more uniform in texture. The Beauharnois stone is about the same distance from Cornwall as the Iroquois or Cardinal stone, that is, between 30 and 40 miles.

TABLE I

LOCATION AND CHARACTER OF MATERIALS SAMPLED

First Series

101.102 - Old quarry owned by C.H. Clare, 0.5 mile N.W. of McAlpine. Fine-grained limestone with some shale films.

101.104 - New township quarry, 1 mile N.W. of Plantagenet. Fine-grained limestone with many shale films and a few shaly seams.

105.106 - Old quarry known as Stewart Quarry, 1.5 miles S.W. of Rockland. Fine-grained limestone with some shale films.

107.108 - Old quarry on the property of Philip T. Empey, 1 mile N. of Mille Roches. Very fine-grained limestone with many shale films.

109.110 - Road cut opposite Leo Cloutier's property, on which there are many outcrops. Lots 23, 24; Con. IX, Finch Township. Hard, medium fine-grained limestone with many shaly or bituminous films.

111.112 - Silvertone Black Marble Quarries, Ltd., 0.5 mile W. of St. Albert Station. Very fine-grained limestone with but few thin shale films.

113.114 - Old highway quarry, 3.5 miles N. of Johnstown. Very fine-grained, hard and tough dolomite.

115.116 - Old highway quarry, 2.7 miles S. of Franktown. Hard, fine-grained dolomite and soft, medium fine-grained sandstone.

117.118 - Old quarry known as Henniger Quarry, 3.5 miles E. of Perth. Hard, fine-grained calcareous sandstone, more or less rusty on surface.

119.120 - Old highway quarry, 1.2 miles N.W. of Newbliss. Very fine-grained dolomite, partly weathered and hard.

121.122 - Old highway quarry, 1.5 miles S.W. of Addison. Fine-grained hard dolomite of magnesian limestone.

TABLE I (cont'd)

123.124 - Talus at the foot of a cliff along creek emptying into Butternut Bay. Fine-grained calcareous sandstone.

125.126 - Highway quarry at Jones Creek. Fine-grained calcareous sandstone, quite rusty along joints. Sample includes some rusty stone.

127.128 - Old quarry known as McAdoo's quarry, 1.1 miles S.W. of Kingston Mills. Sample from lower part of face is fine-grained, porous magnesian limestone.

129.130 - Road cut 2.5 miles S.E. of Napanee. Very fine-grained limestone with some shale or bituminous films. Sample taken from the broken up top beds.

131.132 - Low cliff along shore of Lake Ontario, 1.5 miles E. of Sandhurst. Medium-grained, hard limestone with some shale films.

133.134 - Quarry operated by H.J. McFarland Construction Co., Roblindale Station. Very fine-grained to dense limestone with some shale films. Sample includes stone which holds less shale than quarry average.

135.136 - Same as 133.134.

137.138 - Quarry operated by H.J. McFarland Construction Co., 2.5 miles N. of Belleville. Limestone varies in texture but generally coarse with some shale films.

139.140 - Same as 137.138.

141.142 - County quarry, 1 mile N. of Foxboro. Very fine-grained to dense limestone with many thin shale films.

143.144 - Quarry owned by Building Products, 3 miles E. of Havelock. Limestone is generally fine with some shale films. Sample taken from bed of coarse stone with more shale films than quarry average.

TABLE I (cont'd)

145, 146 - Gravel pit, owned by J. L. Tremblay, 1 mile S. of La Ratière, Que. Sample taken for testing the anorthosite pebbles.

147 - Gravel pit owned by John A. Chisholm, 2 miles E. of Glen Robertson.

148, 149 - gravel pit operated by Menard Construction Co., Ltd., 1.7 miles W. of Green Valley. Sample 148 is crusher run material and 149 is from the pit bank.

150 - Gravel pit owned by W. J. Cummings, 1.3 miles S. W. of Monckland.

151 - Gravel pit operated by Coleman and Munro, Ltd., 1.1 miles N. W. of Bonville.

152 - Gravel pit owned by Frank Ezard, 1.5 miles S. W. of Lunenburg.

153 - Gravel pit owned by Olivier Papineau, 3 miles E. of Crysler.

154 - Gravel pit operated by S. Lachapelle and Sons, 2.3 miles S. of Finch. Sample of crusher run material.

155 - Gravel pit operated by J. S. Sloan, 2 miles W. of Bedell.

156 - Gravel pit operated by E. T. Pitman, 1.5 miles S. of Roebuck.

