MONTANA STATE UNIVERSITY

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
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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 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

Submitted to the Graduate Faculty

in

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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.

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[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

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[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

[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.

MATERIALS

Cement

No specific data for the type II cement was available, however, none of the samples of this type of cement checked by the Ideal Cement Co. chemists at Trident, Montana ever showed more than 0.6% total alkalies reported as soda equivalents.

The high alkali cement was received from the Portland Cement Association and designated as lot number 15698, with the following characteristics:

Na_2O = 1.13%

K_2O = 0.44

C_3S = 44.30

C_2S = 28.60

C_3A = 9.80

C_4AF = 7.60

Gypsum = 3.00

S.A. = 1855 sq. cm. (ASTM method)

Admixtures

The fly ash was sent to the laboratory by the Bureau of Reclamation concrete laboratory at the Canyon Ferry Dam project, near Helena, Montana.

The air-entraining agent used was a commercial product called Protex.

Aggregates

The following is a list of aggregates used in this study.

1. Belgrade (Gallatin Valley)
2. Havre (Milk River)
3. Billings (Middle Yellowstone Valley)
4. Logan (Upper Missouri River)
5. Missoula (Big Blackfoot River)
6. Judith Gap (Sweetgrass River)
7. Livingston (Upper Yellowstone Valley)
8. Ashland (Tongue River)
9. Great Falls (Middle Missouri River)

All of the aggregates used in the tests were in an air-dry condition. The per cent absorption ranged from 0.44 to 3.63 per cent. The water content was adjusted for absorption in all mixes.

The sieve analysis and physical characteristics of the aggregates were furnished by the Montana Highway Department and are shown in Table II.

Mineral compositions of the aggregates were determined by Dr. C. C. Bradley, of the Montana State College Geology Department. The results of these determinations are shown in Table III.

TABLE II

PHYSICAL CHARACTERISTICS OF SANDS

SIEVE NUMBER	Material Source and Lot Number								
	1 Belgrade	2 Havre	3 Billings	4 Logan	5 Missoula	6 Judith Gap	7 Livingston	8 Ashland	9 Great Falls
Passing 3/8 inch %	100	100	100	100	100	100	100	100	100
Passing 4 mesh "	98	99	99	97	100	99	99	95	99
" 8 " "	86	92	83	81	90	73	88	72	82
" 16 " "	74	76	77	69	77	58	78	51	63
" 30 " "	56	60	72	44	61	45	65	27	48
" 50 " "	25	21	27	16	14	11	27	10	22
" 100 " "	9	5	5	9	4	1.5	10	5	5

MISCELLANEOUS INFORMATION

Fineness Mudulus	2.52	2.47	2.37	2.84	2.54	3.12	2.33	3.40	2.65
Specific Gravity	2.63		2.62	2.54	2.57		2.59	2.58	
Color Metric Test	#1		#1	#1					
Wt. Per Cu. Ft.	107.0		98.0	98.0	101.5		99.0	103.0	

TABLE II - Continued

PHYSICAL CHARACTERISTICS OF COARSE AGGREGATE

SIEVE NUMBER	Material Source and Lot Number									
	1 Belgrade	3 Billings	4 Logan	5 Missoula	Judith Gap 6	7 Livingston	8-Coarse Ashland	8-Medium Ashland	9-Coarse Gt.Falls	9-Medium Gt.Falls
Passing $1\frac{1}{2}$" %	100	100	100	100	97	100	100		100	
" 1" "	62	70	76	77	63	78	46		44	98
" 3/4" "	33	49	53	64	31	57	11	100	10	86
" 1/2" "	17	27	33	46	11	36	.7	64	4	52
" 3/8" "	10	16	20	29	2	24	.3	34	2	30
" #4 "	1.5	0.5	3.5	3.0	0	7.0	0	0.2	0.5	5.0

MISCELLANEOUS INFORMATION

Fineness Mudulus	7.55	7.36	7.23	7.12	7.69	7.12	7.88	6.66	7.88	6.79
Specific Gravity	2.63	2.65	2.53	2.60		2.60	2.60	2.60		
Wt. per Cu. Ft.	106.0	104.0	109.0	107.5		110.0	89.0	86.5		

No data available on Havre Coarse.

