RELATION BETWEEN DURABILITY OF CONCRETE AND DURABILITY OF AGGREGATES

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INTRODUCTION

This report consists of two parts.

1 A short general discussion of durability of concrete, with special reference to the relation of aggregates to durability, including certain suggested outlines of research along lines commented upon in the discussion

2 A bibliography of literature upon the subject

DISCUSSION

During the course of the Symposium on Mineral Aggregates held during the 1929 meeting of the American Society for Testing Materials, many of the authors stressed the importance of knowing more about the effect of quality of aggregates upon the durability of concrete Information concerning this essential property of concrete is of special importance to the highway engineer because of the severe weathering conditions to which concrete employed in highway construction must of necessity be exposed Knowledge of the strength characteristics of concrete becomes to him therefore of secondary importance to a knowledge of methods of securing durability In spite of this, almost all of the research data regarding concrete which have been made available in the past deal with strength rather than durability However this is a natural development, due to the fact that the first investigations in concrete were in connection with its use in building construction, where the material is in general protected from the weather and strength becomes, therefore, the essential characteristic With the expanding use of concrete into many fields involving exposure to the action of the elements, such as pavements, bridges, dams, stadiums, retaining walls, etc , has come the realization that designing for strength in accordance with the old accepted methods does not necessarily insure durability This truth has been brought home many times during recent years by reason of the weathering of many exposed structures in which the concrete, measured by the conventional yardstick, strength, met every requirement.

The writer has been assigned the task of preparing an outline of research on the problem "Relation Between Durability of Concrete and Durability of Aggregates." It will be necessary before proceeding to the preparation of such an outline to consider briefly the general question of "durability" in concrete, the conditions which affect it and the means which may be used to insure it The word "durability" in this discussion will be assumed to mean the ability to resist insofar as possible the destructive effects of water, ice and temperature change as they would normally occur and does not include resistance to such destructive agencies as strong alkali or acid waters, sea water, etc Of course when we speak of durability or resistance to weathering in concrete we speak in relative terms, just as we would speak of durability in any other structural material No material is permanent in the sense that it will resist for all time the external forces of weathering All that we can hope to do with concrete is to so select the constituent materials and so control the manufacturing processes that the product will be as nearly resistant to the natural forces of disintegration as our present knowledge makes possible

The function of the aggregate in contributing to the above end is the subject with which we are primarily concerned The aggregate is, however, only one of a number of factors which influence durability Moreover, the behavior of an aggregate in concrete may be quite markedly affected by these other variables so that a study of the aggregate factor in reality involves a study of all of the variables, including both materials and methods of manufacture, which may contribute to durability or the lack of it

In all discussions over durability of concrete the rôle of water as a destructive agent has been greatly emphasized All authorities agree that, if corrosion or weathering is to be minimized, water must be excluded, although they do not always agree as to the exact nature of the chemical or physical action which takes place during weathering For instance, it has been commonly assumed that most of the examples of concrete disintegration, especially those in the northern states, are due to alternate freezing and thawing The action in such cases is of course purely mechanical, and is due to the formation of ice crystals within the pore spaces of the concrete, the resulting expansive forces eventually producing disruption Attention has recently been called, however, to the possibility that such effects may in many cases be due to the deposition of crystals of chemical salts within the pore spaces of the concrete rather than to ice crystals Anderegg[1] has noted the possibility that even normal ground water may carry enough acid in solution to react with the constituents of the cement forming crystal compounds and that the growth of these crystals within the hardened concrete may easily produce the effects noted It is not the purpose to go into the matter in any detail in this discussion It must be apparent, however, that, irrespective of whether the action is chemical or physical or a combination of the two, water is the root of the trouble The production of concrete

[1] Proceedings American Concrete Institute, 1929, p 332

which has the greatest possible resistance to the entrance of water (impermeability) should be the goal of every Engineer and construction foreman charged with the duty of producing weatherproof concrete The selection of the proper aggregates is only one of a number of steps which must be followed to this end Moreover, the aggregates play a double rôle in the production of durable concrete They must not only be composed of sound and durable particles (which may be termed a fundamental requirement) but these particles must be so graded in size as to produce concrete of plastic and workable consistency with the least amount of water in proportion to the amount of cement required. It seems at times that possibly too much emphasis is placed on the character of the aggregate and not enough on the proper design of the mixture and the placing of the concrete The condition surveys which have been conducted by the Committee on Destructive Agencies of the American Concrete Institute[2] have indicated that the vast majority of failures through disintegration are due primarily to failure to produce concrete which is uniformly impermeable to water and that in only a relatively small number of cases can the trouble be traced definitely to lack of durability in the aggregates This may be due to the fact that aggregates from established commercial sources of supply are employed in the great bulk of the total yardage of concrete placed in this country However, economic considerations dictate that, wherever feasible, local aggregate supplies be considered and it is in such cases that definite assurance must be had of the durability of the aggregate to be used There are, moreover, a sufficient number of cases on record where failure can definitely be traced to the character of the aggregate to warrant a thorough investigation of durability from this standpoint

What are the inherent characteristics of aggregates which affect their durability in concrete? How is the resistance of an aggregate to destructive agencies affected by the other characteristics of the concrete such as permeability, water absorption, etc ? To what extent may it be possible to protect a doubtful aggregate with a cement paste of high quality? Is it possible to develop laboratory tests for durability of concrete which will simulate actual weathering in the field?

The above are just a few of the questions which come to mind when discussing this subject They must be answered before any real progress can be made in solving the problem Isolated attempts have been made by independent investigators to throw light on specific phases of the problem which have resulted in the accumulation of a mass of unrelated data which can not be correlated and which for this reason is of doubtful value The bibliography attached to this report illustrates

[2] Journal A C I, Vol 1, page 41, Proc A C I, 1929, p 27, Proc A C I, 1926, p 64

the point The need is for an agency which can direct and coordinate an adequate investigation of the problem both in the laboratory and in the field in such a manner that the results secured by each investigator can be correlated with those obtained by others and sound, authorative conclusions drawn from the whole The Highway Research Board is the logical agency to direct such an investigation, due to the prime importance of durability as an essential characteristic of concrete used in highway construction

METHOD OF ATTACKING THE PROBLEM

It would seem necessary to attack the problem from both the field and laboratory standpoint A field survey of existing structures the history of which is known is absolutely essential before the results of laboratory tests and investigations on either the concrete or the aggregates can be interpreted By the same token, laboratory tests under controlled conditions are equally necessary in order to verify field indications Laboratory investigations are necessary also in order that suitable tests for durability may be developed It is obvious that a coordinated laboratory study of durability can not be undertaken until a test or tests for durability have been standardized

Any test for durability which may be made upon an aggregate, as for instance, the sodium sulphate soundness test, is only of value insofar as it is possible to correlate it with the behavior of the concrete in which the aggregate is used It is the durability of the concrete in which we are interested and for this reason it would seem logical that tests for durability, especially those of a research nature, should be conducted upon the concrete rather than upon the aggregate This is especially important when it is realized that the behavior of an aggregate in concrete may be influenced by other variables, such as water-ratio, cement content, etc In other words, it may very well be possible that an aggregate which is unsatisfactory when used in a lean concrete having a high water ratio may prove satisfactory in a rich concrete protected by a cement paste of high quality

On the other hand, the quality of the aggregate may not be the critical factor when a high water-cement ratio is used, failure in this case being due to the poor quality of paste which would cause disintegration regardless of the quality of the aggregate used

What are the most significant tests by which we may measure durability? In the first place it is recognized that frost action is undoubtedly a factor in the weathering of concrete For this reason, most investigators of weathering have utilized the freezing test in an effort to simulate such action in nature No effort has been made as yet, however, to standardize a freezing and thawing test of concrete In working out a program of research along this line we are faced with a number of questions which must be answered as, for instance, how are the results affected by variations in

1 The size and shape of the test specimens

2 The nature of the surface exposed to frost action, as for instance a surface molded against a form, a surface finished by means of a strike-off, trowel, etc , and a sawed surface which exposes the aggregate

3 Method of insuring saturation of the specimen at time of freezing, that is, should the specimen be frozen (a) wholly in water, (b) partially immersed, or (c) saturated and then frozen in air

