THE DURABILITY OF CONCRETE

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This paper is primarily a progress report on the work of the Engineering Experiment Station of the Kansas State College which for over six years has been investigating the durability of concrete and concrete aggregates Use has been made of information and material gathered by other investigators associated with the author on committees of national societies and in cooperative research programs The author desires especially to acknowledge the assistance of Mr E Viens of the Department of Public Works, Ottawa, Canada, Mr F R McMillan, Director of Research for the Portland Cement Association, Chicago, Illinois, Mr L V Haegert of the A T & S F Railway Company, Chicago, Illinois, Mr A D Conrow, Special Engineer for the Ash Grove Lime & Portland Cement Company, Chanute, Kansas, and Mr Harold Allen of the Kansas State Highway Commission Much of the material of this paper was included in papers presented to the American Society for Testing Materials

WEATHERING OF CONCRETE

The durability of concrete, in its broadest sense, is represented by its ability to resist the natural disintegrating agencies of weathering action, including the freezing and thawing of water in the concrete, the solution and chemical action by ground water of streams in contact with or passing through the material, and the fatigue resulting from volume changes due to temperature variations and changes in the moisture content of the concrete All of these agencies are powerful disintegrating forces which have reduced the most durable of rocks built in nature's workshop to fertile soil now covering our plains and valleys These same forces are continually at work actively reducing our concrete as they do rocks similarily exposed While studies of the durability of concrete have in recent years been receiving especial attention, they are not new and this property of concrete has long been the subject of investigation In fact, the search for a hydraulic cement more durable than the natural cements and hydraulic limes then available led to the development of portland cement by Joseph Aspdin in 1824

EARLY STUDIES OF THE DURABILITY OF CONCRETE

Most of the early studies of the durability of concrete were chiefly concerned with its use in sea water The weathering from all agencies

is of course, most rapid where the material is exposed to sea water The greatest number of cycles of wetting and drying, and of freezing and thawing, combined with severe attacks of solvents and other chemical agents occur on structures exposed to sea water In many cases the mechanical action of pounding water containing sand, gravel, and other solids is in itself very severe Most of these studies have placed nearly if not all, of their emphasis upon the chemical action taking place between the hydrated cement in the concrete and the salts in the sea water The author has no desire to question the soundness of the conclusions drawn by these investigators, but does seriously question the wisdom of giving so little attention to other disintegrating agencies A very interesting report of a research conducted by the Society of Scandinavian Portland Cement Manufacturers in 1896 was made as a result of the study of concrete blocks exposed for ten years to the action of sea water along the coasts of Denmark, Norway and Sweden [1] Poulsen reported that from observations on these blocks the following conclusions appeared to be justified

"1 Chemical action of sea water alone does not cause destruction of Portland Cement mortars and concretes

"2 Climatic conditions, principally the mechanical action of the tides and frost, are chiefly responsible for the disintegration of concrete and mortar mixtures in sea water The hydraulic lime from Teil was especially adversely affected by the midtide treatment at Vardo

"3 Mixtures containing mortars leaner than 1 2 should not be used in maritime construction

"4 From the experiments on artificially graded mixtures, sands for marine concrete work should contain from one-third to two-thirds of particles passing a No 30 sieve

"5 The addition of small percentages of pulverized trass or very finely ground sand to the cement is advantageous"

It is interesting to note that Poulsen at this early date recognized that the chief disintegrating factor was not a chemical action but was the normal weathering agencies that are prevalent throughout all temperate and frigid zones

Most of the investigations of concrete durability in other locations than where exposed to the action of sea water have been concerned chiefly with the effects of alkali soil, of sulphates of sodium and magnesium, of various acids found in ground waters, sewage, etc , or of the many chemical compounds of a greater or less stability that may, under certain conditions, be set up in the hydration of cements In nearly all cases it has been assumed at the outset that when disintegration occurs some adverse chemical action takes place either through exposure to

[1] Cement in Sea Water, A Poulsen, Copenhagen (as quoted in Johnson's "Materials of Construction," John Wiley & Sons)

unusual external agencies or in the cement itself. The author takes no exception to the conclusions drawn by these capable investigators as to the effects of various injurious chemicals in solutions, but would like to point out that most of these are special cases, and, where one structure is disintegrating due to the presence of alkali water or other harmful chemical agents, thousands are showing the injurious effects of ordinary weathering conditions due to defects that can be easily controlled with but little added expense, and that the precautions taken to remedy these defects will result in concrete offering very high resistance to the injurious chemical agents.

TABLE I

CHEMICAL ANALYSES OF WATER FROM STREAMS OF SOUTHWESTERN KANSAS SAMPLED ABOUT JULY 1, 1926

All values are parts per million

	Ca	Mg	Cl	SO_4	CO_2 combined	NaCl, equivalent of Cl	Na_2SO_4 equivalent of SO_4	Total solids
Arkansas River (Oxford)	54	10	256	94	68	422	139	713
Argonia (Chica-Kia)	52	11	14	48	89	23	71	291
Arkansas River (Hutchinson Main St Bridge)	178	88	4,620	517	31	7,617	765	8,661
Cow Creek (Hutchinson Pioneer St Bridge)	94	18	462	143	99	762	212	943
Arkansas River (Ellinwood)	153	35	84	537	64	138	794	1,160
Cimarron River (Freedom, Okla.)	300	139	18,200	807	47	30,005	1,194	31,496
Bluff Creek (North of Sitka)	97	29	25	204	99	41	302	598
Lone Tree Creek	66	18	39	72	124	64	107	461
Bear Creek (Ashland)*	75	33	18	196	75	30	290	594
Snake Creek (South of Sitka)	131	51	25	329	91	41	487	822
Big Sand Creek (N. of Englewood)	59	23	277	85	99	457	126	822
John's Creek	67	19	203	54	79	334	80	649

* Sampled December, 1925

THE PROBLEM IN KANSAS

In 1923 or 1924 the problem of the durability of concrete in Kansas was first brought to the attention of the Engineering Experiment Station of the Kansas State Agricultural College. It developed as a result of the deterioration of concrete structures in the Arkansas River, the Cimarron River, and the tributaries of these streams in southwestern Kansas. Since most of these streams are slightly alkaline as shown in Table I, it was assumed that the deterioration was largely due to the action of the alkalis and the problem was to develop means of making concrete which would resist this action. As a preliminary step, a sur-

vey was made of the structures in this region and this survey together with subsequent surveys, made by other engineers as well as the author, has led to the development of the method of testing described in this paper, and to many of the conclusions drawn

DEFINITIONS OF TERMS USED

At the outset of such an investigation one of the first needs was the development of a suitable terminology descriptive of the conditions observed in the structures in service Committee C-9, on Concrete, of the American Society for Testing Materials has for several years been studying the durability of concrete through its Sub-committee XVII of which Mr E Viens is Chairman This sub-committee has developed and is now studying proposed definitions and explanations for various technical terms which will be used in this paper and they are here presented with but few modifications

1 *Construction joint* A plane of separation in a structure made necessary by the exigencies of construction Not necessarily indicated on the plans The proper location, development, and treatment of construction joints are very important in many structures Deterioration may start at such joints

2 *Expansion joint,* sometimes called Contraction Joint A definite break in the structure designed to provide for expansion and contraction All such joints should be located on the plans and fully detailed

3 *Fill planes* Visible surfaces of demarcation between sections of concrete deposited one above the other at different times Usually horizontal or approximately horizontal, although sometimes inclined at a considerable angle These are very critical places in most structures where evidences of water gain and segregation with consequent loss of durability are most apparent

4 *Incrustation* A deposit consisting chiefly of calcium carbonate formed on the surface of concrete by the carbonation of calcium hydroxide dissolved from the concrete While very unsightly, and evidence of the solvent action of water, a great many structures badly incrusted are still in excellent condition

5 *Efflorescence* A water soluble deposit formed on the surface of concrete by evaporation

6 *Concrete disintegration* This term should be used to describe actual disintegration of the concrete itself, that is, the breaking down of the mass from any cause whatsoever As examples of concrete disintegration, the following cases may be cited Breaking up of the mass due to freezing of entrapped moisture, disruption or loss of cementing value of the paste by solution or chemical action, and breaking up through disintegration of the aggregates themselves

7. *Structural disintegration* A concrete structure may present the

appearance of being badly disintegrated as a structure, although the concrete itself may not be disintegrating Familiar examples of this are the disruption which follows corrosion of the reinforcement, and spalling at improperly designed expansion joints