TABLE III

MINERAL COMPOSITION OF COARSE AGGREGATE

Aggregate	Mineral Composition
Great Falls Medium	40% Quartzite and metamorphic argillites 30% Lava-andesite 10% Gneiss and syenite 10% Limestone and dolomite 10% Serpentine Very little lime coating, no clay
Great Falls Coarse	50% Lava-andesite and trachyte 30% Quartzite and metamorphic argillites & arkoses (sandstone not all quartz-feldspar) 10% Syenite 5% Gneiss 5% Limestone Very little coating, no clay
Emigrant Coarse	35% Gneiss 50% Lava-andesite 10% Quartzite 5% Sandstone Lava unweathered. Sandstone connected with small amount of lime & essentially no clay.
Belgrade Coarse	40% Gneiss 40% Lava-andesite 10% Limestone 10% Sandstone with lime cementation Some clay & medium coating of lime
Billings Coarse	40% Gneiss and Granite 50% Lava-andesite 10% Quartzite Some lime coating & clay
Logan Coarse	80% Quartzite or similar metamorphic rock 10% Lava-andesite & Rhyolite 10% Gneiss Slight amount of Lime coating

TABLE III - Continued

MINERAL COMPOSITION OF COARSE AGGREGATE

Aggregate	Mineral Composition
Blackfoot Coarse	60% Gneiss & fine grain Diorite 10% Chalcedony 30% Quartzite Coating negligible Clay negligible
Judith Gap Coarse	98% Limestone & dolomite 2% Chert (Chalcedony) All pebbles lime coated
Ashland Coarse	15% Andesite or Basalt, Rhyolite 25% Chalcedony 25% Limestone Dolomite 10% Sandstone 25% Shale (Clay) Trace Gneiss Lime coating, high clay & iron oxide content

TABLE III - Continued

MINERAL COMPOSITION OF FINE AGGREGATE

Aggregate	Mineral Composition
Judith Gap	Limestone & dolomite Carbonaceous shale Chalcedony, quartz, feldspar Massively cemented by lime & with lime coating. Very little clay, poorly sorted
Blackfoot	Much same as coarse with higher percentage of quartz. (Gneiss, diorite, chalcedony, quartzite)
Emigrant	Essentially same as coarse (Gneiss, lava, quartzite, sandstone) Gneiss is broken up into constituent minerals Fine grain lava pebbles
Billings	80% Quartz 5% Magnetite 10% Lava-andesite 5% Feldspar Trace of lime, essentially no clay, well sorted
Logan	90% Quartz 10% Quartzite & lava Medium sorting very little clay or lime
Belgrade	40% Quartz 40% Lava-andesite 5% Magnetite 5% Gneiss 5% Feldspar 5% Mica Trace of chalcedony & limestone, little clay
Havre	40% Quartz & Quartzite 25% Lava - mainly andesite 20% Chalcedony 15% Limestone, sandstone & metamorphic rocks Poorly sorted - medium coating of lime - some clay present

MIX DESIGN DATA

Records concerning the particular structures that were evidencing deterioration were not available. It was decided, therefore, to select aggregates for the tests that were being used during the construction of nine different structures throughout the state.

The nine samples of aggregate were incorporated in the mix design data as indicated by the Montana State Highway Department for class "A" concrete. This particular class of concrete was used in the nine structures that incorporated the aggregates used for study.

The mix design data for class "A" (2400 psi) concrete varies slightly for the different aggregates. The reason for this, according to R. H. Gagle, Research Engineer, Montana State Highway Department, is that the mix design was based on the Duff A. Abrams method, and varied as the fineness modulus of the different aggregates varied. Also the trial laboratory mixes and the field mixes were adjusted until a suitable mix was obtained by visual inspection.

Since no data was available as to the W/C ratio used in the field, the author endeavored to select a water content sufficient to produce a workable concrete.

Mixes were made using the nine aggregates with the following cement and admixture combinations:

(1) Type II cement, no admixture (nine aggregates). Mark-A

(2) Type II cement, Protex air-entraining agent (nine aggregates). Mark-AT

(3) High-Alkali cement, no admixture (three aggregates). Mark-AH

(4) High-Alkali cement, fly ash (six aggregates). Mark-HP

The reason all nine aggregates were not used in all four combinations was because of the small supply of material available. The aggregates that were shown to be highly reactive, from the chemical tests, were combined with the high alkali cements wherever possible.

The concrete mixtures that were used for the field structures did not contain either the high-alkali cement or the admixtures that were used for the laboratory mixes; however, as mentioned under the purpose of this research, it was hoped that some information could be obtained as to their effect under the conditions of the tests.

The air-entrained concrete has $1\frac{1}{2}$ oz. of Protex per sack of cement, as recommended by the manufacturer. The only adjustment in the mix was in the water content which was made in an effort to maintain a normal slump. In the concrete containing the fly ash the quantity was determined by substituting 15 per cent of the weight of the cement with fly ash.

Because of the small volume of all batches, the measured yield was not used because of inaccuracy; however, the C/F was calculated from the computed yield and the air content from the air-meter determinations.

Table IV lists the summary mix design data.

