Concrete durability studies
by Robert A Wallace

A THESIS Submitted to the Graduate Faculty in partial fulfillment of the requirements for the degree of Master of Science in Civil Engineering
Montana State University

Abstract:
Fine and coarse aggregate from nine Montana sources were incorporated in standard State Highway mix. designs using high- and low-alkali cements. Admixtures of "fly ash" and Protex, an air-entraining agent, were used in conjunction with the above mixes.

Compression tests were made using 6" x 12" cylinders, outdoor weathering specimens were made using 6" x 6" cubes, and freezing and thawing specimens were made using 3" x 6" cylinders.

The nine aggregates were known to have varying degrees of "alkali-reactivity", as a result of previous chemical tests.

The results from the weathering and freezing and thawing tests were correlated with the chemical reactivity tests of the aggregate and mortar-bar expansion specimens.

The chemical tests showed that some of the aggregates were reactive, however, the mortar-bar expansion specimens only indicated expansions ranging from 0.002 per cent to 0.017 per cent after twelve months, After the concrete had been subjected to 73 cycles of freezing and thawing, the concrete evidenced no signs of disintegration that could be discerned by visual inspection.

The concrete containing the two admixtures, in general, had lower 28 day compressive strengths than the concrete made with Portland cement, which was expected.

CONCRETE DURABILITY STUDIES

by

ROBERT A. WALLACE

A THESIS

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Chairman, Examining Committee

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TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

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ABSTRACT

Fine and coarse aggregate from nine Montana sources were incorporated in standard State Highway mix designs using high- and low-alkali cements. Admixtures of "fly ash" and Protex, an air-entraining agent, were used in conjunction with the above mixes.

Compression tests were made using 6" x 12" cylinders, outdoor weathering specimens were made using 6" x 6" cubes, and freezing and thawing specimens were made using 3" x 6" cylinders.

The nine aggregates were known to have varying degrees of "alkali-reactivity", as a result of previous chemical tests.

The results from the weathering and freezing and thawing tests were correlated with the chemical reactivity tests of the aggregate and mortar-bar expansion specimens.

The chemical tests showed that some of the aggregates were reactive, however, the mortar-bar expansion specimens only indicated expansions ranging from 0.002 per cent to 0.017 per cent after twelve months. After the concrete had been subjected to 75 cycles of freezing and thawing, the concrete evidenced no signs of disintegration that could be discerned by visual inspection.

The concrete containing the two admixtures, in general, had lower 28 day compressive strengths than the concrete made with portland cement, which was expected.

INTRODUCTION

Purpose and Importance

Two questions immediately present themselves at the beginning of any investigation. They are: (1) Why should the investigation be undertaken? (2) What should the investigation determine?

In answering the above two questions it is hoped that the purpose and intent of this thesis will be made clear.

Why should the investigation be undertaken?

Ever since the discovery of concrete the problem of durability has been manifest. Certain construction projects have been expedited by the use of concrete over another material; however, when in some instances apparently "good" concrete has failed to exhibit the expected durability, the question arose as to what particular factor might be responsible.

Various state and government agencies have spent large sums of money and considerable time relative to the problem of concrete durability. Here in Montana, some of the structures built by the State Highway Department have been showing signs of deterioration. Several of these structures have shown some deterioration after having been subjected to exposure for only five years.

Since it was not definitely known what particular factor was responsible for the deterioration, it was suggested that an investigation concerning concrete durability be undertaken. It is hoped that the results of this thesis may aid in preventing a part of the deterioration that is occurring in the concrete structures and pavements throughout the State.

What should the investigation determine?

Since the investigation is concerned with concrete durability, there evidently could be a considerable number of factors involved. Therefore it was decided to approach the problem from the standpoint of (1) the cement and (2) the resistance of concrete subjected to freezing and thawing cycles.

The investigations were carried on in four parts. They included the following:

Part I Chemical tests for alkali-reactivity of aggregates and mortar-bar expansion tests.

Part II The use of pozzolanic materials as an aid in eliminating excessive expansion in concrete resulting from the cement aggregate reaction.

Part III The effect of pozzolanic materials upon the resistance of concrete to freezing and thawing.

Part IV The effect of air-entrainment upon the resistance of concrete to freezing and thawing.

It was decided that Part I of the preceding list would lend itself to separate research.

