

The potential alkali-aggregate reactivity of Montana concrete aggregates
by Thomas Gould Stewart

A thesis submitted to the Graduate Faculty in partial fulfillment of the requirements for the degree of
MASTER OF SCIENCE in Civil Engineering
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Abstract:
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Conclusive evidence showed four of the six aggregates to be reactive and one aggregate to be nonreactive. Results for one aggregate indicated possible reactivity, but the evidence was not conclusive.

Excessive mortar bar expansions occurred for the four reactive aggregates. Three types of low alkali cements, and two types of pozzolans, when tested with these aggregates, demonstrated their ability to prevent this excessive expansion.

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ABSTRACT

The potential alkali-aggregate reactivity was determined for the fine aggregates from six major concrete aggregate sources in the State of Montana. The aggregates' reactive capacity was determined on the basis of three different laboratory test methods. They were the mortar bar test, the chemical test and the petrographic analysis.

Conclusive evidence showed four of the six aggregates to be reactive and one aggregate to be nonreactive. Results for one aggregate indicated possible reactivity, but the evidence was not conclusive.

Excessive mortar bar expansions occurred for the four reactive aggregates. Three types of low alkali cements, and two types of pozzolans, when tested with these aggregates, demonstrated their ability to prevent this excessive expansion.

CHAPTER I

INTRODUCTION

For the past twenty years alkali-aggregate reaction has been an important subject in the study of concrete durability. The reaction occurs between the alkalies, released by the hydrating cement, and susceptible siliceous rocks and minerals in the aggregate. The product of this reaction is an alkali-silica gel which has the property of swelling through osmosis. This action can cause expansive deterioration of the concrete. When expansive deterioration occurs in a relatively short time, the identification of alkali-aggregate reactivity is usually unmistakeable due to the characteristic pattern cracking and the exudation of silica gels appearing on the surface of the concrete. However, in most cases, deterioration occurs over a considerable period of time. Positive identification of the original cause of deterioration is then obscured by the multitude of factors involved.

Successful corrective measures have been used to counteract the alkali-aggregate reaction. Three of these measures are: the use of non-reactive aggregate, the use of low alkali cement, and the use of pozzolanic additives.

A few concrete structures in the State of Montana are experiencing minor deterioration, but it is difficult to relate the cause of deterioration directly to alkali-aggregate reactivity. In 1950, a concrete durability study was insti-

tuted at Montana State College in co-operation with the Montana State Highway Commission. Tests were included in the durability study to determine the potential reactivity of various aggregate sources. The results of these tests are presented in a Master's Thesis written in 1952 at Montana State College by R. A. Wallace.

An accelerated mortar bar test and a chemical test were used to determine the potential reactivity of the aggregates. The chemical test showed that seven out of nine aggregate sources tested were potentially reactive. However, the corresponding mortar bar tests failed to give significant expansions to support the chemical tests. On this basis, it was not possible to make definite conclusions concerning the potential reactivity of the aggregate sources. The author felt that further investigation of the potential alkali reactivity of the aggregate sources would be of considerable importance.

The primary purpose of this thesis was to evaluate, based on laboratory tests, the potential alkali-aggregate reactivity of six major concrete aggregate sources. These included five of the nine sources used in the previous durability study by Wallace.

The secondary purpose of this thesis was to evaluate, based on laboratory tests, the capabilities of three common

cement types and two pozzolan materials in preventing expansive reaction with any aggregate sources found to be potentially reactive.

One of the most common practices for controlling alkali-aggregate reactions is to use only low alkali cements with all concrete aggregates. However, this practice cannot be justified in all situations without the knowledge of an aggregate's reactive capacity, since, in some cases, this practice may be unwarranted; while in others, inadequate. The following considerations indicate that it is desirable, and, in certain cases, nececessary to have knowledge of an aggregate's potential reactivity:

1. Researchers express concern over the question of what percentage of alkali in the cement would be safe for all types of aggregate, or, what is actually the safe dividing line between low and high alkali cements. The safe dividing line could be established for a given aggregate source with a knowledge of the aggregate's potential reactivity.

2. The amount of alkalies present in Portland Cement depend primarily on the natural characteristics of the quarry material used in the production of the cement. Material high in alkali content can be controlled in the production process, but it is not economically feasible to eliminate all the alkalies. Since a certain amount of alkalies are always present, it would be desirable to know the potential reactivity of a given cement and aggregate.

3. Certain aggregate material may be the source of additional alkalies which could raise the total alkali content in a concrete mix to a potentially dangerous amount. In such cases knowledge of the

potential reactivity of the aggregate would be necessary to design a safe mix.

4. If the aggregate is known to be reactive, low cost pretested additives can be used as a safeguard without knowledge of the alkali content of the cement. This is an advantage to smaller organizations who do not have facilities to check alkali contents in cements.

5. Concrete made with low alkali cements and reactive aggregate usually experiences a limited reaction. Little is known as to whether this limited reaction significantly contributes to poor concrete durability. An evaluation of the aggregate's potential reactivity with low alkali cements would aid in determining the effects of a limited reaction.

Awareness of the alkali-aggregate reaction was a result of rapid deterioration of certain costly concrete structures. Knowing the potential reactivity of concrete aggregates enables one to make the proper selection of materials to assure against similar occurrences in the future. It is hoped that the results of this investigation can be used to further improve the durability of concrete in the State of Montana.

Chapter II presents a review of literature on the subject of alkali-aggregate reactivity with emphasis on the progress made on the subject in the past ten years.

The first part of Chapter III describes the equipment and materials used for the laboratory studies. The second part of Chapter III describes the planning of the laboratory tests and the procedures used.

Chapter IV gives the results and interpretation of the laboratory investigations. The first half of the chapter is an evaluation of all tests conducted for the purpose of determining the potential reactivity of the aggregates. The second half of the chapter is an evaluation of the low alkali cements and pozzolans tested for the purpose of counteracting the alkali-aggregate reactivity.

Conclusions and recommendations for further investigation appear in Chapter V.

CHAPTER II

THE REVIEW OF LITERATURE

In 1940, the cause of certain badly distressed concrete structures was determined to be an expansive reaction between water soluble sodium and potassium alkalies of the cement and various forms of siliceous materials in the aggregate. This initiated some extensive research that was mainly directed to seeking out the types of potentially reactive aggregate, developing tests to predict the suitability of the cement and aggregate, and testing various additives to prevent incompatible cement-aggregate combinations from reacting. Theoretical considerations of the reaction were secondary, and the few hypotheses set forth to explain the phenomena lacked supporting evidence. Due to both the complexity involved in the exact interpretation of the alkali-aggregate reaction and the lack of standardized tests, laboratories engaged in similar studies sometimes presented anomalous results. In general, by 1950, enough knowledge of the alkali-aggregate reaction had been gained to prevent a recurrence of any dramatic and costly damage.

Much remained to be done to more thoroughly understand, evaluate and control the reaction. From roughly 1950, to the present, a considerable amount of the research was directed to the theoretical considerations in an attempt to put the explanation of the phenomena on a sound basis. The

hypotheses presented were supported with newly designed laboratory techniques, and the earlier more reliable laboratory tests for potential reactivity were refined to give suitable test correlations and to give understandable reasons for any non-correlations. In recent years valuable long-time test results from various laboratories are appearing in the publications.

The discussion of the literature between 1940 and 1950 covers particularly well established facts. Results that have been of major controversy are also presented and reviewed in light of the more recent progress, which comprises the major part of the review. The discussion will include:

1. The general nature of the reaction and important factors influencing it.
2. The development and use of the most reliable tests to determine the reactive potential of aggregates.
3. The known types of reactive minerals and rocks and their relative degree of reactivity.
4. The most widely used methods to prevent the occurrence of harmful alkali-aggregate reaction in concrete.

THE NATURE OF THE REACTION

It has been found that the reaction is basically a progressive chemical attack by an alkali hydroxide on particular forms of silica present in the aggregate.

The chemical reaction and the product formed have been

clearly and fundamentally explained by T. C. Powers and by H. H. Steinour (23).[1] In order to carry out their explanations they imagined, for simplification, that only a hydrous silica particle surrounded by sodium hydroxide solution was present. The interior portion of the silica particle would consist of silicon atoms surrounded, in a tetrahedral configuration, by four oxygen atoms. At the surface, however, the oxygen atom could only be bonded by one silicon atom instead of two. The resulting surface would consist of oxygen ions having one unsatisfied negative charge and silicon ions having one unsatisfied positive charge. This condition would bring about a surface hydration in the presence of water, i.e., one hydrogen ion joining the oxygen ion and the left-over hydroxyl ion joining the silicon ion. The hydrogen ion that joined the oxygen would be loosely bonded, and in an aqueous medium the surface would ionize to form a silica particle of weak acidity. Mr. Powers discussed the nature of reaction of such a particle in the presence of sodium hydroxide, a strong alkali. The initial reaction would be an acid-base neutralization, since the surface of the silica particle is acidic. If the sodium hydroxide concentration was strong, it would not only remove and neutralize the

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[1] Figures in parenthesis indicate references on page 178. (LITERATURE CITED)

surface hydrogen ions, but also break silicon-oxygen-silicon linkages, forming a new surface susceptible to attack and identical to the initial surface of attack. Thus the particle would be reduced to a gel substance with the silica in the form of colloidal particles which Powers called a "silica sol".[2]

The resulting softened gel-like product contains sodium, silicon, and oxygen, and when any alkali is involved it is commonly called an alkali-silica complex. This complex is capable of imbibing water and swelling. It has been shown that this swelling is capable of producing pressures within concrete sufficient to rupture the concrete, and is believed to be the fundamental cause of the expansion in concrete experiencing alkali-aggregate reaction.

MECHANISM OF EXPANSION

The mechanism by which this expansion occurs was first postulated by W. C. Hanson (10) to be an osmotic phenomena.

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[2]A general term and definition for this particular type of sol defined by Hiller and Herber (14) is a "Lyophilic sol" -- "A solution of high polymers dispersed molecularly in suitable solvent. Such a sol is made up of particles that have an attraction to the liquid medium and tend to disperse spontaneously by a process called 'Peptization'." Hiller and Herber define a gel as a semisolid elastic structure which contains large amounts of solvent loosely held together by an open network of solute molecules where solvent and small solute particles can readily migrate through the gel structure, demonstrating properties not greatly different from liquids.

He considered the alkali-silica complex around a reactive particle a solution, water a solvent, and the mortar about the particle a semi-impermeable membrane, and that the actual expansion of the concrete was due to hydraulic pressures produced through an osmotic transfer of water to the solution side of the membrane. The net effect of osmosis as described by Hiller and Herber (14) is to cause a transfer of solvent molecules through the pores of a semi-permeable membrane to the solution side; the actual motion being due to an unequal vapor pressure between the areas separated by the membrane. The hydrostatic pressure required to balance the process is termed the osmotic pressure of the system. The difference in vapor pressure is explained in terms of a kinetic mechanism in which the solvent atoms that are in the solute (the solution side) have a lower energy level than the pure solvent side. Thus, there would be fewer collisions of the solvent atoms on the solution side of the membrane than there would be on the pure solvent side, resulting in a net movement of solvent atoms to the solution side. The relative vapor pressures then would be a measure of the available energy in the solvent side that could be imparted to the solution side. Powers and Steinour used this explanation to further support Hanson's osmotic pressure theory. They considered the alkali-silica complex a solution containing water that

is lower in energy than the free water in the mortar. The net effect would be a migration of free water to the solution area with consequent swelling of the alkali-silica complex. If the alkali-silica complex (usually in the form of a gel) were sufficiently confined, pressures high enough to rupture the concrete could be produced before reaching the osmotic pressure required to equalize the process.

Hanson attributed the entire expansion to this hydrostatic pressure of a confined gel deposit. However, Brown (7) maintained that the major portion of harmful concrete expansion was due to direct swelling of the aggregate particles. Verification of this was attempted with the presentation of some photographs of thin sections sawed from highly reacted concrete and mortar bars. These showed altered reacted particles with characteristic reaction rims along with sharply defined cracks through an unreacted internal portion. These cracks stopped abruptly at the internal edge of the reaction rims. Radial cracks extended out through the mortar from the reacted particles, with some reaching the surface of the concrete specimen.

The important observation by Brown was that these particles were obviously causing the greatest expansion in the concrete and were the source of most surface cracks. Sharply defined cracks in the internal portion of these reacted

particles were lacking signs of gel. Brown suggested that the reaction rim, while still in a highly viscous stage, produced swelling sufficient to cause harmful expansions. The attack on a particle was presumed to proceed inward, thus the viscosity of the reaction rim would increase inwardly, and the tendency would be for the less viscous or more liquid gel to move outward through the radial cracks to the surface, or to available air pockets in the matrix.

The hydrostatic pressure of a confined deposit of a liquid gel might then be considered a secondary cause of disruptive expansion. However, as Powers pointed out, the line of demarcation between the softened solid reaction rim and a liquid gel is not clearly distinguishable, nor is the interpretation of hydrostatic pressure of such a substance.

For the purpose of describing the basic alkali-aggregate reaction and the formation of the alkali-silica gel complex capable of swelling, Powers and Steinour imagined that only the sodium or potassium alkalies were available. The acid-base neutralization of sodium or potassium ions previously referred to could also take place with the calcium ions which are abundant in cement mortar. This would produce a lime-silica complex, or more likely a lime-alkali-silica complex, since ions of both are present. It has been shown, depending upon the amount of calcium hydroxide in the complex, that the

reactive products of the lime-alkali-silica complex are relatively insoluble, and that the gel formed is incapable of the unlimited swelling associated with alkali-silica gel.

It has been concluded by most investigators that an alkali-silica complex must be formed to cause alkali-aggregate expansion in concrete.

FACTORS INFLUENCING THE EXPANSION OF CONCRETE DUE TO THE ALKALI-AGGREGATE REACTION

The Lime-Alkali-Silica Complex

Probably the most important factor influencing the degree of expansive reaction is the relative amounts of alkali-silica complex and lime-alkali-silica complex that can be formed in a potentially reactive cement and aggregate mix. More specifically, the type of reaction product is in relation to the relative amounts of sodium and calcium that can diffuse into the reaction site. Although there is always a great abundance of the calcium ion available, the alkali-silica complex still manages to form. This suggests that there must be a hindrance to the diffusion of the calcium ion to the reaction site. From the evidence of experimental data, Powers and Steinour (23) conclude the following reason for this hindrance of calcium ion diffusion:

> "It thus seems to be established that the initial attack of the alkali and lime builds up a zone of lime-alkali-silica complex which, when it reaches requisite thickness, hinders the diffusion of cal-

> cium ions across the boundary region of the reactive particle, but at the same time allows alkali and water to pass. This enables deposits of pure alkali-silica complex to form and remain in concrete for an indefinite period."