TABLE IV - SUMMARY MIX DESIGN DATA

Mark	Source	Termini*	Date Cast 1951	Size of Batch	C/F	W/C	Slump	Air Content	Mix Proportions By Weight	Cement Types	Admix.	Remarks
1A	Belgrade	M.S.C. Campus	1/12	1.33	5.23	6 gals/sk	1"	2.1%	1:1.90:4.42	II	None	Harsh
2A	Havre	City Sew. Plant	1/15	1.33	5.26	6	0	1.85	1:1.90:4.42	II	None	
3A	Billings	Huntley Bridge	1/22	1.25	5.40	6½	7"	1.1	1:1.95:4.38	II	None	
4A	Logan	Madison Bridge	1/23	1.25	5.26	6½	8"	0.7	1:1.98:4.35	II	None	
5A	Missoula	Milltown Bridge	1/25	1.25	5.41	6	5"	1.1	1:1.73:4.59	II	None	
6A	Judith Gap	G.N.R.R. Bridge	1/29	1.25	5.38	6	2"	2.0	1:1.73:4.59	II	None	
7A	Livingston	Emigrant Bridge	1/30	1.25	5.38	6	1"	1.6	1:1.90:4.42	II	None	
8A	Ashland	Crow-Agency Broadus-Rd.	2/9	1.25	5.40	7	0	—	1:2.49:3.78	II	None	Very Poor No work-ability
9A	Gt. Falls	Gt. Falls Bridge	2/12	1.25	5.36	6½	10"	0.3	1:1.98:4.35	II	None	
1AT	Belgrade	M.S.C. Campus	2/6	1.33	4.90	6½	7"	3.8	1:1.90:4.42	II	10 cc Protex	Equiv. 1-1/3 oz. Protex/sk
2AT	Havre	City Sew. Plant	2/27	1.0	5.25	6½	6"	2.9	1:1.90:4.42	II	8 cc Protex	
3AT	Billings	Huntley Bridge	3/2	1.0	5.19	6	4½"	6.0	1:1.95:4.38	II	8 cc Protex	
4AT	Logan	Madison Bridge	3/5	1.0	5.25	6	2"	2.7	1:1.98:4.35	II	8 cc Protex	
5AT	Missoula	Milltown Bridge	3/8	1.0	5.25	6	5"	4.9	1:1.73:4.59	II	8 cc Protex	

*Termini refers to the structure that contained the aggregate corresponding to the mark number for the laboratory tests.

TABLE IV – SUMMARY MIX DESIGN DATA (Continued)

Mark	Source	Termini	Date Cast 1951	Size of Batch	C/F	W/C	Slump	Air Content	Mix Proportions By Weight	Cement Types	Admix.	Remarks
6AT	Judith Gap	G.N.R.R. Bridge	3/12	1.0	5.35	6	3"	2.8	1:1.73:4.59	II	8 cc Protex	
7AT	Livingston	Emigrant Bridge	3/13	1.0	5.27	6	2"	3.5	1:1.90:4.42	II	8 cc Protex	
8AT	Ashland	Crow-Agency Broadus-Rd.	3/14	1.0	5.66	7	1"	4.5	1:2.50:3.00	II	8 cc Protex	50/50 Split on C. A.
9AT	Gt. Falls	Gt. Falls Bridge	3/15	1.0	5.25	6	8"	3.7	1:1.98:4.35	II	8 cc Protex	
3AH	Billings	Huntley Bridge	2/22	1.0	5.35	6	2"	3.6	1:1.95:4.38	High Alkali	None	
7AH	Livingston	Emigrant Bridge	2/26	1.0	5.14	6½	5¼"	5.3	1:1.90:4.42	High Alkali	None	
8AH	Ashland	Crow-Agency Broadus-Rd.	2/19	1.0	5.10	7	0	--	1:2.50:3.00	High Alkali	None	
2HP	Havre	City Sew. Plant	3/17	0.8	4.52	7	3½"	--	1:1.90:4.42	High Alkali	FlyAsh 15% by Wt. of Cem.	
3HP	Billings	Huntley Bridge	3/23	1.0	4.66	6½	6"	--	1:1.95:4.38	High Alkali	FlyAsh	
4HP	Logan	Madison Bridge	3/24	1.0	4.49	6½	3"	--	1:1.98:4.35	High Alkali	FlyAsh	
6HP	Judith Gap	G.N.R.R. Bridge	3/27	1.0	4.57	6½	4"	--	1:1.73:4.59	High Alkali	FlyAsh	
7HP	Livingston	Emigrant Bridge	3/28	1.0	4.57	6½	3"		1:1.90:4.42	High Alkali	FlyAsh	
9HP	Gt. Falls	Gt. Falls Bridge	3/29	1.0	4.66	6	6"		1:1.98:4.35	High Alkali	FlyAsh	

RESULTS AND CONCLUSIONS

Chemical Tests and Mortar Bar Expansions

Table V shows the values for S_c, R_c, and the ratios of S_c/R_c for the aggregates resulting from the chemical tests. Table VI gives the results of mortar-bar expansion tests at the end of 12 months for these same aggregates using the high-alkali cement described previously.

Details of the procedure for conducting these tests are compiled in Appendix A.

In discussing the results of the chemical tests the term S_c expresses the concentration of dissolved silica in millimole per liter and R_c expresses the reduction in titratable hydroxyl ion in millimoles per liter.