4 Minimum temperature at which freezing should take place

5 Rate of freezing, including (a) time required to reach minimum temperature and (b) time to hold at minimum temperature

6 Method of evaluating specimens after test, i e , by (a) visual examination, or (b) strength tests compared to strength of corresponding specimens stored under normal conditions

The following outline of research is suggested as the basis for an investigation of methods of establishing a standard test procedure

A Equipment In addition to the usual equipment for conducting tests of concrete, either a room or compartment in which freezing tests can be conducted will be necessary Such a compartment should be designed so that not only minimum temperatures but rate of drop in temperature can be controlled

B Materials Single standard brand of Portland cement
Concrete sand of known satisfactory quality
Crushed stone of known durability
Crushed stone of known unsatisfactory quality from the standpoint of durability

C Procedure Variables to be studied

1 Size and shape of specimen
  (a) Six inch by 12 inch cylinders
  (b) Six inch cubes (molded)
  (c) Six inch cubes sawed from 6 by 6 by 30 inch beams

2 Character of surface of specimen
  (a) To be investigated by observing relative action on sawed cubes 1 - (c)

3 Saturation of specimen
  (a) Wholly in water Specimens to be placed in thin metal containers of slightly larger capacity than the specimens and the containers filled with water To be frozen in this condition
  (b) Partly in water Specimens to be saturated, then placed in pans and supported on racks in such a manner that approximately only one inch of concrete is immersed in water To be frozen in this condition

(c) In air Specimens to be thoroughly saturated and then immediately removed to freezing compartment and frozen in air

4 Minimum temperatures

Specimens to be frozen at 20°F , 10°F , and 0°F

5 Rate of freezing.

Specimens to be frozen rapidly, so that the minimum temperature is reached in approximately one hour after start of tests and slowly so that the minimum temperature is reached in about —— hours after start of test

Specimen to be (1) removed immediately after reading minimum temperature and (2) held at minimum temperature for —— hours

6 Thawing temperatures

Specimens to be thawed at 70°F

Each of the above variables should be investigated with at least five classes of concrete, as follows

Class 1 Water-cement ratio	0 6
Class 2 Water-cement ratio	0 7
Class 3 Water-cement ratio	0 8
Class 4 Water-cement ratio	0 9
Class 5 Water-cement ratio	1 0

as well as with two combinations of aggregates, as follows

Combination A Above cement and sand with coarse aggregate of known durability

Combination B Above cement and sand with coarse aggregate of known unsatisfactory quality

The above outline is offered merely as an illustration of the character and amount of work involved in a study of this kind It is obvious that it would require a laboratory having somewhat unusual facilities as regards both equipment and funds to undertake a complete program of research along this line It is possible that the work might be divided among several laboratories, each being assigned a specific phase of the problem In any event an investigation of the technique of the freezing test should be undertaken and further information obtained as to the effect of variations in procedure before carrying out a general investigation of durability

Assuming that a freezing test is a true indication of durability and that a standard method has been agreed upon, we are in a position to investigate durability in the laboratory This phase of the study should be carried on in conjunction with field studies of aggregates Tests should be made on concrete containing aggregates of various types and carrying various percentages of presumably deleterious substances and the relative behavior of the concrete noted In connection with each aggregate investigated tests should be made on concrete of various water-cement ratios ranging from, say 0 5 to 1 0, in order to determine effect of richness of mix as related to kind of aggregate The results obtained should be correlated with the quantity of such materials in the aggregate as chert, shale, clay seams, etc , in crushed stone, shale, chert, soft or rotten particles in gravel, shale in sand, etc A thorough study along these lines should furnish data which would enable the specification writer to set more definite test limits for deleterious substances in aggregates than is now possible

FIELD SURVEY

The writer feels that a systematic and thorough field study of concrete in use, from the standpoint especially of aggregates employed, would be highly desirable Such a survey should be carried out by an entirely disinterested agency such as the Highway Research Board A competent investigator should be appointed who could give full time to the work and who might function under the general direction of the Committee on Aggregates in a manner similar to the procedure followed in the study of methods of curing concrete pavements recently conducted by the Board It would be the duty of such an investigator to make a detailed study of existing concrete structures in which questionable aggregates have been employed, procuring in each case as complete a history as possible regarding the exact materials used, methods of construction and other details A study of this nature should develop valuable indications as to effect of aggregates upon service behavior which could be correlated with the laboratory investigations previously discussed.

THERMAL EXPANSION

The possibility that there may be enough difference in the thermal coefficient of expansion of certain types of aggregate as compared to the concrete in which they are used to develop internal strains of sufficient magnitude to cause failure has been advanced

A series of thermal expansion tests should be conducted on concrete for the purpose of determining what weakening effect, if any, may result from the use of such materials as flint, etc Paralleling this work, tests should be made to determine the thermal coefficients of expansion of the aggregates themselves Such tests might be made on 1-inch cores drilled from the material to be tested, and the determination made by means of a small linear comparator, on specimens of approximately 4 inches in length There is a possibility that interesting developments might result from a study of this kind The effect upon the concrete might be determined by subjecting concrete specimens, say 6-

by 12-inch cylinders, to a number of alternations in temperature (maximum range about 100°F) and comparing the strength with similar specimens stored under the same conditions except that a constant temperature is maintained It would be interesting to investigate in this connection the effect of size of aggregate, on the theory that the total internal pressure developed at any point would be in proportion to the size of the individual fragments of aggregate In other words, it might develop that an aggregate which would prove dangerous when used in fragments up to, say 3 inches in diameter, would be entirely satisfactory were the maximum size limited to ¾-inch

SODIUM SULPHATE TEST

In connection with this test the writer is giving below the text of a statement prepared by Messrs A T Goldbeck, Stanton Walker, H J Love and Fred Hubbard, acting on behalf of the three aggregate associations, and prepared in connection with a discussion of recently proposed revisions in federal specifications for aggregates

"The following are some of the difficulties experienced with the test procedure as outlined in U S D A Bulletin 1216, page 20, 1928 revision

(a) Sample too small
(b) Sample source not definite
(c) Test seems to apply to rock only and not to gravel and slag
(d) Has no adaptation for fine aggregates
(e) Gives no specific number of cycles
(f) Gives no means for accurately interpreting the test results in terms of failure or acceptance, since "marked disintegration" may mean anything or nothing
(g) The test procedure states nothing about temperature of the immersing solution, which is a very important factor
(h) The temperature of saturation (70°F) is too low to avoid undersaturation much of the time

Because of the serious objections to the present test procedure, of which the one outlined in U S D A Bulletin 1216, page 20, 1928 revision, is the most widely accepted, the following procedure is suggested, which is free from many of the inaccuracies previously encountered This procedure is worthy of consideration for five reasons

1 It makes more definite the source and selection of samples and increases the sample to a more satisfactory size
2 It is adaptable to all types of coarse and fine aggregates
3 A definite control of temperature of saturation and of maintaining the solution throughout the test is stipulated, which guards against test inaccuracies.

4 A quantitative means of measuring distress during the soundness test is given so that results may be comparable and have meaning
5 Definitions of "failing," "doubtful" and "acceptable" material are given

SODIUM SULPHATE SOUNDNESS TEST

Samples

Source In conducting the test the sample shall be taken whenever possible from material prepared for commercial use Every care shall be taken to make the sample truly representative of the material to be used

Size If the material is to be used for concrete coarse aggregate the sample shall consist of at least fifty (50) pieces between 2 inches and 1 inch, square opening sieve, (and) or of 2500 grams of material between 1 inch and ½ inch If the material is to be used for concrete fine aggregate the sample shall consist of 1000 grams carefully screened between any desired sieves, such as 4–8, 8–14, or 14–28 mesh, etc

Selection All samples shall be secured by quartering or dividing to the desired numbers or amounts, thus eliminating as much as possible the personal element from the selection of the samples

Solution

The solution of sodium sulphate shall be prepared in the following manner

Anhydrous sodium sulphate (Na_2SO_4) or the decahydrate (Na_2SO_4 - 10H20) shall be added to hot water at the rate of 400 grams or 900 grams per liter, respectively, or in round numbers, 0 9 pound or 2 pounds per quart of water The solution shall be heated one-half hour to 85° to 90°F with frequent stirring to prevent caking in the bottom and to effect solution quickly After this it shall be set aside for at least 12 hours before use During the preparation and use of this solution there shall be present at all times excess crystals of the salt (decahydrate) to insure saturation The solution may be conveniently kept in a large earthenware covered crock when not in use Suitable receptables for the individual sample solutions are one gallon earthenware crocks The fine aggregate samples should be contained in fine mesh wire baskets which can be lowered into the solution contained in one-half gallon crocks These may be covered easily, have poor thermal conductivity, are not attacked by the solution and are readily cleaned

Test procedure

Immersion The selected sample shall be examined for fractures and cracked pieces, any loose fragments being removed before the test is begun The sample is then plainly marked and thoroughly dried for at least four (4) hours at 212° to 225°F , carefully weighed and then completely immersed in the solution The soaking period shall continue for nineteen (19) hours with the temperature of the solution maintained between 80° and 85°F.