Shortly after the publication of Powers and Steinour (23), there appeared an interesting and valuable osmotic pressure study by G. S. Verbeck and C. Gramlich (26). They concluded that the degree of calcium ion diffusion to the reaction site depended upon the difference in the availability and mobility of the calcium ions and the ions of sodium and potassium. Due to this concept of availability and mobility, they felt that the reaction of calcium and alkali ions with the silica proceed on a competitive basis. The effect of calcium hydroxide was studied by adding increasing equal amounts of solid calcium hydroxide to two osmotic chambers containing a fixed amount of sodium hydroxide solution.[3] The reaction chamber, in addition, contained opal as the reactive aggregate. The

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[3]To arrive at their conclusions they devised a simplified osmotic apparatus consisting of the following: Two chambers separated by a membrane of cement paste. Reactive aggregate, solid calcium hydroxide and alkali solution are placed in one chamber to simulate the zone at the surface of aggregate in concrete. In the other chamber, separated by the cement paste membrane, additional solid calcium hydroxide and alkali solution are added. Capillary tubes are attached to each chamber enabling measurements of the flow rate through the membrane brought about by the reaction product imbibing water and swelling. The osmotic pressure is the hydrostatic pressure required to stop the flow of liquid through the membrane.

results showed a marked decrease in flow rate (expansive reaction) with increased calcium hydroxide addition. The important observation was that it took an exceedingly large amount of $Ca(OH)_2$ to decrease the flow rate, and that this amount was far more than necessary to make the complete reaction a non-expansive calcium silicate reaction. The tests were further extended by comparing these results with the flow rate resulting from mixing the calcium hydroxide with the aggregate. The mixed sample gave a significant reduction in flow rate. Therefore, it was assumed that, in order for the reaction to be of the non-expansive calcium silicate type, the calcium hydroxide must be in very close proximity to the reaction site. These results were sufficient to conclude that the calcium hydroxide ions have a considerably lower mobility in aqueous solutions than the sodium hydroxide ions. Verbeck and Gramlich attributed the mobility rates to a phenomena called "hydration of ions" in aqueous solution, in which the ion surrounds itself with a sphere of water molecules. This effectively increases the total size of the ion's influence and decreases its mobility. Table I, taken from Verbeck and Gramlich's paper shows a definite correlation between the observed flow rate (expansive reaction) and the ion hydroxide of the pertinent ions.

TABLE I

OSMOTIC FLOW RATES AND HYDRATION VALUES FOR VARIOUS IONS

Hydroxide	Average Rate of Flow Cm. per day per 1% sodium hydroxide equivalent	Average number of H_2O molecules per ion
Potassium	0.70	5.4
Sodium	0.53	8.4
Lithium	0.24	14.0
Calcium	----	24.0

Pessimum Amount

It had been demonstrated by Vivian (23), and verified by others that by keeping the amount of alkali constant and increasing the percentage of reactive component of the aggregate a "harmful optimum", or "pessimum" percentage exists which will give the maximum expansion in mortar bar specimens. Depending on the alkali concentration and the type and amount of reactive component, pessimum proportions of the reactive component have been found ranging from as little as 0.5 per cent to 100 per cent in aggregates tested.

It is believed that percentages of reactive material ranging from zero to that giving the pessimum amount increases the expansion due to the increasing amount of available

surface area of reactive material. The decrease in expansion from the maximum by a further increase in the percentage of reactive material is explained by Verbeck and Gramlich, based on their osmotic cell studies:

> "As the amounts of reactive aggregate increases, the alkali per unit area will be reduced while the calcium hydroxide available per area surface will remain essentially constant, since it is only that particular calcium hydroxide immediately adjacent to the surface that is available for reaction. The ratio of available alkali to available calcium hydroxide is, therefore, reduced and lesser proportions of the deleterious alkali silicate are produced as the gross quantity of reactive aggregate is increased."

The proportions necessary to obtain the pessimum amount are relatively critical and are dependent on many factors. It is apparent that consideration must be given to the pessimum phenomena in the analysis of field and laboratory specimens or for evaluations of aggregates to be used in future projects. Some inaccurate conclusions were made in test results before this important factor was discovered.

Degree of Reactivity of Potassium and Sodium Alkalies

There has been some discrepancy in literature as to the degree of reactivity of potassium and sodium alkalies contributing to the total expansion of concrete. Mr. Lerch (15) found that sodium hydroxide gave greater expansion than potassium hydroxide when tested using mortar bar prisms with

graded Pyrex glass as aggregate.[4] Verbeck and Gramlich (26) acknowledge that from the consideration of the standard electromotive series of the alkalies, one would estimate, and as Lerch had found, sodium to be the greatest contributor. However, they evidenced just the reverse in their osmotic cell studies. Their conclusion was that the potassium ion had greater mobility due to the lesser ion hydration of the potassium ion. This can be seen in Table I on page 16.

In view of the more recent results found by Verbeck and Gramlich, it is possible that the earlier findings of Lerch can be logically explained. Since the aggregate consisted entirely of reactive aggregate, mobility of the alkali ions would most likely not be a factor since the alkali hydroxides would already be in close contact with reactive particles. Therefore, since the sodium alkali is higher in reactivity on the electromotive series, a more reactive attack by the sodium than by the potassium would account for Lerch's results. The percentage of reactive particles in actual concrete aggregate is small and movement of the alkali ions to the reaction sites would depend considerably on the mobility factor. Therefore, it appears that potassium over sodium would be the likely order of reactivity in concrete.

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[4]Pyrex Glass is a reactive silica glass capable of producing abnormal expansion when used as an aggregate.

There is an interesting point bearing on this recent finding. At present, the widely accepted method of expressing the total sodium and potassium oxides of the cement is based on sodium being the most reactive. The reactive capacity of the combined effects of sodium and potassium oxides is expressed as a sodium equivalent. The method is described in the Bureau of Reclamation's 1951 Concrete Manual (24):

> "Sodium and potassium are both undesirable components of cement, but a given weight of Na_2O is more active than the same weight of K_2O, each per cent of K_2O being chemically equivalent to 0.658 per cent of Na_2O. This relationship enables the total alkalies in cement to be expressed as a single equivalent percentage by weight, computed as the sum of the percentage of Na_2O plus 0.658 times the percentage of K_2O."

It is possible that, in the future, this method will be modified to account for the mobility of the ions.

Effects of Water-Cement Ratio

Until recently very little information has appeared in the literature directly related to the effect of the water-cement ratio on the expansion associated with alkali-aggregate reactivity. It appears that the water-cement ratio affects both the alkali concentration and the permeability of the cement paste, which, in turn, affects the expansive reaction.

Lerch (15) hypothesized that the abnormal expansion of concrete depended upon the alkali hydroxide concentration in the free water, and that, with a fixed amount of alkali, the

concentration would depend considerably upon the water-cement ratio. In support of this hypothesis, results of mortar bar tests showed that abnormal expansion occurred in test bars having a water-cement ratio of 0.35 and cement containing 0.5 per cent total alkalies, while no evidence of expansion was evidenced in bars having water-cement ratio of 0.5 and cement containing 0.7 per cent total alkalies.

In the osmotic cell studies by Verbeck and Gramlich (26), the flow rate was measured using a series of cement paste membranes varying only in their water-cement ratio. This enabled a measurement of the permeability of cement paste having a varying water-cement ratio. It was found that the flow rate increased very slowly from a water-cement ratio of zero to a water-cement ratio of 0.4; from a water-cement ratio of about 0.4 to about 0.7 the flow rate increased rapidly; and from about 0.7 water-cement ratio on the flow rate began to decrease. The conclusions were that low water-cement ratios result in low permeability of the paste which retards the movement of water to the reaction site, thus reducing the rate of expansion. At high water-cement ratios the effect of a semi-impermeable membrane was lost and a reduction of osmotic pressure occurred. It was also believed that a counter-diffusion of sodium silicate occurred in the high water-cement ratio pastes. Considerable quantities of the gel

were observed exuding through the paste opposite to the reaction chamber for the membranes made with water-cement ratios higher than 0.65. They concluded that, depending upon this one variable, at some intermediate point between water-cement ratios of 0.4 and 0.65 a maximum rate of expansion would occur.

Combining the evidence found by Lerch and Verbeck, it appears that a water-cement ratio range between approximately 0.35 and 0.65 could give the greatest expansion. Unfortunately, practical concrete mixes normally have a range of water-cement ratios that approximately coincide with these values of water-cement ratios.

Particle Size

The deleterious reaction in concrete is affected by the particle size of the reactive aggregate. However, in what manner the reaction is affected is not clearly understood. In concrete the reactive aggregate particles are im various siliceous forms making it possible for one type of reactive aggregate to produce more expansion at a larger size than another type at a smaller size. By using a relatively pure opal as the reactive component, it has been found that with the amount, by weight, of the opal material held constant, and the particle size a variable, a decrease in particle size to approximately the 200 sieve size results in an increase in expansive

reaction (11). However, it has also been shown that when the particle size reaches the 200 to 325 sieve size, there is a favorable nonexpansive reaction. This will be discussed in more detail in the section dealing with the effects of pozzolans as inhibitors of expansion.

Verbeck and Gramlich (26), with their osmotic cell studies, found considerably more expansive reaction for No. 50 to No. 100 sieve size material than for minus No. 400 sieve material. Their conclusions were:

> "As the average size of the aggregate particle is reduced the surface area becomes greater, and the alkali becomes less available in comparison to the calcium hydroxide per unit of reacting area, and a greater proportion of the innocuous calcium silicate type of product is formed."

Powers and Steinour (23) in their interpretations arrived at essentially the same conclusions.

High and Low Alkali Cements

The amount of water soluble alkalies of sodium and potassium formed in the production of cement is a variable factor. Since it has been proven that these alkalies, together with a reactive aggregate, could produce abnormal expansion in concrete, more control has been effected in cement production to keep the alkali percentage at a minimum. There had been sufficient evidence gathered through earlier laboratory testing and field observations to set 0.6 per cent

total (sodium equivalent) alkali as the maximum allowable alkali content in cement when it was to be used with a known reactive material. In the literature, low alkali cement is usually referred to as that having less than 0.6 per cent sodium equivalent, and high alkali greater than 0.6 per cent sodium equivalent.

As more people began to investigate and study the alkali-aggregate reaction in concrete, the dividing line between low and high alkali cement became more debatible. Both laboratory and field studies have sometimes shown abnormal expansion with low alkali cements. In recent years, this has led to a more critical examination of the effects of alkali content.

Verbeck and Gramlich (26) were able to isolate the effect of alkali concentration with their osmotic cell and showed a linear increase in expansive reaction with an increase in alkali concentration. It was also shown in the pessimum considerations that, with a fixed amount of alkali and a variable amount of reactive aggregate, an optimum expansion could be obtained with a particular quantity of a given aggregate. It then is conceivable that by varying both the amount of alkali and the amount of reactive aggregate, proportions could be reached where an expansive reaction could occur with a low alkali cement, or a nonexpansive reaction with a high alkali cement.

It was also shown that the alkali concentration was influenced by the water-cement ratio. Due to this affect alone, the fixed alkali content of a particular cement would give varying results in the degree of expansive reaction.

Thus, considering all the factors involved, a maximum alkali content of 0.6 per cent may not prohibit the deleterious reaction in every situation.

Powers and Steinour (23), in their "Interpretation of Published Researches," summarized the following:

> "Cements with less than 0.6 per cent alkali are usually safe in the mortar bar tests, and in concretes containing reactive silica apparently because the amount and fineness of the reactive silica usually meets the requirements mentioned in 4a.
>
> 4a. For cements containing up to about 0.6 per cent alkali oxide, the alkali concentration appears to be low enough for safe initial reaction. For safe conditions to continue the amount of reactive silica must either be negligible or more than a certain minimum determined both by the amount of alkali and the fineness of the silica."

On the basis of their hypothesis Powers and Steinour (23) made some predictions of possible field occurrences:

> "Expansive reaction with low alkali cements is liable to occur if the particle size is relatively large. Coarse aggregate containing opal used with a sand free from reactive mineral could develop expansion in the presence of a small amount of alkali, or a sand containing reactive mineral and unusually deficient in fines might cause trouble with low alkali cement."

Pressure

The visible crack patterns observed in structures affected by the alkali-aggregate reaction exhibit many forms. Photographs of structures under restraint generally show the major cracks due to expansion formed parallel to the direction of greatest restraint (4, 21). Long concrete walls, for instance, would have major cracks running parallel with the top edge, with the cracks near the top being wider than those near the bottom. Hand rails on bridges, pavements, and similar lighter and less restrained structure components exhibit a random cracking pattern. S. K. McGowan and H. E. Vivian (16) studied the effects of superincumbent loads on the expansion of 1 x 1 x 10 inch mortar bars. They found it required a load of 50 pounds to prevent serious expansion in the bars. Loads of five and ten pounds caused crack patterns to orient in a direction parallel to the load. It was believed that the main effect of any amount of superincumbent load was in the reduction of serious cracking or crack widening, and that the initial expansion pressure caused by the swelling particles would be very difficult to restrain. R. G. Pike (22) demonstrated that this initial swelling could develop pressures in excess of 2,000 psi.

Temperature

It appears that the expansion reaction is primarily

affected by temperature in two ways. The first is that it influences the rate of chemical reaction taking place, and the second that it influences the physical properties of the reaction product.

Laboratory tests have produced accelerated expansions when using temperatures of 100°F to 110°F (4). For the commonly accepted mortar bar test, the storage temperature is established at 100°F. For temperatures below 100°F, the expansive reaction generally proceeds at a slower rate; while temperatures over 100°F have resulted in a rapid reaction, but with less total expansion. Vivian (11) demonstrated that the gels formed became mobile or less viscous at 109°F, amd when cooled became more viscous. He suggests that this could explain a decreased expansion at high temperatures.

Here again there seems to be an interdependency of reaction rate and viscosity such that, at some temperatures, an optimum condition will exist which, of course, depends upon the aggregate and cement being used. Verbeck and Gramlich (26) found in their osmotic cell studies that at 12 days very little expansive reaction occurred at 50°F, whereas a very great expansive reaction occurred at 100°F.

Their conclusions present the difficulties encountered in isolating the effects of temperature:

> "It is, at present, difficult, however, to anticipate the effect of temperatures above the normal

range studied in the course of reaction, because of the combined influence of factors such as mobility effects, normal chemical acceleration due to temperature, decreased calcium hydroxide solubility, and decreased viscosity of the sodium silicate product."

REACTIVE AGGREGATES

Through the years of experience with the alkali-aggregate reaction, investigators have identified and reported types of materials found to be reactive. An excellent summarization of rocks, minerals, and synthetic substances known to be deleteriously reactive is given in Table II.

TABLE II

DELETERIOUSLY REACTIVE ROCKS, MINERALS AND SYNTHETIC SUBSTANCES (12)

Reactive Substance	Chemical Composition	Physical Character
Opal	$SiO_2 \cdot nH_2O$	Amorphous
Chalcedony	SiO_2	Microcrystalline to cryptocrystalline; commonly fibrous
Certain Forms of Quartz	SiO_2	(a) Microcrystalline to cryptocrystalline (b) Crystalline, but intensely fractured, strained, and/or inclusion filled
Cristobalite	SiO_2	Crystalline
Tridymite	SiO_2	Crystalline

TABLE II (Continued)

Reactive Substance	Chemical Composition	Physical Character
Rhyolite, dacitic, latitic, or andesitic glass or cryptocrystalline devitrification products	Siliceous with lesser proportions of Al_2O_3, Fe_2O_3, alkaline earths, and alkalies	Glass or cryptocrystalline material as the matrix of volcanic rocks or fragments in tuffs
Synthetic siliceous glasses	Siliceous, with lesser proportions of alkalies, alumina, and/or other substances	Glass

The most important deleteriously alkali-reactive rocks (that is, rocks containing excessive amounts of one or more of the substances listed above) are as follows:

Opaline Cherts
Chalcedonic cherts
Quartzose cherts
Siliceous limestones
Siliceous dolomites
Rhyolites and tuffs
Dacites and tuffs
Andesites and tuffs
Siliceous shales
Phyllites
Opaline concretions
Fractured, strained, and inclusion-filled quartz and quartzites

Note: A rock may be classified as, for example, a "siliceous limestone" and be innocuous if its siliceous constituents are other than those indicated above.

Even though one or a combination of these minerals may be present in an aggregate, a deleterious reaction may not occur, obviously due to the many factors discussed previously.

It is seen from Table II that all the reactive minerals contain silica in one form or another. Vivian (27) studied the degree of reactivity of various forms of silica used as aggregate in mortar bar tests. He found a correlation between

increasing reactivity and decreasing crystallinity of silica.

Opal (amorphous) is the most reactive, while pure quartz shows negligible or no reactivity. It is interesting to note that the basic difference in the three principal crystalline forms of silica (quartz, tridymite, and crystobalite) is the atomic arrangement of the silica-oxygen atoms (14). In crystobalite the atomic arrangement results in the most loosely packed of the three. Tridymite has a still closer packing arrangement, while quartz has the closest of the three.