Results of chemical investigations summarized in previous investigations[17] prove that deleteriousness of aggregates is not a simple function of any one aspect of chemical instability. However, the general relation between certain types of reactivity and deleteriousness suggests that combination of several properties may prove to be diagnostic. Study of the data confirms results of earlier tests in that the amount of silica dissolved is related only in general to deleteriousness, and reduction in alkalinity alone is no clue to deleteriousness.

The degree of deleteriousness should correlate with the quantity of gelatinous silica adherent to the aggregate material in the chemical test. This accumulation of gelatinous silica effects a reduction in the alkalinity of the N_aOH solution, consequently, the magnitude of the

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[17] R. C. Mielenz, and K. T. Greene, "Chemical Tests for Reactivity of Aggregates with Cement Alkalies; Chemical Processes in Cement-Aggregate Reaction," Journal ACI, XIX, No. 3 (1947), 198.

TABLE V

RESULTS OF CHEMICAL TESTS FOR ALKALI REACTIVITY

Aggregate	S_c Silica Dissolved (mM/L)	R_c Reduction in Alkalinity (mM/L)	S_c/R_c
Belgrade			
Coarse	95	80	1.2
Medium	120	67	1.8
Fine	130	56	2.3
Havre			
Coarse	125	121	1.0
Fine	75	151	0.5
Billings			
Coarse	700	107	6.6
Fine	365	118	3.1
Logan			
Coarse	98	108	0.9
Fine	660	168	3.9
Missoula			
Coarse	53	109	0.5
Fine	113	204	0.5
Judith Gap			
Coarse			0.6
Fine			0.5
Livingston			
Coarse	668	102	6.5
Fine	760	182	4.1
Ashland			
Coarse	674	125	5.38
Medium	620	130	4.76
Fine	82.5	122	0.7
Great Falls			
Coarse	101	158	0.6
Medium	50	205	0.2
Fine	442	153	2.9

TABLE VI

MAXIMUM EXPANSION AT 1 YEAR OF MORTAR BARS

Aggregate		Expansion in Per Cent
Belgrade	Coarse	0.016
	Medium	0.014
	Fine	0.012
Havre	Coarse	0.008
	Fine	0.016
Billings	Coarse	0.002
	Fine	0.003
Logan	Coarse	No Results
	Fine	"
Missoula	Coarse	0.010
	Fine	0.016
Judith Gap	Coarse	0.017
	Fine	0.016
Livingston	Coarse	0.015
	Fine	0.015
Ashland	Coarse	0.005
	Medium	0.002
	Fine	0.016
Great Falls	Coarse	0.016
	Medium	0.008
	Fine	0.010

quantity R_c should correlate with the mortar expansion caused by deleterious aggregates.

Since the ratio of released silica to alkalinity reduction appears to be significant the factor S_c has been plotted against R (Fig. 1). On this basis the innocuous can be separated from the deleterious materials by a line whose locus approximates $S_c/R_c = 1$. For innocuous materials, S_c/R_c is less than 1; for deleterious materials, S_c/R_c is usually greater than 1; i.e., deleterious materials are characteristically those which utilize the alkalies more efficiently in liberation of silica. The materials represented by points in the upper left corner are those which would be least deleterious to concrete because they release little silica, but greatly reduce the alkalinity. The materials indicated in the lower right theoretically would be very dangerous to concrete because they utilize the alkalies efficiently and the reactions are long continued. The field at the lower left comprises those materials which are comparatively stable and innocuous, yet small amounts of silica are liberated progressively at moderately efficient rates. The materials at the upper right are the least stable, releasing large quantities of silica at high rates.

This method of analysis demonstrates that not only the ratio S_c/R_c, but also the magnitude of the quantities S_c and R_c are necessary for full interpretation of the deleterious or innocuous character of the aggregate.

Several data points fall very close to the line separating deleterious from innocuous materials, and it appears probable that some aggregates of unusual composition may be diagnosed erroneously by this