Examination At the end of each soaking period the specimen (of the larger sizes) shall be examined individually, with great care, for any sign of disintegration, such as cracking, checking, splitting, crumbling, etc The portions which can be removed with the fingers shall be taken off, weighed, set aside for later consideration and calculated to per-cent loss for that cycle A sample breaking into three or more pieces shall be considered as failing and shall be removed from the test, weighed and considered lost The number of pieces affected during the cycle shall also be noted Smaller aggregates and sands shall be examined visually after each cycle for apparent distress After each five cycles the samples shall be dried, sieved and the per cent of material determined which now passes the lower size sieve

Drying After examination the specimen shall be placed in a previously heated drying even and be held for four (4) hours at a temperature of 212° to 225°F Then the sample shall be cooled for one (1) hour before immersion in the sodium sulphate solution One cycle shall consist of four (4) hours drying, one (1) hour cooling, nineteen (19) hours soaking, and an examination of the material The test on concrete aggregates shall be run for five (5) cycles.

Interpretation of test

An individual specimen breaking into three or more portions (each portion being more than 10 per cent of the original weight of the piece) or losing more than 20 per cent of its weight by chipping or flaking shall be considered to have failed in the test A sample having 20 per cent or more of its pieces failing shall be considered unsound Likewise, when 20 per cent or more by weight of chips and flakes are formed during the test passing the ½ inch screen (square openings) this shall constitute unsoundness in the sample A sample shall be classed as of "doubtful soundness" when 15 to 20 per cent of its pieces fail or if 15 to 20 per cent of its weight is lost in chips and fragments Such material shall be tested again for durability If it is classed as "doubtful" the second time this behavior shall be construed to indicate the unsoundness of the sample

Materials for smaller aggregates and sands shall be classed as unsound when more than 20 per cent by weight is reduced in size during the test to pass the original sample's lower sieve limit At the end of the test the remaining portion of the sample shall be freed from Na_2SO_4 by a repeated boiling and soaking process, the wash water being renewed four or five times After drying and weighing, the total loss during the test is determined by the difference between the original and the final weights of the sample

Materials not falling in the above classification shall be considered sound

Materials failing shall not be used unless their durability has been demonstrated by service behavior

A considerable amount of work has been done recently along the line of soundness investigations by the Sanitary Committee of the A S C. E The above recommendations are based quite largely on these investigations and on work along the same line which has been carried on by members of the National Crushed Stone Association "

There seems to be no question but that the method of conducting the sodium sulphate test as now specified in Bulletin 1216 is inadequate because of failure to specify the test procedure in sufficient detail Investigations should be conducted with the view to standardizing procedure The proposed method would form an excellent starting point

The sodium sulphate test has also been of limited value due to lack of information as to the relation between the effects observed in the test and results in service Until more information can be secured along this line it will be necessary to use the test simply as an indication of possible unsoundness and not as a definite specification requirement

SUMMARY

In conclusion the writer believes that the problem of determining the relation between durability of concrete and durability of aggregates may be logically divided into two parts, as follows:

A Laboratory studies leading to the standardization of tests for durability of

1 Aggregates as such
   - (a) Immersion in sodium sulphate, etc
   - (b) Freezing and thawing

2 Aggregates in concrete (concrete tests)
   - (a) Freezing and thawing
   - (b) Thermal expansion.

B Laboratory and field investigations of aggregates for the purpose of correlating results of tests with service behavior with the ultimate object of establishing definite limits for various constituents of aggregates which lack durability

1 Laboratory studies

(a) Effect of varying percentages of certain mineral constituents in sand, such as shale, feldspar, chert, etc , on durability of mortars and concrete, as follows

1 Sodium sulphate and freezing tests on the aggregates

2 Freezing and thawing tests on mortars containing the aggregates in mixes having a range in water ratio of from 0 5 to 0 9

(The effect of shale, feldspar, etc , in sand should be investigated on samples taken from various localities and prepared so as to contain definite predetermined percentages of the material being investigated)

(b) Effect of chert in gravel or crushed stone on durability of concrete

1 Sodium sulphate and freezing tests on aggregates

2 Freezing tests on concrete containing the aggregate in mixes having a water-cement ratio of 0 6 to 1 0

3 Alternate heating and cooling of concrete specimens containing chert in predetermined quantities and of variable maximum size Range in temperature to be about 100°F

(This series should include tests on samples of deposits containing chert from various localities and should include studies on the concrete containing definite, predetermined percentages of chert as well as a complete petrographic study of the character of the chert in each case)

(c) Effect of shale in gravel on durability of concrete

(1) Sodium sulphate and freezing tests on aggregates

(2) Freezing tests on concrete containing the aggregate in mixes having a water-cement ratio of 0 6 to 1 0

(d) Effect of shaley and argillaceous limestone on durability of concrete

(1) Sodium sulphate and freezing tests on aggregates

(2) Freezing tests on concrete containing the aggregate in mixes having a water-cement ratio of 0 6 to 1 0

(This series should include tests on limestones from various localities and varying through a considerable range in quality as regards impurities which are apt to produce unsoundness)

2 Field studies

Any field study to be of real value should be undertaken by a qualified investigator working under the guidance of an agency such as the Highway Research Board

His duties would be to survey existing structures located in those sections where trouble from aggregates might be expected, obtain in each case a complete history insofar as possible of the installation, description of the failure, samples of the concrete and the aggregates, etc He should also study structures which are still in good condition with the idea of obtaining information which will indicate conditions under which the same aggregates are giving satisfactory service

In order to avoid duplication of effort any field survey such as that indicated above should be preceded by a thorough study of available information obtained as the result of surveys by other agencies, such as the American Concrete Institute and the Portland Cement Association

DISCUSSION

ON

RELATION BEWEEN DURABILITY OF CONCRETE AND DURABILITY OF AGGREGATES

MR H F GONNERMAN, *Manager of Research Laboratory and* MR G W WARD, *Geologist, Portland Cement Association* Mr Jackson has presented a very interesting and timely discussion of the various factors involved in researches designed to bring out the relation of aggregates to the durability of concrete While this subject is one on which there is not a great deal of information, a number of laboratories are studying the problem and much valuable data will, no doubt, be available soon

Some studies along the lines proposed by Mr Jackson were begun in the Research Laboratory of the Portland Cement Association early in 1928 in connection with a general program of tests on the factors affecting the durability of concrete These studies were prompted by some isolated instances of faulty concrete which appeared to be due to the use of unsound aggregates and which came to our attention during surveys of concrete pavements and structures in various sections of the country

While in most localities there is an abundance of durable aggregates, both fine and coarse, there are a few localities in which more care must be exercised in the preparation and selection of aggregate materials if good results are to be obtained Even in localities where durable aggregates are abundant, attention must be given to their mineral composition and preparation in order to insure a clean product free from injurious amounts of unsound materials

Our investigations have included examinations of pits and quarries in several states, as well as extensive laboratory investigations on the aggregates themselves and on mortars and concrete made from them The general procedure in carrying out these tests is as follows· Examinations are made of the sources of supply, to obtain information on the character of the deposits and their constituent materials, and the probable continuance of an adequate supply of similar material Particular effort is made to discover whether materials known to be unsound exist in quantity in the pit or quarry Note is taken of the amount of overburden and method of removal as well as the cleanness of the material produced In quarries, careful examination is made of the working face to determine the number and character of ledges Representative samples of the final product and in some cases samples of ledge or bank material are selected and shipped to the laboratory where they are subjected to the following tests