The purpose of this thesis was to investigate Parts II, III, and IV of the preceding list, and to correlate them if possible with the results from Part I.

A sequent discussion of some of the theories involved in connection with the four parts of the investigation is hereby presented.

PREVIOUS WORK

Alkali-Reactivity of Aggregate

The chemical interaction between reactive aggregate and high-alkali cement (over 1% $Na_2O + K_2O$) is known to have caused serious disintegration. A great deal of research has been conducted concerning this phase including petrographic and physical-chemical investigation.[1]

According to Hansen:

> The expansion and cracking of the concrete result from pressures caused by osmosis of water by alkali-silica gels which form through the interaction between certain "reactive" aggregates and the alkalis liberated by the high alkali cement during hydration. These pressures exceed the tensile strength of concrete and cause the formation of fractures, which probably are sufficiently extensive to account for the increase in volume and decline in strength.[2]

Based upon results of investigations already published the following facts are known:

> (1) deterioration results from interaction between certain aggregates and high-alkali cements; (2) deterioration can be prevented or retarded by limiting the alkali content and restricting the perecntage of reactive aggregates; (3) the deterioration is caused by expansion; (4) the rate and magnitude of deterioration are influenced by the physical characteristics of the concrete and by conditions of curing, temperature, and moisture; (5) all mortars and concretes affected by this kind of deterioration contain impure silica gel within particles of aggregate, in voids, in cracks in the concrete, and as exudations on the exposed surfaces.[3]

There is a possibility that the expansion is motivated by crystal growth within the cement paste.

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[1] D. McConnell, R.C. Mielenz, W. Y. Holland and K. T. Greene, "Cement-Aggregate Reaction in Concrete," Jrnl ACI, XIX (1947), No. 2, 93.

[2] W.C.Hansen, "Studies Relating to the Mechanism by which the Alkali-Aggregate Reaction Produces Expansion in Concrete," Jrnl ACI, SV(1944), 213

[3] Ibid., p. 215

Another theory, presented by Rockwood, which might explain the deterioration effect of the alkali-aggregate reaction is:

> An alkali silicate solution will absorb more silica than it contains Na_2O. As the content of silica increases in proportion to the Na_2O, the liquid becomes more and more viscous. At some stage then the siliceous aggregate and its attacking alkali hydroxide become enclosed in a film or membrane of viscous alkali silicate, which serves to screen out the minerals in colloidal solution in the outside water, but will allow the water itself or an electrolyte such as alkali hydroxides to pass through, by the chemical process known as dialysis. The solution of alkali oxides, the hydroxides, have great affinity for water, which means they will draw water from the outside through the silicate membrane. Were the enclosing membrane free to expand, like a balloon, it would constantly grow in size, but it is confined by the walls of the cavity that the solution of the aggregate particle has made in the mortar or concrete matrix. The result is that hydraulic pressure is built up by the water trying to get inside the envelope, or membrane. If the alkali silicate membrane is kept sufficiently dilute, that is, not viscous, it probably does not dialyze the surrounding solutions, and that is why 0.6 per cent combined alkali oxides reduce expansion.[4]

The Bureau of Reclamation evolved five techniques by which they identify reactive concrete aggregates. They are: (1) chemical tests, (2) mortar expansion tests, (3) wetting and drying, (4) examination of concrete in structures, and (5) petrographic examination.

The chemical tests are conducted in conjunction with expansion tests of mortar-bars made from the same aggregates. Appendix A gives a description of the procedure used in conducting the chemical tests and the mortar-bar expansion tests. The wetting and drying technique was not used in this research and will therefore not be discussed. The examination of concrete in structures is discussed in the results and conclusions of this thesis. A brief description of the petrographic examination is herewith presented.

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[4]Nathan C. Rockwood, "A New Approach to the Study of Concrete," Rock Products, XXV (May 1949), 69.

Reports describing petrographic examination of proposed aggregates to be used in concrete include tables which summarize analyses of coarse fractions. Actual percentages of each rock type are recorded, and brief descriptions included. Each petrographic type is classified as to physical and chemical quality. The physical quality is summarized in a separate table. Degrees of chemical quality are "innocuous" and "deleterious". These words are defined according to Rhoades and Mielenz as follows:[5]

> "Deleterious" materials will produce excessive expansions in concrete through chemical reactions which take place after hardening of the cement. Constituents designated as "deleterious" because of susceptibility to attack by alkalies in cement generally do not yield to reaction if the cement contains less than 0.60 per cent total alkalis ($Na_2O + K_2O$, expressed as soda equivalents).
>
> "Innocuous" constituents do not participate in chemical reactions harmful to concrete.

