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OBSERVATION OF FIELD PERFORMANCE OF PORTLAND CEMENT CONCRETE AND LESSONS FROM A STUDY OF THE FAILURES

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It behooves us to study the prerequisites of sound durable concrete as applied to each type of structure or exposure condition and endeavor to so conduct our construction operations as to avoid long time as well as short time deterioration.

Logically, the most fertile source of information on which to base the principles of sound concrete is a study of good and bad concrete to the end that means may be developed to insure satisfactory long time performance.

An effort will be made to present the fundamental principles of sound concrete under California climatic conditions, as observed from field experience, supplemented by laboratory studies.

PART I

(1) Sound Aggregates and Cement

It is assumed that precautions to insure that sound aggregates and sound cement, as determined by standard methods of test, are taken at all times. Such standard quality tests as the Los Angeles Rattler Abrasion and Sodium Sulphate Soundness Tests for aggregate and strength and Autoclave soundness tests for cement will usually insure the quality of the ingredients and need not be elaborated on in this discussion.

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(2) Impermeable Concrete

The expansion of water at the moment of freezing or the formation of certain salt crystals, such as from the sodium and magnesium sulphates in alkali soils and sea water exert a powerful disruptive force on the concrete which, if repeated often enough and of sufficient intensity, will ultimately rupture the concrete mass; at least to the depth and extent of the penetration. When combined with a destructive action of the salt on some constituent of the cement, the failure is further accelerated and magnified.

It is obvious, therefore, that the first consideration for a concrete resistant to repeated cycles of freezing and thawing or attack by a deleterious salt is impermeability which may be secured through proper gradation and combination of the aggregates and sufficient cement to fill the voids with fines and/or hydration products, and a minimum amount of mixing water consistent with the long time hydration requirements.

To demonstrate the importance of impermeability a series of laboratory tests were undertaken, starting some fifteen years ago, in which relatively porous sand cement mortars were stored in sea water from the Pacific Ocean and in alkali soil from the Willows area in the Sacramento Valley. Some of the results of these tests on the role of permeability are shown in Fig. 1.

The greater durability of high cement content concrete as compared with a low cement factor is further well illustrated in Figs. 2 and 3 which show the condition of specimens in the Portland Cement Association Long Time Study of Cement Performance in Concrete Project 7, Sacramento before and after one and three years exposure to an alkali soil of high sodium sulphate content.

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(3) Type of Cement

Next in importance to an impermeable concrete, in so far as resistance to sulphate attack is concerned, is the type of cement.

You are probably informed that A.S.T.M. Specifications include five standard type cements:

Type I for general use

Type II for moderate sulphate resistance and moderate heat of hydration

Type III for high early strength

Type IV for low heat of hydration

Type V high sulphate resistant

This discussion on cement types will be confined primarily to a discussion of Type I versus Type II.

The other three types are special use cements where high early strength is desired, or a low heat of hydration in the case of mass concrete, or a highly sulphate resistant cement to serve the most severe conditions.

In order that there may be a clearer understanding of the role of the Type II cements it seems desirable to first present the essential differences between this type cement and most Type I cements, although it should be clearly understood that specifications for Type II cement simply place certain limitations on composition which do not appear in the specifications for a Type I cement. Therefore, a Type II cement in every important or essential respect complies with the specifications for a Type I cement; it is simply a Type I cement plus.

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A Type II cement is more sulphate resistant and, therefore, more suitable for use in the presence of sulphate bearing waters or soils than a Type I cement containing a higher percentage of certain compounds than permitted in a Type II cement. The fundamental characteristics of a Type II cement are illustrated in Fig. 4 and Table 1.

As will be noted the fundamental requirements of a Type II cement supplemental to the standard requirements for a Type I cement, are that the potential compound of tri-calcium silicate (C_3S) shall not exceed 50% and tri-calcium aluminate (C_3A) 8%.

The case for the limitation on the C_3A at 8% is better established than for the limitation on the C_3S at 50%, in so far as the studies conducted by the Materials and Research Department of the California Division of Highways are concerned, as will be seen from a study of the tests illustrated in Figs. 5,6,7 and 8.