157 - Gravel pit operated by a contractor from Brockville, 2.7 miles S. W. of Maynard.

158 - Gravel pit owned by Dan Kyle, 3.3 miles S. E. of Merrickville.

U to Z - Same as 133, 134.

TABLE I (cont'd)

Second Series

201.202 - Road cut and old highway quarry, 1.4 miles N. of Alfred. Fine-grained limestone with closely spaced shale films.

203.204 - Old quarry along river bank, 0.5 mile N. of Casselman. Fine-grained, hard limestone with shale films.

205.206 - Small quarry recently opened but not in operation, Lot 7, Con. XII, Finch Township. Very fine-grained, almost dense limestone with few shale films.

207.208 - Road quarry, 2 miles S. of Crysler. Fine-grained limestone with shale films; also coarse limestone with few shale films. Sample includes fine stone only.

209.210 - Same as 207.208. Sample includes only coarse stone.

211.212 - Old road quarry, 1.6 miles W. of Finch. Fine-to-medium-grained limestone with shale films.

213.214 - Quarry operated by Campbell Sandstone Quarries, Limited, 2 miles W. of Bells Corners. Medium fine-grained sandstone.

215.216 - Old quarry owned by Gerald Ross, 2.5 miles N.W. of Brockville. Fine-grained dolomite.

217.218 - Old quarry known as Atkin's quarry, Kilbirnie. Fine-grained magnesian limestone; also very fine- to medium fine-grained hard limestone. Sample includes only the magnesian limestone.

219-220 - Old quarry owned by Jeffrey and Hector Hughes, 1.5 miles N.W. of Pinehill. Brick red, medium-coarse, soft sandstone.

221.222 - Road quarry, 2 miles S.E. of Elginburg. Limestone with thin shale films; coarseness varies between beds. Sample of very fine-grained stone with closely spaced, very thin

TABLE I (cont'd)

223.224 - Quarry operated by Chown, Limited. Very fine-grained, dense limestone with shale films, underlain by medium fine-grained, soft magnesian limestone. Sample includes only the magnesian stone.

225.226 - Road quarry, 1 mile E. of Collins Bay. Medium coarse-to very fine-grained and dense limestone with shale films and thin layers of calcareous shale. Sample does not include the calcareous shale.

227.228 - Road quarry, 0.7 mile E. of Westbrook. Stone similar to 225.226, but with more shale films. Sample does not include the calcareous shale.

229.230 - County quarry, 0.7 mile N.W. of Waupoos. Medium fine-grained limestone with irregular shale films.

231.232 - Road quarry, 0.5 mile S. of Consecon. Fine-grained limestone with many shale films.

233.234 - Road quarry, 9 miles N. of Orillia. Very fine-grained limestone with chert and some shaly partings.

235.236 - Old quarry, 1 mile N. of Longford. Fine-to very fine-grained and dense limestone, underlain with very fine-grained magnesian limestone. Sample includes only the magnesian stone.

237.238 - Old quarry now owned by Limestone Products, Limited, Medonte Station. Stone similar to 235.236, except that the magnesian limestone is more or less argillaceous. Sample includes only the latter stone.

239.240 - Quarry operated by A. Cope and Son, Limited, 2 miles S.W. of Stoney Creek. Fine-grained dolomite with some shale films.

241.242 - Same quarry as above. Sample of shaly dolomite from quarry bottom.

TABLE I (cont'd)

243.244 - Quarry operated by Haldimand Quarries and Construction, Limited, E. of Hagersville. Fine-grained cherty limestone underlain with very fine-grained dolomite. Sample includes only the dolomite.

245.246 - Same as 243.244. Sample includes only fresh cherty limestone.

247.248 - Same as 243.244. Sample includes only weathered cherty limestone.

249.250 - Same as 243.244. Sample includes more chert than other two samples.

251.252 - Quarry operated by Gypsum, Lime and Alabastine Co., Limited, S.W. of Puslinch. Fine-grained, soft dolomite.

253.254 - Same as 251.252.

255.256 - Quarry operated by Rockwood Lime Co., E. of Rockwood. Medium fine- to medium coarse-grained dolomite, underlain by finer and harder dolomite. Sample includes only the latter stone.

257.258 - Quarry operated by Canadian Gypsum Co., 1.3 miles W. of Guelph. Light-buff, fine-grained, soft dolomite, underlain with brown, hard, fine-grained dolomite. Sample includes only the upper buff stone.

259.260 - Same as 257.258. Sample includes only the lower brown stone.