8 *Deterioration* This term should be used to describe a structure or concrete which is beginning to show the effects of weathering or other destructive agencies but in which the effect has not progressed to the point where the term *Disintegration* can be properly applied

9 *Failures* Very few structures can be referred to as failures even though considerable deterioration or disintegration has occurred This term should be reserved for those cases where the conditions have developed almost to the point where the structure can no longer perform the services intended If the structure can be repaired, it is not strictly a failure It is only when complete rebuilding or replacement is necessary that this term properly applies

10 *Raveling or unraveling* A type of concrete disintegration in which the concrete appears to be breaking up through disruption of the mortar or loss of bond, leaving at any stage coarse aggregate particles which are partially embedded

11 *Surface scaling* Surface scaling may be of several types representing as many causes The following types can be recognized

(a) *Manipulation scaling* is found on pavements in very thin layers like sheets of cardboard It usually occurs only in a single layer, but sometimes in two or more layers extending to a depth of $\frac{1}{16}$ to $\frac{1}{4}$ inch A similar scaling is often found on the finished surface of large concrete masses In such cases, the thickness may be considerably greater than on pavements A characteristic of the scaled layer is the complete absence of all particles of aggregate except the finest Such scaling is usually not progressive as regards depth

(b) *Frost scaling* somewhat resembles the manipulation scaling except that it is more irregular in thickness This type of scale results from a freezing of the surface before the concrete has thoroughly hardened, but subsequent to final set Frost scale can frequently be recognized by the presence of the pattern of the frost crystal still plainly visible in the concrete, particularly between the coarse aggregate and the mortar The author has found these patterns in concrete more than 25 years old which was supposed to be disintegrating due to alkali water See Figure 1

(c) *Progressive scaling* is characterized by the fact that it continues deeper and deeper into the mass This type of scaling is really an exfoliation of the surface

12 *Exfoliation* A type of disintegration consisting of a splitting of thin sheets of concrete at either edge or surface A common form appears at the edges, either vertical or horizontal, where two exposed sur-

faces meet. Figure 2 illustrates a case of this nature in concrete which contains no coarse aggregate.

13. *Spalling.* The breaking off of pieces or spalls, usually from the edges and corners. Spalling also occurs along the lines of reinforcement where corrosion is in progress.

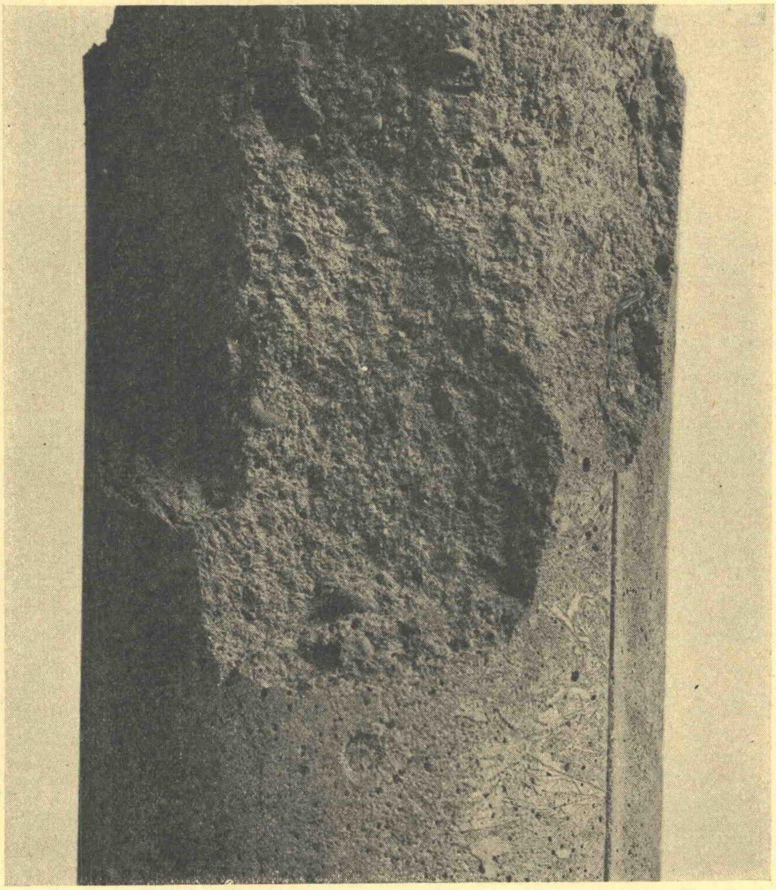


Figure 1. A Concrete Test Specimen Frozen before the Concrete Was Fully Set

Note the imprint of the frost crystals on the broken surface of the concrete as well as on the surface which was next to the form. Concrete damaged by frost while green will usually contain such a record. The strength of this specimen was reduced 70 per cent by freezing.

14. *Popping.* A type of spalling which occurs on a concrete surface from some expansive force originating within the mass, but near the surface. Usually caused by expansion of a piece of aggregate either from moisture or temperature change. May also be caused by swelling of a lump of clay or a piece of wood.

15. *Cracks.* Cracks in structures are of several kinds depending upon the location and cause.

(a) *Structural cracks* are in some way related to the structural service. They may be the result of excessive stresses due to inadequate reinforcement, overloading, settlement, or some extraneous force not anticipated in the design. Except as they may be coincident with shrinkage cracks, it is generally quite easy to identify them.

(b) *Shrinkage cracks* occur in a structure due to the normal shrinkage which may be expected of concrete. Their location, distribution, and size are determined by the amount and distribution of the reinforcement, size and arrangement of members, and the character of the concrete.

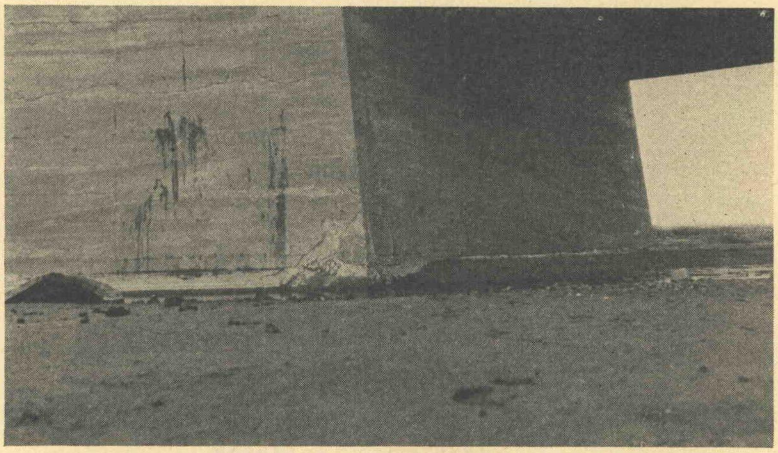


Figure 2. Sand Gravel Concrete Abutment of Garden City Bridge over the Arkansas River

Note the typical example of exfoliation, the construction joint between the foundation and the abutment and the slightly inclined fill planes showing on the face.

Shrinkage cracks often occur at points where the section is reduced, such as through window openings in a building wall or stair or elevator openings in a floor. They also occur at points where large changes in the amount or position of the reinforcement occur; as for example, where the bars are bent from one face of a beam to another. Where the structure is uniform in section with no wide variations in the amount or character of the reinforcement, shrinkage cracks will usually occur at quite regular intervals. In unreinforced walls or similar masses of concrete shrinkage cracks are likely to occur at intervals of 15 to 25 feet.