At room temperature quartz has the lowest energy state, while crystobalite and tridymite exist in metastable phases, crystobalite being the highest in energy (25).

Although no relationship of these structural arrangements and energy states to alkali-aggregate reactivity has been seriously investigated, it is interesting to note that Vivian found a decreasing order of reactivity going from crystobalite (highest), to tridymite (moderate), to quartz (nil).

R. C. Mielenz (17) described certain mineral types that can release additional alkalies to the concrete, possibly raising the total alkali content (including the cement alkalies) to critical proportions. One group of these are the zeolites which are not reactive, but may release alkalies

by a cation exchange with the calcium solution in the concrete. Another group having the same characteristics are the claystones and shales containing montmorillonite, or kaolinite.

DEVELOPMENT OF TESTS TO DETERMINE POTENTIAL ALKALI-AGGREGATE REACTIVITY

In 1938, extensive field investigations were conducted on certain severely distressed concrete pavements and structures in Monterey and Los Angeles Counties, California (4). It was found that most of the distressed structures were built using a fine aggregate from the Salinas River. Even though this same aggregate went into other structures that had not shown distress, there was sufficient evidence to believe that this fine aggregate had much to do with the trouble. Mortar bars containing the fine aggregate were made in an attempt to produce a measurable expansion, similar to the field expansion, by subjecting the bars to various types of exposure. The results were negative. Among various test specimens made, one 2 by 4 inch mortar cylinder had been capped and placed in a tin container. Upon examination of the bar after a year's time, it was found to be covered with blotches and cracks similar to those in the structures investigated.

It was suspected that sodium and potassium alkalies in the cement were reacting with certain types of aggregate

particles in the fine aggregate from the Salinas River. The results of a series of mortar bar tests cured in sealed containers verified the results of the 2 by 4 inch cylinder specimen, and correlated very favorably with the distressed field concrete. These early mortar bar tests had not only established the fact that expansive reaction was related to the alkali contents of cements and certain siliceous aggregate types, but had established the first reliable method to determine potential reactivity of cement aggregate combinations.

The most reliable tests developed have been adopted as ASTM Standard Tests, and these will be briefly discussed.

MORTAR BAR TEST - ASTM, DESIGNATION C227-61T (1)

Basically, this is a physical test which involves fabricating mortar bars made of the cement-aggregate combinations to be investigated. The bars are stored under certain conditions and the per cent of length change is calculated from periodic length measurements. Bryant Mather (11) gives an excellent account of the development of this test and the following is a summary of this account.

In 1950, the ASTM Committee C-1 adopted ASTM Designation: C227--Method of Test for Potential Alkali Reactivity of Cement Aggregate Combinations. It provided for aggregates to be graded 20 per cent between each of six sieves, Nos.

4, 8, 16, 30, 50 and 100. The aggregate is made into 1:2.25 mortar in two bar batches using water to give a flow of 100-115 per cent after twenty-five 1/2 inch drops in 15 seconds. Bars 1 by 1 by 11 5/8 inches are provided with end gage plugs giving a ten inch effective gage length. The bars are fabricated and moist cured in the mold for twenty-four hours. They are then put in sealed containers in an upright position and stored at 100°F and 100 per cent humidity in a storage cabinet. The average per cent length change of four bars constituted the test result. The aggregate specifications, ASTM C33, provided that aggregate showing mortar bar expansions of 0.05 per cent in six months or 0.10 per cent in one year, when made with a cement containing not less than 0.8 per cent alkalies generally results in harmful reaction in corresponding field concrete.

The only major changes in the procedures occurred in 1955, when the water requirement was changed by specifying a flow of 105-120 per cent after ten 1/2 inch drops in six seconds. This, on the average, raised the resulting water-cement ratio of a given mortar mix.

A fixed gradation of the aggregate was changed to allow testing of fine aggregate having any gradation meeting the requirements of project specifications. Fine aggregates being tested for other than project specifications, along with

crushed coarse aggregates were to be graded as follows:

Passing	Retained On	Per Cent by Weight
No. 4	No. 8	10 Per Cent
No. 8	No. 16	25 Per Cent
No. 16	No. 30	25 Per Cent
No. 30	No. 50	25 Per Cent
No. 50	No. 100	15 Per Cent

The aggregate specification C33 made a relatively major change in the classification of aggregate from mortar bar results by changing the expansion limits of 0.05 per cent expansion from six months to three months, and 0.1 per cent from one year to six months; cutting the testing time in half. Aggregates tested were not to be classified as reactive if the expansion exceeded 0.05 per cent in three months unless it also exceeded 0.1 per cent in six months (3). The Corps of Engineers standardized the method in 1948. Their methods were only slightly different than those of ASTM. In particular, they made three bar batches with a fixed water-cement ratio of 0.5 and a fine aggregate grading meeting field requirements. After a series of tests to improve the mortar bar test, they revised their standard to essentially follow ASTM C227. The results of their studies suggest the following:

"1. Test results are not improved by use of distilled water for mixing mortar in preference to local tap water.

2. Continuing the measurements to a specimen age of one year is sufficient.

3. Aggregate combinations with low alkali cement generally give more variable results than do those with high alkali cement.

4. Mortar specimens containing reactive aggregate generally give smoother curves for length change versus time, than do those with non-reactive aggregate.

5. Specimens made from mortar proportions to constant flow (variable proportions) generally give less variable results than those proportioned to constant weights of all ingredients (variable flow).

6. Storage at high temperatures (100°F) with length changes measured at normal temperature (73.4°F) gave larger and more uniform expansion results than both storage and measurement at high temperatures."

Probably the greatest disadvantage of this test is that it takes several months to obtain results. However, the advantages are many, such as:

1. It provides the closest means known, at present, to predict from laboratory results the actual field conditions that would occur.

2. It provides a means to study inhibitors that could reduce or eliminate expansion.

3. It provides a means to observe surface conditions characteristic of alkali-aggregate reaction.

4. The test is simple, inexpensive and easily performed.

The test is not an absolute guarantee that the aggregate tested will perform exactly as predicted by the test results. There have been several cases where the test has proven unreliable. A major case was discovered during studies of some severely distressed concrete in the Central Plains region of the United States. The reaction has not been directly attributed to the alkali-aggregate reaction, although similar in many respects, but was characteristic of the sand-gravel deposits in this region. A. D. Conrow (9) found that to produce, under laboratory tests, the abnormal expansions similarly encountered in the field required a cyclic process similar to a natural exposure, and that continuous storage of mortar bars failed to produce the abnormal expansions encountered.

The basis of the tests Conrow had performed led to the adoption by ASTM of the Conrow test, ASTM Designation: C342 (6). The use of the test is recommended when the cement aggregate reaction similar to those found in the Central Great Plains is suspected. However, where the reaction type has been definitely the alkali-aggregate type, the constant temperature storage provided by the mortar bar test has proven to be more reliable than the Conrow test. In an evaluation of various aggregates for potential reactivity in Wyoming by M. E. Moss (20), it was found by using both the Conrow and the

Standard Mortar Bar Test, that, in all cases, except two, the Standard Mortar Bar Test gave greater expansions when reactive aggregate was encountered. It was noted by Moss that the two aggregates which produced greater expansion with the Conrow test had characteristics similar to those of the sand-gravel in the Central Great Plains.

PETROGRAPHIC ANALYSIS

Microscopic examinations of aggregates has become increasingly important since the recognition of the alkali-aggregate reaction. Many examinations of reacted concrete were made, and the types and amounts of reactive constituents were identified.

The U. S. Bureau of Reclamation and the Waterways Experiment Station of the Corps of Engineers have done considerable research in their petrographic laboratories which has led to standard petrographic examination techniques. The work of Katherine Mather and Bryant Mather (11), established the basis for the ASTM Standard Test for Petrographic Examination of Aggregates for Concrete, ASTM Designation: C295 (2).

Briefly, the examination of a given aggregate consists of an identification of the rock types found in representative samples of each sieve size. The results are tabulated to show the percentage of the total number of particles of a given

rock type found in each sieve size. Additional notes are taken during the examination covering the general condition of the aggregate. Some items that would be noted are: pebble coatings, general weathering, porosity, particle shapes, mineral composition, and constituents found that may cause deleterious chemical reactions in concrete.

R. C. Mielenz (11) points out that a series of problems are faced by the petrographer in the evaluation of potential alkali-aggregate reaction in a petrographic examination:

"1. What are the potentially deleterious substances?

2. How abundant are the potentially deleterious substances?

3. Are the potentially deleterious particles sufficiently abundant to require the limitations on the use of the aggregate?

4. Are there properties such as alkalies available from the aggregate, excessive porosity or range of particle size, which will modify the decisions with respect to the anticipated degree of alkali reactivity and the justification for use of the aggregate with low alkali cement?"

It is seen that in the use of ASTM C295 for the specific purpose of identifying potential reactive aggregate considerable background knowledge of the phenomena is required by the petrographer. In testing the reliability of the petrographic analysis to predict the reactive potentiality of an aggregate, the Bureau of Reclamation has demonstrated that all aggregates

concluded to be innocuous were confirmed by the mortar bar test, but those aggregates that were determined to be deleterious were not always confirmed by the mortar bar test (11).

As an aid in determining potential reactivity, the Bureau established the following limits on the known reactive rocks found in a given aggregate:

Rock Type	Maximum Content Permitted unless use of low alkali cement is recommended
Opal and Opaline chert	0.25 Per Cent
Chalcedonic or Quartzose chert	5 Per Cent
Glassy to Cryptocrystalline rhyolites, dacites, latites, or andesites and their tuffs	3 Per Cent

Some of the advantages of the petrographic analysis should be mentioned. Probably the greatest advantage of the test is that it can be completed in two or three work days. Other information relative to the quality of the aggregate for use in concrete can be made simultaneously. Aggregates found to contain little or no reactive particles (percentages given above are conservative) can be classified as innocuous to alkali-aggregate reactivity, and no further testing would be needed for classification.

Probably the greatest disadvantage is that it requires a skilled petrographer with a good background in concrete

problems, and that it requires fairly expensive equipment.

Mielenz (11) made the following conclusions about the use of the petrographic analysis to evaluate the potential alkali-aggregate reactivity of aggregates for concrete:

"1. Petrographic examination in accordance with ASTM Recommended Practice C295 is a dependable means to evaluate the potential deleterious alkali reactivity of aggregate for concrete.

2. Validity of the results depends on the training, experience and diligence of the petrographer. However, with proper training and adoption of uniform techniques and nomenclature, subjective elements in the examination are not significant.

3. Conclusions concerning potential alkali reactivity based on petrographic examination are likely to be conservative because even trace amounts of potentially deleterious substances can be detected. Unrealistic conclusions concerning potential alkali-aggregate reactivity can be avoided by application of the maximum permissible limits for various rocks and minerals...."

QUICK CHEMICAL TEST

The need for a quick, but inexpensive, method of testing for potential reactive aggregate led to the development of a chemical test by R. C. Mielenz (11) in 1947. The value of the test is based on sufficient correlation of the test with that of the more reliable mortar bar test. ASTM adopted the test in 1952, and it was designated C289-52T (5).

In general, the test measures the amount of reaction that takes place during twenty-four hours at 80°C, between a 1

normal sodium hydroxide solution and an aggregate crushed and sieved to a definite size. After the twenty-four hour reaction period the filtered solution is analyzed to determine the amount of silica in solution and the reduction in alkalinity of the solution.

In developing the test, the test data were empirically correlated with the results of mortar bar tests using the same aggregate (4). On a graph with the amount of dissolved silica in millimoles per liter as the ordinate, the results of the chemical test were plotted. It was found that a line approximately representing a ratio Sc (dissolved silica) to Rc (reduction in alkalinity) equal to unity divided the innocuous and deleterious aggregate as determined from corresponding mortar bar tests. A ratio greater than one had corresponding mortar bar expansions greater than 0.1 per cent in a year, and a ratio less than one had corresponding mortar bar expansions less than 0.1 per cent in one year.

With the refinement of test procedures for both the chemical test and mortar bar tests, there has been a consequent slight shifting of the dividing line.

The latest revision of ASTM Designation: C289-61T has included a graph like that of Figure 1 (5). The ASTM's single dividing line is shown as the solid line in the figure. Generally, points falling to the right of the line

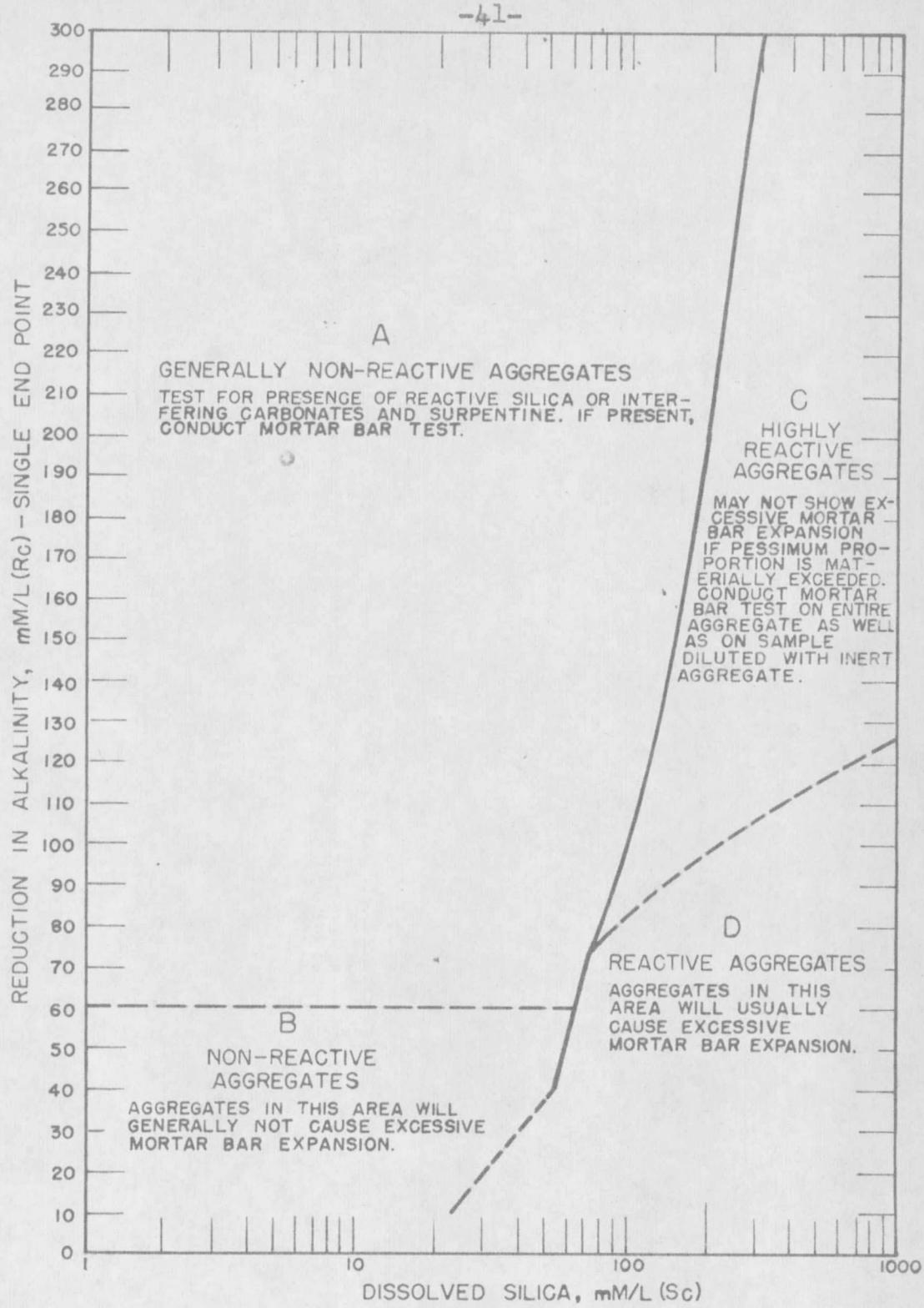


Figure 1 - Chemical Test Graph

indicate a potentially reactive aggregate, and those to the left indicate innocuous aggregate.