261.262 - Quarry operated by Gypsum, Lime and Alabastine Co. Limited, 1 mile S.W. of Beachville. Very fine-grained, soft limestone and magnesian limestone.

263.264 - Quarry operated by Chemical Lime Co., 1.7 miles E. of Ingersoll. Fine-grained limestone overlain with medium fine-grained, soft sandy dolomite. Sample includes only dolomite.

TABLE I (cont'd)

265, 266 - Quarry operated by Elgin Keeling, E. of Owen Sound. Fine-grained, hard dolomite with some shale films.

267, 268 - Old quarry known as Chalmers quarry, S. W. of Owen Sound. Very fine-grained dolomite.

269, 270 - Quarry operated by J. S. Cook and Son, 2.7 miles W. of Wiarton. Fine-grained dolomite.

271, 272 - Beaver asbestos mine, owned by Asbestos Corporation, Limited, S. of Thetford Mines, Que. Very fine-grained and dense serpentine with veinlets of asbestos.

273, 274 - Gravel pit operated by Consolidated Sand and Gravel Co., Limited, 1.3 miles W. of Waterford. Sample of pebbles.

275, 276 - Gravel pit operated by Telephone City Supply Co., 3 miles W. of Brantford. Sample of coarser crushed material.

277, 278 - Gravel pit operated by Consolidated Sand and Gravel Co., Limited, E. of Paris. Sample of coarse crusher run material.

279 - Gravel pit operated by Howard Sand and Gravel Co., Aldershot.

280 - Gravel pit operated by J. Cooke Concrete Blocks, Limited, Aldershot.

281 - Township gravel pit, 3.5 miles S. W. of St. Raphael West. Sample of crusher run material.

282 - Gravel pit operated by Coleman and Munro, Limited, Lot 34, Con. VI, Cornwall Township. Sample of crusher run material.

283 - Same as 282. Sample from the pit bank.

284 - Gravel pit operated by E. L. Blair, 3.5 miles N. W. of Avonmore. Sample of crusher run material.

TABLE I(cont'd)

285 - Same as 154. Sample from the pit bank.

286 - Gravel pit operated by John Laughlin, 1 mile N. W. of Hallville. Sample from crushed run material.

287 - Gravel pit, 3.5 miles N. W. of Merrickville. Owner unknown.

Third Series

301, 302 - Quarry operated by Bertrand Frères, 1 mile N. W. of Plantagenet. Fine-to medium coarse-grained limestone with some shale films.

303, 304 - Quarry operated by Jos. Gareau, 2 miles S. of St. Isidore. Fine-to medium fine-grained limestone with some shale films.

305, 306 - Same as 109, 110. All specimens prepared from same sample.

307, 308 - Quarry operated by Donat Grandmaitre, E. of Eastview. Medium coarse-to fine-grained limestone with few shale films. Sample includes only coarser stone.

309, 310 - Old quarry on property line of Arthur Hamilton and Archie Morrison, 0.7 miles N. of Glen Robertson. Very fine-grained limestone with few shale films.

311, 312 - Sample taken from outcrops, 0.25 miles W. of St. Albert Station. Very fine-grained, hard magnesian limestone.

313, 314 - Old quarries owned by Clifford Thompson, 1.5 miles N. W. of Mille Roches. Very fine-grained limestone with no visible shale films.

315, 316 - Old quarry now owned by a Mr. Lavigne, 1 mile S. of Little Rideau. Medium coarse-to coarse-grained fossiliferous, shale-free limestone.

TABLE I (cont'd)

317.318 - Old quarry owned by Mrs. Oliver Fisher, 1.5 miles W. of Iroquois. Very fine-grained, silty dolomite with some shale films.

319.320 - Old quarry owned by J. T. Liezert, 2 miles W. of Iroquois. Fine-grained, hard dolomite or magnesian limestone.

321.322 - Quarry owned by Jos. Robert Hurteau, 3 miles N. of Cardinal. Fine-grained dolomite or magnesian limestone with few shale films.

323.324 - Old quarry owned by Carman Brown, 1.5 miles W. of Cardinal. Fine-grained siliceous dolomite.

325.326 - Same as 113.114, but sample 325.326 is from fresher stone.

327.328 - Old road quarry, 1 mile S. of Ventnor. Very fine-grained, hard and tough dolomite.

329.330 - Sample taken from outcrops, N. of Spencerville. Fine-grained dolomite. Outcrops show very little weathered stone.