(c) *Checking* is a rather indefinite term. It is usually applied to rather large irregular cracks which occur in a mass of concrete during

the plastic state or in the first few hours of the hardening period They are generally not continuous and have no relation to any of the other features of the structure or other types of cracking They result from the rapid drying of the mass during the early period or from a disturbance of the surface while in the plastic state

(d) *Map cracking* refers to a type of crack which resembles the irregular boundary lines of political subdivisions on a map The most common example is found in the surface of a mud flat which has dried out In describing map cracking in a structure, it is essential to indicate the general spacing, such as 2 in , 6 in , or 24 in as cracks are likely to occur

FORM FOR CONDITION SURVEY OF CONCRETE STRUCTURES

Date By

GENERAL DATA

Name or Identification

Type of Structure Age

Location

CHARACTER OF CONCRETE

Aggregates Give source and general characteristics of each

Cements Give all known data

Proportions, whether rich or lean, over or under sanded, evidence of water gain, segregation, etc

Detailed description of evidence of deterioration

Note conditions of exposure, secure samples of water for analysis if indicated

Secure Photos and make Sketches showing location and nature of disintegration and location of water line, joints, and fill planes

in almost any such spacing The cause of such cracking is sometimes difficult to determine, but is appears to be related to some form of mass shrinkage Occasionally, map cracking is found which appears to be the result of some expansive force, but such cases are very rare The cracking of the rich mortar finish on a concrete floor is a common form of map cracking in small patterns

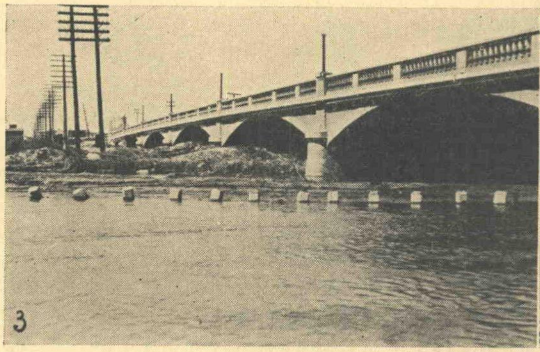
(e) *Crazing* is a term applied to map cracking of very small pattern

16 *Segregation* A term used to refer to separation of the ingredients of concrete in the operations of transporting and placing it The term may refer to the segregation of the coarse aggregate from the mor-

tar or of the water and lighter material from the heavier material. Segregation may be due to a gross excess of water, a poorly designed mix, or improper methods of placing.

17. *Water gain.* A term applied to the accumulation of water in the upper portions of a layer of concrete which is under construction. It is the result of one type of segregation. It is probably the most fruitful cause of disintegration which so frequently occurs at fill planes and at the tops of footings of piers, abutments, and retaining walls.

18. *Honeycomb.* An accumulation of coarse aggregate due to segregation or to the use of mixes containing altogether too high a proportion of coarse aggregate. Honeycomb sometimes results from loss of mortar through a leaky form.



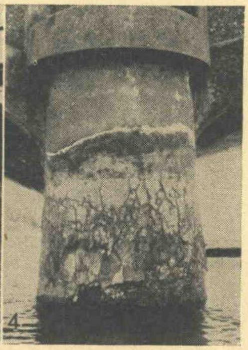


Figure 3. General View of the East Main Street Bridge over the Arkansas River at Hutchinson, Kansas

Test specimens can be seen in the foreground nearly submerged in the river

Figure 4. A Pier of the Bridge Shown in Figure 3

Note the white efflorescence at the elevation of the springing line and the deep scaling at the water line.

INVESTIGATIONS OF FIELD STRUCTURES

In making studies of concrete structures under service it is important that the work be done in a systematic way. The author has used the form on page 139 quite successfully. He believes this calls for the minimum of information which should be secured wherever possible.

The scope of this paper does not permit the inclusion of many of the details of the results of the field investigations and only a few typical illustrations can be given.

One of the major structures examined was the East Main Street Bridge at Hutchinson, over the Arkansas River, shown in Figure 3. This bridge consists of a series of spandrel filled reinforced concrete

arches on concrete piers This structure was built in 1905 using as coarse aggregate a limestone which is quite characteristic of the limestones of central and southeastern Kansas The proportions of concrete were approximately 1 3 5 in the piers and probably about 1 2 4 in the arch ring There is no record as to when disintegration was first observed, but by 1924 it was so advanced that repairs to several of the piers were necessary Figure 4 shows the appearance of one of these piers All have been repaired since this photograph was taken On the under side of the structure is marked evidence of popping due to unsound stone The main disintegration appears to be a very severe deep scaling or exfoliation followed by raveling to a considerable depth While the deterioration at first appeared to be due to unsound stone, later investigations indicate that the mortar was probably but little better than the stone An examination of seventeen concrete structures in this same city built between 1910 and 1922 and using similar concrete and aggregate showed evidence of disintegration within ten years time Richer mixes, some of which were used later in this period, have not yet begun to show distress, and some 1 3 mortar concrete decorative units exposed to equally severe conditions show no distress after over twenty years of exposure

An examination of old irrigation structures in the vicinity of Lakin, Kansas using the natural mixtures of sand and gravel locally available and rather lean proportions revealed that they were in excellent condition after twenty-five years of exposure

Examination of over 100 railway structures built on different transcontinental railway systems in Missouri, Kansas and Colorado revealed that, without exception, where the unsound argillaceous limestones usually containing some chert were used, rather marked disintegration had occurred in from 10 to 20 years In concrete where good stone was used in the lean mixes prevalent a few years ago, the difficulties were less marked but trouble was usually developing to a more or less serious extent at fill planes and other critical points where water gains had occurred

The effect of different conditions of exposure was a striking feature brought out in these investigations On highway structures generally, the places where deterioration was developing were usually at the water line of piers or abutments and over piers in arch bridges of several spans where the accumulation of water in spandrel filled arches kept the concrete thoroughly saturated during freezing weather It was interesting to note that, in many cases where water was seeping through the construction joint between the haunch built on the pier and the arch rib, the concrete in the piers was disintegrating due to the water gain at the top while the concrete of the arches was still in perfect condition

Usually incrustations and efflorescence at these places gave a very much exaggerated appearance of deterioration.

In railway structures the most severe conditions of exposure seemed to be prevalent at abutments and bulkheads. Water coming down the ballast pocket in the grade would accumulate back of the abutments and along the wings and would slowly saturate the concrete, thus causing disintegration of poor concrete through freezing and thawing. A leaky ballast deck in some cases caused deterioration of pier caps.

Figure 5. A Concrete Pavement Ten Years Old on Route 4 in Kansas

It is two course construction using flint in the wearing course and an unsound limestone containing chert nodules and shale-like material in the base course. The disintegration became apparent in about 3 years. Note pop-outs and general disruption of the mass. Traffic on this road is not heavy.

In Figures 5 and 6 is illustrated the disintegration of a concrete pavement due to unsound stone. This road, now about ten years old, began to show distress in two to four years after it was placed. The coarse aggregate is an argillaceous limestone containing some chert formation. Pop-outs of chert may be seen in the illustration, but the real failure is due to the general breaking down of the unsound stone all through the mass. The road does not carry heavy traffic, but the general appearance of the surface might lead one to believe that the pavement was failing due to excessive loads. Evidence of distress appeared first in portions of the pavement placed on a subgrade subject to the seepage of water. Some of these portions have been replaced. Portions of the road where

good drainage was secured are just now beginning to show definite disintegration.

In general, the defects could by no stretch of the imagination be attributed to poor cement, or to alkali or acid water conditions. The same disintegration was in evidence in the fresh water streams as in the alkaline streams. With 80 per cent of a structure in perfect condition, it would not be reasonable to suppose that a bad batch of cement caused the bad foot of concrete at the fill plane or that the water penetrating the concrete was different at that point than at any other.

The method of curing and the degree to which hydration has been allowed to proceed before drying out or freezing greatly affects durabil-

Figure 6. A General View of the Pavement Shown in Figure 5

ity. The freezing of green concrete has been responsible for many more unsatisfactory concrete jobs than is generally realized. The author has observed dozens of pavements and floors, where unsatisfactory results had been attributed to bad cement or alkali water, which on examination showed well defined prints of frost crystals. Such prints on a laboratory specimen are well illustrated in Figure 1. Such concrete never develops a satisfactory durability even when the strength is adequate to carry the designed loads.

After considering these facts it was decided that the difficulty was a general lack of durability in the concrete itself rather than the unusual conditions to which it was exposed; and that the problem was not so

much one of protecting concrete from unusual conditions as of generally improving its quality A search of technical literature yielded no information about the weathering resistance of different concretes so it appeared desirable to undertake an investigation of the durability of concrete both in the field and in the laboratory These investigations are still in an unfinished state In general, the results of field and laboratory studies have been very consistent with but few exceptions

FIELD SPECIMENS

To check our conclusions as to the character of the action observed in the field, it was decided to plant field specimens of concrete of various

TABLE II

DATA ON FIELD SPECIMENS AT LAKIN BRIDGE, KEARNY COUNTY

Specimen number	Where made	Cement	Mix	Slump	Water-cement ratio	Aggregate
				inches		
5	Laboratory	Portland	1 2 4	2	0 70	Blue River sand and limestone
10	Laboratory	Portland	1 2 4	3	0 66	Blue River sand and limestone
15	Laboratory	Portland	1 3	2¾	0 70	Blue River sand
25	Laboratory	Portland	1 4	2¼	0 90	Blue River sand
35	Laboratory	Portland	1 6	1¾	1 33	Blue River sand
20	Laboratory	Lumnite	1 3	2¼	0 64	Blue River sand
30	Laboratory	Lumnite	1 4	2	0 97	Blue River sand
40	Laboratory	Lumnite	1 6	1¾	1 25	Blue River sand
3-v	Field	Portland	1 3	—	*	Arkansas River gravel
5-v	Field	Portland	1 5	—	*	Arkansas River gravel
7-v	Field	Portland	1 7	—	*	Arkansas River gravel
9-v	Field	Portland	1 9	—	*	Arkansas River gravel