Fine Aggregate
- Silt
- Colorimetric
- Sieve Analysis
- Unit Weight
- Sodium Sulfate Soundness (aggregate alone)
- Freezing and Thawing (aggregate alone)
- Freezing and Thawing of 2-inch Mortar Cubes
- Compression Tests of Mortar
- Mineralogical Analysis
- Thermal Expansion of Certain Minerals and Rock Fragments

Coarse Aggregate
- Visual examination for cleanness
- Sodium Sulfate Soundness Test (aggregate alone)
- Freezing and Thawing (aggregate alone)
- Freezing and Thawing in Concrete
- Thermal Expansion on Aggregate Alone, Dry and Saturated with Water
- Compression Tests of Concrete

Sodium sulfate soundness tests on coarse aggregates are carried out on 2000- or 2500-gram samples (about 30 pieces) following a procedure which a careful study and numerous tests of the sodium sulfate test itself indicated was most suitable from the standpoint of accuracy and reproducibility of results The procedure used in many respects parallels the method reported by Mr Jackson In determining failure of coarse aggregates, we have considered particles breaking into two pieces or showing only incipient cracks to be sound Disintegrated particles, those breaking into three or more pieces of about equal size and particles badly laminated, or showing a loss of approximately 20 per cent by weight due to scaling, flaking, or sloughing are considered unsound

Soundness tests on fine aggregates are made on 500- to 1000-gram samples sieved into five or six sizes (100–48, 48–28, 28–14, 14–8, 8–4, 4–$\frac{3}{8}$-inch) A separate test is made on the material retained on each sieve Microscopic examination is made of the material passing the 100-mesh sieve to determine the presence of undesirable minerals At the end of a given number of cycles the samples are again sieved over the sieves on which they were originally retained and the loss in weight determined The total percentage loss in weight is calculated from the results of tests on each sieve and the amounts of material originally retained on each sieve in the original sieve analysis. Coarse particles that break up due to a laminated structure but which are retained on the various sieves are given consideration in determining the acceptability of the sample.

For comparison with sodium sulfate soundness, freezing and thawing tests on the fine and coarse aggregates are made following so far as possible the procedure specified by the A.S.T.M. specification for drain tile (Serial Designation C4–24).

As pointed out by Mr. Jackson the final test of an aggregate's durability is the behavior of the concrete in which it is used. In our tests the behavior of 2-inch mortar cubes and of 6-inch concrete cubes after exposure to a large number of alternations of freezing and thawing is being studied. The specimens are moist cured at 70°F. for 14 days and then stored in air for 14 days. At 28 days they are immersed in water at room temperature for 72 hours and then subjected to freezing. During freezing the saturated 2-inch mortar cubes are immersed in about ½ inch of water in covered metal pans. The 6-inch concrete cubes after saturation are frozen immersed in water in metal containers slightly larger than the specimen itself. All specimens are frozen in a room the temperature of which can be dropped to 14°F. in thirty minutes after introducing the specimens. The temperature of the room is maintained at from -5°F. to -20°F.

Four water contents are used in the mortar cubes ranging from a very rich mortar (about a 1:1½ mix by weight) containing 4½ gallons of water per sack of cement to a lean mortar (about a 1:4 mix) containing 9 gallons per sack. In the concrete cubes 3 water contents are used—5½, 7 and 9 gallons per sack. Examination of the specimens is generally made at the conclusion of every 10 cycles and if they show evidences of breaking down their compressive strength is determined and compared with the strength of parallel control specimens that have been kept in the moist room at 70°F. The cubes are weighed from time to time in order to determine the rate of loss under the freezing and thawing treatment.

In addition to the sodium sulfate and the freezing and thawing tests for soundness the fine aggregates are examined under the microscope and counts made of the particles considered to be unsound in an attempt to correlate the results of such counts with those of the soundness tests on the aggregates alone and in mortar. Since many of the fine aggregates contained appreciable amounts of shaly particles several recommended methods of determining the amount of shale using liquids of known specific gravity were tried. These were not successful due to the fact that the specific gravity of the shale particles was close to that of the other particles; consequently a petrographic count was relied upon to determine the shale content of the various sands.

From the data now available it is difficult to set limits for the amount of failure to be permitted in the sodium sulfate soundness test since the quality of the concrete as well as that of the aggregate has an important bearing on the performance of concrete structures Mr Jackson's report contains a suggestion that 20 per cent loss in weight at 5 cycles be permitted It would seem that this amount is too great to be permitted in aggregates which are to be used in structures subjected to severe exposure We have considered that until more information is available on the behavior of various types of concrete made with aggregates containing various amounts of non-durable particles, the percentage of failure at 5 cycles should not be more than about 15 per cent in the case of coarse aggregates and not more than about 10 or 12 per cent in the case of fine aggregates In fixing limits for specification purposes, two important factors that should be considered are the type of exposure to which the concrete will be subjected and the character of the unsound material As regards the latter our experience has shown that shales and similar thinly laminated materials and some cherts are the most dangerous and hence should be allowed in only small amounts The service record of any aggregate also should be taken into account in passing final judgment on its suitability from the standpoint of soundness

PROF F C LANG, *Professor of Highway Engineering*, and PROF C A HUGHES, *Assistant Professor of Structural Engineering, University of Minnesota* Since Minnesota is a northern state subjected to extremes of temperature, the durability of concrete and concrete materials, particularly their resistance to freezing and thawing, is a matter of prime importance to us For some years past considerable experimental work bearing on this question has been done at the Experimental Station of the University of Minnesota Data from some of the earlier tests have already been reported in the Proceedings [1] The University and the State Highway Department have worked separately and in cooperation To date we have been as much concerned with apparatus and procedure as with the evaluation of the effects of variables It has been our experience that durability is an elusive subject More frequently than not, what are apparently well conceived programs yield no usable data It is far easier to obtain data than it is to interpret it even if only from the laboratory standpoint Correlation with field work is a yet more difficult problem

Mr Jackson has very ably discussed the many variables involved in freezing and thawing tests and has pointed out the great need for standard procedure As he truly states, a very extensive investigation is required before standard procedure can be formulated In the hope that

[1] Résumé of Sodium Sulfate Tests for Soundness Made on Various Stones Proceedings of the Fourth Annual Meeting of the Highway Research Board, 1925

our experience may be of some value in laying out the program for such an investigation we wish to describe briefly the methods used in our laboratory

Our initial experimental work with freezing and thawing was concerned with its effect on the compressive strength and volumetric change

TABLE I

HIRSCHWALD'S ABSORPTION TESTS

	Percentage by weight				Percentage of pore volume			
	1	2	3	4	1a	2a	3a	S
Sandstone	4 89	5 66	7 89	9 23	52 97	61 30	85 46	0 613
Sandstone	6 90	7 33	10 80	11 31	61 06	64 88	95 48	0 648
Marble	0 35	0 49	0 55	0 59	59 47	84 27	94 67	0 831
Limestone	7 51	7 88	19 08	21 19	35 46	37 20	90 04	0 372
Slate	0 51	0 55	0 70	0 70	72 92	79 16	100 00	0 786
Tuff	22 11	23 41	30 25	33 75	65 51	69 37	89 64	0 694
Granite	0 51	0 91	1 07	1 25	41 20	57 71	85 54	0 728

(1) Absorption after rapid submersion, (2) absorption after slow submersion, (3) submersion under vacuum; (4) submersion under 50 to 150 atmospheres pressure 1a–3a represent the percentage of the pore volume filled by the water in each case (S) is the saturation coefficient and = $\frac{2}{4}$ (Taken from Reis and Watson's "Engineering Geology," page 455, Third edition)

TABLE II

HIRSCHWALD'S FREEZING AND THAWING TESTS—EFFECT OF FREEZING A STONE WITH PORES PARTIALLY AND COMPLETELY FILLED

Kind of rock	Treatment during thawing period	
	Soaking under normal atmospheric pressure	Soaking in a vacuum
Limestone	31 times, no effect	5 times, broken in two
Marble	25 times, no effect	3 times, cracked
Sandstone	25 times, no effect	8 times, spalled off
Tuff	25 times, no effect	14 times, many cracks
Coarse granite	Unaffected	8 times, mica scaled detached

(Taken from Reis and Watson's "Engineering Geology," page 472, Third edition)

of mortars, using what we will call the ordinary method of freezing and thawing, that is a period of submersion at room temperature followed by a period of low temperature, the specimens being frozen either in air or wholly or partly submerged

We next became interested in methods for accelerating freezing and thawing The use of pressure during the submersion period at room temperature was suggested by data from tests by Hirschwald[2] quoted in Ries and Watson's Engineering Geology, and by the short reference to Kreuger's[3] tests in the 1926 report of the Building Research Board.[4] For convenience Hirschwald's data are given in Tables I and II. Both of the above investigators showed that the number of cycles necessary for disintegration was materially reduced by the more complete filling of the voids resulting from the use of pressure during the soaking period. Krueger gives 80 per cent as the critical ratio of absorbed water to voids.