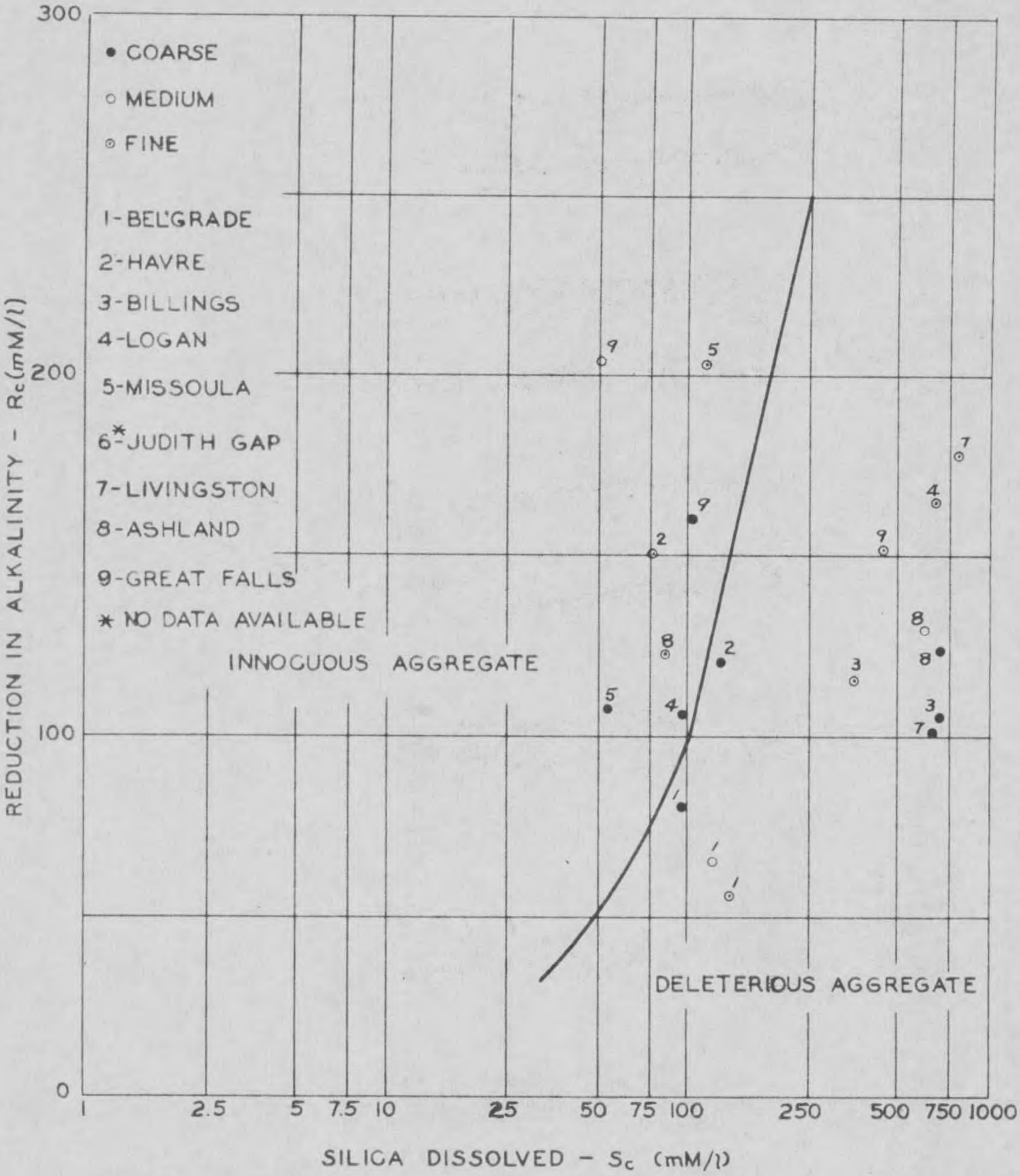

FIG. 1 - RESULTS OF CHEMICAL TESTS WITH NaOH SOLN.

test. Such a circumstance is most likely for those deleterious aggregates containing substances which reduce alkalinity by reactions other than those through which silica is liberated, thus shifting the data points upwardly into the field in which S_c/R_c is less than 1.

The complete range of values for the mortar-bar expansion specimens for 12 months, made with the high-alkali cement, was between 0.002 per cent and 0.017 per cent.

According to Mielenz[18], aggregates causing mortar expansion in excess of 0.2 per cent linearly in one year in tests using high alkali cement (1.3% Na_2O + 0.12% K_2O) should be expected to cause rapid, intense, and readily identifiable expansive deterioration of concrete if used with high-alkali cement in exposed situations. Therefore, it is suggested that aggregates causing mortar expansion in excess of 0.1 per cent linearly in one year should be used only with cements low in alkalis.

The fact that all of the mortar-bar specimens had exceptionally low values of linear expansion, whereas a number of the aggregate samples used showed values of S_c/R_c as high as 6.55, might be explained in light of the "pessimum"[19] proportion. The so-called "pessimum" proportion has long been the subject of conjecture and discussion. It would appear to be entirely possible that the phenomenon of the "pessimum" proportion might represent the operation of the opposing characteristics of cement-aggregate reaction, namely: the tendency for increased expansion of the mortar as

[18] Ibid., p. 22

[19] A word used by T. E. Stanton to designate the proportion of reactive substances in an aggregate at which maximum mortar expansion occurs. T. E. Stanton, "Expansion of Concrete Through Reaction Between Cement and Aggregate," Proceedings ASTM, LXVI (1940), 1781.

progressively more reactive particles are made available for attack; and the tendency for decrease in the silica-producing reaction as the available alkalies are more and more rapidly depleted by adsorption and liberation of silica over the greater and greater surface area exposed to attack. If these deductions are correct then the pessimum proportion should be low for those aggregate materials which considerably reduce the alkalinity of the solution during the chemical test, and it should be large if the reduction in alkalinity is small.