331.332 - Quarry operated by Canada Crushed and Cut Stone, Limited, E. of Prescott (Windmill Point). Fine- to medium fine-grained, hard and tough dolomite.

333.334 - Sample from outcrops in the steep, rocky shore of the St. Lawrence river, E. of Prescott (Windmill Point). Sample taken opposite 331.332 in similar dolomite but from lower beds.

335.336 - Old quarry owned by Ernie Connell, 1.7 miles N.W. of Prescott. Fine- to very fine-grained, hard and tough dolomite.

337.338 - Sample from large outcrop area, 2.5 miles W. of Prescott. Fine- to medium fine-grained dolomite.

339.340 - Old quarry owned by Leonard Conklin, 4 miles N. of Maitland. Very fine- to medium coarse-grained dolomite and magnesian limestone.

341.342 - Sample from large outcrop area, 4 miles N. of Maitland. Very fine- to medium fine-grained dolomite and magnesian limestone.

TABLE I (cont'd)

343.344 - Old quarry owned by W.H. Seeley, 1.5 miles S.W. of Maitland. Fine-grained, hard dolomite.

345.346 - Quarry operated by Johnston and Clarke, 1 mile E. of Brockville. Fine- to very fine-grained dolomite.

347.348 - City quarry, N.E. end of Brockville. Fine- to medium coarse-grained calcareous sandstone, more or less silty or argillaceous.

349.350 - Same as 125.126. Sample represents quarry average.

351.352 - Same as 125.126. Sample includes only fresh stone.

353 - Quarry operated by Building Products, Limited, 3 miles E. of Havelock. Medium fine- to very fine-grained, hard and tough basalt.

355.356 - Sample from outcrop, N.E. end of George Island, P.E.I. Very fine-grained, dense, hard and tough dolerite.

357.358 - Gravel pit operated by Johnston and Clerk, Grenadier Island. Sample of pebbles.

359.360 - Same as 357.358. Sample from pit bank.

TABLE II. - FIRST SERIES

Test Results on Concrete Specimens after 149 Cycles of Freezing and Thawing

Mix No.*	Proportions	W/C ratio by Wt.	Rock Type	Compr. Strength psi	Soniscope Wave Velocity ft./sec.	Failed** (cycles)	Remarks
101	1:2:3.5	0.57	Trenton limestone	8300	15500	......	Some shaly partings
102	"	"	" "	....	.....	44	" " "
103	"	"	" "	7400	14300	......	Many shaly partings
104	"	"	" "	....	.....	37	" " "
105	1:2:3	0.55	" "	6800	13900	......	Some shaly partings
106	"	"	" "	....	.....	81	" " "
107	"	"	Black River limestone	4900	9900	......	Many shaly partings
108	"	"	" "	....	.....	23	" " "
109	1:2:3.5	0.57	Trenton limestone	6000	14600	......	Some shaly partings
110	"	"	" "	....	.....	50	" " "
111	"	"	Black River limestone	5500	15100	......	No shaly partings visible
112	"	"	" "	....	.....	32	" " " "
113	1:2:3	0.55	Beekmantown dolomite	6900	15200	......	Slightly weathered
114	"	"	" "	7200	15000	......	" "
115	1:2:3	"	Beekmantown dolomite and sandstone	8200	14900	......	Dolomite partly weathered; sandstone, soft
116	"	"	" "	7400	14500	......	" " "
117	1:2:3.5	0.55	Beekmantown calcareous sandstone	5100	13200	......	Slightly weathered
118	"	"	" "	....	.....	74	" "
119	1:2:3	0.55	Beekmantown dolomite	4900	15200	......	Partly weathered
120	"	"	" "	3000	14900	......	" "
121	1:2:3.5	"	" "	7600	14700	......	Slightly weathered
122	"	"	" "	4400	13000	......	" "
123	"	0.51	Beekmantown calcareous sandstone	5600	12800	......	Partly weathered
124	"	"	" "	4900	12100	......	" "
125	1:2:3.5	0.57	" "	6200	13100	......	" " and rusty
126	"	"	" "	....	.....	105	" " "
127	"	0.41	Black River magnesian limestone	5700	13300	......	Porous absorption 5.3% by wt.
128	"	"	" "	....	.....	74	" "
129	1:2.5:5	0.57	Black River limestone	5400	13000	......	Some shaly partings
130	"	"	" "	....	.....	99	" " "
131	"	"	Trenton limestone	6800	15200	......	" " "
132	"	"	" "	....	.....	105	" " "
133	1:2.5:4	0.57	Black River limestone	5900	15300	......	Very few shaly partings
134	"	"	" "	....	.....	39	" " "

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* Odd numbers mean specimens with concrete sand as fine aggregate; even numbers, with screenings as fine aggregate.