* Water used in the field mix was the maximum that could be used without having free water on the surface of the specimens The aggregate was secured from under water at the bridge site and measured inundated and the water-cement ratio not determined

known qualities and to observe the action of the elements on these specimens A sufficiently wide range was planned to insure concrete so poor in quality as to give early results These have been secured

Field specimens of concrete were planted in the early fall of 1925, all nearly submerged, in locations as follows at Hutchinson in the Arkansas River (see Figure 3), at Lakin in the Arkansas River, at Ashland in Bear Creek, and at Englewood in Big Sandy Creek At all of these locations except Lakin, extensive disintegration of concrete was occurring At Lakin a concrete structure built in 1916 of the local sand and gravel aggregate is still in excellent condition It is interesting to note that the most rapid disintegration of field specimens has occurred at this place

The field specimens were 10 by 10 by 30-inch blocks reinforced with four light rods in the corners, and provided with an eyebar in the center of one end. Some of the specimens were cast in the laboratory and others in the field using the local sand and gravel aggregate which occurs at the sites. The field specimens ranged from 1:3 to very lean mixes,

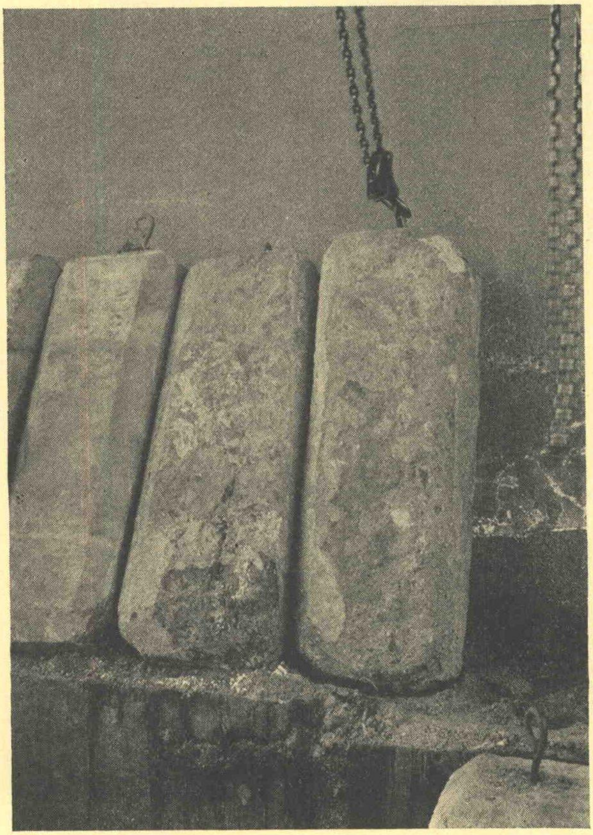


Figure 7. Specimens of 1:7 and 1:9 Gravel Concrete at the Lakin Bridge over Arkansas River Raised for Inspection after Two Years Exposure

The 1:7 and 1:9 specimens have now, after 5 years exposure, almost completely disintegrated. The specimen on the left is 1:2:4 concrete made in the laboratory and is still in perfect condition.

such as were used in the construction for some of the badly disintegrated structures. Table II gives the data on specimens planted at Lakin which were typical of the specimens placed at the other stations.

The portland cement used in making the field specimens made in the laboratory was a standard brand purchased from the local dealer. It satisfactorily passed the A. S. T. M. standard tests for portland cement.

The Lumnite cement was furnished by the Atlas Lumnite Cement Company The cement used in the specimens made in the field was a standard brand of portland taken from the respective county warehouses The Blue River sand used in the laboratory specimens was a siliceous sand of excellent quality showing a strength ratio in tension briquettes as compared with standard Ottawa sand of 148 per cent The stone was a local limestone having a specific gravity of 2 30 with loss by abrasion in the standard Deval test of 9 7 per cent This stone satisfactorily passed the sodium-sulfate soundness test as specified by the American Association of State Highway Officials (5 cycles) It is not a superior quality of stone although similar stone has been used in concrete with very good results for a period of over 25 years

Some of the specimens are shown in figure 7 as they appeared after two years exposure The most recent examination of these specimens was made in October, 1930 about five years after they were placed While but little difference in the condition of the specimens of any one mix could be observed in the different locations, the amount of deterioration appeared to be greatest at Lakin, and then in descending order, at Englewood, Ashland, and Hutchinson To correspond with numbers shown in Table II, the data taken at Lakin are given All specimens were still in perfect condition except as follows

No 30 1 4 concrete with Lumnite cement Badly disintegrated to a depth of about 2 inches

No 40 1 6 Lumnite concrete Completely disintegrated

No 7-v 1 7 field made specimen portland cement Nearly as bad as 9-v

No 9-v 1 9 field made specimen with portland cement More than half disintegrated One reinforcing rod had fallen out

It might be interesting to note that laboratory investigations show that about 20 cycles of freezing and thawing are required to completely break down such concrete as that in No 9-v If this relationship holds true and 5 years exposure represents 20 cycles, our best concretes which successfully withstand 400 to 800 cycles of freezing and thawing should last from 100 to 200 years or more under similar conditions of exposure

It is believed that these tests on Lumnite concrete are not fair to this material The concrete was made and cured under warm conditions and it is probable that the curing temperatures were too high for this kind of concrete Laboratory tests for durability of properly cured Lumnite concrete show very good values

LABORATORY FREEZING AND THAWING INVESTIGATIONS

Laboratory investigations of the durability of concrete by freezing and thawing were started in 1925 using ice and salt as a refrigerating medium This method was slow, permitting only one cycle of freezing

and thawing per day Since then two refrigerating machines have been installed in the laboratory and are giving very satisfactory service Both units operate continuously, the automatic feature having been eliminated The manufacturers would not recommend this equipment for such low temperature work, but no trouble has been experienced The lowest temperature reached has been —42°F , the normal operating temperature being —20° to —30°F Both machines are Frigidaire units, the first being a small ice cream storage unit, while the second is the largest standard unit built by this company This latter unit consists of a Model C Compressor with a one horse power motor The box is cooled with three No 21 coils Alcohol is used around the coils

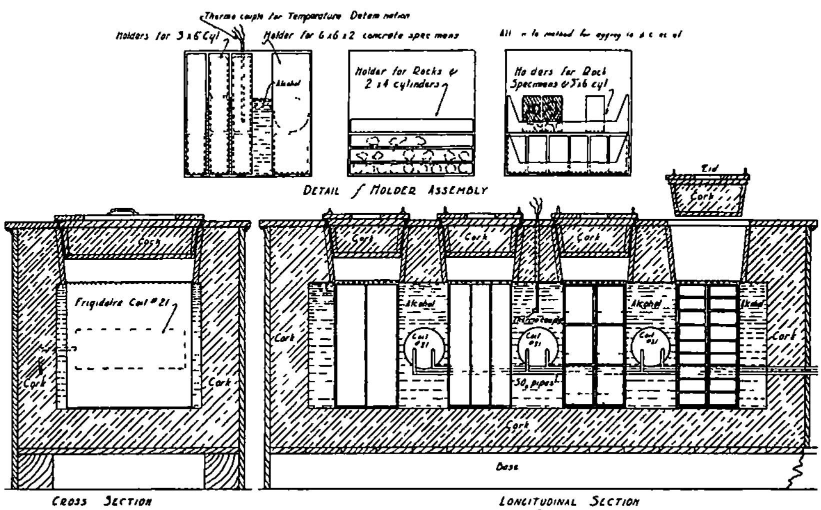


Figure 8. Sectional View of Refrigerator Used in Laboratory Freezing and Thawing Investigations

The cooling fluid is supplied to the coils by a Model C Frigidaire Compressor operated by a one-horse power electric motor. No automatic temperature control is used.