Highly reactive aggregates may cause a smaller expansion than considerably less reactive aggregates because the content of reactive constituents exceeds the pessimum proportion. The best method is to add various percentages of a suspected aggregate to one that is innocuous and determine the percentage at which maximum expansion occurs. It is possible that in the tests performed as part of this research the percentage may have exceeded the pessimum proportion.

Mineralogical Analysis

From numerous petrographic examinations correlated with chemical reactivity tests and mortar expansion tests it has been possible to list some of the reactive minerals.[20] As can be noted from Table VII, the minerals that are known to have caused excessive expansions with high alkali cements have been designated as reactive. All of the aggregates are seen to contain some material that is reactive. The determination of the exact amounts was not possible because the examinations were made

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[20] R. C. Mielenz and L. P. Witte, "Tests Used by the Bureau of Reclamation for Identifying Reactive Concrete Aggregates," Proceedings A.S.T.M., XLVIII (1948), 1284.

megascopically.

If suitable petrographic equipment had been available, thin sections would have been made and a more comprehensive study could have been conducted.

The chemical tests for the coarse aggregates were fairly well correlated with the mineralogical determinations. The fine aggregate did not show the same degree of correlation.

Table VII is a summary of the chemical tests and the mineralogical examination for the aggregates, which is presented here to show the degree of correlation.

Compression Tests

Table VIII lists the results of the 28 day compression tests. Because of the fact that a constant mix ratio and water content were not maintained between the different mixes it was not possible to obtain any correlation to the other tests. The original intent was to use the same mix, as nearly as possible, as was used in the field structures.

It can be observed that in general all the cylinders tested complied with the design strength of 2400 psi. From the results of the compression tests the values were so scattered that no definite conclusion could be drawn as to the effect of the admixes on the compressive strength.

In general if the W/C remains constant the addition of an air-entraining agent to a concrete mix will result in a lowering of the 28 day compressive strength.

The specimens containing the fly ash had lower 28 day strengths, as was expected.

TABLE VII

COMPARATIVE SUMMARY DATA
BETWEEN CHEMICAL TEST AND MINERALOGICAL EXAMINATION

Location	Aggregate Type	S_c/R_c	Deleterious or Innocuous	Reactive Constituents from Mineralogical Examination in %
Livingston	Coarse	6.5	D	50% Lava-Andesite
	Fine	4.1	D	Essentially same as coarse
Billings	Coarse	6.6	D	50% Lava-Andesite
	Fine	3.1	D	10% Lava-Andesite
Ashland	Coarse	5.4	D	15% Andesite & Rhyolite 25% Chalcedony
	Medium	4.8	D	-----
	Fine	0.7	I	-----
Havre	Coarse	1.0	D or I	-----
	Fine	0.5	I	25% Lava-Andesite 20% Chalcedony
Great Falls	Coarse	0.6	I	50% Lava-Andesite and Trachyte
	Medium	0.2	I	30% Lava-Andesite
	Fine	2.9	D	-----
Logan	Coarse	0.9	I	10% Lava-Andesite & Rhyolite
	Fine	3.9	D	10% Lava-Andesite
Missoula	Coarse	0.5	I	10% Chalcedony
	Fine	0.5	I	10% Chalcedony
Belgrade	Coarse	1.2	D	40% Lava-Andesite
	Medium	1.8	D	-----
	Fine	2.3	D	40% Lava-Andesite Trace of Chalcedony
Judith Gap	Coarse	0.6	I	2% Chert (Chalcedony)
	Fine	0.5	I	5% Chalcedony

TABLE VIII

28 DAY COMPRESSIVE STRENGTHS

Mark	Average of two 28 day tests - psi	Mix Proportions	W/C Gal./Sack	Admixture
1-A	3280	1:1.90:4.42	6	None
2-A	4000	1:1.90:4.42	6	"
3-A	2700	1:1.95:4.38	6½	"
4-A	2065	1:1.98:4.35	6½	"
5-A	2735	1:1.73:4.59	6	"
6-A	3590	1:1.73:4.59	6	"
7-A	3050	1:1.90:4.42	6	"
8-A	1550	1:2.49:3.78	7	"
9-A	2550	1:1.98:4.35	6½	"
1-AT	2530	1:1.90:4.42	6½	Protex-AEA*
2-AT	2350	1:1.90:4.42	6½	"
3-AT	2810	1:1.95:4.38	6	"
4-AT	2880	1:1.98:4.35	6	"
5-AT	2675	1:1.73:4.59	6	"
6-AT	3490	1:1.73:4.59	6	"
7-AT	3805	1:1.90:4.42	6	"
8-AT	2550	1:2.50:3.00	7	"
9-AT	2580	1:1.98:4.35	6	"
3-AH	2590	1:1.95:4.38	6	None
7-AH	3050	1:1.90:4.42	6½	"
8-AH	2440	1:2.50:3.00	7	"
2-HP	2380	1:1.90:1.42	7	Flyash
3-HP	2545	1:1.95:4.38	6½	"
4-HP	2555	1:1.98:4.35	6½	"
6-HP	2870	1:1.73:4.59	6½	"
7-HP	2775	1:1.90:4.42	6½	"
9-HP	3210	1:1.98:4.35	6	"

*Air-Entraining Agent

Field Structures

Photographs were taken and visual examinations were made of all nine of the field structures containing the aggregates under test, during field visits to each structure.