** Failure when bottom face completely spalled.

TABLE II (cont'd) - FIRST SERIES

Test Results on Concrete Specimens after 149 Cycles of Freezing and Thawing

Mix No. *	Proportions	W/C ratio by Wt.	Rock Type	Compr. Strength psi	Soniscope Wave Velocity ft./sec.	Failed** (cycles)	Remarks
135	1:2:3.5	0.58	" "	4800	14300	......	" " "
136	"	"	" "	....	.....	42	" " "
137	"	0.59	Trenton limestone	5800	14800	......	Some shaly partings
138	1:2.9:5	0.85	" "	....	.....	39	" " "
139	1:2.5:4	0.59	" "	4800	14300	......	Some shaly partings
140	"	"	" "	....	.....	42	" " "
141	1:2:3.5	0.56	" "	6100	13000	......	Many shaly partings
142	"	"	" "	....	.....	32	" " "
143	1:2:3	0.55	Black River limestone	5700	14700	......	Some shaly partings
144	"	"	" "	....	.....	52	" " "
145(1)	1:2:3.5	0.58	Precambrian anorthosite	7300	14600	......	Crushed gravel pebbles
146	"	"	" "	2200	10200	......	" " "
147	1:1.5(2)	0.60	Gravel	3000	12200	......)	Only minus No. 4 used
148	"	"	"	3600	12500	......)	
149	"	"	"	6300	13900	......)	
150	"	"	"	5600	12800	......)	
151	"	"	"	4500	12800	......)	
152	"	"	"	4700	12800	......)	
153	"	"	"	5200	13200	......)	
154	"	"	"	3300	12400	62)	
155	"	"	"	5400	14300	......)	
156	"	"	"	5600	13600	......)	
157	"	"	"	6300	14000	......)	
158	"	"	"	4800	13000	......)	
U	1:3:3	0.55	Black River limestone	3800	14800	......	Very few shaly partings Run only 82 cycles

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(1) Like 146, made with screenings as fine aggregate.

(2) No coarse aggregate in gravel specimens.

TABLE III. - SECOND SERIES

Test Results on Concrete Specimens after 164 Cycles of Freezing and Thawing

Mix No. *	W/C ratio by Wt.	Rock Type	Compr. Strength, psi		Soniscope Wave Velocity, ft./sec.				Failed** (cycles)	Remarks
			0 cy.	164 cy.	0 cy.	125 cy.	164 cy.	% Decrease at 125 cy.		
U	0.55	Black River limestone	3800	1700	14800	13300	14300	10	......)	
V	"	" "	2600	....	13600	.....	.....	..	34)	
W	"	" "	2800	2800+	13900	12000	.....	14	125)	
X	"	" "	1400	....	13000	.....	.....	..	18)	Very few shaly
Y	"	" "	1600	....	12100	.....	.....	..	55)	partings
Z	"	" "	1100	....	11500	.....	.....	..	18)	Run 246 cycles
201	"	Chazy limestone	3900	3400	13900	12500	14200	10	......)	
202	"	" "	2700	....	12700	.....	.....	..	124)	
									)	Some shaly
203	"	Trenton limestone	3800	3700	14100	12900	14200	9	......)	partings
204	"	" "	2100	....	12700	.....	.....	..	65)	
205	"	Black River limestone	3200	3500	14100	13000	13900	8	......	Few shaly partings
206	"	" "	3900	2000+	13700	11900	.....	13	125	" " "
207	"	Trenton limestone	3800	3300	14200	13500	14500	5	......	Some shaly partings
208	"	" "	2100	....	13500	.....	......	..	11	" " "
209	"	" "	5300	3700	14900	13600	14300	9	......	Very few shaly partings
210	"	" "	3400	....	14000	.....	.....	..	100	" " " "
211	0.55	Trenton limestone	5000	6300	15000	13800	14500	8	......	Some shaly partings
212	"	" "	3600	3600	13900	12500	13800	10	......	" " "
213	"	Potsdam sandstone	3200	3500	13400	12100	12000	9	......	Rather soft
214	"	" "	2500	2400	12200	11400	11400	6	......	" "
215	"	Beekmantown dolomite	4600	4000	14500	13500	12900	8	......	Partly weathered
216	"	" "	2300	2900	13100	11900	11300	9	......	" "
217	"	Black River magnesian limestone	4000	3100	13300	12500	13100	6	......	Moderately porous
218	"	" "	2600	3400	13400	12600	12400	7	......	" "
219	0.55	Potsdam sandstone	3700	2200	11800	11000	10900	7	......	Soft and porous
220	"	" "	2900	3100	11200	10500	10700	6	......	" " "
221	"	Black River limestone	3700	3300	14400	13200	13800	9	......	Many very thin shaly partings
222	"	" "	2700	....	13900	.....	.....	..	18	" "
223	"	Black River magnesian limestone	4000	5100	13500	13000	12900	7	......	Porous
224	"	" "	4400	2600	13300	12500	12500	6	......	"
225	0.55	Black River magnesian limestone	3600	3200	13700	12500	13000	9	......	Some shaly partings
226	"	" "	2100	2000+	13400	.....	.....	..	100	" " "
227	"	" "	3000	2600+	14100	11900	.....	16	125	Many shaly partings
228	"	" "	1200	....	11500	.....	.....	..	109	" " "