With the intention of still further increasing the ratio of water to voids a vacuum applied ahead of the pressure was the next development.

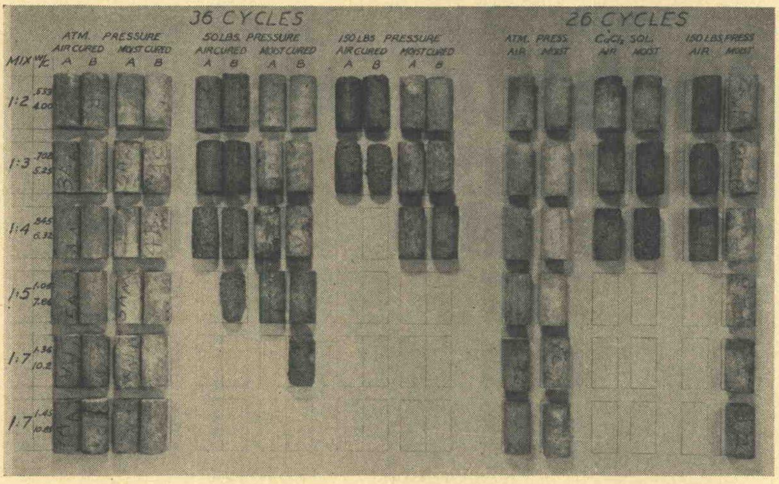

Figure 1. Effect of Various Cycles on the Resistance of Mortars to Freezing and Thawing

Blank spaces represent specimens that reached their end points

Placing the saturated specimens directly in brine in order to speed up the rate of freezing was suggested by the 1927 Report of the Building Research Board.[5] The rate of disintegration is much more rapid using this method. In the above report it is stated that this more drastic effort is the result of faster freezing. "The effect does not appear to be due to any direct action of the brine itself since the same results were obtained when the specimens were protected from direct contact with the brine by covering them with rubber or lead foil."[6] The report is not clear as to just what building materials were tested.

[2] Handbuch der bautechnischen Gesteinsprufung, Berlin, 1909.

[3] Utredning Rörandé Klimatisk Inverkan Pa Bygynadfasader, H. Kreuger, Ingeniörs Vetenskaps Akademien, Stockholm Handlingar, Nr. 24, 1923.

[4] Department of Scientific and Industrial Research, Great Britain.

[5] Ibid.

[6] Department of Scientific and Industrial Research, Great Britain.

Thawing was then accelerated by immersion in boiling water followed by immersion in ice-water. The immersion in ice-water was used chiefly to reduce the load on the freezing machine though it probably increases the percentage of absorption at the same time.

We have tried a number of combinations of the above steps on mortars, concretes and concrete aggregates.

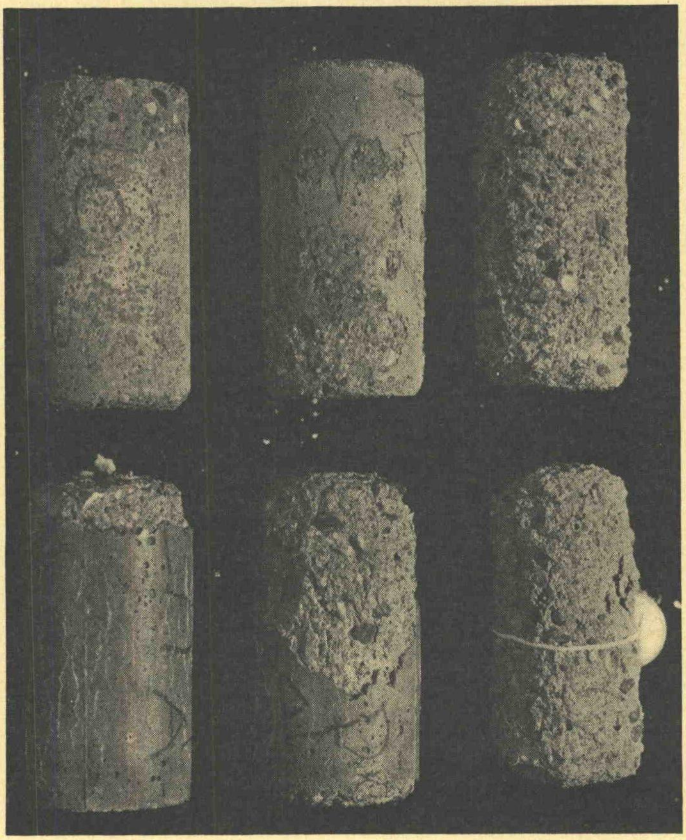

Figure 2. Effect of Treatment on the Method of Disintegration

The top three specimens were frozen directly immersed in $CaCl_2$ brine. The lower three were stored in water at room temperature under 150 pound per square inch pressure. The cores of the lower specimens are quite hard and strong. The upper specimens softened uniformly throughout.

The effect of various combinations on mortars of different water-cement ratios is shown in Figure 1. These tests were made in the spring of 1930 by two senior students[7] in a partial fulfillment of an advanced course in Plain Concrete. The specimens consisted of 2 by 4 inch cylinders of mortar varying from 1:2 to 1:7 mixes by weight, and having

[7] E. L. Porter and Paul R. Staffeld, Structural Engineering Division, University of Minnesota.

water cement ratios of 4 0 to 10 85 gallons per sack of cement Two methods of curing prior to freezing and thawing were used, namely moist and air-curing for 27 days following 1 day in the molds All specimens except as noted below were frozen in the saturated condition in air at 0°F and atmospheric pressure During the room temperature period the specimens were submerged under three pressures, atmospheric, 50 pound per square inch and 150 pound per square inch for the three separate groups One set of specimens was immersed in calcium chloride brine during the freezing period These were stored

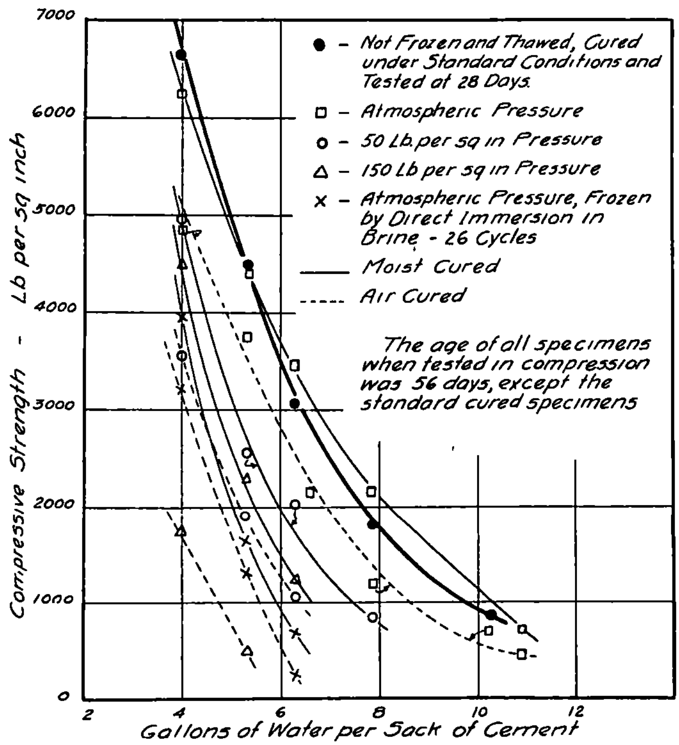

Figure 3 Compressive Strengths after 36 Cycles of Freezing and Thawing Average of A and B Specimens See Figure 1

under water at atmospheric pressure during the room temperature period The cycles were made at the rate of $1\frac{1}{2}$ per day, the changing times being 8 30 A M , 1 00 P M , and 5 30 P M Thus there was an alternate long cycle for each group every other day