However, to effectively classify an aggregate using this method of test, careful interpretation of the results is required. Experience with some aggregates shows poor correlation with the mortar bar tests.

With some aggregates the chemical test did not give reliable results due to the interference of certain carbonates. This interference generally tends to place a potential reactive aggregate in the innocuous region on the graph. In other aggregates the chemical test indicates a highly reactive aggregate, but the same aggregate fails to give mortar bar expansions that could be classified as reactive.

In 1960, Bernard Chaiken and W. S. Halstead (8) presented an excellent paper on this subject. Their efforts were directed to improving the interpretation of the chemical test to give a more reliable estimate of potential reactivity of an aggregate. After review of past research on the subject, they suggested the area subdivisions shown in Figure 1 by the dashed lines.

Based on corresponding mortar bar tests available, the areas are interpreted briefly as follows:

> Area B: Points lying in this area in most all cases resulted in mortar bar tests that indicated no harmful expansions. It is suggested that results lying in this area require no further investigation of the

aggregate to properly classify the aggregate as nonreactive.

Area D: Results lying in this area in almost all cases resulted in mortar bar tests giving excessive expansions. It is suggested that results lying in this area require no further investigation to properly classify the aggregate as potentially reactive.

Area C: Mortar bar tests in this area did not always produce excessive expansion. It was found that most of those that did not display harmful expansion had aggregate containing the amount of reactive material necessary to exceed the pessimum amount. It is suggested that further testing be done to evaluate the aggregate's potential reactivity. ASTM Designation: C289-61T (5), recommends that for results lying approximately in this area mortar bar tests in accordance with C227 should be made replacing the test aggregate with percentages of an inert aggregate ranging from 95 to 50 per cent. A graded chert-free limestone, quartz, or Ottawa sand is recommended for the inert aggregate.

Area A: Aggregates that fell in Area A generally produced safe expansion results from the mortar bar test. Several discrepancies in this area were found to be due to minerals causing an increase in reduction in alkalinity unrelated to the alkali-silica reaction. R. C. Mielenz (11) found the interference to be caused by carbonates of magnesium or ferrous iron:

> "This effect results from precipitation of hydroxide as a hydroxide of magnesium or ferrous iron and a consequent increase in Rc above the value produced as a result of the alkali-silica reaction. The data point representing the aggregate thus is shifted upwardly and possibly across the boundary between innocuous and deleterious materials."

The interfering minerals reported by Mielenz are dolomite, magnesite, siderite and serpentine. On this basis, B. Chaiken and W. S. Halstead concluded that for aggregate lying in Area A, further tests would be necessary

to determine the presence of reactive material and the interfering minerals mentioned.

Studies conducted by Mielenz and Benton (18) in order to improve the reproducibility of the test, resulted in finding a significant improvement by subjecting the reaction vessels to continuous agitation during the twenty-four hour reaction time. Mielenz reported that the most fundamental cause of difficulty in obtaining satisfactory reproducibility in the test was lack of attainment of equilibrium in the reaction vessels. He felt that if the contents of the reaction vessels were maintained in a "quasi-homogeneous" condition, the reactions could proceed further and more closely approach a condition of equilibrium.

However, Mielenz suggests that further study of this change should be made before adoption into the standard test, since it would require shifting of the main boundary line in Figure 1 considerably to the right.

In conclusion, the test provides a quick and low cost means to evaluate an aggregate's potential reactivity. It establishes the need for more detailed studies of aggregates giving tests results in Areas A and C, along with questionable borderline cases.

Mielenz recommends petrographic examination be conducted in conjunction with the chemical tests because the chemical test does not evaluate certain important physical properties

such as porosity and particle size distribution.

Of the various laboratory tests developed to predict the potential reactivity of concrete aggregate, the three just reviewed are the most reliable and widely used. However, as Mielenz recently concluded:

> "...it should be kept in mind that, at present, there exists no completely reliable and satisfactory reproducible procedure to determine the potential alkali reactivity of concrete aggregate." (18)

METHODS OF PREVENTING EXPANSIVE REACTIONS

Sometimes there are conditions such as accessibility or economic reasons which require the use of a known reactive aggregate. Through considerable laboratory and field testing, effective preventative methods have been developed. Some of the most widely used methods will be discussed.

Use of Low Alkali Cements

Except for very highly reactive aggregate or special conditions requiring a mixture of aggregates from different sources, or aggregates having material that releases water soluble alkalies into the mortar, the use of cements containing 0.6 per cent or less of sodium and potassium alkalies provides the most effective and reliable means to deter the harmful reaction. According to Lerch (15), when the cement is the only source of alkali, a limit of 0.6 per cent total

sodium and potassium alkalies will be as effective as any lesser value. He showed that the 0.6 per cent limit established from mortar bar tests is usually conservative since concretes generally required more alkali to produce excessive expansion.

Pozzolans

A pozzolan is defined as a siliceous material that, while in itself possessing no cementitious value, will, when finely divided, chemically react with calcium hydroxide at ordinary temperatures to form compounds possessing cementitious properties.

Pozzolans provide many beneficial properties when used in concrete. When properly tested and used, pozzolans may increase the durability of concrete. Certain pozzolans have been successful in controlling the expansive alkali-aggregate reaction. The most effective type of siliceous material in a pozzolan is one which has the highest degree of reactivity with the alkalies. Cement replacements of 15 to 20 per cent with a pozzolan high in opal can prevent an expansion reaction in concrete containing cements very high in alkali content. Investigations have shown that pozzolans containing a more glassy silica generally require larger cement replacements.

Pozzolans consisting of clays, opaline shales, diatomites or volcanic glasses have shown significant improvement in their

ability to counteract the alkali-aggregate reaction after being calcined at various temperatures (19).

Fly ash, an artificial pozzolan, is a precipitated residue from the burning of powdered coal. It consists mainly of solid or hollow spherical particles of siliceous and aluminous glass, and has an overall fineness equal to, or finer than, Portland Cement. Fly ash is probably one of the most extensively tested and used pozzolanic materials known today.

Because fly ash contains the glassy type of silica, its effectiveness against expansion due to alkali-aggregate reaction generally is not as good as those pozzolans containing the more reactive silica such as opal, and thus requires slightly higher percentages when used primarily to prevent expansive alkali-aggregate reactions.

Fly ash has been used in many large dam projects by the Bureau of Reclamation. The primary reason for its use usually is for a lower heat of hydration. When potentially reactive aggregate is encountered, the combined use of both low alkali cement and fly ash has given successful results.

T. C. Powers and H. H. Steinour (23) suggest the following explanation for the effectiveness of pozzolanic additions in preventing expansive reactions with high alkali

cement:

> "When we add a powdered reactive mineral we thereby expose a large area of reactive surface to the solution in addition to the coarser reactive particles already present. For a given amount of reaction and thus a given lowering of the alkali concentration, the penetration of the coarser particles is thus greatly reduced. If the amount of fine particles is adequate, the initial reaction decreases the alkali concentration to what it would be for a safe reaction with low alkali cement and the coarser particles may then continue their reaction safely."

Recalling the explanation for the pessimum amount discussed previously, it appears that when the proper amount of an effective pozzolan is added to a potential expansive reaction combination, in essence, it creates a condition greatly exceeding the pessimum amount, and thus results in a safe reaction. Correspondingly, it also appears that if an insufficient amount is added, it could give a cement aggregate combination, potentially low in expansive capabilities, the amount of reactive material necessary to create a pessimum condition.

W. Lerch (15) feels that caution should be used when selecting a pozzolan type for such use. Many materials considered to be pozzolanic gave no improvement, while some actually aggravated the expansion and pattern cracking associated with the alkali-aggregate reaction. He also expressed the need for careful interpretation of results for

mortar bars tested with pozzolans that were stored under the standard 100°F storage temperature. He found that moderately reactive pozzolans effective at 100°F did not effectively inhibit the expansion at 70°F, and some even less effectively at 45°F. For pozzolans that were highly reactive, temperature made little difference.

The alkalies of sodium and potassium which are present in some pozzolans are believed to contribute to the total water soluble alkalies of the mix (13). This being a possibility, pozzolans having such characteristics could change a safe combination of low alkali cement and reactive aggregate into one which is unsafe.

In view of the general nature of pozzolans just discussed, there appears to be a need for careful laboratory testing or past experience with a particular pozzolan before it can be safely recommended for use.

In summary, it should be mentioned that when it is positively known that the breakdown of concrete would be from excessive expansion due primarily to the alkali-aggregate reaction, the use of any one or a combination of the above discussed curative methods has been proven to be highly effective. On the other hand, many researchers have expressed concern over the lack of knowledge on the part the alkali-aggregate reaction plays in the durability of concrete when

it appears that only a slight or limited alkali-aggregate reaction has taken place. It is believed by some that small nonexpansive reactions are, in fact, beneficial through improved bonding characteristics.

CHAPTER III

EQUIPMENT, MATERIALS AND TESTING PROCEDURES

EQUIPMENT

Mortar Bar Storage Facilities

A storage cabinet for the mortar bar test, ASTM Designation: C227-61T, was constructed using a household refrigerator shell. The back wall of the refrigerator was cut out and the remaining portion was laid horizontally on top of a shallow concrete tank. The tank contained six inches of water at the bottom with a "U" shaped 2,000 watt heating element suspended horizontally at mid-depth in the water. The storage containers for the bars were held three inches above the water by transverse angle irons. The containers were made in accordance with ASTM Designation: C227-52T, and had a capacity of 36 mortar bars per container. Tightly fitted metal covers were used for the containers. This type of covered container is referred to as the "sealed container" method in this thesis. The 100°F temperature and high humidity prescribed by the ASTM standard test was controlled by a Fenwal Thermoswitch immersed in the water. The thermoswitch was connected in series to a relay switch (located on the outside of the cabinet), and then to the heating element. A small capacitor was connected in parallel with the relay switch to eliminate fluttering of the relay contact points. A plot of time versus temperature showing the normal operating range can be

found in the Appendix on page 119, Figure 23. The maximum temperature was 100.3 ± 0.3°F, and the minimum temperature was 99.3 ± 0.3°F. It took approximately 32 minutes for the temperature to fall from the maximum to the minimum, at which time the thermoswitch would turn on, bringing the temperature to the maximum in approximately 1½ minutes. The cabinet held eight containers allowing a total storage capacity of 282 mortar bar specimens. Figure 2 is a photograph of the storage cabinet and the eight mortar bar containers in their storage positions.

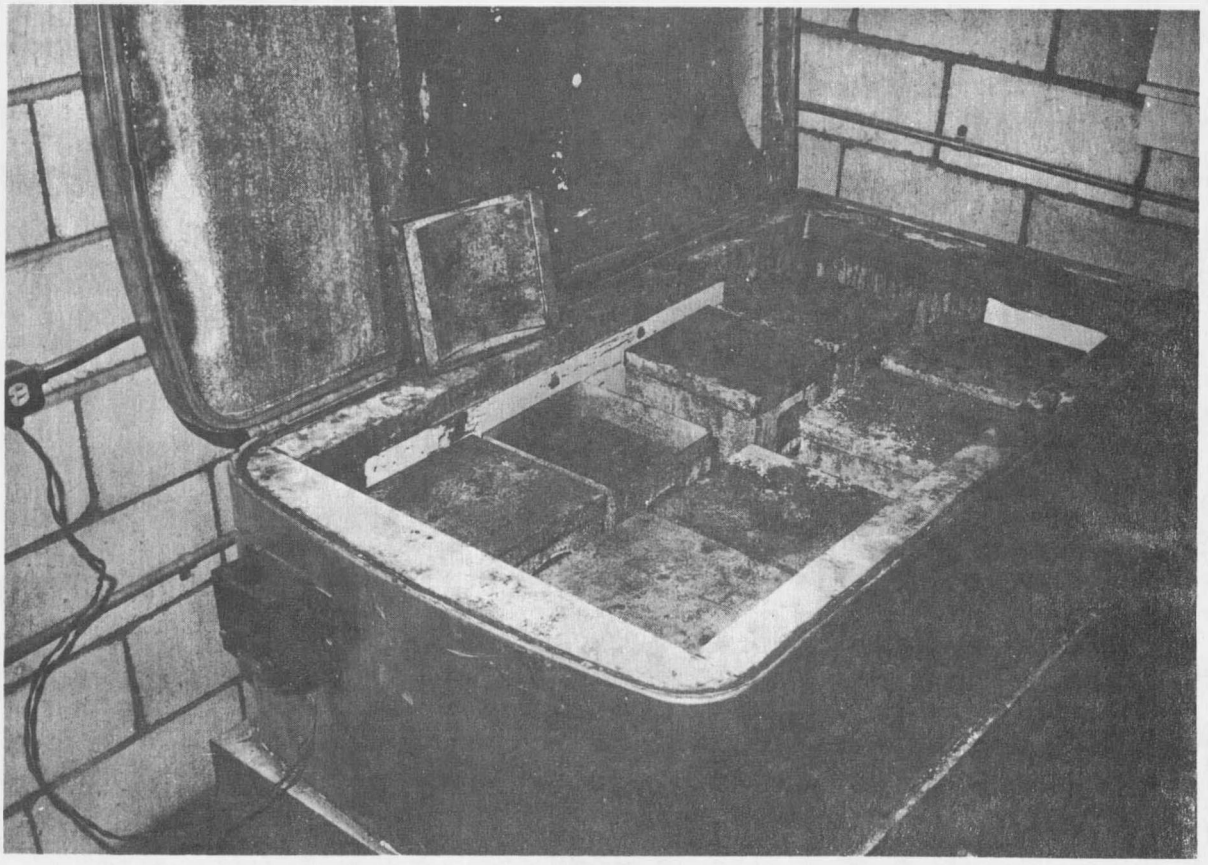


Figure 2 - Mortar Bar Storage Cabinet

A storage rack was also built for storing mortar bars in the standard cure room. The rack was made to hold the bars similar to the 100°F storage method. A metal roof was placed over the rack to protect the bars from heavy water drops, but, unlike the sealed container method, the bars were exposed to the atmospheric condition of the standard cure room.

OTHER EQUIPMENT

Mortar bars were fabricated using an eight bar mold manufactured by the Central Scientific Company, in accordance with ASTM Designation: C227-52T.

A Cenco Menzel comparator manufactured by the Central Scientific Company was used to measure length changes of the mortar bars. The comparator was equipped with a dial micrometer graduated to read in 0.0001 inch units. Additional minor equipment used to conduct the mortar bar tests was that prescribed by ASTM Designation: C227-61T.

The apparatus and chemical reagents required for the chemical test, ASTM Designation: C289-61T (Photometric Method), were used. The photometer used was a Beckmen Model B Spectrophotometer. This model was equipped with both a transmittance and an absorbance scale (optical density scale). The reaction vessels were the 50 ml capacity type made of stainless steel.

The petrographic analysis was conducted with the use of

a binocular microscope and a petrographic microscope equipped with a mechanical stage. Immersion oil with an index No. 1.540 was used as an aid in identifying important aggregate constituents. Cross-section specimens were cut from the mortar bars using a diamond blade cut-off machine.

MATERIALS

Aggregates

Representative samples of coarse and fine aggregate from six major aggregate sources were supplied by the Montana State Highway Department. These sources were previously coded for the durability studies by Wallace, therefore, these code numbers were maintained in this study.[5] The code numbers and the general location of the aggregate sources are given below:

Code Number	General Area in Montana
1	West South Central
3	East South Central
4	West South Central
7	South Central
8	South East
9	North Central

Only the fine aggregate from each source was used for

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[5] Aggregate No. 9 is not the same source previously used in the durability studies, but is from the same drainage area.

this study. A sieve analysis was made on each fine aggregate, and the results are presented in the Appendix on pages 120 to 125. Various total sample weights for the sieve analysis were tried. It was found that approximately 600 grams was suitable to give a representative particle size distribution. The dashed lines on the particle distribution graphs represent the allowable range prescribed by Montana State Highway fine aggregate specifications.