The Type II cement is likewise frequently referred to as a moderate heat of hardening cement as well as a moderate sulphate resistant cement.

The reason for this is apparent from a study of the curves shown in Fig. 9, wherein it will be noted that the earliest hydrating and hence early heat producing compounds are the C_3A and C_3S. It is, therefore, apparent that any limitation on the presence of these two compounds, particularly the C_3A, assists in holding down the early hydration heat development.

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Fig. 10 is another excellent illustration of the effectiveness of low C_3A as well as high cement content in producing an alkali resistant concrete.

However, with the low C_3A cement of this series (3.5%) even the 4 sack mix shows a relatively high resistance to sulphate attack. At the same time the benefit of lowered permeability through increase in cement content is very obvious.

(4) Air Entraining Agents

One of the outstanding developments in concrete fabrication of recent years is the use of an air-entraining cement or the addition of an air-entraining agent at the mixer to improve the resistance of concrete to freezing and thawing and to sulphate attack, although air-entraining agents are also used for other reasons which will be discussed later.

There is some differences of opinion as to just how air-entrainment operates to improve durability; some contend that the minute air pockets serve as relief valves, as it were, and provide a space for the ice or salt crystals to expans without rupturing the concrete. Others are of the opinion that a more impermeable concrete results and that as the moisture cannot penetrate as readily, the durability is thereby improved. Probably there is a measure of truth in both contentions.

The first suggestion is still in the realm of theory; whereas, there appears to be quite positive evidence that air-entrainment does render a concrete more impermeable and, therefore, more resistant in the same manner as impermeability resulting from proper mix design.

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Other advantages of air-entrainment are, improved workability, lower water cement ratio, less bleeding and consequently less subsidence; also air entrained concrete can be transported longer distances without segregation.

On the adverse side we have the fact that air-entraining agents usually serve to reduce the strength of the concrete, to an extent depending on the amount of air entrained, failure to take full advantage of the opportunity to lower the water cement ratio and the nature of the air-entraining agent.

To insure against material loss in strength, care must be taken to insure no reduction in the net amount of cement per cubic yard. This is usually accomplished both by a reduction in water and in the amount of fine aggregate. The amount of air-entraining agent should be limited to that sufficient to produce only the amount of air-entrainment desired.

There are differences of opinion with reference to the optimum amount of air, some contending that 3 to 4% air is sufficient to accomplish the desired end under normally adverse exposure conditions; whereas, others are sold on a high air content, particularly under the most severe exposure conditions. Considerable research along this line is still in order.

Ordinarily, however, little reduction in strength need be anticipated if not over 0.01% of either neutralized Vinsol Resin or Darex is used; full advantage is taken of the opportunity to lower the water content, and the mix is properly re-designed to hold the cement yield constant. Other air-entraining agents, such as Puzzolith,

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should be used under the advice of the manufacturer, and then only when of proven quality.

The beneficial effects of air-entrainment as well as further evidence on the effects of cement composition are well illustrated in Figs. 11 and 12 showing the condition of concrete specimens of high and low C_3A and variable cement content, with and without an air-entraining agent, after 30 months exposure to an alkali soil high in sodium sulphate.

The fact that at least a portion of the improved durability through the use of an air-entraining agent is in the reduction in permeability is illustrated in Fig. 13, which figure likewise illustrates the lowered permeability resulting from an increase in cement content.

Although of uncertain cement content or composition, Figures 14, 15, 16, and 17 are shown to illustrate concrete still in good condition after 36 to 54 years exposure to sea water, as well as some not so good.

Particular attention is called to the concrete in Fig. 16; note the form marks. All 1200 of the original concrete jacketed piles in this structure are still in excellent condition after 36 years exposure to sea water.