The box is insulated with 6 inches of cork on sides, bottom, and top, opens at the top, and is divided into four compartments each 10 by 24 by 24 inches Temperatures are measured with Leeds & Northrup resistance thermometers The apparatus is shown in Figure 8

In use the refrigerating chambers are kept partially filled with alcohol and the test specimens are placed in close fitting metal containers which are then immersed in the alcohol This gives very rapid and very uniform cooling Filling the space between the specimens and the container with water still further increases the rate of temperature change and insures constant conditions during test Figures 9 and 10 show rates of freezing for different conditions The temperatures inside the

specimens were measured with a resistance thermometer embedded in the concrete

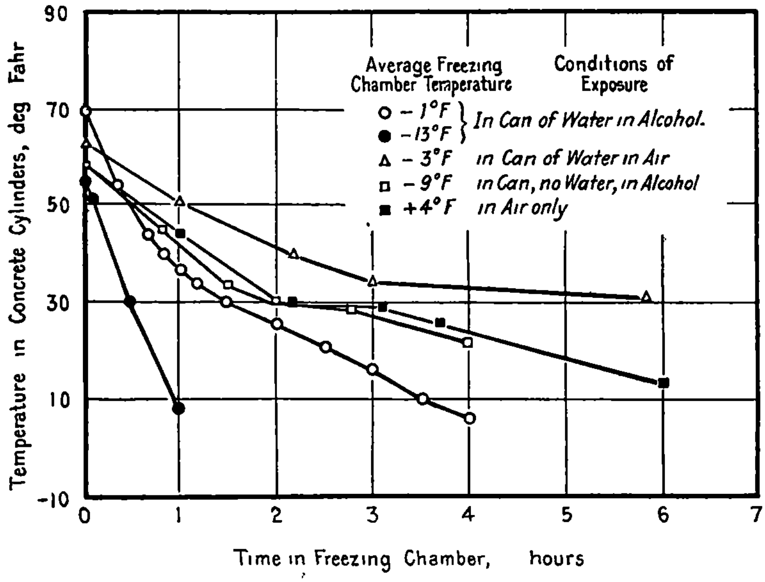


Figure 9. Showing Time Required to Freeze 6 by 12-inch Concrete Cylinders under Various Conditions of Exposure

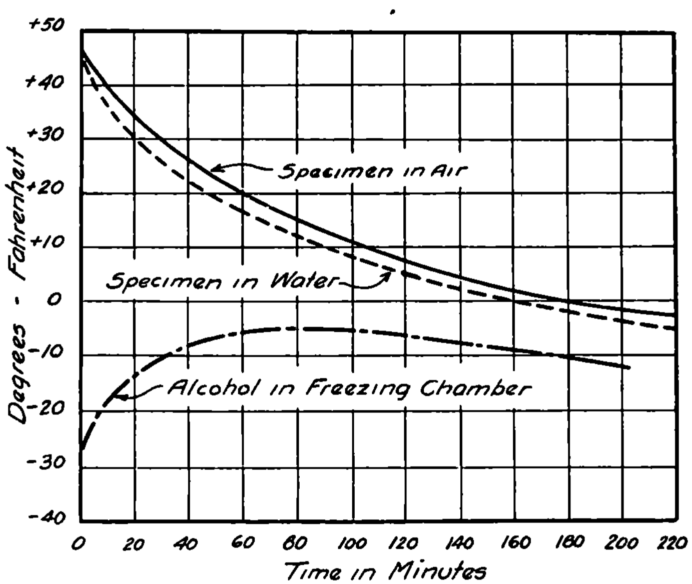


Figure 10. Showing Time Required to Freeze 3 by 6-inch Concrete Cylinders

Figure 11 shows the rate of thawing All thawing has been done in tap water at from 55° to 65°F

In testing aggregate the stone or gravel is placed in shallow rectangular pans which are nested together and placed in large containers which are immersed in the alcohol of the freezing chamber Each sample is kept separate and water about ½ inch deep is placed in each pan

In normal operation, three or four cycles of freezing and thawing are possible per day The specimens can be removed early in the morning, thawed one-half hour, placed in the refrigerator and frozen for 2½ hours, thawed one-half hour, and placed back in the refrigerator before noon Two similar cycles can be secured in the afternoon and the specimens left in the refrigerator over night If the machine is loaded to capacity,

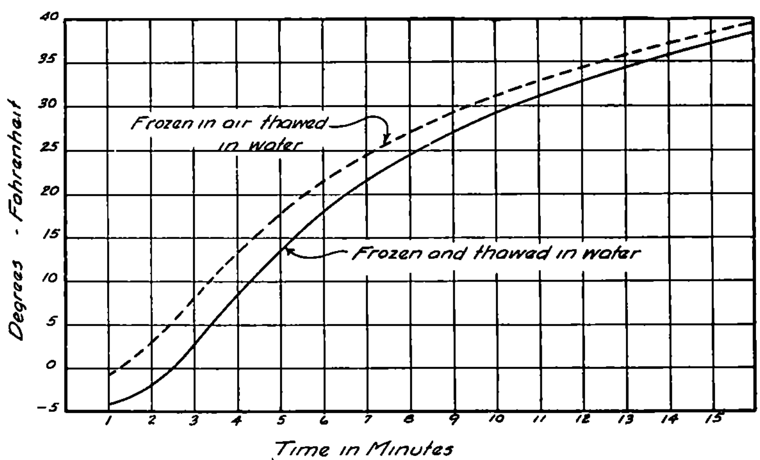


Figure 11. Showing Time Required to Thaw 3 by 6-inch Cylinders

however, the chambers are warmed up so much that three cycles are all that can be secured in a day

The size and shape of specimens for a freezing and thawing test is important Because of the limited space available in the freezing chambers, specimens have been kept as small as possible For mortar specimens it has been found that 3- x 6-inch cyblinders give excellent results For concrete with coarse aggregate the specimen should be large enough so that the failure of a piece of coarse aggregate near one side will not disrupt the whole mass The least dimension of a specimen should be not less than three times that of the maximum size of aggregate It has been found that sections cut from the original mass of concrete with either a shot drill or a carborundum saw give good results Specimens cut with hammer and chisel have been found unsuitable because pieces are loosened in this operation and it is difficult to interpret the results secured in the test In order to reduce the amount of re-

frigeration space required, specimens should be made or cut to such size and shape that they can be placed in close fitting containers

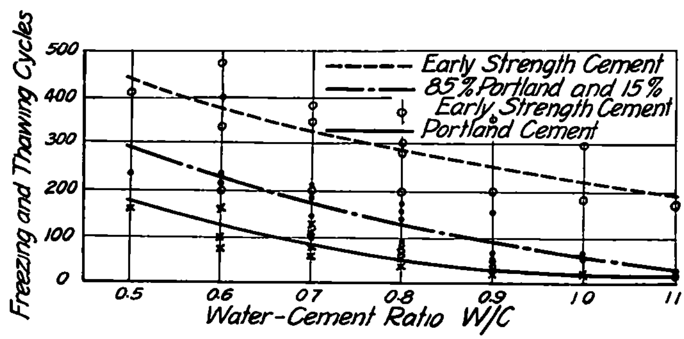


Figure 12 Resistance to Freezing and Thawing as Affected by the Cement and the Water-Cement Ratio

The extent of disintegration was determined by visual inspection and carried to the same point for all specimens. The high values shown for the early strength portland cement should be noted

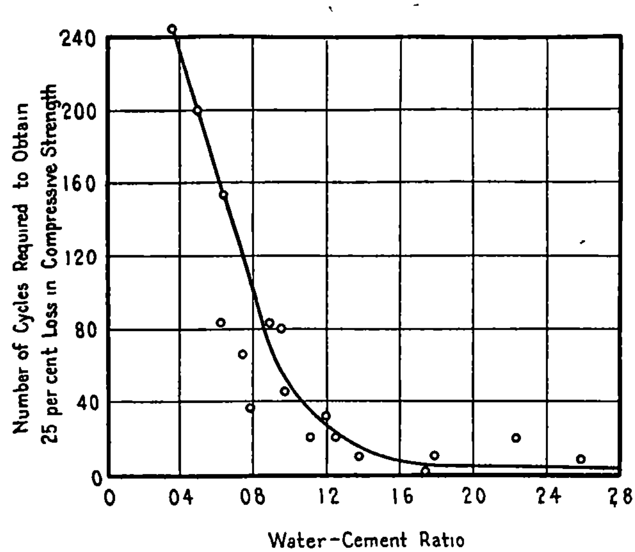


Figure 13. Effect of Water-Cement Ratio upon the Number of Cycles Required to Give a 25 Per Cent Loss in Strength

These were mortar specimens of normal consistency 2 by 4-inch and were frozen at −15° to −20°F., and thawed at 70°F.