Table I shows the rocks and minerals which are deleteriously reactive with high-alkali cements. This analysis was conducted by Mielenz.[6]

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[5] Rogers Rhoades and R.C. Mielenz, "Petrography of Concrete Aggregates", Journal ACI, Proceedings, XVII (1946), 581-98.

[6] R.C. Mielenz, "Petrographic Examination of Concrete Aggregate", Geological Society of America, LIX (1946), 309-18.

TABLE I

ROCKS AND MINERALS WHICH ARE DELETERIOUSLY REACTIVE
WITH HIGH-ALKALI CEMENT

Reactive Minerals	Chemical Composition	Physical Character
Opal	SiO_2 n H_2O	Amorphous
Chalcedony	SiO_2	Cryptocrystalline fibrous
Tridymite	SiO_2	Crystalline

Reactive Rocks	Reactive Component
Siliceous Rocks	
Opaline cherts	Opal
Chalcedonic cherts	Chalcedony
Siliceous limestones	Chalcedony and/or opal
Volcanic Rocks	(Volcanic glass, devitrified glass, and tridymite)
Rhyolites and rhyolite tuffs	
Dacites and dacite tuffs	
Andesite and andesite tuffs	
Metamorphic Rocks	
Phyllites	Hydromica
Miscellaneous Rocks	
Any rocks containing veinlets, inclusions, or grains of the reactive rocks or minerals listed above.	

Effect of Pozzolanic Materials on Concrete Durability

Definition of pozzolan: Pozzolans are siliceous materials which, though not cementitious in themselves, contain constituents which at ordinary temperatures will combine with lime in the presence of water to form compounds which have a low solubility and possess cementing properties.[7]

The use of pozzolans in concrete result in distinct advantages.

[7] F. M. Lea, "The Chemistry of Pozzolans," Proceedings Symposium on the Chemistry of Cements, (Stockholm, 1938), 460.

The reactive substances of pozzolan, such as amorphous silica or siliceous compounds, are converted by the reaction with the calcium hydroxide released by hydration of portland cement, into stable substances, many of which are cementitious.

Fly ash is one of the numerous pozzolanic materials available and was the material used in this research. Fly ash is a very fine flue dust precipitated from the stacks at some steam power plants burning pulverized coal.

One of the advantages of fly ash as an admixture in concrete is its ability to eliminate, or at least greatly retard progress of reaction between cement alkalies and aggregates.

It has been shown that fly ash inhibits the cement-aggregate reaction in concrete by combination with the alkali released by the hydrating cement. The alkalies thus retained are unable to attack the aggregate.

The reduction in alkalinity achieved by fly ash in the chemical test is high. It also exhibits good reduction in expansive reaction in the Pyrex glass test. The reduction being expressed as a percentage between the test mix and a reference mix which uses Pyrex glass as the aggregate. These two factors reflect that fly ash will be beneficial in reducing excessive expansion in connection with alkali-aggregate reactivity.

Freezing and thawing durability is usually decreased by use of a pozzolanic material, however, this is not always true.

Lean mixes possess the undesirable qualities of harshness and a tendency to segregate, but they do produce concrete of high permeability. By adding fine pozzolanic materials to an otherwise lean concrete it is possible to eliminate these undesirable qualities, which would be a distinct advantage with respect to freezing and thawing durability.

The physical effect of pozzolans upon concrete are related particularly to the low specific gravity (from 2.3 to 2.8), as a result of which the pozzolan occupies a greater volume than the weight equivalent of portland cement. If the ratio of cement to aggregate by weight is held constant, use of a pozzolan effectively increases the volume of cement in the concrete, giving increased workability and plasticity.

A summary of some of the characteristics and advantages of fly ash as a pozzolan, found by H. S. Meissner, are hereby presented.[8]

If used in judicious proportions fly ash will contribute equally with portland cement to the later strength of concrete and improve its durability. Concrete containing a 30 per cent replacement of the cement with fly ash has only two-thirds of the strength of portland cement concrete at 28 days, it gains strength more rapidly after 28 days and at 180 days has almost 90 per cent as much strength and apparently will equal the strength of the portland cement concrete by the end of the year.