Cements

Four cement types were used in the study. Type I, Type II and Type V cements were supplied by the Ideal Cement Company, and a high alkali cement (0.88 per cent Na_2O equivalent) was supplied by the Portland Cement Association. The chemical analyses are listed in Tables III and IV.

TABLE III

CHEMICAL COMPOSITION OF THE HIGH ALKALI CEMENT
Lot No. 20126

Total Alkalies % Na_2O Equivalent = 0.88

Chemical Compound	Per Cent of Total
SiO_2	22.06
Al_2O_3	4.67
Fe_2O_3	2.99
CaO	63.05
MgO	3.18
SO_3	2.19
Na_2O	0.14
K_2O	1.12
Loss	0.83
Insoluble Residue	0.08
Free Lime	0.65

TABLE IV

CHEMICAL COMPOSITIONS AND CEMENT COMPOUNDS
OF THE LOW ALKALI CEMENTS

	Type I	Type II	Type V
Total Alkalies % of Na_2O Equivalent	0.39	0.35	0.35
Chemical Compound	**Per Cent of Total**		
SiO_2	22.78	23.22	23.04
Al_2O_3	4.36	4.28	3.56
Fe_2O_3	4.00	3.64	4.64
CaO	63.83	63.74	63.93
MgO	1.20	1.34	0.68
SO_3	1.77	1.80	1.80
Na_2O	0.07	0.05	0.04
K_2O	0.49	0.45	0.47
Loss	1.53	1.38	1.82
TOTAL	99.98	99.90	99.98
Cement Compounds			
CaO	0.48	0.40	0.30
C_3A	4.8	5.2	1.5
C_4AF	12.2	11.1	14.2
C_3S	46.6	43.9	49.5
C_2S	30.2	33.5	28.8
$CaSO_4$	3.0	3.1	3.1
TOTAL	96.8	96.8	97.1

Pozzolans

A commercial fly ash and one Montana State produced pozzolan designated "A" were used in the study. Chemical analyses were made for these by the Ideal Cement Company. The results of the analyses are given in Table V.

TABLE V

CHEMICAL COMPOSITION OF THE POZZOLANS

Chemical Compound	Fly Ash	Pozzolan "A"
	Per Cent of Total	
SiO_2	46.6	65.6
Al_2O_3	17.9	18.2
Fe_2O_3	17.8	6.0
CaO	6.8	2.4
MgO	0.2	2.2
SO_3	2.2	1.1
Loss	3.4	1.7
TOTAL	94.9	97.2

Basalt Aggregate

Several attempts were made to obtain a graded inert aggregate filler. Limestone or Ottawa sand are ideal for this purpose, but the desired gradation sizes were unobtainable at the time. Therefore, a fine grained basalt rock taken from the upper West Gallatin River was used for an inert filler. This material was crushed and graded in accordance with ASTM Designation: C227-61T.

Pyrex Glass

For an artificial reactive aggregate, a Corning glass in the form of rough lumps and tailings was purchased from the Corning Glass Company. The glass was crushed and graded in accordance with ASTM Designation: C227-61T.

TESTING PROCEDURES

Three ASTM standard tests were utilized in the study. They are:

1. Mortar Bar Test - ASTM Designation: C227-61T.
2. Quick Chemical Test - ASTM Designation: C289-61T.
3. Petrographic Analysis of Concrete Aggregate - ASTM Designation: C296-54.

Mortar Bar Tests

The major portion of the laboratory investigation was based on the use of the mortar bar test method. This was not only because the test is considered the most reliable of the three to determine the potential reactivity of the aggregate, but also because it enables comparison of the effects of various cements and pozzolans on mortar bar expansions due to alkali-aggregate reactivity.

High alkali cement (0.88 per cent Na_2O equivalent) was used to test all six aggregates. For the purpose of determining an aggregate potentially reactive, it is recommended that a cement containing at least 0.8 per cent total alkalies expressed as Na_2O equivalent be used. (1)

The possibility of the aggregates, from each source, containing the amount of reactive material in excess of the pessimum proportion was a major consideration. To check this possibility aggregates from all six sources were tested using

a combination of high alkali cement with 25 and 50 per cent replacement of the natural aggregate with crushed basalt aggregate. This same procedure was also carried out using Type I and II cements having low alkali contents. As seen from the sieve analyses (Figures 24, 25, 26, 27, 28, and 29 in the Appendix) the gradation of the fine aggregates lies within the acceptable range for Montana State Highway fine aggregate specifications, with the exception of a few minor borderline cases between Nos. 50 and 100 sieve sizes. It was decided to use these natural gradations for the major portion of the mortar bar tests. In one series of tests aggregates Nos. 1, 3, 4, 7 and 8 were artificially graded, washed and combined with high alkali cement. The grading used is given in the standard ASTM test, and is the following:

Sieve Size Retained On	Per Cent by Weight
No. 4	0%
No. 8	10
No. 16	25
No. 30	25
No. 50	25
No. 100	15

Aggregate No. 3 was tested using an additional grading as specified in ASTM Designation: C227-54T.

The purpose of the graded aggregate tests was to compare the resulting expansions with those tests using the natural gradation of the aggregates. A different grading can some-

times either increase or decrease an expansive reaction.

There was a need for test bars to provide a general control for all mortar bars tested. A series of bars were made for this purpose using a combination of high alkali cement, crushed and graded basalt aggregate, and basalt aggregate replacements with Pyrex Glass (artificial reactive aggregate), using percentages of 0, 2, 5, 10, 20, 30, and 50 per cent. Two of the four bars made for each of these treatments were stored under ASTM standard conditions, and the other two bars were stored in the standard cure room. These control bars enabled comparison of the effects of the two storage conditions, and they also provided a check on the possible reactivity of the basalt aggregate which was used as an inert aggregate.

Mortar bars were made using the three low alkali cements (Types I, II and V) with each of the six aggregates. All bars containing Type I cement were stored under the standard ASTM test conditions. However, limited space under these conditions made it necessary to divide the four bars of each treatment using the Type II and Type V cements, thus storing two bars under the ASTM standard conditions and two bars in the standard cure room.

The mortar bar test was used to test the effectiveness of the fly ash and pozzolan "A" in reducing excessive expan-

sion. Early indications showed signs of reactivity for aggregates Nos. 1, 3, 4, and 7 used in mortar bars with the high alkali cement. Therefore, 20 and 30 per cent replacements of high alkali cement with fly ash and 20 per cent replacements with pozzolan "A" were tested individually with these four aggregates. The bars were all stored under standard ASTM storage conditions.

The mortar bars fabricated having the combinations just described represent a total of 336 mortar bar specimens. Of this total number, 274 bars were stored in the standard storage cabinet prescribed by ASTM, and the remaining 62 bars were stored in the standard cure room in the additional storage rack that was previously described on page 53 under Equipment.

It was necessary to develop a coding system for the bars. The following system was used:

Code Symbol	Translation
H	High Alkali Cement
I	Type I Cement
II	Type II Cement
V	Type V Cement
C20	20 Per Cent Cement Replacement with Fly Ash
C30	30 Per Cent Cement Replacement with Fly Ash
T20	20 Per Cent Cement Replacement with Pozzolan "A"
G	Graded Aggregates - Graded in Accordance with ASTM C227-61T
G20	Graded Aggregates - Graded in Accordance with ASTM C227-54T

Coding System (Continued)

Code Symbol	Translation
0	Basalt Aggregate - crushed and Graded in Accordance with ASTM C227-61T
025	25 Per Cent Replacement of the Natural Aggregate with Graded Basalt Aggregate
050	50 Per Cent Replacement of the Natural Aggregate with Graded Basalt Aggregate
X2, X5, X10, X20, X30, X50	Pyrex Glass Aggregate - Crushed and Graded in Accordance with ASTM C227-61T and Replacing 2, 5, 10, 20, 30 or 50 Per Cent of the Base Aggregate
1, 3, 4, 7, 8 and 9	Prefix Numbers Representing the Six Aggregate Sources
-1, -2, -3, and -4	Suffix Numbers Representing One of Four Replicate Bars Which are Stored Under ASTM Standard Conditions
-1s, -2s	Suffix Numbers Representing One of Two Bars Which are Stored in the Standard Cure Room

The following is an example of the use of this coding system:

Bar No. 3HT20-3: Represents a combination of fine aggregate No. 3 used in its natural gradation, high alkali cement, and 20 per cent cement replacement with pozzolan "A". This bar is the third bar of four replicate bars stored under ASTM standard storage conditions.

The aggregate for the mortar bar tests was obtained by the quartering method. Approximately 180 pounds of fine aggregate from each source, as received, was thoroughly mixed, then split by the quartering method and stored in two close-knit canvas bags. The required amount of aggregate for each

batch mix (675 grams to fabricate two bars) was obtained by reducing one bag of aggregate by the quartering method to approximately ten pounds, then further reduction to the required amount was accomplished using a sample splitter.

Chemical Tests - ASTM Designation: C289-61T

Two complete chemical tests were performed on each aggregate source. This gave six separate determinations of dissolved silica and reduction in alkalinity for each aggregate. In addition, one complete test was performed on the basalt aggregate.

Approximately 400 grams of aggregate was prepared for each source in accordance with the ASTM standard procedure. To obtain the required 25 grams of test sample for each reaction container, the 400 grams was reduced each time by the quartering method. The testing procedures prescribed by ASTM were followed quite rigorously with the exception of procedure 5(e). At this point in the test the filtrates were transferred to polyethylene containers and transported to another laboratory. The remaining steps in the test were commenced approximately ten minutes after the completion of the filtration. The photometer was used to determine the dissolved silica. A calibration curve was plotted for both the transmittance reading against dissolved silica and absorbence reading against dissolved silica. The latter was

used for the tests since the curve was a straight line function enabling an accurate interpolation of the curve for the tests.

Petrographic Examination of the Aggregates - ASTM Designation: C295-54

The purpose of using this test was to aid in the interpretation of results of the two test methods previously described. A complete particle count as described in the ASTM test was only possible for the fine aggregate from two sources. Early trends observed in mortar bars using aggregate No. 8 indicated nonreactive aggregate, while the chemical tests showed aggregate No. 8 to be a highly reactive aggregate. It became apparent that aggregate No. 8 should have a complete petrographic analysis. Early trends observed in mortar bars using aggregate No. 3 indicated that this aggregate had the highest degree of reactivity. This high degree of reactivity was substantiated by the results of the chemical test. A complete particle count was made on this aggregate with hope of establishing rather definitely the cause of the high reactivity found. Therefore, the fine aggregates Nos. 8 and 3 were prepared for a complete particle count as described by the ASTM standard test. A representative sample of the coarse aggregate for each of these sources was prepared to aid in identifying constituents of the fine aggregate.

For aggregates Nos. 1, 4, 7 and 9 a general and less rigorous examination of the aggregate constituents were made. The examination of these aggregates was accomplished by using thin sections made from the mortar bars along with corresponding samples of coarse aggregates.

Additional Tests

A total of 11 mortar bars were taken from storage and cut into cross-section specimens (1/8 inch slabs) using the diamond blade cut-off machine. Six specimens, each containing aggregate from a different source, were reduced to thin sections for petrographic analyses.

The remaining specimens were observed under a microscope for signs of reacted particles and gel deposits. Particles found to be altered due to reaction were photographed and then examined by the petrographer in order to identify the particles.

The bar code number and the age in days at which storage was discontinued for the 11 bars are:

HOG-1S	66 Days,	4I-1	141 Days,	7I-1	130 Days,
3II-2	126 Days,	1I-2	121 Days,	7H-2	169 Days,
1H-3	170 Days,	8H-3	159 Days,	3H-1	153 Days,
4H-4	158 Days,	9H-1	158 Days.		

The results and analysis of the laboratory tests just described follow in Chapter IV.

CHAPTER IV

TEST RESULTS AND ANALYSIS

The first half of this chapter is the presentation and analysis of results for the mortar bar tests, chemical tests, petrographic analysis, and supporting tests conducted in order to evaluate the potential reactivity of the six aggregates.

The second half of the chapter is the presentation and analysis of the mortar bar test results conducted using the low alkali cements and pozzolans. A record of all mortar bar measurements, represented in graphical form, appears in the Appendix on pages 131 to 177. Each graph represents a particular combination or treatment, and a summary of the particulars is included. Each curve in the graph represents a single replicate mortar bar, and its code number and water-cement ratio is listed. In cases where a number of replicate bars had no significant variations in expansion, the curves on the graph were enclosed by a shaded area.

The chemical test data for each individual test, and the equations for computing the dissolved silica and reduction in alkalinity appear in the Appendix in Table XV, pages 126 to 128.

RESULTS OF TESTS FOR THE POTENTIAL REACTIVITY OF THE SIX AGGREGATE SOURCES

In Figure 3 are shown the summary curves of per cent mortar bar expansion versus days for the six aggregates tested

with high alkali cement. Each curve represents the average of all replicate bars for the particular cement-aggregate combination. The number of bars represented in the average changes at a certain point, since one bar from each aggregate was discontinued for cross-section specimens. This is shown on the curves by a small dash mark with the number of bars the curve represents indicated on either side of the mark.

The boundary lines intersecting 0.05 per cent expansion with 90 days, and 0.10 per cent expansion with 180 days represent limits established by ASTM (ASTM Designation: C33-61T), in order to classify the aggregate's potential reactivity. The following explains the use of these boundary lines for aggregate classification:

> "...combinations of aggregate and cement which have produced excessive expansions in this test usually should be considered potentially reactive. While the line of demarcation between nonreactive and reactive combinations is not clearly defined, expansion is generally considered to be excessive if it exceeds 0.05 per cent at three months or 0.10 per cent at six months. Expansions greater than 0.05 per cent in three months should not be considered excessive where the six month expansion remains below 0.10 per cent..." (14)

It is seen from Figure 3 that significant expansions occurred for aggregates Nos. 1, 3, 4 and 7, while little change occurred for aggregates Nos. 8 and 9. The final measurements for these bars were taken at an age of approximately 300 days. However, the rate of expansion indicates