In any testing operation it is highly important that, in so far as possible, all the conditions be kept constant The methods of exposure outlined above insure very nearly constant conditions and the results secured have been highly satisfactory. The test is very discriminating,

poor concrete having been completely disintegrated in 20 cycles, while some good mortars have been scarcely damaged at 1500 cycles Unsound aggregate can readily be detected either as aggregate or in concrete Consistent results are secured on successive tests of the same material

One difficulty has been in finding a suitable method by which the relative disintegration or deterioration can be measured The method first used was visual inspection and handling with the hands or tapping lightly with the hammer, a method in which the personal equation is a considerable factor and which is admitted by all to be not entirely satisfactory It does, however, give much useful information and is perhaps as satisfactory as any that has yet been devised Figure 12 shows the results of tests on specimens of different qualities of concrete

A method in which the relative loss in strength is determined has been used with considerable success but it has many drawbacks The results of such a test are shown in Figure 13 This was a test of 2- x 4-inch mortar cylinders of varying proportions A large number of cylinders of each proportion were made and after proper curing, one-half of each mix were placed on test and one-half were kept in normal storage From time to time as the visual examination indicated, three test cylinders and three check cylinders were broken and by plotting the data thus secured it was possible to estimate the number of cycles required to cause a certain loss in strength The curves are plotted for a 25 per cent loss of strength This method requires a very large number of specimens and consequently limits the amount of work it is possible to carry on, and is not applicable to the examination of any concrete other than specially molded specimens

It has been suggested that the extent of damage might be determined by placing the test specimens in some type of tumbler after a series of freezing and thawing cycles and determining the loss in weight after a certain number of revolutions This method has not been used but is being seriously considered and will probably be tried in the near future For certain types of disintegration produced by cherty limestone and gravel it will be of little value as for these materials the first indication of failure is a breaking down of the entire mass When the failure is due to the breaking up of the cement paste the method would seem to have some real possibilities

The exact action that causes the disintegration of concrete under this test is not definitely known Probably the chief action is due to the expansion of entrapped water as the specimen freezes There is no doubt but that keeping the specimen immersed during the freezing period increases the severity of the action It would seem that the sudden temperature changes from —15° or —20°F to a tap water temperature of about 70°F might, by the sudden volume change, cause some

of the disintegration With this thought in mind some tests were run on alternate heating and cooling The concrete was placed in a chamber to which were alternately admitted at intervals of about 15 minutes, steam at a pressure of 100 pounds, and tap water at 60° to 70°F The results were very marked, the concrete breaking down in 25 to 30 cycles but not in a condition similar to that produced by freezing A cement mortar broken down by freezing and thawing is softened and made friable while the mortar broken by the alternate heating and cooling was broken into rather small harsh fragments Lowering the temperature on the heating cycle merely prolonged the time required to break down the concrete

The sodium sulphate test now used for aggregate no doubt offers possibilities as a substitute for the freezing and thawing test However, the known chemical reactions that occur between sulfates and hydrated cement, and the fact that different cements are known to offer variable resistance to sulfate action would seem to make it inadvisable to use this method in testing the weathering ability of concrete for ordinary conditions of exposure

Omitting for the time being consideration of the aggregate which should of course be sound, the durability of concrete appears to be most influenced by the quality of the cement paste and by the degree of exposure to disintegrating forces

The quality of the cement paste is, of course, markedly affected by the quality of the cement With high grade cements, probably the water-cement ratio is the chief factor affecting the quality of the cement paste Tests of thousands of specimens all indicate that the property of resistance to freezing and thawing is very sensitive to the water cement ratio Figures 12 to 14 show graphically the results of several series of tests all bearing out this relationship Field investigations show fully as striking results

High early strength portland cements have shown very excellent results when tested by alternate freezing and thawing as indicated by Figure 12

The relative absorption or permeability of concrete has long been

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Figure 14. Effect of Varying Proportions of Mortar on Resistance to Repeated Freezing and Thawing

All specimens have been subjected to 25 cycles The proportions and water-cement ratios were as shown below.

Cylinders	Mix	Water-Cement Ratio
No. 1	1 2	0 58
No. 2	1 3	0.8
No 3	1 4	1 15
No. 4	1 5	1.39
No. 5	1 7	1 8
No. 6	1 9	2.64

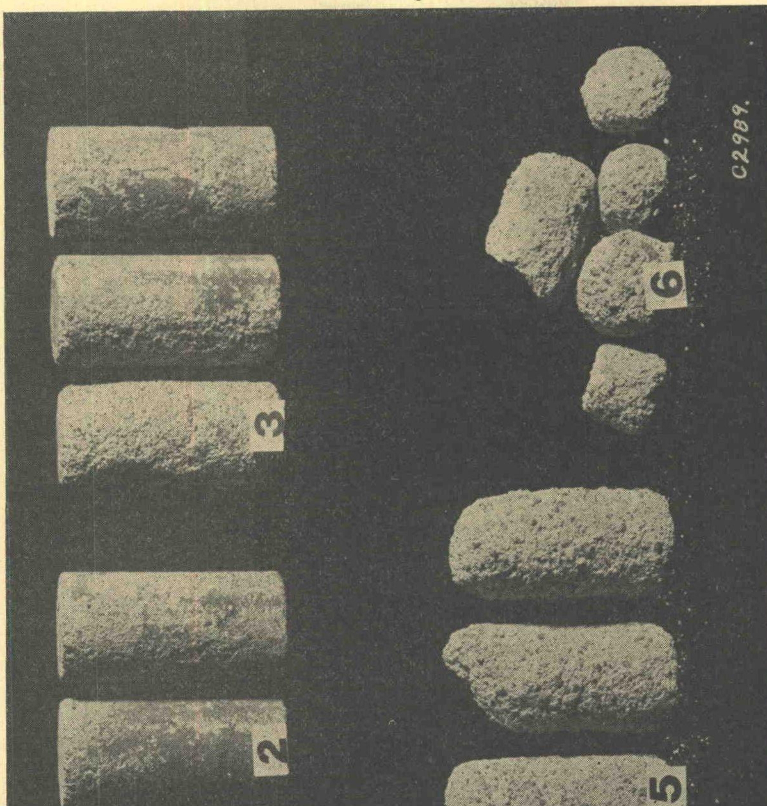

FIG. 14

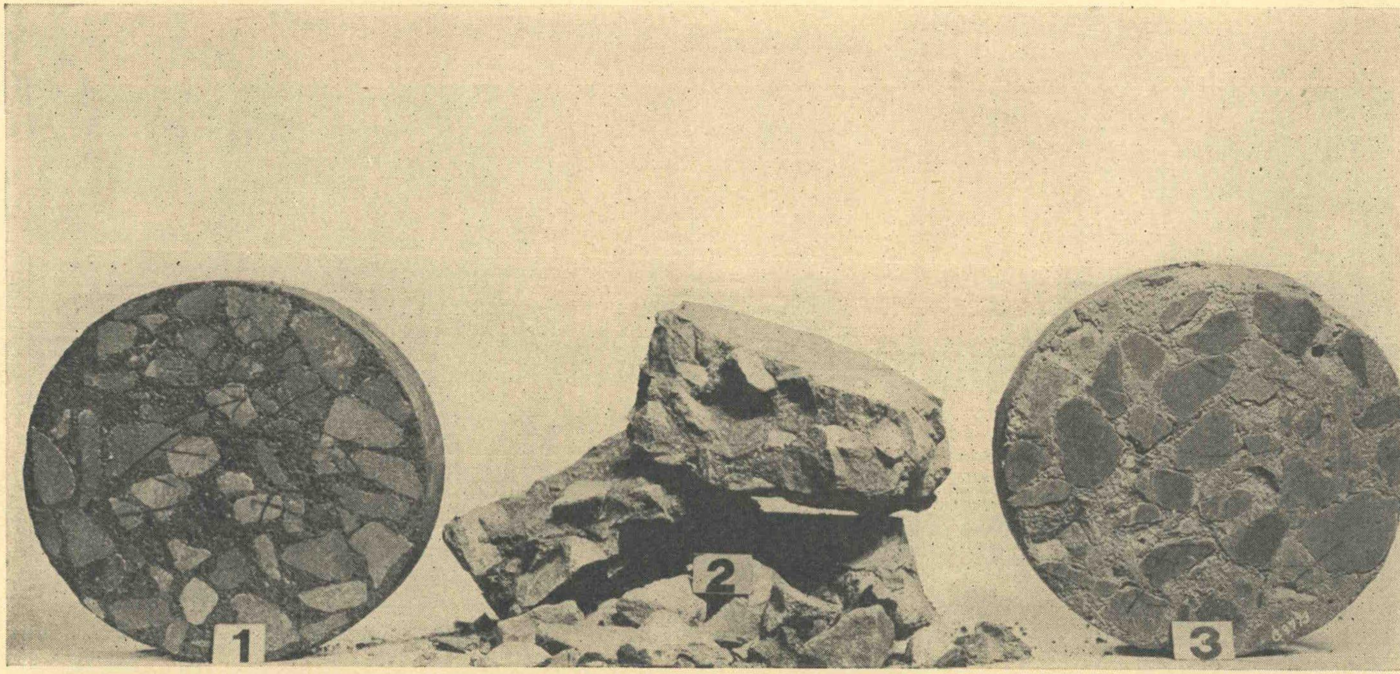

Figure 15. Effect of Fine Aggregate upon the Durability of Concrete

1. 1:2:4 concrete w/c = 0.77. Fine aggregate good, well graded river sand. After 18 cycles of freezing and thawing, is still in perfect condition.