That fly ash imparts great workability to concrete may be appreciated by considering its particle shape. Being minute spheres, each of the grains of fly ash act essentially as small ball bearings between aggregate particles, reducing friction between them and imparting great freedom to their movement during mixing and placing of the concrete.

Effect of Air-Entrainment on Concrete Durability.

[8] H. S. Meissner, "Pozzolans used in Mass Concrete," Copy of a paper presented at the National Meeting of the ASTM, (San Francisco, 1949).

A brief description of the part played by air-entrainment in concrete durability is hereby presented.

Air-entraining materials are classified by the Portland Cement Association according to the following general type of materials:[9]

(1) Natural wood resins, such as rosin, Vinsol resin, and N-tair.
(2) Animal or vegetable fats and oils such as tallow, fish oil and fatty acids, such as stearic and oleic acid.
(3) Various wetting agents such as alkali salts of sulfated and sulfonated organic compounds.
(4) Water-soluble soaps of resin acids and animal and vegetable fatty acids.
(5) Miscellaneous materials such as sodium salts of petroleum sulfonic acids, Nacconal, hydrogen peroxide, aluminum powder, etc.

The air-entraining agent used in this thesis was Protex, a sulfonated hydrocarbon (Type 3).

Lerch says, regarding the nature of air-entrained concrete that:

> The presence of the intentionally entrained air bubbles materially alters the properties of both the plastic mixture and the hardened concrete. The air bubbles serve as reservoirs that accomodate the expansion resulting from the freezing water within the concrete. As the freezing of the water within the capillaries progresses, the expansion pressure is relieved by forcing the excess water into the air bubbles where the expansion during freezing can occur without disrupting the concrete. When thawing occurs the air compressed in the bubbles forces the water back into the capillaries. Thus the bubbles continue to serve their purpose during repeated cycles of freezing and thawing.

Air-entrainment reduces the compressive strength of concrete somewhat; however, it also has several beneficial properties. Air-entrainment increases the workability and cohesiveness of the mix: it reduces segregation and bleeding; it increases the resistance of hardened concrete to the aggressive action of sulfate waters; it reduces the tendency of

[9] William Lerch, "Basic Principles of Air-Entrained Concrete," Research Laboratory Bulletin, Portland Cement Association, P. 2.

hardened concrete to scale; and it increases the resistance of concrete to freezing and thawing cycles.

Specimens containing air-entraining agents when subjected to scaling tests showed only slight scaling after 375 cycles, while companion specimens without air-entrainment showed severe scaling.

Concrete containing a minimum air content of 3 per cent showed excellent resistance to freezing and thawing, with aggregates of $1\frac{1}{2}$ to 2 inches. With air contents only slightly below 3 per cent, the resistance to freezing and thawing decreases rapidly. Concretes with 3 per cent air showed about as good resistance as those with higher air content.

REVIEW OF LITERATURE

Numerous investigations have been conducted concerning the problem of concrete durability and certain valuable results have been discovered, however, a considerable amount of work remains to be done.

At the beginning of any study of this nature it is necessary to ascertain what particular factors may cause concrete to disintegrate. Listed below are some of the major factors involved:

(1) Composition of the cement.

(2) Mineralogical composition of the aggregate.

(3) Effect of moisture and absorption of the aggregate.

(4) Aggregate gradation in the concrete.

(5) Curing of hardened concrete.

(6) Rate of freezing and thawing of concrete.

A brief summary of several recent investigations, concerning concrete durability, and directed along the lines suggested by the above mentioned factors are presented here.

Mattimore[10] found as a result of tests on the freezing and thawing durability of concrete that cements having the higher ratio of Al_2O_3/Fe_2O_3 were more resistant to freezing and thawing than lower ratios of these oxides. Cements high in tri-calcium sulfate (C_3S) were the most resistant.

It was also discovered that too fine a cement caused internal cracking.

Aggregate is a major constituent of concrete by bulk. It would appear, therefore, that concrete investigations should include as elaborate a study of lithologic variations in aggregates under considerations as any other part of the concrete.