The end of the University year prohibiting continuation of freezing and thawing, the specimens that had not reached the "end point" were tested in compression The data from the compression tests for the A and B sets (36 cycles) are given in Figure 3 The data for the 26 cycle specimens give similar relations

It will be observed that increase in pressure resulted in a marked increase in the rate of disintegration and in the loss of strength The use of direct immersion in $CaCl_2$ solution had even more effect than the use of the 150 pound pressure The method of disintegration was markedly different for the specimens thawed under pressure and those immersed directly in brine as is shown by Figure 2. The pressure specimens disintegrated by spalling off concentric layers (exfoliation) leaving a hard strong core Disintegration of those immersed in brine was characterized by popping of the aggregate and a general softening of the whole mass The 1 7 specimens frozen in air behaved similarly to the brine-immersed specimens in that the whole mass disintegrated more or less uniformly

Following these tests a cooperative series of freezing and thawing tests was begun by the State Highway Department and the University of Minnesota for the purpose of finding a substitute for the abrasion and other tests as a measure of aggregate quality After some preliminary investigation we adopted a very rapid cycle consisting of 5 minutes in boiling water, 5 minutes in ice water, and 30 minutes directly immersed in $CaCl_2$ brine at about 0°F The apparatus used in these tests is shown in Figure 5 Typical results of the investigation now under way are shown in Figure 6, 7, 8, and 9

Agreeing with Mr Jackson that tests of aggretates are only of value insofar as they indicate the behavior of the aggregates in concrete, we are also testing concrete specimens made from the aggregates used in the freezing and thawing tests We believe however that if satisfactory correlation can be shown between aggregate and concrete tests, that the aggregate test is preferable because of its greater simplicity and rapidity

While we have no data which will give a conclusive answer to any of Mr Jackson's "questions which must be answered," from our tests we have developed certain opinions which we will give under the respective headings of the variations suggested by Mr Jackson We use the word "opinion" advisedly for we have raised so many questions in our own tests that we believe very much work is required before definite statements can be made

1 Size and shape of specimen Assuming that the standardized freezing and thawing test will be used as an acceptance test of aggregates, the apparatus required must not be so large, nor so expensive, as to be beyond the budget of the ordinary laboratory Since even accelerated tests take an appreciable time to make, the testing of a large number of samples requires either a large freezing machine or the use of small size specimens While fully realizing that we will approach field exposures more nearly with a large than with a small specimen, the saving in both labor and apparatus resulting from the use of the small specimen is great enough to warrant the inclusion of a small sized specimen in the investigation We soon discovered that the ratio of concrete specimen to particle diameter is important and believe that the ratio should preferably be 4 and not less than 3 The size of aggregate would therefore be limited in small sized specimens However we have found from our tests of aggregates that the disintegration of the smaller-sized particles ($\frac{1}{2}$–$\frac{1}{4}$ inch) is in general proportional, (though somewhat greater) to that of the larger sized particles $1\frac{1}{2}$–1 inch and 1–$\frac{1}{2}$ inch)

As to the shape of the specimen we prefer one for which it is possible to determine either the end point (defined limit of disintegration) or the loss in strength by means of a flexure test Either 3 by 3 by 6 prisms or 3 by 6 inch cylinders would appear to be satisfactory for material graded from $\frac{1}{2}$-inch (square mesh) down

2 Nature of exposed surface We have made no tests along this line, all our specimens being made in the ordinary way For a standard test from the standpoint of practicability and economy of labor it would appear advisable to adopt a specimen requiring no special preparation as to surface As in the case of the shape of specimen the desirability of any type of surface will depend on the method of evaluating the specimens after test If carried to an end point by accelerated methods the aggregate in specimens made by ordinary methods is exposed for a considerable percentage of the total number of cycles For tests carried to a definite number of cycles the character of the surface may be an important factor particularly if evaluation is by visual inspection and (or) loss of weight

3. Method of insuring saturation of specimen During the school year of 1928–29 a number of tests were made[8] for the purpose of showing the relative durability of mortars made with five different kinds of cement The program included compression tests of 2 by 4 inch cylinders of neat cement and 1 3 mortars cured in three ways, as follows

1 Under water at 70°F for 46 days
2 Under water at 70°F. for 7 days, then subjected to 15 cycles of freezing and thawing completely submerged
3 Under water at 70°F for 7 days and then subjected to 15 cycles of freezing and thawing submerged only to one-half the height

The freezing and thawing cycle consisted of 12 hours in a cold room at plus or minus 0°F and variable periods at room temperature The specimens were tested in compression at an age of 46 days, all being submerged for 48 hours immediately prior to testing

Table III shows the strengths of specimens completely submerged and half submerged during the freezing period relative to the strengths of similar specimens cured under water at 70°F. Since three gradings of sand were used for each cement and there were three specimens of a

[8] By C H Sandberg, then research fellow in Structural Engineering

TABLE III

Effect of Submerging or Half Submerging Specimens during the Freezing Period

Mix—1 3 by weight
Water cement ratio—0 65
Age when tested—46 days
Condition when tested—saturated (48 hours immersion)
Number of cycles of freezing and thawing—15
Initial curing of frozen and thawed specimens—1 day molds, 6 days under water at 70°F

A Effect of different cements Average percentage strengths based on moist-cured specimens

Treatment	1 3 mortars (average of 12 specimens)					
	A	B	C	D	E	Average
Frozen and thawed wholly submerged	86 4	90 1	92 9	87 3	91 1	89 6
Frozen and thawed half submerged	*83 2	94 0	94 8	88 9	90 1	90 2
Average	84 8	92 0	93 8	88 1	90 6	
Reduction in strength	15 2	8 0	6 2	11 9	9 4	
	Neat (average of 3 specimens)					
Frozen and thawed wholly submerged	97 5	99 0	101 8	3–13C	76 8	
Frozen and thawed half submerged	1–14C 58 3	70 6	2–4C 1–12C	3–6C	1–14C 89 1	

* Two specimens disintegrated, one at 9 cycles and one at 12 cycles
1–14C, etc, indicates complete disintegration (fracturing into two or more pieces) of one specimen

B Effect of grading Average of percentage strengths for all cements Based on moist cured specimens

Treatment	1 3 mortar (average of 15 specimens)				
	Grading of sand				
	Neat	Fine	Medium	Coarse	Ottawa
Frozen and thawed wholly submerged	*93 8 †75	84 7	88 4	93 5	97 8
Frozen and thawed half submerged	*72 7 †43 6	87 5	90 5	93 7	102 1

* Broken cylinders not included in average
† Broken cylinders taken as zero and included in average

kind each value is the average of 9 specimens The upper half of the table is arranged to show the effect of the brand of cement while the lower shows the effect of the grading

When a limited number of cycles is used from Table III it would appear that there is little if any difference between the effect of submerging or half-submerging during the freezing period on the compressive strength of 1 3 mortars A similar conclusion was reached by the Department of Scientific and Industrial Research of Great Britain On page 29 of the Report of the Building Research Board for the year 1927 is found the following

"Some authorities recommend that the specimen should be frozen while immersed in water, others recommend that the specimen should be half immersed From the tests carried out at the station there does not seem to be a very marked difference between the effects in the two cases Sometimes a specimen which was fully immersed has failed before that which was half immersed—sometimes the effect has been the reverse of this "

If however the cycles are continued to an end point it would appear from the data of the neat cement specimens that half-submerging is considerably more severe than totally submerging Half submerged, 60 per cent of the neat specimens and 2 mortar specimens failed before 15 cycles whereas completely submerged only 20 per cent of the neat specimens and no mortar specimens failed The type of fracture for the two treatments was quite different, those fully submerged fracturing at no definite angle whereas the fracture lines for the half-submerged specimens was in all cases parallel or nearly so to the water-line

The small difference in the compressive strengths of the two treatments is regarded more as an indication that the compressive test is not a suitable one for measuring the effect of freezing and thawing rather than as a true measure of the relative effects of the two treatments A good illustration of the lack of sensitivity of the compression test is the fact that one of the 3 neat specimens of E cement failed at 14 cycles whereas the other two showed on the average only a loss of about 11 per cent

The difference in the resistance of the different brands of cement suggests that this variable should also be added to those listed by Mr Jackson