2 and 3. 1:2:4 concrete w/c = 1.00. Fine aggregate, stone screenings with large excess of dust. This dust required an increased quantity of water to produce workability. After 18 cycles both 2 and 3 are in a state of complete disintegration, and can be crumbled apart in the hand as was done with 2.

recognized as one of the chief factors affecting durability in concrete. It is the author's opinion that its importance has been somewhat overestimated. The chief factor is without question the quality of the cement paste, while variations in permeability and absorption, except as the quality of the paste varies with these factors, merely vary the degree of exposure to which the concrete is subjected. In general, for plastic workable concretes, those conditions which tend to produce a high quality of paste usually tend also to produce impermeable concrete with low absorption; but this is not true in every case, particularly with certain types of admixtures and fine aggregates which contain

Figure 16. A Failure of Chert after 12 Cycles of a Freezing and Thawing Test

When chert embedded in concrete fails in this way the disruptive forces are sufficient to break out large pieces of concrete. Some chert which appears sound when tested alone, breaks down when embedded in concrete.

stone dust or clay in excessive quantities. In general, durability and impermeability are in agreement but there are some outstanding exceptions. Figure 15 shows results of freezing and thawing tests on concrete using fine aggregate containing a large excess of stone dust as compared with concrete using good sand. The concrete containing the stone dust was impermeable but absorptive and very low in resistance to freezing and thawing action.

The effect of unsound aggregate upon the durability of concrete is revealed by this test in a very striking manner. In general, it takes one of three forms of disintegration. The most destructive and probably the most common type is that shown by absorptive chert. It

matters little whether this chert is in the form of gravel or occurs as flinty concretions in limestone. This material appears to expand and break when frozen in concrete saturated with water and the expansive forces are sufficient to disrupt large masses of concrete. The author has observed structures in which pieces of concrete fifteen inches in diameter and four to six inches in depth have been broken out by a single piece of chert. The large disruptive forces set up by such material make the use of aggregate containing any unsound chert very questionable. The type of disruption observed in the field appears to be identical with that produced by this test. It seems that some material which is not broken down when frozen alone does break down when frozen embedded in concrete. Figure 16 shows a sample of chert frozen in water which did disintegrate in this manner. Because of the tendency above mentioned,

Figure 17. Freezing and Thawing Test of a Concrete Core Cut from the Pavement Shown in Figures 5 and 6

After only 12 cycles the specimen was almost completely disintegrated

of some materials to appear sound when tested alone, and to be unsound when tested in concrete, the author recommends that all tests of doubtful aggregate be made upon concrete in which the sample to be tested is used as the aggregate.

If concrete is made using shale-like argillaceous stone, or other soft stone of doubtful quality, the character of the disintegration is less serious. This material does not usually break down with such large volume change and consequent disruption of the whole mass. If any considerable part of the aggregate shows this type of unsoundness the whole mass will become weak and disintegrate, but the presence of a small quantity of such unsound material is not significant. Figures 5 and 6 show a concrete road in which the stone used was largely composed of unsound argillaceous limestone containing some unsound chert. Figure 17 shows the results of freezing and thawing tests on a core taken

Figure 18. Blue Limestone of Good Quality after 100 Cycles of Freezing and Thawing in One-Half Inch of Water Showed 12 Per Cent Loss

All loss occurred at the water line or below. The material on the right was lost from the specimen during the test

from this road. After twelve cycles of freezing and thawing it was almost completely disintegrated.

When tested separately, most stone even if of good quality will usually show evidence of distress by a slight scaling in thin layers along the bedding planes or the breaking off of small fragments such as shown in Figure 18. The sample shown in this illustration is of good quality. The small fragments which have broken off under the test would not have caused trouble if it had been embedded in concrete.

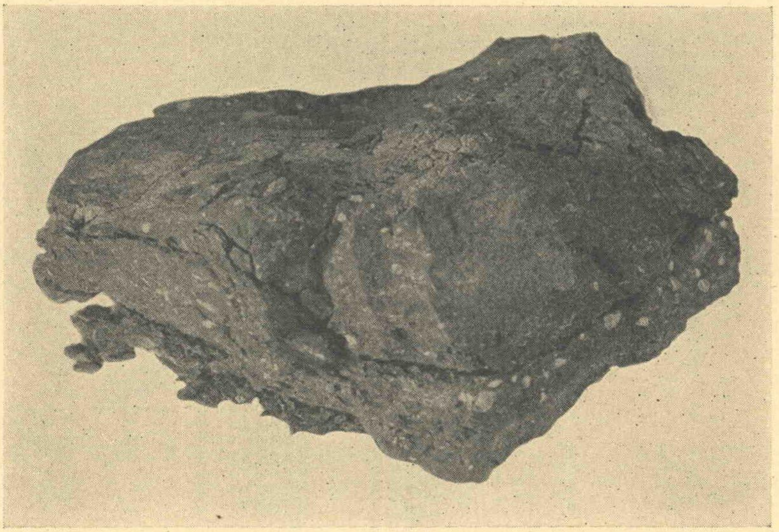

Figure 19. An Argillaceous Limestone Which Failed after 5 Cycles of Freezing and Thawing

Such stone if used in concrete, produces results like those shown in Figures 5, 6 and 17.

Stone such as was used in the pavement shown in Figures 5 and 6 would fail as shown in Figure 19. This was an argillaceous limestone which failed in only a few cycles of freezing and thawing.

A third type of disintegration which it is believed should be attributed to the coarse aggregate but in many ways resembles a mortar failure, frequently occurs with chert or other material with a glossy, smooth surface which at times appears to be almost a greasy surface. In this type of disintegration there appears to be a complete loss of bond between the mortar and the aggregate with only an occasional breaking of the aggregate. In this, it closely resembles a mortar failure but the same quality of mortar with a different type of coarse aggregate will show very satisfactory results. This type of failure has been observed in

both the field and the laboratory and while of rather rare occurrence, it is generally of a serious nature, usually penetrating deeply into the mass.

Large or flat pieces of aggregate in concrete are not advantageous from the point of view of durability. If the concrete is so wet as to permit of much water gain, this water with laitance tends to accumulate

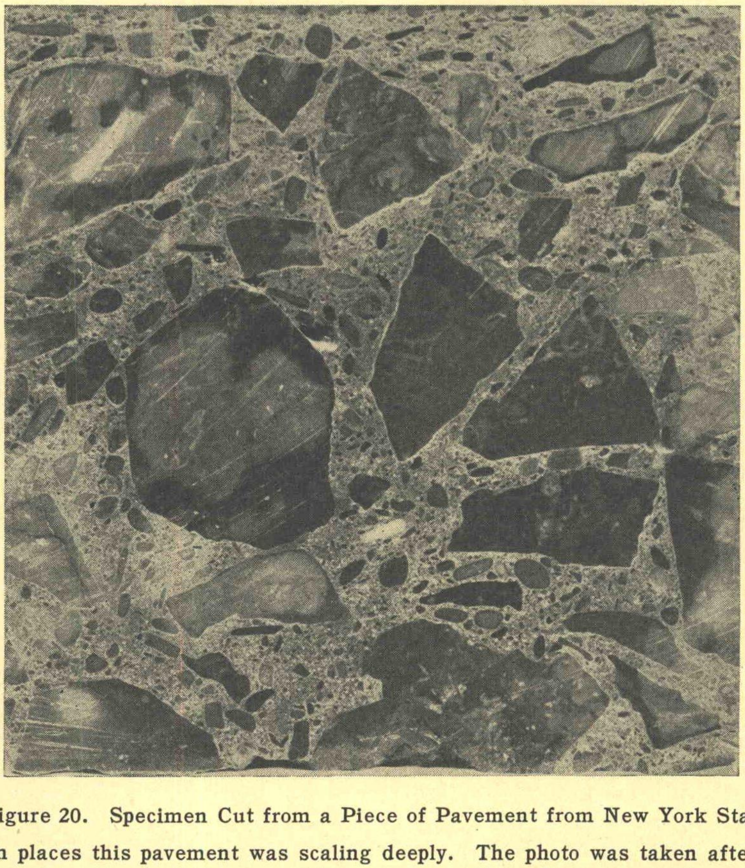

Figure 20. Specimen Cut from a Piece of Pavement from New York State

In places this pavement was scaling deeply. The photo was taken after 25 cycles of freezing and thawing of the specimen. Note the horizontal lines near the top. These indicate disintegration of the mortar. After the photo was taken the upper part was removed and crumbled by hand. The scaling might be classified as manipulation scaling and is evidence of excessive finishing. After 100 cycles the upper 21 per cent of this block was completely disintegrated due to failure of the mortar.