Rhodes and Mielenz[11] conclude that the surest way of determining the properties of the individual particles constituting an aggregate is by petrographic methods. The above referenced article states:

> Properties of aggregate are numerous and complex, and they originate in several ways. The original nature of the rock may control its concrete making qualities. Thus, rock containing gypsum are always somewhat soluble, opaline materials react chemically with alkaline solutions, and shales are usually soft and absorptive. Conversely, many properties are not directly related to the rock type, but were induced by ground waters, by fracturing and jointing related to the geologic history of the region or by some other natural alteration. Thus, granites may be either hard or disintegrated, and sandstones may either be friable or tightly cemented, with resulting variations in strength and porosity. Therefore, petrographic study of concrete aggregates must be dual: (1) properties inherent in the rock must be interpreted in relation to (2) the natural alteration which it may have experienced.
>
> Few, if any, rocks or minerals are chemically inert while enclosed in portland cement. There are four main ways an aggregate may be

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[10] H. S. Mattimore, "Durability Tests of Certain Portland Cements," Proceedings Highway Research Board, XVI (1936), 135-166.

[11] Rhoades, Roger and R. C. Mielenz, "Petrography of Concrete Aggregates," Journal ACI, XVII (1946), 581-598.

chemically deleterious:

(1) It may contain water-soluble constituents which can be leached. Leached material may form unsightly efflorescence or indirectly lead to surface scaling.

(2) Soluble constituents or products of oxidation may retard or modify hydration of cement.

(3) Certain aggregates are attacked by high-alkali cements. The reactions lead to internal expansion, external cracking, and decreased elasticity and strength.

(4) Certain minerals are capable of base exchange. The alkalies in the minerals are therefore released to attack susceptible aggregate particles.

Some of the other considerations of the quality of the aggregates are: surface texture, porosity, internal fractures, particle shape, thermal expansivity, surface coatings, properties affecting drying and shrinkage, strength and elasticity, specific gravity, and specific heat.

Petrographic methods represent a useful approach toward these and other objectives. The principal values of these methods are: (1) unique fundamental information not derived from standard tests is obtained; (2) quick preliminary estimates of quality can be made; (3) they permit interpretation and amplification of the results of other acceptance tests; (4) petrographic identification of chemically deleterious substances is the only reliable means by which chemical instability of new aggregates can be quickly estimated; and (5) new aggregates may be compared with other aggregates for which service data are available.

Another characteristic of aggregates that is related to concrete durability is the effect of moisture and absorption of the aggregate.

F. N. Wray and H. J. Lichtefield[12] made a series of preliminary tests

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[12] F. N. Wray and H. J. Lichtefield, "The Influence of Test Methods on Moisture Absorption and Resistance to Freezing and Thawing," Proceedings A.S.T.M., XL (1940), 876.

in 1938 on gravel obtained from its natural sources and frozen while in a stream wet condition. They showed severe deterioration. Some disagreement was found as compared with the usual testing procedures. Because of this disagreement, a definite program of testing was initiated and numerous methods of preparing the aggregate for freezing and thawing were compared.

The relative effects of oven drying and air drying on moisture loss and the increases in the rate and amount of absorption induced by vacuum treatment of the aggregate prior to soaking were investigated. The relation between the degree of moisture saturation and the resistance of the material to freezing and thawing was studied.

One of the outstanding results of the investigation was that the A. S. T. M. tentative methods for freezing and thawing produced less deterioration than other methods.

Some of their results and conclusions were:

(1) It was found that a 24 hour soaking period for the aggregate, which previously had been oven dried, was sufficient only to saturate it to about 70 per cent of its original moisture content.
(2) Evacuation of samples prior to soaking proved to be a very effective means of attaining a high degree of saturation.
(3) The moisture content of the smaller particles when stream-wet was greater than that of the coarser sizes; also the absorptive capacity and the rate of absorption were greater for the smaller sizes.
(4) Stream-wet gravel, which contained the greatest amount of moisture, showed the greatest failure on freezing and thawing, while samples prepared according to A.S.T.M., which produced only partial saturation, showed a minimum of disintegration.
(5) After freezing and thawing, the fragments resulting from the failure of the original particles contained considerably more moisture than the sound material.

After the material constituents have been combined to form the concrete there are several factors that present themselves as criteria for the durability of the hardened concrete.

One of these factors is the gradation of the aggregate. Mattimore[13] found that: (1) Neither very large or very small aggregate is best. A lesser overall volume change is obtained with the use of large aggregate, but at the expense of greater internal stresses and cracking and (2) one gradation is probably better than any other. Present indications are that the best gradation is such that the sieve analysis plots as a smooth curve.