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PART II

Durability of Concrete as Affected by Adversely Reactive Cement-Aggregate Combinations

Within this State no evidence of unsound concrete as affected by the aggregates has been observed except the excessive concrete growth which has developed in pavements and other structures where the alkali constituents of Portland cement have adversely reacted with certain type minerals in the aggregates. These alkali constituents of the cement occur in the form of sodium and potassium oxide and when present in a combined quantity greater than 0.60 per cent equivalent Na_2O react with certain types of silica in the aggregate to produce excessive quantities of silica gel or sodium potassium silicate. This gel when it forms in the interior of a concrete mass where there is no relief, exerts an enormous pressure, sufficient to rupture the concrete. In California two of the mineral constituents which cause trouble of the above nature have been identified as opal in the opaline cherts and the glass matrix of some volcanic rocks, such as andesite.

The extent of the rupture depends, of course, on the extent of the reaction which, in turn, is influenced by the percentage of alkalies in the cement and reactive ingredients in the aggregates. One of the phenomena of this action is the fact that if the percentage of reactive aggregate particles exceeds a certain amount (which has sometimes been designated as the pessimum amount) the measurable effects of the reaction decreases until finally entirely non-existent.

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HISTORICAL

First, to briefly review some of the original studies to discover the cause of the extensive concrete failures along the coast between the Palos Verdes area in Los Angeles County in the south and Monterey County in the north.

That shale and chert (subsequently identified as opaline) were involved in at least part of the failures throughout this area was first deduced from observation of numerous popouts on the faces of concrete structures where particles of shale and/or chert were found to be at the base of the popouts. The action was at that time considered to be entirely physical and the solution appeared to be to limit the percentage of such particles. It was for this purpose that the California Division of Highways adopted the sulphate soundness test for aggregates.

Salinas Valley Pavement Failure

Early in 1938, a section of concrete pavement north of the town of Bradley in the Salinas Valley, Monterey County, failed through excessive expansion. The failed pavement was built in the fall, winter, and spring of 1936-37. Most of it had passed through only two winters when portions began to show distress in the spring of 1938. The distress became manifest in the form of excessive expansion which caused buckling at the joints and a severe cracking throughout the entire length of certain slabs. (Figure 20)

The fine aggregate came from two sources; one the local deposit from which all of the coarse aggregate was secured, and the other a commercially operated deposit near San Jose. The sands from these two deposits were used on alternate days so that from the Resident Engineer's daily reports, it was easy to identify the

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source of the fine aggregate in each section or day's run. An inspection of all sections readily disclosed that excessive expansion had occurred only in those sections in which the local fine aggregate had been used, and it was obvious, therefore, that these local aggregates were at least partially responsible for the trouble.

Earlier Failures

The Bradley pavement failure culminated a series of concrete failures along the coast area from Monterey County in the north to the southwesterly part of Los Angeles County in the south, throughout which aggregates of the same typical characteristics are encountered.

The first structure in which distress developed to such an extent as to attract attention was the King City Bridge built in 1919-1920 across the Salinas River at King City, Monterey County. Within three years after construction, well-defined cracks were in evidence in the caps of the piers. Later, these cracks extended into the columns. By July, 1924, all of the piers were more or less affected. (Figure 21)

Subsequent to the King City Bridge trouble, several concrete trestles in Monterey County, in which fine aggregate from the Salinas River or its tributaries had been used also developed serious distress. (Figures 22 and 23)

During this period similar pavement and structure failures were developing in Los Angeles, Ventura, Santa Barbara, San Luis Obispo and Monterey Counties, where the aggregates were

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of the same general type, containing from 4% to 15% of shale, cherty shale, and chert. A number of the more extensive failures were some sections of pavement and sea walls in Ventura and Santa Barbara Counties. (Figures 24 to 30)

Although the sulfates in sea water undoubtedly contributed to the ultimate serious deterioration of the sea walls, it was obvious that this deterioration was accelerated by the infiltration of the sea water through cracks resulting from other causes and the deposit of an excessive amount of salt residues as the sea water evaporated.

The concrete walls of a school building in Santa Barbara, built in 1931, had cracked to such an extent by 1934 as to require at least partial reconstruction, (Figure 31). Other school buildings and a concrete stadium of what is now an adjunct of the University of California at Santa Barbara (Figures 32 and 33), the reconstructed Santa Barbara Mission and the Senior Seminary near Camarillo (Figure 34), were found to be similarly affected. All of the failures noted followed the same general pattern and were obviously due to the same underlying cause.