under these pieces leaving an open porous place where water accumulates and disintegration due to freezing of the moisture will occur. The larger the aggregate, the more difficult will the whole problem of bond between mortar and coarse aggregate become. Figure 20 is an illustration of this action. This section of concrete was cut from a pavement in New York State and was taken from a section which had shown pro-

gressive scaling The photograph was taken after 25 cycles of freezing and thawing and at this time the upper one-half inch could be removed by hand The light white lines running horizontally across the top indicate disintegration of the mortar and it is probable that excessive finishing brought an accumulation of water and laitance to the top, helping to cause the conditions observed Under all of the pieces of coarse aggregate lying nearly horizontal at the top of this section can be seen a white film of laitance This is not apparent near the bottom of the section After 100 cycles the upper 21 per cent of this block was completely disintegrated

PROPOSED STANDARD METHODS OF PROCEDURE

The author believes that there is sufficient interest in the freezing and thawing method of testing concrete and aggregates to justify the development of a standard method of procedure The following general regulations are suggested

1 All concrete should be frozen immersed in water, preferably in close-fitting metal containers (See Figure 21)

2 The temperature of test, condition of exposure, and size of specimen should be such that the concrete will be completely frozen in not less than 2 hours To secure this condition with cylinders 6 inches in diameter, a temperature of —25°F will be required with metal containers immersed in alcohol or brine as described in this bulletin

3 Test specimens of concrete should be approximately cubical or cylindrical in shape with the least dimension not less than 3 times that of the largest aggregate (See Figure 22)

4 Test specimens taken from finished structures should be obtained with suitable drills or saws Care should be exercised not to confuse slight failure on the cut surface due to local heating of aggregate in cutting, with failure in the test Such slight failure on the cut surfaces is especially likely to occur with the siliceous aggregates

5 No tests on specimens of portland cement concrete should be started in less than 60 days, preferably, 90 days, The resistance to disintegration seems to increase much more rapidly than even the strength

6 Tests of aggregate should include tests in concrete before any source of supply is condemned In such tests the use of a high grade early strength cement will make possible the starting of the test within 72 hours

7 Aggregate when tested separately, should be frozen immersed in water to one-half inch depth in close fitting containers which are immersed in alcohol or brine

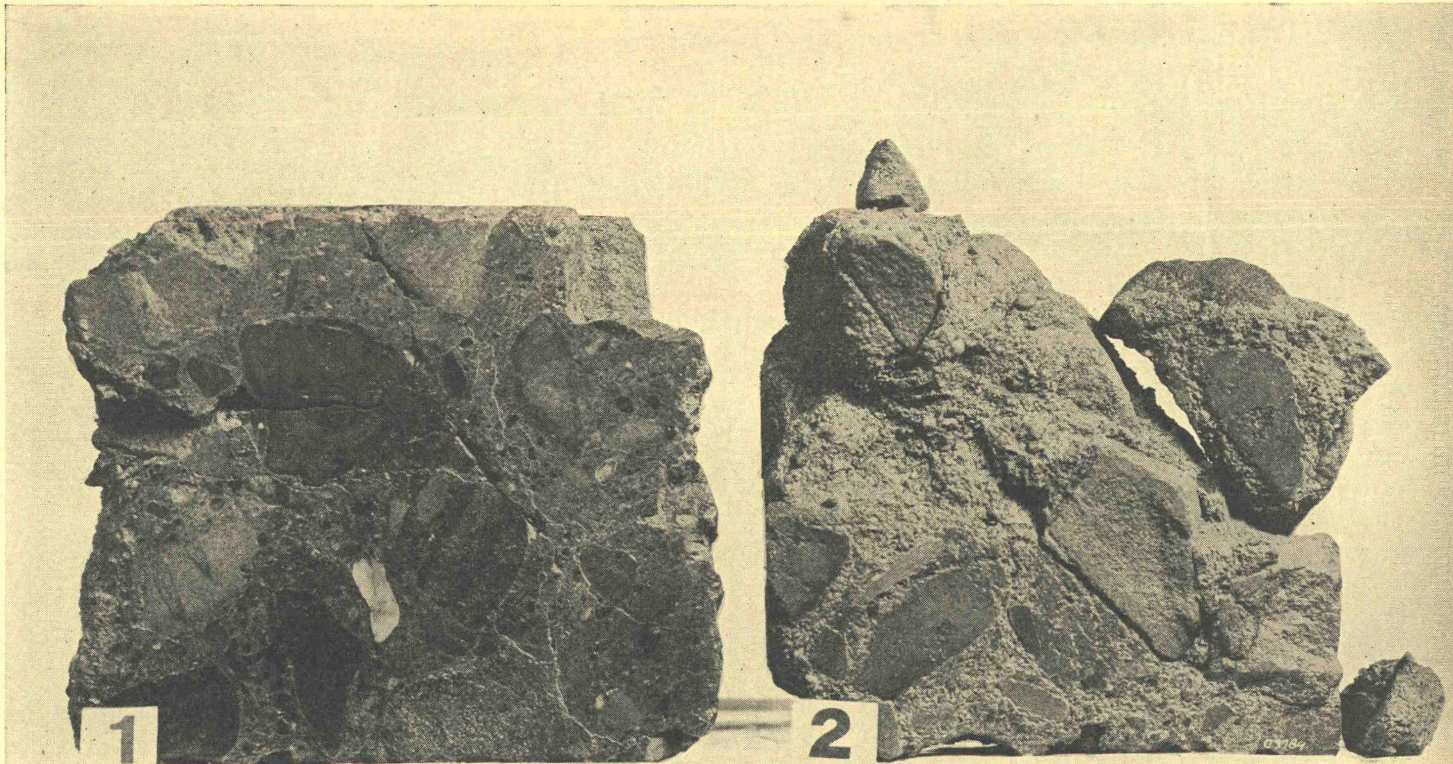

Figure 21. Effect of Freezing Saturated Concrete in Air and Immersed in Water (200 cycles)

(1) Frozen in air. (2) Frozen immersed. Immersion insures absolutely constant conditions of exposure and water content during test, and accelerates the action. The author recommends that all tests of concrete be made with the specimen surrounded by water.

Figure 22. Effect of Size of Specimen

Number (2) was 2 inches thick while the other specimens were 4 inches thick. All have been subjected to 100 cycles. The 4-inch specimens are still in very good condition. It is recommended that the least dimension of a specimen of concrete be at least three times that of the largest dimension of the aggregate.

CONCLUSIONS

While the durability of concrete is yet an excellent field for continued investigation, the author believes that the following conclusions are justified at this time

1 Alternate freezing and thawing is a valuable method of studying the durability of concrete and concrete aggregates

2 The durability of concrete is greatly affected by the quality of the cement paste

3 A water-cement ratio of 0 8 or more is not likely to give a concrete of adequate durability if the conditions of exposure are severe

4 The proper placing, handling and curing of the concrete are fully as important as the design of the mix An examination of existing structures indicates generally that improper construction methods and requirements have been a major cause of most of the difficulties involving the durability of the concrete

5 Watertight layers formed either by excessive manipulation, or by wash coats, plasters or other treatments reduce the resistance of concrete to weathering unless they are placed on those portions of the structure where water would otherwise enter

6 The use of unsound aggregate produces unsound concrete, the resistance of the mortar to disintegration being only slightly effective in protecting the aggregate

7 Any aggregate containing absorptive chert should not be used until after very careful investigation The character of the failure in the aggregate is fully as important as the extent of the failure Material which breaks into only a few pieces but with sufficient force to disrupt the mass, being much more detrimental to the structure then material which may completely disintegrate up but not with such force as to cause the failure of the surroundng mortar