No sign of any disintegration was noted in any of the structures.

The age of the oldest structure in the group is about three years. The location of the photographs have been recorded and at some future date similar field inspections will be made and photographs taken of the same locations to use as a criteria for estimating the degree of deterioration.

Freezing and Thawing Cycles

At this time a maximum of 75 freezing and thawing cycles have been performed on the concrete specimens.

The original intent was to measure the degree of durability of the concrete by determining the loss in weight of the specimens. None of the specimens have lost any weight whatsoever. There is no visual evidence of any deterioration of any kind.

At one time it was suggested that the degree of durability could be determined by measuring the loss in the dynamic modulus of elasticity by the sonic method. After making a thorough investigation of the equipment necessary for making the dynamic modulus determinations by sonic vibration it was decided that the method would not be suitable for the 3" x 6" cylinders because of the high frequencies necessary.

It has been estimated[21] that 20 freezing and thawing cycles are

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[21] R. B. Young, "Concrete Durability; 25 Years of Progress," A.C.I. Journal, XLX (April 1948), 732-41.

approximately equal in effect to 5 years of actual weathering of the concrete in the field. On this basis, the freezing and thawing specimens have been subjected to the equivalent of over 15 years of weathering in the field.

From information secured from an article by F. H. Jackson[22], it has been suggested that concrete capable of withstanding 200 freezing and thawing cycles, without showing any deleterious effects, should be classified as being of good durability.

There is one factor concerning freezing and thawing cycles of concrete made with aggregates that have been termed deleterious that seems to need further investigation, and that is the effect of the freezing cycle on the chemical reaction that takes place with a high-alkali cement. It would appear that the chemical reaction might be slowed down somewhat by the cold temperatures.

Aggregates that form the silica gels when in combination with high-alkali cements do not necessarily need to be rejected for use with low alkali cements. In other words, even though the aggregate may be chemically unstable with high-alkali cements, it is no assurance that the aggregate would not produce a durable concrete when used with low-alkali cement, whether or not it was subjected to freezing and thawing.

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[22] F. H. Jackson, "Use of Admixtures to Increase Resistance to Freezing and Thawing," A.C.I. Journal, XXII (Sept. 1950), 26-31.

APPENDIX A

CHEMICAL TESTS FOR REACTIVITY AND MORTAR-BAR EXPANSION TESTS[23]

Chemical Test to Determine Reactivity of Concrete Aggregate with Cement Alkalies

Procedure

Screen sufficient aggregate to provide at least the following quantities of the various size fractions: 1000 g. each of the $1\frac{1}{2}$ to 3/4 in., 3/4 to 3/8 in., and 3/8 to 3/16 in., and 200 g. each of the 3/16 in. to No. 8, No. 8 to No. 16, No. 16 to No. 30, No. 30 to No. 50, and No. 50 to No. 100 sizes. Prepare a sample of coarse aggregate to be tested by combining 1000 g. of each of the three indicated coarse aggregate sizes, then crush and repeatedly screen the composite sample over the No. 50 and No. 100 screens until virtually all of the material passes the No. 50 screen. Wash the material retained on the No. 100 screen to remove the dust and undersize material. Prepare similarly the sample of fine aggregate for use in the chemical test, except that the composite may be prepared by combination of 200 g. each of the five sand sizes. Dry the sample to constant weight at 110° C.

Weigh out in duplicate 25.0 g. of the dry No. 50 to No. 100 material into small stainless steel or other nonreactive metal containers. Add 25 ml. of freshly prepared 1.000 ± 0.010 N NaOH solution. Stir the mixture to remove entrapped air; then seal the containers. Immediately thereafter place the containers in a liquid bath or oven capable of maintaining a temperature of 80 ± 1°C. for 24 hr. After 24 hr., remove the containers

[23] Mielenz and Witte, op. cit., pp 43-47

from the oven or bath, cool for 15 min. in water maintained at 25°C, and as quickly as possible filter the solution from the aggregate material by the following procedure. Use a porcelain Gooch crucible (Coors Size No. 4) with a disk of filter paper (equivalent to Schleicher and Schuell Co. No. 604) cut to fit the bottom of the crucible in a filter tube fitted with Gooch tubing. With aspirator in operation or vacuum line open decant a small quantity of the solution onto the filter paper so that it will seat properly in the crucible. Pour the remainder of the free-flowing solution into the crucible. With a steel spatula remove as much as practicable of the aggregate sample from the container and pack into the crucible. Continue the filtration until all of the filtrate extractable by this method has been obtained. Do not flush sample in any way to extract the residuum of solution absorbed within or adherent to the aggregate particles.