The solution of the problem was complicated by the fact that although without exception cracking of the nature described was noted only when local fine aggregates had been used, there were numerous instances where the same local aggregates had performed in an entirely normal and satisfactory manner.

As an illustration, immediately north of the Bradley pavement failure in Monterey County is a section of pavement

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constructed at least six years earlier, in which fine aggregates from the same general source (the Salinas River) were used, but which in 1949, after 17 years, is still in excellent condition and shows no evidence of excessive expansion or cracking.

CEMENT

It was found that when specimens of certain aggregate-high alkali cement combinations are kept in sealed containers, or at least protected from drying out, but at the same time protected from any leaching of salts due to excess moisture, such as by constant immersion or alternate wetting and drying, a chemical reaction develops under optimum moisture conditions which, with certain cement-aggregate combinations, causes an excessive expansion of the concrete with resultant failure (Figures 35 and 36).

The relation of the cement composition to the reaction was determined from a study of other concrete structures in the Bradley area, in which the same type of local sand but a different cement was used and which had never developed distress at any age. Observation of this fact gave rise to the suspicion (subsequently confirmed) that the expansion resulted from a chemical reaction between certain ingredients in the aggregate and some ingredient in the cement. Alkali in the cement in the form of the sodium and potassium oxides was suspected and, as the cement used in the Bradley concrete contained approximately 1.14% total alkalies, the tests were repeated with another cement low in alkali (0.45%). There was little, if any, expansion with the low alkali cement

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in combination with the local sand which had shown so much expansion with the high alkali cement.

The tests have been repeated many times not only with the two cements referred to, but with many other cements ranging from low to high alkali content and sands from within and without the coast area.

The resultant expansion has invariably been roughly proportional to the alkali content of the cement, whenever used in combination with aggregates containing minerals readily soluble in sodium hydroxide. On the other hand, sands containing negligible percentages of opaline shale and chert or volcanic glasses, readily soluble in sodium hydroxide, have developed little, if any, expansion even with high alkali cements.

It is, therefore, obvious that, in the presence of certain minerals, an otherwise sound but high alkali cement is a contributing factor to excessive concrete expansion. Under certain conditions this expansion may not be sufficient to seriously crack or disrupt the structure and may cease as soon as the reaction has been completed in any particular cement-aggregate combination. In other cases, however, the initial cracking although above normal but not excessive, may have very serious subsequent consequences under freezing and thawing conditions or when the structure is subject to attack by sea or alkali waters which, seeping into the concrete mass through fine cracks developed by the primary cause, may take up the work of destruction through corrosion of reinforcing steel or attack on vulnerable compounds of the cement.

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AGGREGATES

The coast aggregates included in the original study consist of mineral particles, predominantly granite and sandstone with some quartz-feldspar, impure limestone, shale and chert. The granite, sandstone and quartz-feldspar, usually comprise from 85% to 90% of the total; the shales and cherts the remainder. None of the adverse reactions have been traced to the first mineral group. Some of the minerals in the second group, however, have been proven reactive under appropriate weathering conditions. Geologists report that the reactive mineral (opal) in this latter group is found primarily in the Upper Miocene sedimentary deposits.

The California cherts may be divided into two main classifications: (1) the deleterious cherts of the opaline types and (2) the less questionable group of quartoze particles. The deleterious particles, classified as opaline, contain opaline silica either in the main or as a cementing material throughout a shale particle.

Field Observation

Over a period of years tests have been made on fine aggregates from all of the commercial sources within the regions affected and from many other sources in the state outside of this area.

Laboratory tests have been confirmed by field observations where, in a study of the extensive popouts observed in numerous structures, including pavements, bridges, and buildings, shale or chert particles are invariably found at the base of the popouts,

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frequently accompanied by a soft viscous substance analysed as a silica gel with some form of sodium silicate. (Figure 37)

In some casea a number of aggregate particles had entirely altered to gel, so that it often swelled out above a freshly cut surface of a concrete specimen. In many cases the reaction has only partly progressed into particles identified as siliceous shales or cherts.