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[*] Odd numbers mean specimens with concrete sand as fine aggregate; even numbers, with screenings as fine aggregate.

[**] Failure when wave velocity decreased by 13% or on complete spalling of bottom face, whichever occurred first.

[+] At failure cycle.

TABLE III (cont'd) - SECOND SERIES

Test Results on Concrete Specimens after 164 Cycles of Freezing and Thawing

Mix No.*	W/C ratio by Wt.	Rock Type	Compr. Strength, psi		Soniscope Wave Velocity, ft./sec.				Failed** (cycles)	Remarks
			0 cy.	164 cy.	0 cy.	125 cy.	164 cy.	% Decrease at 125 cy.		
229	0.55	Trenton limestone	3800	3900	15100	13500	14000	11	......	Some shaly partings
230	0.60	" "	4000	4600	14700	13300	13200	10	......	" " "
231	0.55	" "	3600	3600	14500	13000	13100	10	......	Many shaly partings
232	0.60	" "	3900	....	14800	.....	.....	..	34	" " "
233	0.59	Black River cherty limestone	4800	3600+	15000	.....	.....	..	55	Partly weathered and porous
234	0.69	" "	3200	2700+	14100	.....	.....	..	18	" "
235	0.57	Black River magnesian limestone	3600	3600	14700	13900	13300	5	......	Rather porous
236	0.59	" "	3200	....	13900	.....	.....	..	109	" "
237	0.57	" "	3600	4100	14500	13500	13900	7	......	Rather porous and argillaceous
238	0.65	" "	2400	....	14000	.....	.....	..	40	" "
239	0.55	Nigara dolomite	3700	3000	14400	12900	.....	10	......	Some shaly partings
240	0.60	" "	1800	....	14100	.....	.....	..	34	" " "
241	0.55	" "	2200	2400+	13900	11300	.....	19	125	Shaly
242	0.60	" "	2500	....	13400	.....	.....	..	18	"
243	0.55	Bertie-Akron dolomite	3500	2800+	14500	11800	.....	19	125	Rather porous
244	0.60	" " "	1900	....	14500	.....	.....	..	109	" "
245	0.55	Onondaga cherty limestone	2200	2000+	13400	.....	.....	..	100	Fresh and porous
246	"	" "	1300	....	11500	.....	.....	..	18	" "
247	0.55	Onondaga cherty limestone	3400	1800	13900	.....	.....	..	34	Partly weathered Very porous
248	"	" "	2900	....	13300	.....	.....	..	34	" "
249	"	" "	3500	1500+	13200	.....	.....	..	34	Partly weathered Porous
250	"	" "	1200	....	11900	.....	.....	..	18	" "
251	0.55	Guelph dolomite	3400	4900	15000	13800	13900	8	......)	Soft and rather porous
252	0.60	" "	3200	4200	15200	14400	14500	8	......)	
253	0.55	" "	4200	5200	15500	14100	14200	10	......)	
254	0.60	" "	2400	4600	15300	14100	14500	8	......)	
255	0.55	Niagara dolomite	3700	3400	14500	12900	13300	11	......	Moderately porous
256	0.60	" "	4100	3900	14700	13900	13500	9	......	" "
257	0.55	Guelph dolomite	3700	5200	14500	13500	13500	7	......	Soft and porous
258	0.60	" "	3100	4500	14500	13800	13800	8	......	" "
259	0.55	" "	3300	4900	15400	14400	14200	7	......	Slightly porous
260	0.60	" "	4400	....	15500	.....	.....	..	34	" "
261	0.55	Detroit River limestone	3500	4600	15200	14000	14200	8	......)	Limestone and magnesian limestone; both soft
262	0.60	" " "	3800	3200	15300	14000	14100	7	......)	