Another factor is the curing methods used. According to B. G. Long and H. J. Kurtz[14] a comparison of the rates of decrease in dynamic modulus of two groups of fog cured specimens during freezing and thawing showed very definitely the effects of varying moisture in concrete. Those specimens which were fog cured for 17 days contained about $1\frac{1}{4}$ per cent more moisture at the beginning of freezing and thawing than did the specimens that were fog cured for 14 days and air dried for three days. The specimens that contained the greatest amount of moisture were the least resistant to freezing and thawing.

Of the compound-cured specimens those which lost the most moisture during laboratory air exposure, and absorbed the most moisture during freezing and thawing, showed the least resistance to freezing and thawing. The reason the specimens absorbed moisture during the freezing and thawing cycles was because they were frozen immersed in water and were thawed at

[13] Ibid

[14] B. G. Long and H. J. Kurtz, "Effect of Methods Upon the Durability of Concrete as Measured by Changes in Dynamic Modulus of Elasticity," Proceedings A.S.T.M., XLIII (1943), 1140.

room temperature in the laboratory.

The no-cured specimens lost about $3\frac{1}{2}$ per cent of their total weight (approximately 57 per cent moisture) during laboratory air exposure but absorbed an equal amount during the first few cycles of freezing and thawing and their resistance was inferior to all others (except those continuously fog cured to time of test). No-cured specimens began to spall at 10 cycles. The specimens continuously fog cured for 17 days exhibited little or no spalling, although these specimens gained 4.1 per cent moisture in addition to original gaging water during this period and continued to absorb moisture throughout freezing and thawing cycles. The resistance of this group was lower than the no-cured specimens.

A third factor that has a pronounced effect on resistance of concrete to freezing and thawing is the rate of freezing. Mattimore[15] discovered that the number of cycles required to produce a damaging effect is materially increased if the time interval between 32° and 15°F exceeds seven hours. The method of freezing and thawing concrete prisms half immersed in water and allowed to thaw in air at room temperature appears to have produced some of the most detrimental effects.

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[15] Ibid 1145

EQUIPMENT

Mixer

The mixer used in the laboratory was a 2 cu. ft., 3 blade, Homart mixer capable of handling a $1\frac{1}{2}$ cu. ft. concrete batch. The mixer drum was driven by a Dunlap 1/3 h.p. split phase motor. The motor was geared down so that the drum operated at 25 r.p.m.

Freezing Cabinet

The freezing cabinet used in the laboratory was manufactured locally by the Inter-Mountain Industries Company. The inside dimensions of the box are: depth 19", width 30", and height 60". The walls are 6" in thickness and are insulated with spun glass fiber. The temperature is controlled by a mercury type pressure switch. A York compressor, using freon refrigerant, is powered by a Century 1/3 h.p. single phase capacitor motor. The freezing coils are incorporated into 4 separate shelves which divide the box into approximately 5 equal compartments.

Moist Room

The moist room is 18 ft. in length, 5 ft. deep, and 9 ft. in height. The room is constructed in one end of the laboratory that originally had a glass-block skylight. A two inch layer of Vermiculite (expanded mica) was placed as an insulation on top of the skylight and covered with a 4" concrete slab. A wooden door is made moisture proof by lining the inner side with galvanized iron and then treating the entire door with two coats of oil sealer and a final coat of clear varnish.

Three overhead fog nozzles are utilized for maintaining a relative humidity of 100%. The temperature is controlled at 70°F by coupling the hot and cold water tap through a single manual control value. Wooden racks are used for storage of all specimens.

Thawing Tank

The thawing tank is 27" wide, 75" long, and 9" deep. It is constructed of car flooring and lined with sheetmetal to make it waterproof. A drain is located at one end to permit cleaning. The water is tap water maintained at approximately room temperature.

Molds

The 3" x 6" cylinder molds were cut from 3 in. monel seamless tubing. A longitudinal cut was made in each mold which permitted easy removal of the specimen. Radiator hose clamps were used for tightening the molds.

The 6" x 12" cylinder molds were a commercial cast iron type with machined base plates that fastened directly to the mold.

The 6" x 6" x 6" molds were constructed from existing beam molds made from 11 gage steel. The bottom of the mold and the two side pieces were fastened together by four stove bolts equipped with wing nuts. Two ridges of metal plate were welded to the inside face of the side pieces, at either end, to act as stops for the end plates.