A detailed examination was made of approximately 200 popout and core specimens removed from affected buildings, sea walls, bridges, and pavements over an area extending from Los Angeles in the south to the northern part of the Salinas Valley. Each popout or altered rock particle was found to have associated with it a considerable amount of material identified as opaline silica (Figure 37).

It can be reasoned that the alteration forms in the presence of moisture through the action of alkali in the cement, or possibly in the rock, on some form of silica in the rock, resulting in a gel-like end product consisting primarily of opaline silica, sodium silicates, and water.

In 1940 the U. S. Bureau of Reclamation and the Los Angeles Metropolitan Water District observed and reported on similar concrete failures in the Parker, Gene Wash and Copper Basin Dams in which the nature of the reactive aggregate was determined to be andesite in the sand from the Bill Williams Fork of the Colorado River.

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Subsequent to the discovery of the cause of the trouble along the California coast, similar concrete failures were observed in the vicinity of Fresno, the most serious being at the Belmont Traffic Circle (Figure 38).

Similar evidence on other projects in the same locality led to the conclusion that it is not safe to use San Joaquin River aggregates except with a low alkali cement.

In this case the aggregate trouble can apparently be traced to the volcanic glass matrix in andesitic rock inclusions in an otherwise non-reactive aggregate.

Still later (within the last few years) concrete in the high Sierras, particularly in the volcanic region surrounding Mount Lassen (Figure 39) and along the Truckee River, has developed similar distress which has been traced to the same underlying cause; namely, an adverse reaction between the cement and aggregate.

It is true that the effects of this reaction might not in many cases be serious were it not for certain contingent circumstances which are the real cause of the progressive deterioration, after the initial cracking through the reaction has developed and possibly even expended its energy. I refer particularly to the disintegration of the concrete in the sea walls in Ventura and Santa Barbara Counties where the salts in the sea water infiltrating the cracks resulting from the cement-aggregate reaction have over a period of years caused a complete disintegration of portions of the structures (Figures 28 and 30). In the higher altitudes repeated freezing and thawing of water infiltrating the

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reaction cracks has caused failures far in excess of the deterioration of structures in lower and, therefore, more moderate climatic area where the same type cements and aggregates have been used (Figures 40 and 41).

Laboratory Studies

Information developed during the laboratory tests which led to the discovery of the cause or causes of the excessive expansion of certain aggregate-cement combinations may be of interest.

In the original series of tests (1939) with the high alkali cement which was involved in the Bradley pavement failure, a number of sands from widely separated areas of the state were tested for potential reaction.

Some of the results of these tests are shown in Figure 42.

Sands 1 to 4 inclusive were from deposits along the coast area between Monterey and Ventura Counties, and which were suspected of being contaminated with reactive particles. Excessive expansion will be noted in every case.

None of the other sands in the test (see heavy unidentified lines along the base line) showed any reactive expansion in 36 months except sand #27 which, as will be noted, developed what may be termed excessive expansion, considering the lean mix and mild temperature exposure conditions (1:3 mix stored in sealed containers at 70 F).

Sand #27 was from a hitherto unsuspected source - the San Joaquin River in Fresno County.

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It is interesting to note that a subsequent field observation of the condition of concrete pavements and other structures in which this aggregate had been used confirmed the laboratory test tip-off relative to the potential reactivity of material from this source (Figure 38).

Contemporaneous tests were made with the same sands in combination with cements of high to low alkali content. The results of these tests, up to 12 months, in the case of the reactive Sand #3 from Piru, Ventura County are shown in Figure 43.

While the expansions at the end of six years are not directly proportional to the alkali content of all of the cements, high early expansion (greater than 0.1%) will be noted (in 12 months) in the case of all cements containing in excess of 0.60% alkali as Na_2O, whereas the specimens containing the two cements with less than 0.6% did not develop 0.1% expansion until 31 months in the case of cement BL (0.51% alkali) and approximately 45 months in the case of cement AS(0.45% alkalies).