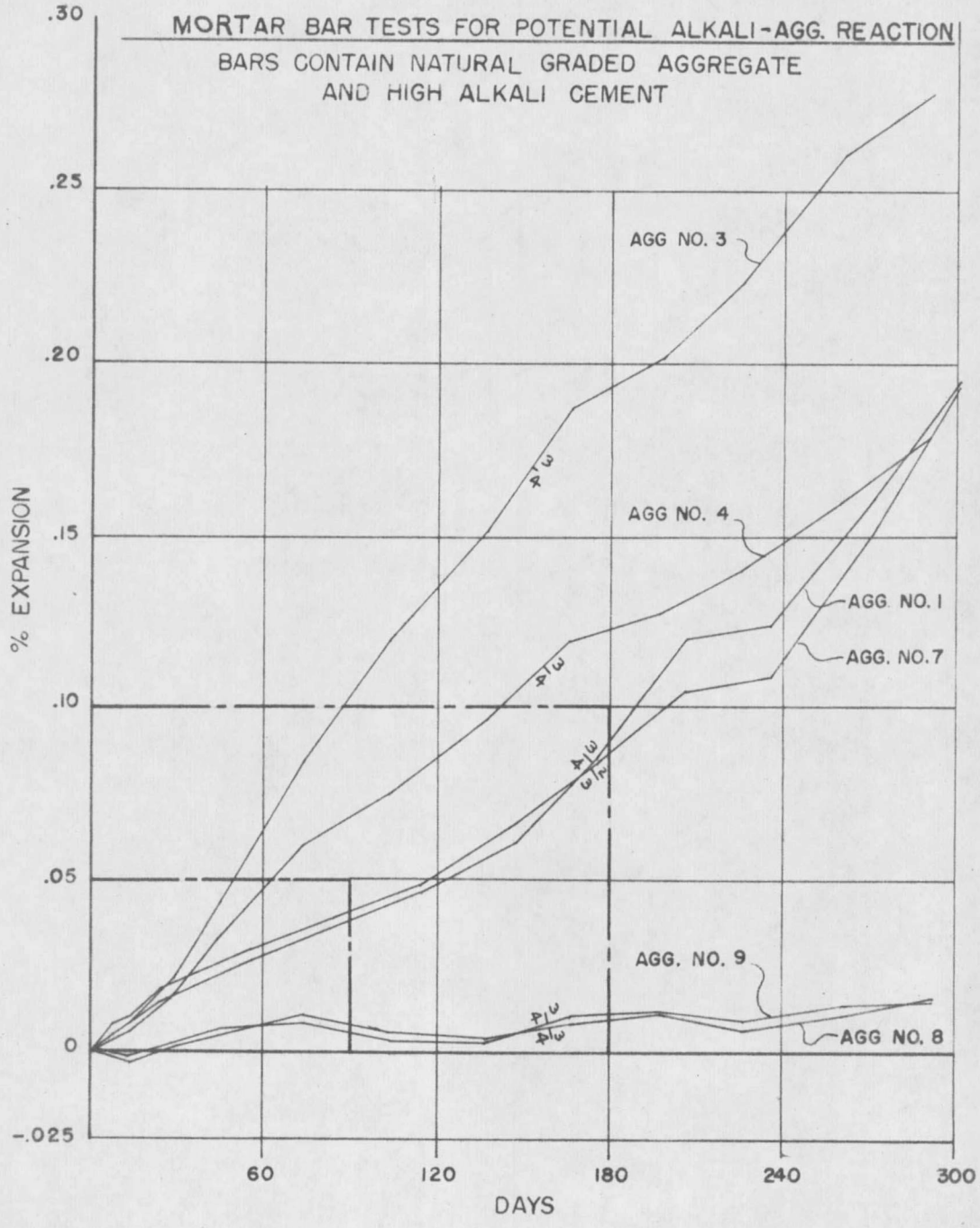


Figure 3 - Mortar Bar Expansions for Reactivity Classification

that greater total expansions may result for aggregates Nos. 1, 3, 4 and 7.

At an age of approximately 204 to 234 days there was a significant decrease in the expansion rate for aggregates Nos. 1 and 7. Within this time period there was a series of electrical power failures. The longest failure time was 41 hours in which the temperature of the storage cabinet probably dropped to room temperature. This drop in temperature could have been the cause of the decrease in expansion rate.

Within 60 days noticeable gel deposits appeared on the surface of bars made with aggregates Nos. 1, 3, 4 and 7. Small cracks appeared in the bars for aggregates Nos. 3 and 4 at approximately 100 days and for aggregates Nos. 1 and 7 at approximately 240 days. A slight warping was noticeable in all of these at 290 days. Small pop-outs were an additional characteristic for the bars containing aggregate No. 4. At the base of these pop-outs were softened and altered yellow particles that were found to be partially crystallized opal.

Figures 4, 5 and 6 are a series of photographs showing the change in surface appearance through aging. Each of these six bars are representative of the replicates for the given treatment, and correspond to the six curves in Figure 3. The bars were removed from their continual storage for approximately ten minutes to be photographed. Surface cracks

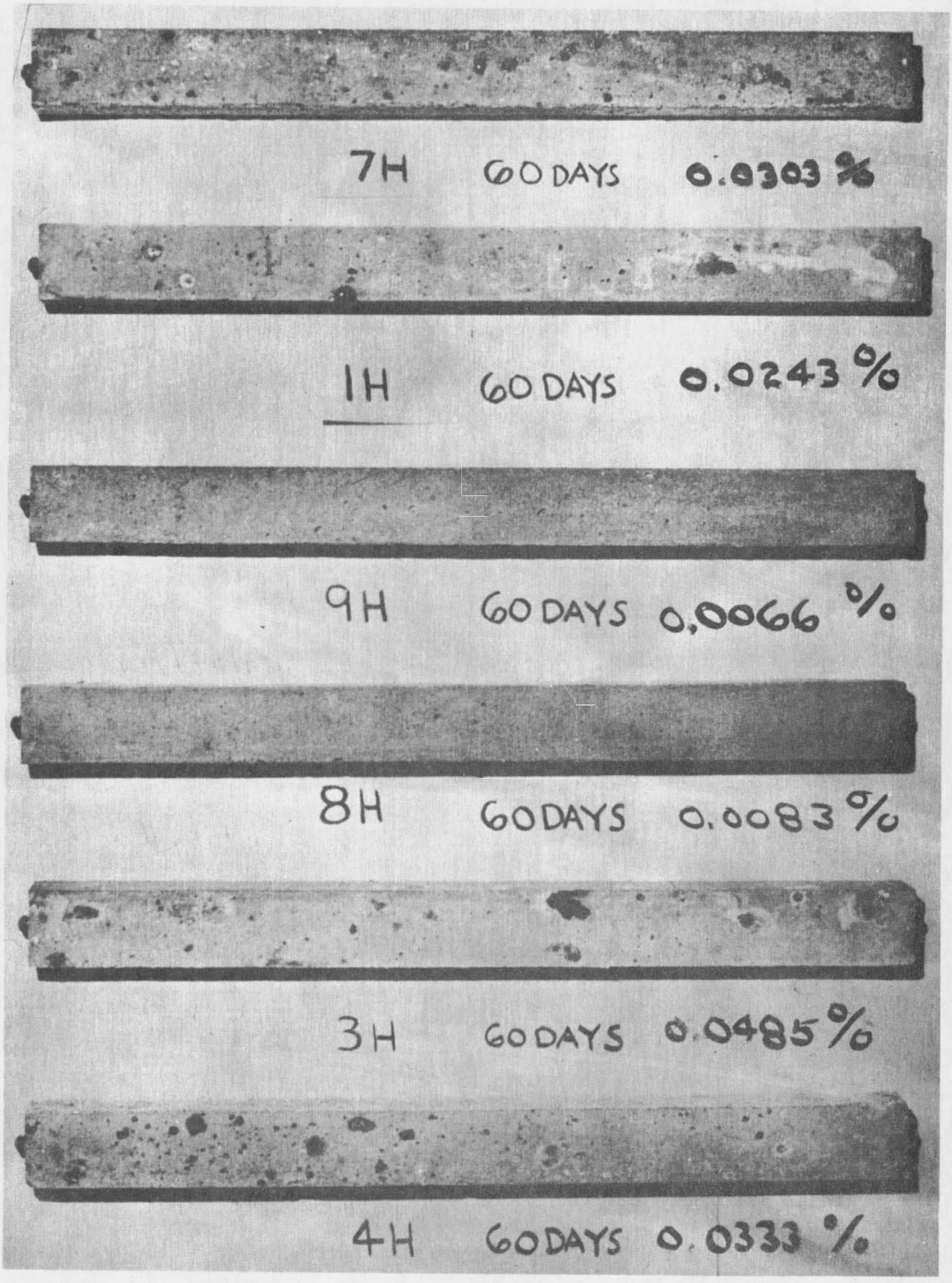


Figure 4 - Appearance of H Bars at 60 Days

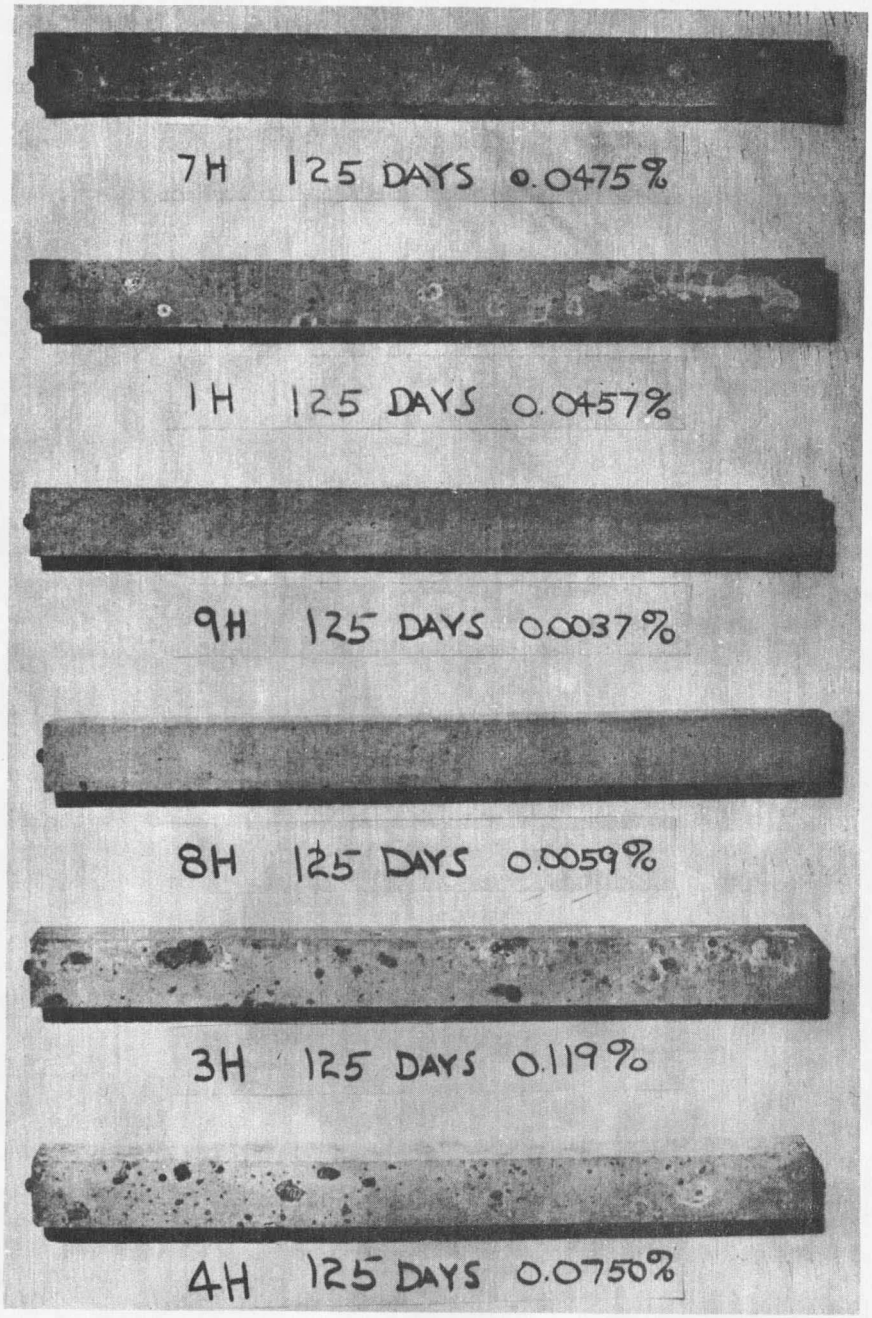


Figure 5 - Appearance of H Bars at 125 Days

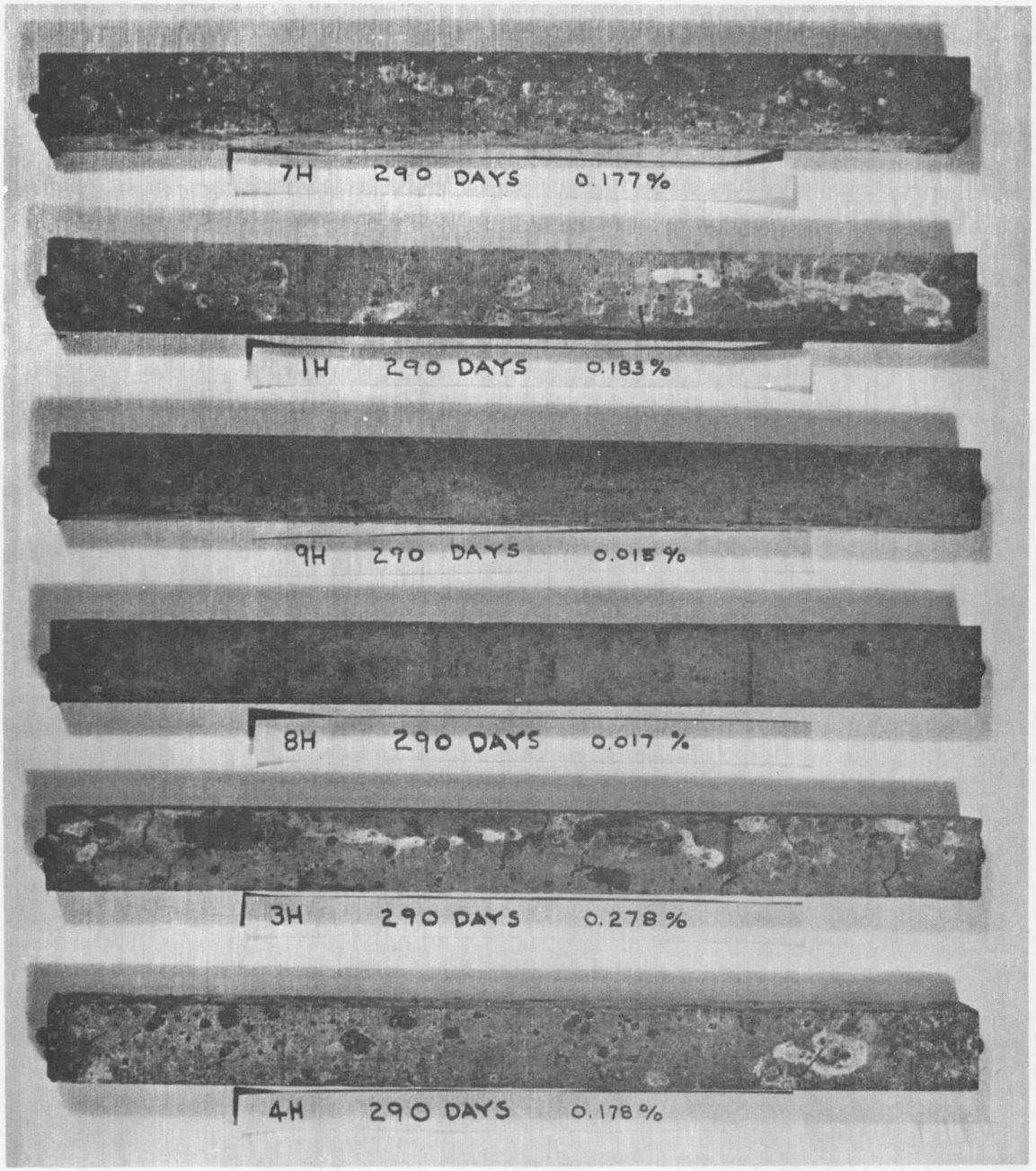


Figure 6 - Appearance of H Bars at 290 Days

were traced in ink in Figure 6. Below each bar is the code number, age in days, and the average per cent expansion at the given age for the total number of replicate bars. The silica gel exudations on the surface of these bars in the photographs appear as either wet (dark) or dried (white) blotches. The relative amount and size of gel deposits on the surfaces approximately correlate with the relative amount of expansion these bars had experienced.

By using the classification boundaries shown in Figure 3, aggregates Nos. 3 and 4 produced excessive expansions, and can be classified as potentially reactive aggregates. Aggregates Nos. 1, 7, 8 and 9 did not produce excessive expansions and can be classified as nonreactive aggregates. It is difficult to accept this classification for aggregates Nos. 1 and 7, since it has already been stated previously that there is no sharp dividing line between reactive and nonreactive classifications. These two aggregates would be classified as reactive based on the earlier limits set by ASTM Designation: C33-54T. This limit was that the aggregate should be considered potentially reactive if the per cent expansion exceeded 0.10 per cent in one year. The curves in Figure 3 indicates that aggregates Nos. 1 and 7 will most likely experience over 0.20 per cent expansion before one year. Further conclusions concerning classifications appear in

Chapter V after the other test results have been discussed.