Scales

All aggregates and the cement were weighed on a Fairbanks Morse platform scale, calibrated to the nearest one-quarter pound. The water was weighed on a Fairbanks scale accurate to the nearest ten grams.

Air Meter

Air contents were measured with an Acme Air-Yield determinator in accordance with the standard test for air content, pressure method, ASTM

Designation C231-49T.

PROCEDURE

Specimens

The 6" x 12" compression specimens were cast according to A.S.T.M. Designation C192-49. The specimens subjected to freezing and thawing were 3" x 6" cylinders. In molding the specimens the molds, lightly oiled, were placed in small metal pans. They were filled in two layers and each layer rodded fifteen times with a 3/8 in. round bullet nosed steel rod. The 6" cube specimens, which comprised the majority of the weathering specimens, were cast in two equal layers and each layer rodded twenty-five times with a 5/8 in. round bullet nosed steel rod.

For each of the 27 different mixes that were used, two 6" x 12" cylinders were cast for compression tests at 28 days. Four 3" x 6" cylinders were cast; two to be used for outdoor weathering specimens. Approximately halfway through the tests the procedure was altered from casting four 3" x 6" cylinders to casting two 3" x 6" cylinders and two 6" cubes, the latter to be substituted for the outdoor weathering specimens.

Mixing

Mixing of the concrete was carried out in accordance with A.S.T.M. Designation C192-44T, for a period of three minutes. It was noted that approximately ten per cent of the mortar remained in the drum. Because of the lack of materials it was advisable to redeem as much of this mortar as possible by hand scraping rather than attempt to "butter" the mixer before each test.

Slump tests were conducted according to A.S.T.M. Designation C143-39. Air content was determined using the Acme Air Yield Determinator according to A.S.T.M. Designation C231-49T.

All concrete was visually inspected for segregation, workability, trowelability, and harshness.

Curing

Immediately upon casting, the specimens were covered with moist burlap and allowed to remain in the laboratory for 24 hours. The specimens were then placed in the moist room for 26 days.

The weathering specimens were moist cured for 90 days before being placed outdoors.

Freezing and Thawing

After the freezing and thawing specimens had been moist cured for 28 days, they were then removed and air dried at room temperature for 24 hours. The specimens were then weighed to the nearest 1.0 gram and placed in the water bath and allowed to soak for 24 hours. The specimens were then removed from the thawing tank and placed, in air, in the freezing cabinet at temperatures ranging between 5° F and 10° F, for 24 hours. The samples were then removed and placed in the thawing tank as before. This freezing and thawing operation was repeated for five cycles and then the specimens were again dried and weighed.

After approximately fifty of these freezing and thawing cycles had been conducted, Mr. Swenson and the author determined the temperature of the concrete while under test.

Results of these tests show that the specimen reached a temperature of 28° F in four hours and was completely thawed in 20 minutes.

From this information it was decided that two cycles of freezing and thawing could be conducted in 24 hours.[16] The specimens were interchanged at 8:00 A.M. and 4:00 P.M. This resulted in an 8 hour and a 16 hour freezing cycle every 24 hours. This procedure was followed throughout the balance of the tests. The specimens were alternated between the long and short cycle so as to give all samples an equal exposure.

Compression Tests

The 6" x 12" compression specimens were tested in accordance with A.S.T.M. Designation C39-49, and capped with plaster of paris. A Baldwin-Southwark, 200,000 pound capacity, hydraulic testing machine was used. The prescribed loading was applied by means of the automatic pacing disc attached to the machine.

Weathering Tests

The weathering specimens were placed outdoors in single tiers on wooden racks protected by chicken screening, and in such a locality so as to receive an average exposure to sunlight and average snowfall.

Chemical Reactivity and Mortar-bar Expansion Tests

Previous investigations carried out by Hugh Jeffries at Montana State College were concerned with chemical reactivity tests and mortar-bar expansions tests. The same nine aggregates used in the concrete durability studies were used by Mr. Jeffries. A brief summary of the techniques used in discussed in Appendix A of this thesis.

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[16] F. D. Swenson, "Durability of Concrete as Affected by Low Air Temperature at Time of Placing," Thesis submitted in partial fulfillment of the requirements for the degree of Master of Science in Civil Engineering at Montana State College, August 1951.