Attention is called to cement HP which showed some shrinkage at six years. This was a high silica or pozzolan type cement, the clinker of which contained 0.78% alkali.

The apparent corrective properties of a pozzolan addition as indicated by the performance of Cement HP (Figure 43) was the occasion for the series of tests, the results of which are shown in Figure 44, in which varying percentages of different siliceous materials ground to pass a 325 mesh sieve were substituted for an equivalent percent of a high alkali cement in a highly reactive aggregate-cement combination.

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It will be noted that in this series, the most effective pozzolans were the opaline chert #28038 and opal.

Next in order was Monterey Shale, the siliceous material used in the manufacture of Cement HP. The least effective material was Ottawa sand.

Relatively little benefit was derived from a straight cement reduction without pozzolan replacement.

Early tests likewise indicated that there is a certain percentage of reactive particles in the aggregate, which produce the greatest expansion. When this percentage is exceeded the measurable effect of the expansive reaction decreases progressively as the percentage of reactive particles increases until the expansion becomes negligible. The percentage producing maximum expansion (sometimes referred to as the pessimum amount) ranges in inverse ratio with the potency of the reactive particles, being least with the highly reactive opal or opaline chert.

To secure data on this interesting phenomena, the series of tests illustrated in Figure 45 were undertaken.

From this Figure it will be noted that the presence of as little as one half of one percent of the opaline chert #28038 in the aggregate produces excessive expansion (over 0.1%) in less than six months. The measurable effects of the reaction reached a peak at 4 percent and then fell off to negligible proportions at 10%.

The fact that excessive expansion was noted with less than 0.5% of the opaline chert #28038 was the occasion of the supplemental tests along the same lines the results of which are shown in Figure 46.

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This latter series included the high opaline chert #28038 and the siliceous magnesium limestone #28039 containing 20% opal.

The tests were designed to determine (1) how much less than 0.50% of the high opal chert #28038 would induce excessive reaction; (2) the pessimum amount of the lower opal content chert #28039, and (3) the expansion of companion specimens of the reactive Saticoy sand which might serve to indicate the probable reactive mineral content (either #28038 or #28039) in this sand.

It will be noted that excessive expansion developed with less than one quarter of one percent (0.25%) of #28038, the pessimum amount of this reactive rock being again fixed at 4 to 5 percent. At the same time the lower opal content chert #28039 showed excessive expansion with slightly over one percent (1.0%) and a maximum at approximately 20%.

When it is noted that the presence of only slightly over five tenths of one percent (0.5%) of the opaline chert #28038 in the Saticoy sand is necessary to produce the expansion shown in Figure 46, it is easy to understand why tests on different samples of the sand from this source may be erratic, depending on very slight variations in the reactive mineral content.

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CONCLUSIONS

(1) Excessive expansion, sufficient to rupture a concrete mass, can frequently be traced to a chemical reaction between certain minerals in the aggregate and the alkali in cement.

(2) This chemical reaction always takes place with the opal bearing cherts and shales in the aggregates from the Miocene (particularly the Upper Miocene)sedimentary deposits along the coast between the Palos Verdes area in Los Angeles County in the south and Monterey County in the north.

(3) Similar experience has been had with some of the Andesites and other volcanic rocks of the Sierra Nevadas and are probably due to a volcanic glass matrix which is readily dissolved by an alkali solution.

(4) The chemical reaction producing excessive expansion apparently occurs only when the Portland cement component contains an appreciable percentage of alkali in the form of sodium and potassium oxides or the aggregate contains a high percentage of alkali to supplement the alkali in a low alkali cement. It is of an intensity roughly proportional to the percentage of the alkalies, apparently being of such low order as to usually be negligible when the alkali content of the cement is less than 0.6%.

(5) The solution of the problem of concrete durability under the conditions which have caused trouble in California appears to be the use of a low alkali cement combined with the greatest practicable reduction in the percentage of the rock types which are definite contributory agents.

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