+ At failure cycle.

TABLE III (cont'd) - SECOND SERIES

Test Results on Concrete Specimens after 164 Cycles of Freezing and Thawing

Mix No. *	W/C ratio by Wt.	Rock Type	Compr. Strength, psi 0 cy.	164 cy.	Soniscope Wave Velocity, ft./sec. 0 cy.	125 cy.	164 cy.	% Decrease at 125 cy.	Failed** (cycles)	Remarks
263	0.55	Onondaga sandy dolomite	3000	3200	12900	12200	12300	7	......)	Friable and porous
264	"	" " "	4000	2500	12100	11300	11400	8	......)	
265	0.57	Clinton dolomite	3200	3100	14200	12500	12300	12	......)	Some shaly partings
266	0.65	" "	1600	....	14000	.....	.....	..	34)	
267	0.58	Niagara dolomite	5000	4300	15200	13600	14200	11	......	Moderately porous
268	0.65	" "	3600	4100	15600	13800	14300	12	......	" "
269	0.55	Guelph dolomite	2700	2800	13300	12300	12900	8	......	Soft and porous
270	0.60	" "	4100	4100	13600	12900	12900	5	......	" " "
271	0.55	Palaeozoic serpentine	1100	2400	13900	13000	12200	6	......)	Holds asbestos
272	0.56	" "	2100	....	9300	.....	.....	..	18)	veinlets
273	0.55	Gravel pebbles	3300	3800	14400	13150	13300	9	......)	Pebbles: dolomite -
274	0.60	" "	3300	3400	14700	13800	13200	10	......)	40%, limestone - 40%
275	0.55	" "	3300	5100	15200	14200	14200	8	......)	
276	0.60	" "	2600	4700	14800	14000	13200	8	......)	
									)	Pebbles:
277	0.55	" "	5400	5400	15000	13900	13500	8	......)	dolomite - 60%
278	0.60	" "	3600	6100	15200	13800	13900	9	......)	
279	0.60	" "	3700	4700	14300	12900	13400	10	......)	Pebbles, mostly
									)	dolomite and
280	0.60	" "	4300	5700	14400	13450	13800	7	......)	limestone
281	0.60	Gravel and sand	800	....	7100	.....	.....	..	0)	
282	0.60	" "	3700	4200 +	13900	11550	.....	17	125)	
283	0.60	" "	3900	3900	13500	12300	13100	9	......)	Only minus No. 4
284	0.60	" "	6400	5100	13000	12150	13000	7	......)	used
285	0.60	Gravel and sandstone	1600	....	12500	.....	.....	..	100)	
286	0.60	" "	3300	3800 +	12700	10850	.....	15	125)	Only minus No. 4
287	0.60	" "	4700	4400	14300	12650	12900	12	......)	used

+ At failure cycle.