Figure 7 shows the results of the mortar bars used for control purposes. There are several significant results indicated in this figure that should be mentioned.

The most obvious result is the difference in the expansion caused by the two storage conditions. This difference can not be attributed to temperatures alone, since the sealed container method was used under the 100°F storage, while, under the 70°F storage, the bars were exposed to the atmospheric conditions of the standard cure room. Under the latter condition the bars were continually wet. The lower expansions encountered for the standard cure room specimens could be a consequence of lesser reactivity at lower temperatures, and a lowering of alkali concentration due to absorption of the readily available water. There were no significant differences in expansions with bars stored under standard cure room conditions that contained 0, 5, 10, 20 and 30 per cent Pyrex Glass. These all appear in the shaded area. The bars containing 50 per cent Pyrex Glass showed some difference, but none of these could be considered to have undergone excessive expansions.

With the standard sealed container method it is seen that there is an increasing amount of expansion for an increase in the amount of Pyrex Glass additions. The 50 per cent addition of Pyrex Glass caused excessive expansion, and the 20 and 30

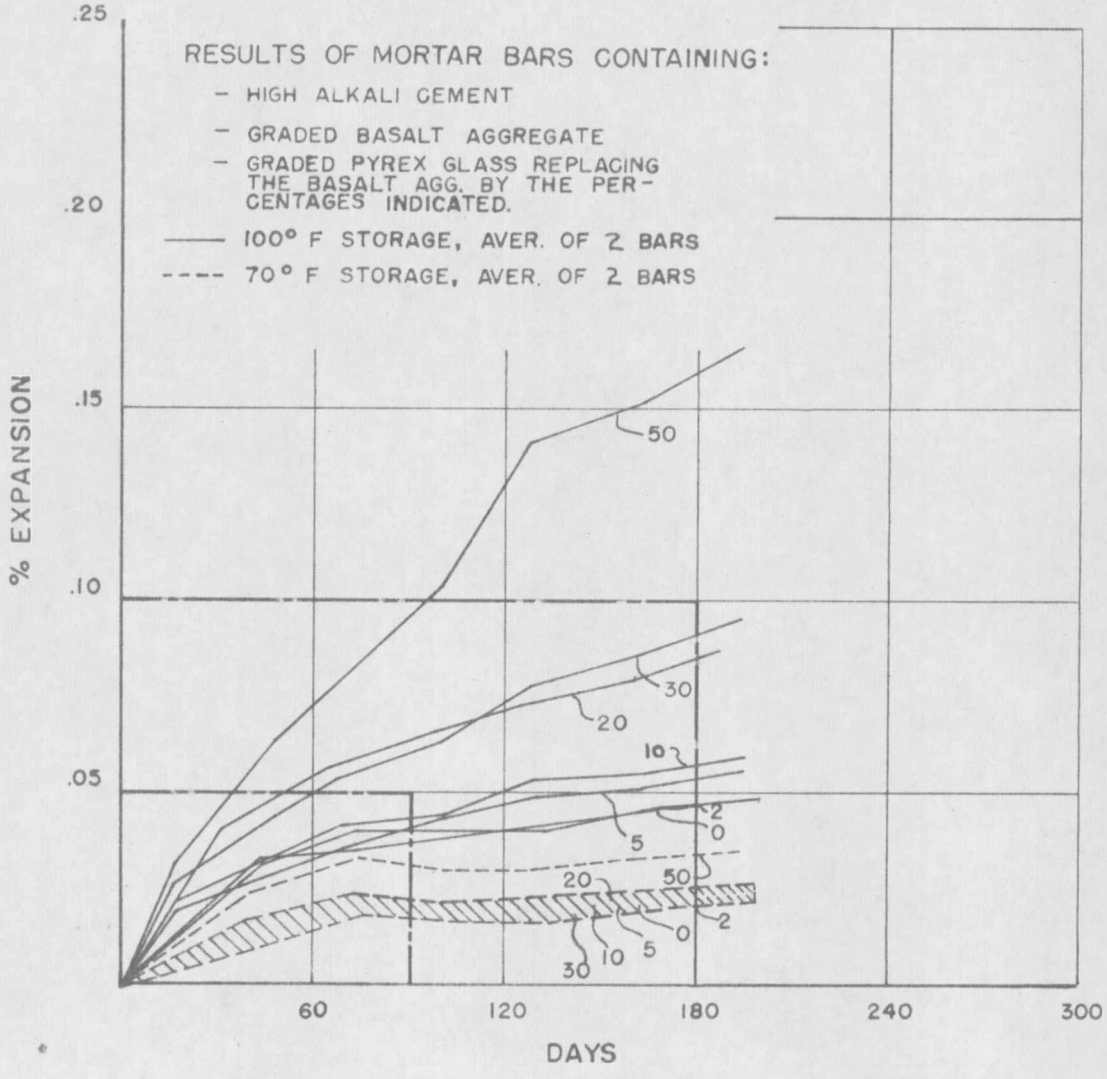


Figure 7 - Control Bars

per cent additions appear to be borderline cases. The results of these expansions suggests that the pessimum amount for the Pyrex Glass must lie above 50 per cent when used with a cement containing 0.88 Na_2O equivalent alkalies.

Unfortunately, there are indications that the basalt aggregate (intended to be an inert material) has an expansive reaction capability. This may be seen in Figure 7 by the solid line curve representing 0 per cent Pyrex Glass. The curve shows that the greater part of the expansion occurred within 60 days, and then began to taper off. Future measurements will probably result in a very small increase in expansion from that which has occurred. Therefore, the basalt appears to have a limited expansive capability. If this were the case, then the test results could be adjusted for those bars made to fine possible pessimum proportions where the basalt was used as the inert aggregate replacement.

A summary of the chemical test results appear in Figure 8. Each point on the graph represents an average of six replicate determinations of dissolved silica and reduction in alkalinity for the indicated aggregate sources. The basalt aggregate is included, and its point on the graph represents an average of three replicates.

The arithmetic mean, standard deviation and coefficient of variation were computed for the test data on the six aggre-

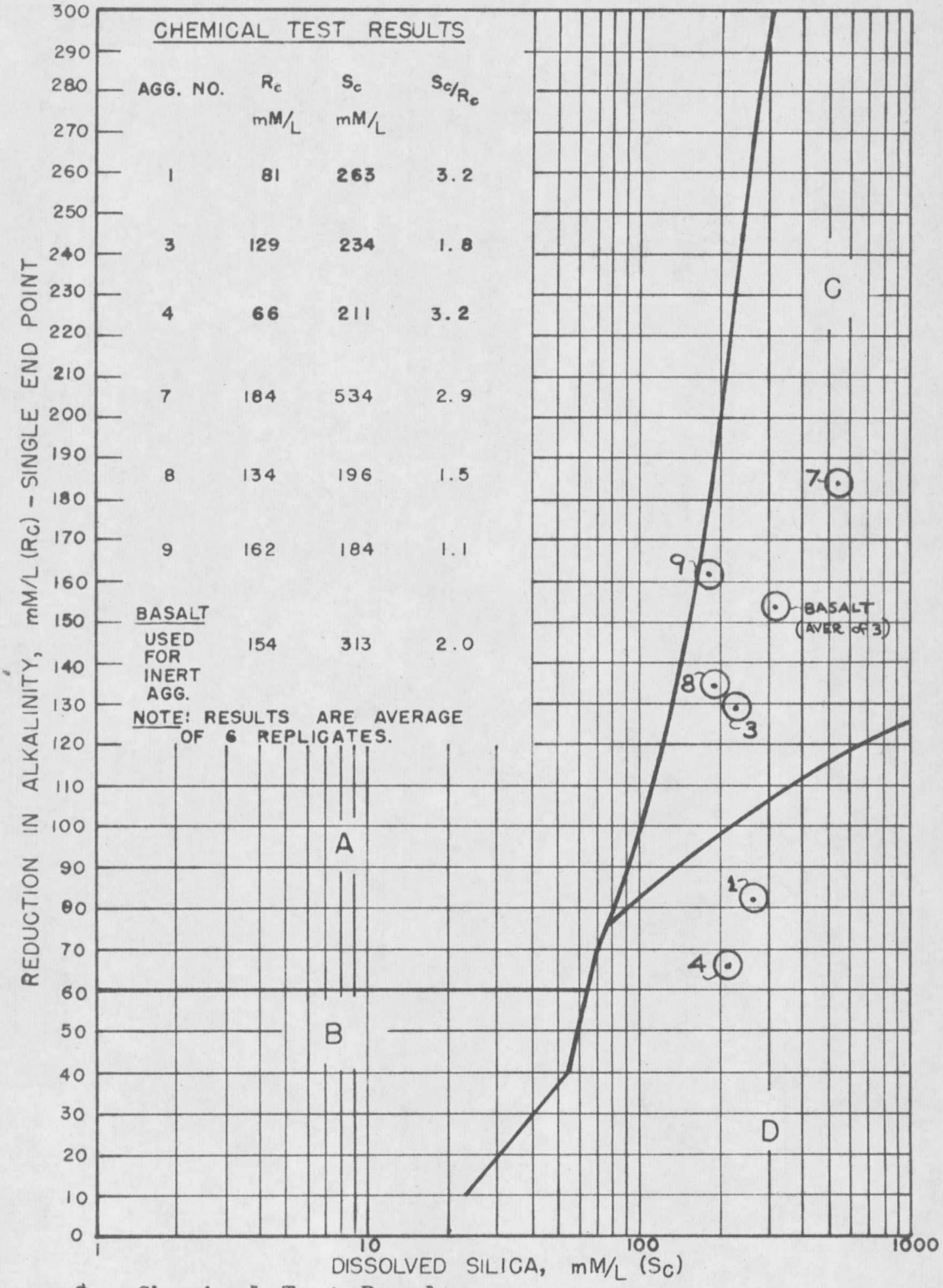


Figure 8 - Chemical Test Results

gate sources and appear in Table VI.

It is difficult to state with assurance the quality of control these coefficients of variability represent without similar test data available for comparison. They do, however, (with the exception of aggregate No. 7) reveal more uniformity in the dissolved silica determinations than for the reduction in alkalinity determinations. In addition, the magnitude of the standard deviations does not significantly affect the location of the points in Figure 8 with respect to the classification of the aggregate.

TABLE VI

STATISTICS OF THE CHEMICAL TEST DATA

Aggregate Source	Sc Dissolved Silica			Rc Reduction in Alkalinity		
	$\bar{x}$ mM/liter	$\pm$ s mM/liter	C.V. %	$\bar{x}$ mM/liter	$\pm$ s mM/liter	C.V. %
1	263	10.36	3.94	81	13.90	17.20
3	234	11.96	5.13	129	15.10	11.70
4	211	7.20	3.31	66	5.53	8.42
7	534	86.40	16.2	184	9.35	5.1
8	196	20.50	10.50	134	18.65	13.9
9	184	12.79	6.95	162	11.06	6.84

By referring to the previous discussion pertaining to the interpretation of Areas A, B, C and D in Figure 1 on page 42,

the aggregate's potential reactivity can be estimated from the chemical test results.

Aggregates Nos. 1 and 4 are reactive aggregates, and can be expected to cause excessive mortar bar expansions. This expectation was substantiated for aggregate No. 4 in the mortar bar test. A similar correlation can be given for aggregate No. 1, since the lines dividing Figure 8 for classification purposes are based on "excessive expansion", meaning that corresponding mortar bars will exceed 0.10 per cent expansion at one year. Aggregate No. 1 caused 0.10 per cent expansion in mortar bars at 190 days.

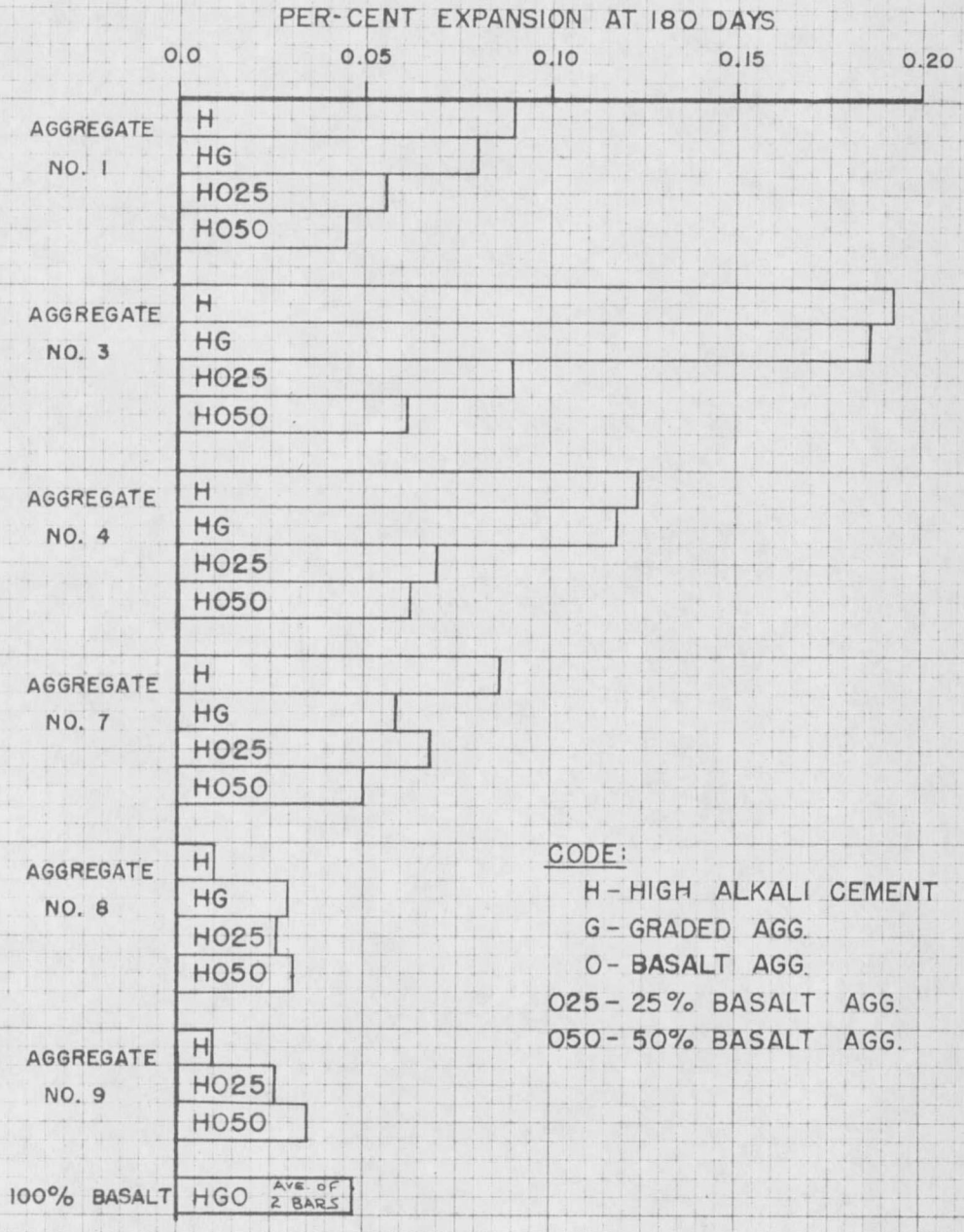
Aggregate No. 9 is clearly a borderline case, and leans favorably to a nonreactive classification, based on no expansion resulting for the corresponding mortar bars.