Freezing saturated specimens in air is not only much simpler but results in a large saving on the work required from the freezing unit While we have no comparative data, Figure 3 shows clearly that freezing in air can be very effective when the saturation coefficient is increased by use of pressure during the high temperature period The type of disintegration shown by pressure specimens in Figure 2 is very similar to that observed in bridge piers and similar structures We believe this method has sufficient merit to warrant considerable investigation

4 Minimum temperature at which freezing should take place Tests made by the Building Research Board[9] and by us indicate that the majority if not all of the water that will freeze at practicable temperatures, freezes a few degrees below 0°C (−2 to −4°C) On freezing water expands about 9 per cent or a relative movement of 0 09 On further cooling the contraction of ice is about 0 000,028 per degree Fahrenheit The contraction of rock materials and concretes is much less than this being about 0 000,005 per degree Fahrenheit Cooling below the temperature at which all the water was frozen would therefore cause a reduction of the stresses caused by the freezing of ice This reduction of stress, however, would be very small in comparison with the stress set up on the change from ice to water and therefore it may be surmized that the effect of variation in the minimum temperature would be small

Minimum temperatures lower than about −10°C would then appear not to be necessary or desirable provided that the specimens were held at this temperature long enough to insure freezing of all the water If an accelerated test is used, however, it is preferable to have a low temperature in order to increase the temperature gradient and therefore the rate of freezing

5 Rate of freezing, including (a) time required to reach minimum temperature and (b) time held at minimum temperature Referring to Figures 1 and 3, if the differences in the disintegration and strengths shown by the specimens frozen in air (left group of Figure 1) and those frozen in brine (5th group from left) are due solely to the rate of freezing then it is evident that the rate of freezing is a very important factor (Also see previous quotation from 1927 Report of British Research Board)

The effect of both variables (rate and duration) acting at the same time on typical aggregates is shown in Table IV The disintegration not only varies in amount but also varies in character for different materials This is particularly evident from the data for limestone and sandstone This difference is attributed to the widely different character of the pores in the two materials The second method of evaluation indicates the splitting of the aggregate particles into fairly large fragments, none passing a No 4 sieve being considered Cycle C caused the limestone to separate into a great number of fragments as shown by the very high rating in Table 4 but formed relatively small quantities of −8 and −100 material as compared with F cycle, the −100 material being exceptionally low The high splitting and low dusting of the C limestone specimen is very marked when compared visually with the low splitting and high dusting F sample The rapid cycle F causes more splitting of the sandstone samples than the slow C cycle This effect

[9] Report of the Building Research Board for the Year 1927 Department of Scientific and Industrial Research, Great Britain, pages 33 and 36

is much greater than is indicated by the data of Table IV since many particles were cracked but did not fall apart on sieving

The splitting of the sandstone is thought to be due to pressure of the absorbed water when expanding below 4°C, its escape and the consequent reduction of pressure being prevented by the ice layer formed on the particles It may be due in part to the rapid temperature changes which would be more severe on sandstone because of its coarser grain

6 *Method of evaluating specimens after test* Evaluation by visual inspection is not satisfactory when used alone in that it (a) lacks definiteness, and (b) is not duplicable for different operators or even the same operators on different days On the other hand it is the only means of differentiating between different methods of disintegration, as for example, with concrete, by popping or spalling, crumbling of the mortar, failure of aggregate bond, etc, or with aggregate such as dusting, cracking, splitting into laminae, etc The recording of the results of visual inspection presents another problem in that it is difficult if not impossible to present a concise description that will convey the same meaning to all Even the necessary definitions of terms used is far from easy Difficulties of description are largely overcome by use of numerous photographs Photographs besides eliminating much of the uncertainty of verbal description also permit comparison of specimens tested at different times

TABLE IV

EFFECT OF TIME HELD AT MINIMUM TEMPERATURES (0°F) AND RATE OF FREEZING FOR VARIOUS AGGREGATES FOR 10 CYCLES OF FREEZING AND THAWING

	Passing No 8 sieve		Ratings based on count of fragments based on sieve analysis		Passing No 100 sieve	
Cycle	C	F	C	F	C	F
Duration of freezing period	16 hours	20 minutes	16 hours	20 minutes	16 hours	20 minutes
Method of evaluation						
	per cent	*per cent*			*per cent*	*per cent*
Trap	0 1	0 2	4	10	0 1	0 1
Limestone	7 9	5 1	3022	111	0 8	3 3
Gravel	0 2	0 4	43	9	0 1	0 2
Sandstone	0 9	3 0	1	207	0 7	1 3

Cycle C—Frozen under water—slow rate of freezing
Cycle F—Frozen in brine—rapid rate of freezing

For mortar or concrete specimens it is believed desirable to continue testing until some end point of disintegration is reached rather than trying to arrive at conclusions from the results of comparative strength tests A simple method that appears to give satisfactory results is to subject the specimens to a cross-bending test The apparatus need consist only of a pair of supports and a loading ring In the tests made to date the end point is considered reached when the specimens do not withstand an apparent stress of 10 pounds, per square inch calculated by the usual flexure formula on the original dimensions When from visual inspection a specimen is considered to be approaching the end point it is slipped into the machine If it does not fail it is subjected to additional cycles This method is easily applied and gives quite definite results The use of the cross-bending test is much preferred to a compression test The tensile resistance is believed to be much more sensitive to the effect of freezing and thawing than the compression test Inspection of fractured specimens shows two types of disintegration In one aggregate particles have broken down into fragments and in the other the bond between aggregate and cement paste has failed The first is typical of soft porous aggregates and the second of strong dense aggregates

When testing aggregate it appears impractical to come to any end point Therefore it is better to make measurements of some kind following a definite number of cycles We have used the following methods of evaluation

1 The percentage passing number 8 sieve
2 The percentage washed through the number 12 sieve
3 The percentage passing the number 100 sieve
4 The percentage difference in surface modulus
5 The percentage difference in fineness modulus
6 The percentage passing the sieves on which 100 per cent of the material was originally retained

In addition we have tried ratings based on counts of particles retained on certain sieves, ratings on disintegrated particles and the like The latter methods are unsatisfactory since either too much depends on the judgment of the operator or they are not universally applicable

The first six methods gave nearly the same relative results Since for the method we are using, the determination of the percentage passing the number 8 sieve is obtained by the least labor, this is the criterion we recommend

The use of a brine solution The chief advantage of direct immersion in a brine solution is the rapidity with which the specimen is frozen Another advantage is the fact that the load on the refrigerating machine is reduced since only a minimum of water (that within the specimen) is frozen Also the brine acts as a reservoir and hence maintains more uniform temperatures This is of especial importance if the refrigerating machine is being used up to capacity

The great difference between the rate of cooling of 2¾ by 5½ inch concrete cylinders is shown in Figure 4. Similar determinations made on pieces of limestone (between 2–1½ sieves) showed that a temperature

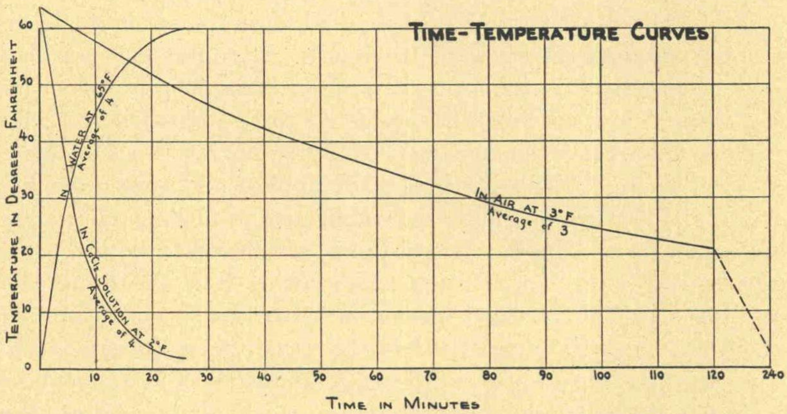

Figure 4. Time-Temperature Relations for 2¾ by 5½ inch Concrete Specimens

Data obtained by use of thermocouples placed at centers of cylinders. Note very rapid drop and rise of temperature when immersed in brine at 2°F. and in water at 65°F.