TABLE IV - THIRD SERIES

Test Results on Concrete Specimens after 149 Cycles of Freezing and Thawing

Mix No.*	Rock Type	Compressive Strength, psi			Soniscope Wave Velocity ft./sec.			Failure** (cycles)	Remarks
		Before	After Dry	After Wet	0 cy.	149 cy.	Decrease %		
301	Trenton limestone	3700	4800	2650	14500	12200	15.6	.....	Some shaly partings W/C -.0.80
302	" "	3400	1600+	....	11500	.....	39.1	30	Some shaly partings W/C - 0.93
303	" "	4300	5400	3600	15500	13350	13.9	.....	Some shaly partings
304	" "	3800	3000+	....	14700	.....	20+	30	
305	" "	5000	5200	4200	15100	13150	13.0	.....	
306	" "	4500	2800+	....	14600	11400	21.9	149	
307	" "	4100	3900	2700	15100	12800	15.5	.....	Few shaly partings
308	" "	3700	3200+	....	15700	.....	30.0	41	
309	Black River limestone	4400	5700	4550	15700	13800	13.0	.....	
310	" "	4000	....	....	14200	.....	45.1	30	
311	Black River magnesian limestone	4550	5100	4150	15300	13250	11.7	.....	Free of shale
312	" "	4000	3250	....	14200	11700	17.6	.....	
313	Black River limestone	5000	5400	3950	15900	13300	16.6	.....	Few shaly partings
314	" "	3200	....	....	14200	.....	36.6	41	" " "
315	Chazy limestone	5250	5300	3950	15300	12650	17.3	.....	Coarse and free of shale
316	" "	6550	5250	....	15100	13300	11.9	.....	" " "
317	Beekmantown dolomite	4000	4900	4050	14700	13400	8.5	.....	Silty; some shale films
318	" "	5200	2000+	....	15100	.....	31.8	41	" " " "
319	" "	5300	6000	4650	14700	13100	10.6	.....	Hard and dense
320	" "	4300	4300	....	14200	13500	4.9	.....	" " "
321	" "	4550	5900	3950	15600	13500	13.3	.....	Few shaly partings
322	" "	5600	4500	....	16100	12800	20.5	149	" " "
323	" "	5200	5000	3700	15200	12850	15.5	.....	Moderately porous
324	" "	4700	3750	....	14400	12400	13.9	.....	" "
325	" "	3800	4900	3700	14700	13400	8.1	.....	Hard and dense
326	" "	3850	4050	....	14900	12800	14.1	.....	
327	" "	4600	4900	3800	14500	13150	9.3	.....	
328	" "	3400	3900	....	13900	12800	8.6	.....	
329	" "	5300	4800	3650	14700	13500	8.2	.....	Fine
330	" "	3750	4400	....	14400	13000	9.7	.....	"
331	" "	4900	6300	4300	15000	12950	13.9	.....	Medium fine
332	" "	5900	5600	....	14900	13000	12.7	.....	" "

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* Odd numbers mean specimens with concrete sand as fine aggregate; even numbers, with screenings as fine aggregate

** Failure when wave velocity decreased by 20%

\+ At failure cycle

TABLE IV (cont'd) - THIRD SERIES

Test Results on Concrete Specimens after 149 Cycles of Freezing and Thawing

Mix No.*	Rock Type	Compressive Strength, psi Before	Compressive Strength, psi After Dry	Compressive Strength, psi After Wet	Soniscope Wave Velocity ft./sec. 0 cy.	Soniscope Wave Velocity ft./sec. 149 cy.	Decrease %	Failure** (cycles)	Remarks
333	Beekmantown dolomite	4050	4800	4150	14700	12950	11.7	.....	Finer than No. 331
334	" "	3900	4900	....	14600	13100	10.3	.....	" " " "
335	" "	3500	4300	3400	14700	12550	14.3	.....	Hard and dense
336	" "	3400	3700	....	13900	11800	15.2	.....	" " "
337	" "	4950	4550	3200	14500	12950	10.7	.....	Medium fine
338	" "	3650	3900	....	14100	13500	4.2	.....	" "
339	" "	4600	5300	3500	13600	12950	4.8	.....	" "
340	" "	3700	4100	....	13800	13300	3.6	.....	" "
341	" "	3400	2050	1950	13300	11250	15.1	.....	Medium fine. W/C - 0.74
342	" "	3000	3000	....	12700	11500	9.4	.....	" " W/C - 0.85
343	" "	4000	4100	2800	14500	12700	12.4	.....	Fine
344	" "	3500	4600	....	14900	12900	13.4	.....	"
345	" "	4900	4900	3850	14900	13350	10.1	.....	Fine
346	" "	4000	2050+	....	14200	.....	20.3	126	"
347	Beekmantown calcareous sandstone	4800	4550	....	15700	12900	17.8	.....	Silty and of variable texture
348	" "	5100	5050	....	15500	11400	26.5	149	" " " "
349	" "	5200	5800	3900	14400	13000	9.4	.....)	Stone partly weathered
350	" "	5300	....	....	13900	.....	36.7	126)	and rusty
351	" "	4650	6200	4050	14600	13300	8.9	.....	Same as 349 but fresher
352	" "	5100	2200+	....	14600	.....	22.6	41	" " "
353	Precambrian basalt	5300	5900	4350	16600	13500	18.7	.....	Hard, uniformly fine stone
355	Carboniferous dolerite	4400	5600	3700	14700	13100	10.8	.....	Hard, dense, magnetic
356	" "	2800	....	....	14100	.....	22.0	41	" " "
357	Gravel	3900	4900	3250	12300	11900	2.6	.....	Fresh, hard, W/C - 0.75
358	"	2800	1600	....	11300	9900	12.4	.....	" " W/C - 0.98
359	"	5200	6000	4000	14600	12950	11.3	.....)	Same as 357, but W/C
360	"	6500	6900	....	14900	13000	12.7	.....)	lower

+ At failure cycle