Immediately following completion of filtration stir the solution to assure homogeneity, then take an aliquot of 10 ml. of the filtrate and dilute to 200 ml. in a volumetric flask. Determine the concentration of silica in the solution. Take an aliquot of 20 ml. of the diluted solution and titrate against 0.05 N HCl to the phenolphthalein end point.

Calculate the silica concentration and reduction in alkalinity of the NaOH solution filtered from the aggregate material as follows: $R_c = N-50v$ and $S_c = 20C$, where R_c equals reduction in alkalinity in millimoles per liter; S_c equals concentration of silica in millimoles per liter; v equals volume in milliliters of HCl solution used in the titration; C equals concentration of silica in the diluted solution, expressed in millimoles per liter; and N equals the concentration of the original

NaOH solution (1000 $\pm$ 10), expressed in millimoles per liter.

Mortar Bar Test to Determine Reactivity of Aggregate With Cement Alkalies

Materials

Use a cement ground to a fineness of 1600 sq. cm. per gram or greater (Wagner Turbidimeter method), containing 1 per cent or more total alkalies (Na_2O and K_2O) expressed as soda equivalents, and a second cement containing less than 0.2 per cent total alkalies. The very low alkali cement being used to establish whether expansive actions other than alkali-aggregate reaction might occur. In addition, cements which may be used in construction might be included in the program to evaluate the significance of marginal degrees of reactivity.

For testing fine aggregate, grade the aggregate 19 per cent by weight for each of the sizes No. 4 to No. 8; No. 8 to No. 16; No. 16 to No. 30; No. 30 to No. 50; and No. 50 to No. 100, with 5 per cent of material passing the No. 100 sieve. Crush coarse aggregate to fine aggregate sizes and grade the aggregates for the mortar 20 per cent by weight for each of the five sizes, omitting the material passing the No. 100 screen. To evaluate the reactivity of aggregates containing abundant deleterious constituents, prepare similarly graded aggregate in which the test material is replaced by 25, 50, and 75 per cent, respectively, of an innocuous aggregate.

Preparation of Specimens

Prepare in triplicate specimens 1 by 1 by $11\frac{1}{4}$ in. in size for each cement-aggregate combination, using a mix composed of 1 part cement to 2 parts aggregate by weight. The net water-cement ratio is maintained at

0.40 by weight. Some adjustment of this ratio is required for testing of lightweight aggregates to maintain a reasonably constant volume relation of cement to aggregate.

Ordinarily, 450 g. of cement, 900 g. of aggregate, and 180 g. of water are sufficient to fabricate the necessary specimens. Mix the ingredients in a bowl (enamelware or other nonabsorbent, noncorroding material) of about 1-gal. capacity by vigorous and continuous stirring, squeezing, and kneading with one hand protected by a rubber glove. Introduce the materials in the following manner: (1) Place the water in the bowl; (2) add the cement to the water and mix for 30 sec.; (3) add approximately one-half of the aggregate and mix for 30 sec.; and (4) add the remainder of the aggregate and mix for $1\frac{1}{2}$ min.

Immediately after mixing, introduce the mortar into the mold in one layer and compact the layer with the forefinger by pressing the mortar into the corners around the reference points and along the surfaces of the mold, until a homogeneous specimen has been prepared. After compaction is completed, cut off the mortar flush with the top of the mold with a straight-edged trowel, using a sawing motion, and smooth the surface with not more than two strokes with the trowel lying flat across the top of the mold. Excessive troweling will form a dense and impervious section of the specimen, which will cause warping if the aggregate is deleteriously reactive.

Curing of Specimens

After fabrication of the specimens, immediately place the molds in a moist closet or moist room maintained at 70° F, where they are permitted to remain for 7 days. Strip molds from the specimens after 24 hr.

Storage of Specimens

After the curing period, determine the length between outer ends of the terminal reference points in a comparator and place the specimens vertically in a storage container in which a small amount of water has been poured to occupy a portion of the space below the platform supporting the specimens. Seal the container and place it in a cabinet or room maintained at 100° F.

Periodic Measurement of Specimens

Determine the length of specimens between outer ends of the terminal reference points at monthly intervals for 2 yr., or until required data are obtained. If desired, dynamic modulus of elasticity is determined also. The specimens are examined for exudations, cracks, popouts, or warping, and if observed, notation is made on the data sheet. The containers are cooled to the temperature of the room in which readings are made (in Bureau practice 70° F) before they are opened. Immediately after the readings have been made, the specimens are returned to the containers, and the containers sealed and stored again at 100° F.

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