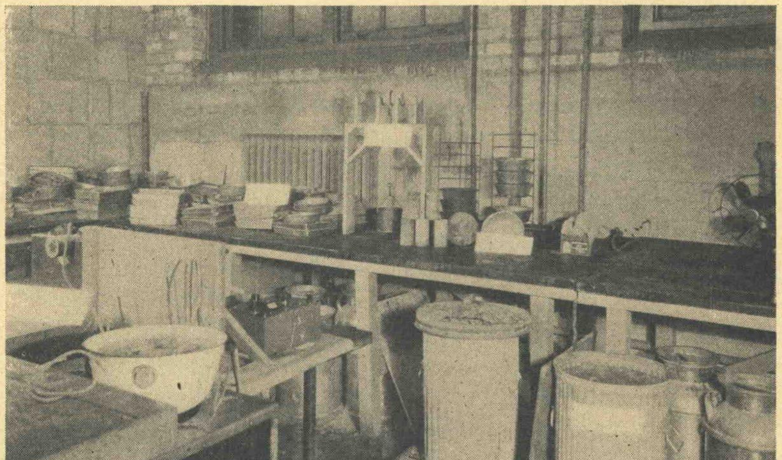

Figure 5. Apparatus Used in Accelerated Freezing and Thawing Tests of Aggregates and Concretes

of 20°F. was reached in about 4 minutes in the brine and about 50 minutes in air. Specimens submerged in water would take still longer to reach the same temperature.

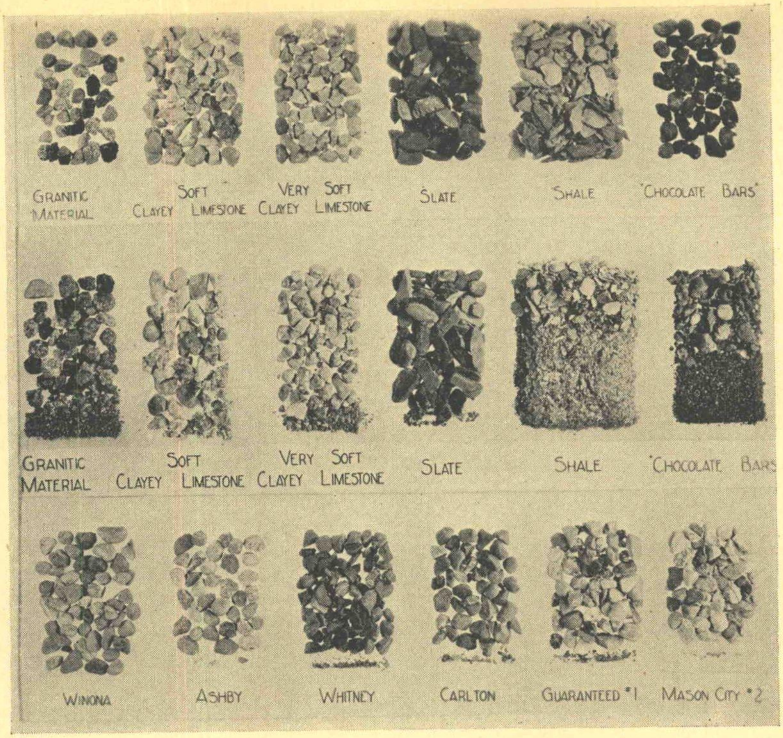

Figure 6. Effect of Freezing and Thawing on Good and Bad Aggregates

The top row are 1½- to 1-inch fractions of hand picked deleterious aggregate. The second row shows the effect of 10 cycles of freezing and thawing (1 day's run, 40 minutes to the cycle). The third row shows the effect of 20 cycles on representative satisfactory-in-service aggregates. All material finer than a No. 12 sieve has been washed from the tested samples.

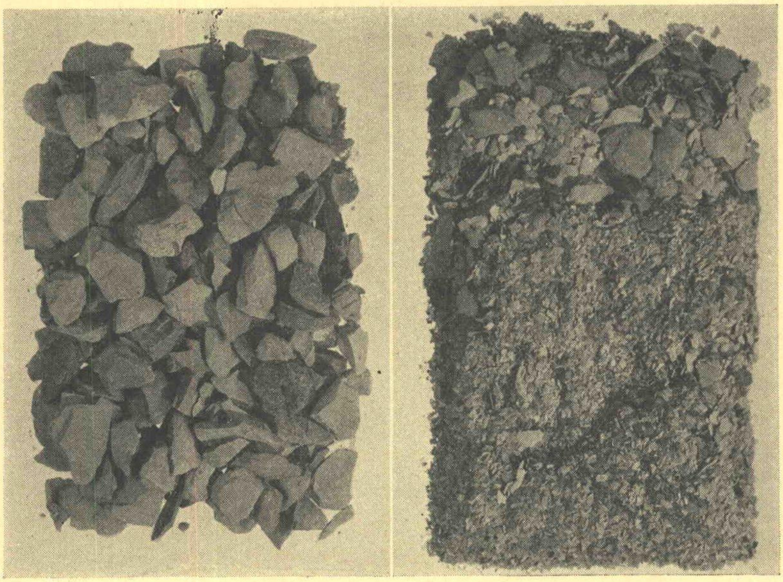

Figure 7. Effect of Freezing and Thawing on Shale

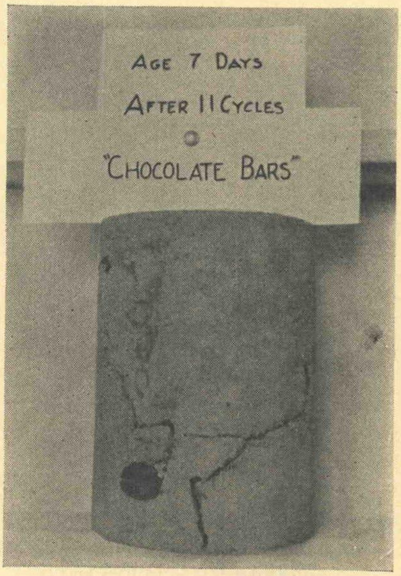

Figure 8. Effect of "Chocolate Bars" (Coated Clay Secretions) Used as Coarse Aggregate, 1½- to 1-inch Material Only, Remainder Good Aggregate

Age at test 7 days, end point 14 cycles, accelerated method, 10 cycles per day

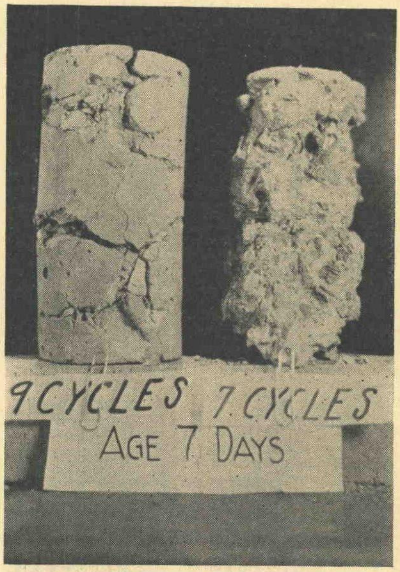

Figure 9. Effect of Chert (left) and Shale (right) Used as Coarse Aggregate

End points 9 and 7 cycles. Age at beginning of test 7 days. Accelerated method, 10 cycles per day. Note expansive action of chert.

The chief objections to a brine solution are (a) that there may be some corrosive action, and (b) that diffusion of the solution in the absorbed water will prevent freezing

After a rather brief investigation of solutions of liquids having sufficiently low freezing points, $CaCl_2$ solution was chosen as the most suitable Since the solution is at low temperature when in contact with the material and since much or all is removed each cycle by immersion in the hot and cold water tanks, it is believed to have little or no chemical action on aggregates Its surface tension being high, the diffusion will be low Of its effect on concretes we are not so certain Referring to Figure 1 it will be noted that the disintegration of the moist cured specimens is more marked than that of the air cured specimens This is contrary to experience and to the evidence of the other methods therefore does not inspire confidence in direct immersion in $CaCl_2$ brine if the paste quality is being tested We believe, however, that it is a satisfactory method when the aggregate quality is in question

The results of comparative tests run with calcium chloride solution and CCl_4 show some differences particularly with limestone However they are too few in number to be conclusive One advantage of CCl_4 as a cooling medium is that it is entirely removed on immersion in boiling water, its boiling point being 170°F It, however, creates a very objectionable odor, and has a marked effect on the health of the operators