Aggregates Nos. 3, 7 and 8 are highly reactive aggregates by the chemical test. Since these results lie in Area C, it is possible that excessive mortar bar expansions may not occur due to the pessimum proportion of the aggregate being materially exceeded. However, aggregates Nos. 7 and 3 did cause excessive mortar bar expansions and the results of the two test methods are in agreement. The indications are that, when these aggregates are diluted with inert aggregates, they are capable of greater or lesser expansions in the mortar bar test.

Aggregate No. 8 did not show any significant mortar bar expansions when used in its entirety. The mortar bar tests using the basalt aggregate dilutions would be especially valuable for the case of aggregate No. 8. However, the basalt aggregate problem is further complicated due to the chemical test result placing the basalt in Area C. This indicates that the basalt itself may have a pessimum proportion.

There are favorable indications, however, that the basalt aggregate has a limited expansion capability, as previously mentioned, for the mortar bar test. Aggregate No. 9 appears to be nonreactive, therefore, the mortar bar pessimum tests conducted on this aggregate could be considered in reverse, i. e., let aggregate No. 9 be considered inert and the basalt being checked for a pessimum amount with replacements of 75 and 50 per cent of aggregate No. 9. These results appear in Figure 64, page 165 of the Appendix. It is seen that the resulting expansions are not excessive and are less than the basalt aggregate used in its entirety (the 0 per cent Pyrex Glass replacement bars). This evidence is not sufficient to make reliable conclusions on the pessimum tests, but the results would give fair indications.

The bar graph shown in Figure 9 shows the effects of the basalt aggregate additions on the mortar bars expansions at 180 days. The mortar bars made with the naturally graded



MORTAR BAR TESTS SHOWING THE EFFECTS OF BASALT AGGREGATE ADDITIONS (AVERAGE OF 4 BARS)

Figure 9 - Pessimum Test Results

aggregate and the artificially graded aggregate are included for comparison purposes. Shown at the bottom of the graph is the resulting expansion of the basalt aggregate used in its entirety. All the bars represented on this graph contained high alkali cement.[6]

Particular attemtion should be given to aggregates Nos. 3, 7, 8 and 9, as they were the aggregates causing chemical test results in Area C. If these aggregates have a pessimum amount, indications are that the amount would be either below 50 per cent of the total aggregate or more than the total aggregate.

The two percentages of basalt (mortar bars H025 and H050) replacements for aggregates Nos. 8 and 9 caused greater expansions than for the aggregates used in their entirety (mortar bars H and HG). However, these expansions seem to be the effects of the basalt itself rather than those of the base aggregate.

In all cases, except aggregate No. 8, the artificially graded aggregate tests resulted in less expansions than the natural graded aggregate tests. For aggregate No. 8 the graded test bars had a significantly higher expansion (but

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[6]The pessimum tests using the basalt and the low alkali cements (Types I and II) resulted in no significant expansions. The results of these tests are in the Appendix on pages 166 to 177.

not excessive) in comparison with the natural graded aggregate. The sieve analysis for this aggregate (Figure 28, page 124, Appendix) shows a relatively high total percentage of fines (12.7 per cent) passing the 100 sieve size, and approximately half of this amount (6.09 per cent) passing the 200 sieve size. It is possible that these fines acted as a pozzolan in the bars made with natural graded aggregate. The particle counts for aggregate No. 8 resulted in a possible 3.5 per cent of reactive material present in material passing the 100 sieve size. It is probable that a fair percentage of this reactive material passes the 200 sieve size, and, hence, would most likely have acted as a pozzolanic material in the mortar bars.

It appears then, that aggregate No. 8 can cause some expansion when material passing the 100 sieve size is eliminated. The chemical test result indicates that this aggregate has expansion capabilities and has a pessimum proportion. The pessimum tests suggest that this proportion is less than 50 per cent, however, pozzolanic action could have taken place in these pessimum tests since the natural gradation was used for the base aggregate. Because of this possibility, the pessimum tests results for aggregate No. 8 cannot be relied upon as the true nature of the aggregate under these conditions. Additional evidence concerning aggregate No. 8

is presented in the results of the petrographic analysis which follows.

Tables VII and VIII are the results of the petrographic analysis on fine aggregates Nos. 3 and 8 respectively. The weighted percentage compositions were calculated from the particle counts by the procedure recommended by ASTM Designation: C295-54. The individual particle counts and percentages for these aggregates are tabulated in Tables XVI and XVII, and can be found in the Appendix on pages 129 and 130 .

The constituents were grouped in Tables VII and VIII according to their reactive capacity. The rhyolites, trachytes, andesites and basalts that were found to contain glass have been placed in the reactive grouping. However, the matrix material for these rock types were generally cryptocrystalline and could not be regarded as being nonreactive, even though most of them did not contain readily identifiable glass material. For this reason, those without glass material were placed in a "possibly reactive" group.

The chert was generally a fine grained quartz material, and could not be ruled out as being nonreactive, therefore, it was also placed in the "possibly reactive" group.

By using the limits established by the Bureau of Reclamation (page 38), it is seen from Table VII that aggregate No. 3 can be classified as highly reactive based on the

TABLE VII

COMPOSITION OF FINE AGGREGATE NO. 3

CONSTITUENTS	Weighted Percentages of Constituents in each sieve fraction						Weighted Composition of Sample	
	8	16	30	50	100	Pass 100		
Quartz	----	----	5.8	8.2	7.5	2.0	23.5	
Feldspar	----	----	2.5	6.3	5.0	0.8	14.6	
Ferromags (amphibole & Pyroxene)	----	----	0.2	0.4	1.0	0.2	1.8	60.5% Non-reactive
Carbonates (mostly limestone)	----	0.1	----	----	----	----	0.1	
Granitic	11.6	8.2	0.4	----	----	----	20.2	
Sandstone	----	----	----	----	----	----	----	
Siltstone & Shale	0.2	0.1	----	----	----	----	0.3	
Rhyolite & Trachyte	6.0	3.2	1.0	3.3	2.5	0.6	16.6	
Andesite & Basalt	4.9	2.6	0.6	4.3	2.9	0.7	16.0	35.3% Possibly
Chert	0.2	0.4	0.4	0.8	0.7	0.2	2.7	Reactive
Rhyolites & Trachytes With Volcanic Glass	----	----	----	0.3	0.4	0.1	0.8	
Opal & Opaline Chert	----	----	----	0.9	0.1	0.1	1.1	4.2% Reactive
Chalcedony & Chalcedonic Chert	----	----	1.2	0.4	0.6	0.1	2.3	
Total in Sieve Fraction	22.9	14.6	12.1	24.9	20.7	4.8	100.0	

TABLE VIII

COMPOSITION OF FINE AGGREGATE NO. 8

CONSTITUENTS	Weighted Percentages of Constituents in each sieve fraction						Weighted Composition of Sample	
	8	16	30	50	100	Pass 100		
Quartz	----	5.1	10.8	12.3	8.3	6.6	43.1	
Feldspar	----	----	4.2	4.2	2.2	1.1	11.7	
Ferromags (amphibole & Pyroxene)	----	0.2	----	1.8	1.1	0.3	3.4	82.6% Non-reactive
Carbonates (mostly limestone)	2.2	1.7	2.6	2.5	1.1	1.2	11.3	
Granitic	1.9	----	----	----	----	----	1.9	
Sandstone	----	0.3	----	----	----	----	0.3	
Siltstone & Shale	5.6	3.9	1.4	----	----	----	10.9	
Rhyolites & Trachyte	0.4	0.7	1.3	0.8	1.7	1.5	6.4	
Andesite & Basalt	0.3	0.3	0.7	0.8	0.7	0.5	3.3	15.0% Possibly
Chert	0.2	0.2	0.7	2.7	0.8	0.7	5.3	Reactive
Rhyolites & Trachytes With Volcanic Glass	----	----	----	----	0.2	0.4	0.6	
Opal & Opaline Chert	----	----	----	----	----	----	----	2.4% Reactive
Chalcedony & Chalcedonic Chert	----	----	0.7	0.5	0.2	0.4	1.8	
Total in Sieve Fraction	10.6	12.4	22.4	25.6	16.3	12.7	100.0	

resulting 1.1 per cent of opal and opaline chert alone.

The constituents grouped under reactive material are of the No. 30 sieve size or smaller. However, many obvious reacted particles of the No. 8 sieve size were found in the cross-section specimens cut from one of the mortar bars. In Figure 10 are photographs of some of these reacted particles. These larger particles were found to be generally rhyolitic material. Therefore, there must be a higher percentage of reactive material than the 4.2 per cent indicated for the reactive group.

With the evidence shown in Table VII, aggregate No. 3 can be classified, based on the petrographic analysis, as potentially reactive when used with high alkali cement. Both the mortar bar test results and the chemical test results support this classification very favorably.

For aggregate No. 8 (Table VIII), 2.4 per cent of the aggregate is reactive and 15.0 per cent possibly reactive. It is difficult to predict what percentage of this 15.0 per cent might actually be reactive material. The thin slabs cut from one of the mortar bars showed no signs of reacted particles or gel deposits. The evidence shown by both the results in Table VIII and the chemical test results suggests that the aggregate very possibly contains enough, or more than enough, reactive siliceous material to be potentially reactive

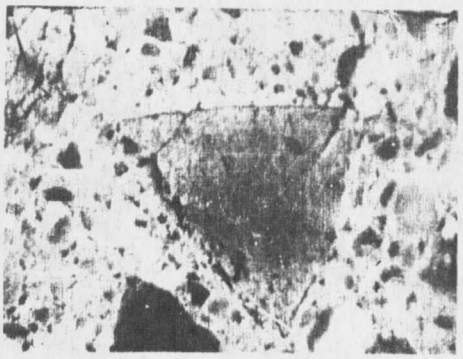


Fig. 10a Rhyodacite or dacite with glass in matrix (No. 4 to 8 sieve size)

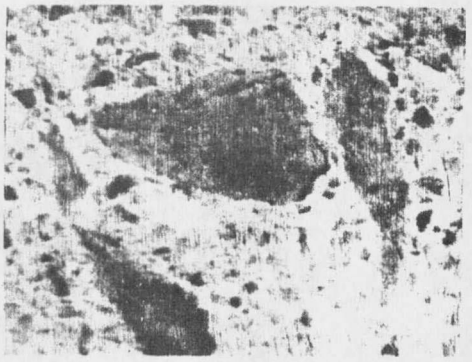


Fig. 10b Devitrified glassy rhyolite, with gel filled air pocket below particle. (No. 4 to 8 sieve size)

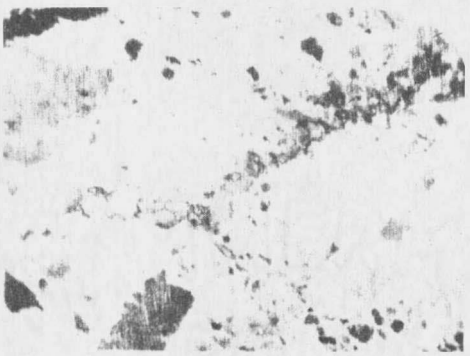


Fig. 10c Acid Volcanic, altered. Not noticeably glassy. Apparent source of surface crack. (No. 8 to 16 sieve size)



Fig. 10d Rhyodacite or dacite with glass in matrix (No. 8 to 16 sieve size)

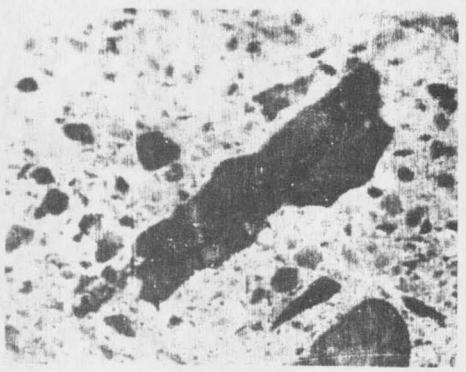


Fig. 10e Rhyodacite or dacite with glass in matrix. Crack extends into mortar. (No. 4 to 8 sieve size)

Figure 10 - Reacted Particles, Aggregate No. 3-Bar No. 3H-1

with high alkali cement. The resulting expansion produced in the mortar bars with artificially graded aggregate (8HG) was not excessive, but indicates expansive capabilities. These results, however, are not sufficient to make conclusions concerning the potential reactivity of aggregate No. 8, but they do indicate a possible danger if the aggregate was to be used with high alkali cement.

Tables IX, X, XI and XII give the approximate percentage compositions for aggregates Nos. 1, 4, 7 and 9. These results cannot be used for classification of the sources, but they do give indications that appear to be in general agreement with the chemical and mortar bar test results.

For aggregate No. 1, Table IX, the volcanic rocks, both acid and intermediate, appear to be the source of reactive material. Thin sections showed some of these rocks to have partly glassy matrices. Some reacted particles were identified as andesitic and acid to intermediate volcanic containing glass. Figure 11 contains photographs of some of these reacted particles. Some zeolites were found in rock cavities which could possibly be a source of additional alkalies.

In aggregate No. 4, Table X, the acid volcanics with a high proportion of chalcedony, together with some opal appear to be the major cause of reactivity that was found in the chemical and mortar bar tests. Thin section studies showed

TABLE IX

APPROXIMATE COMPOSITION OF AGGREGATE NO. 1

Approximate Composition (Per Cent)	Rock Type and Description
40	Granites and granite gneisses, fairly fresh, containing chiefly feldspars, quartz, some biotite and hornblende.
6	Granites and gneisses, somewhat weathered. Micaceous and clayey.
11	Micaceous gneiss and schist. Dark, considerable biotite and hornblende. Some feldspar, quartz. Fresh.
18	Intermediate volcanics, probably basic andesite (black color). Some have phenocrysts of plagioclase feldspar, mostly fresh, but in a few samples altered to clay. A few pieces rich in iron oxide.
3	Intermediate volcanics, similar but also contain some zeolites in cavities.
6	Acid volcanic to shallow intrusive, several varieties: quartz, feldspar phenocrysts. One specimen partly glassy as if devitrifying obsidian.
6	Sandstone, well cemented. No calcareous cement.
5	Limestone, finely crystalline.
3	Dolomite, finely crystalline.
2	Partly silicified limestone.
100 Per Cent	

TABLE X

APPROXIMATE COMPOSITION OF AGGREGATE NO. 4

Approximate Composition (Per Cent)	Rock Type and Description
21	Granites, granitic gneisses, fairly fresh, containing quartz, feldspars, biotite, some hornblende.
2	Micaceous gneiss and schist, fresh, contains biotite, feldspar, quartz.
30	Quartzite and siliceous sandstone, no calcareous cement. Very high per cent quartz.
12	Intermediate to basic volcanics, probably basic andesite, possibly some basalt. Fairly fresh, but locally altered to clays and iron oxide. Occasional piece has thin calcareous coating.
22	Acid volcanics, gray to brown, appear highly silicified, fresh to partly altered. Contain high proportion chalcedony, some feldspar, biotite and quartz. Some glass.
1	Red fine grained siliceous rock, possibly silicified acid volcanic, mixture of chalcedony and yellow punky opal.
10	Chert, mostly light to dark gray. Contains chiefly chalcedony, some quartz. Difficult to distinguish from some silicified acid volcanics.
2	Chert, weathered to powdery white chalcedony.
100 Per Cent	

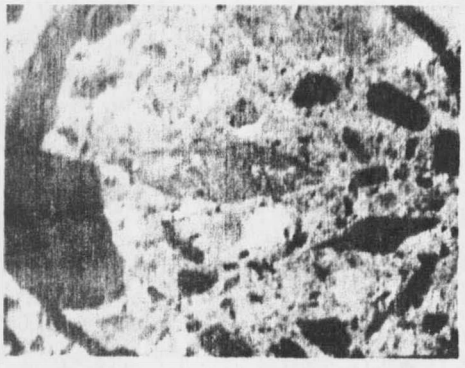


Fig. 11a Acid to intermediate volcanic with some glass. White gel exudations in center of particle. (No. 8 to 16 sieve size)

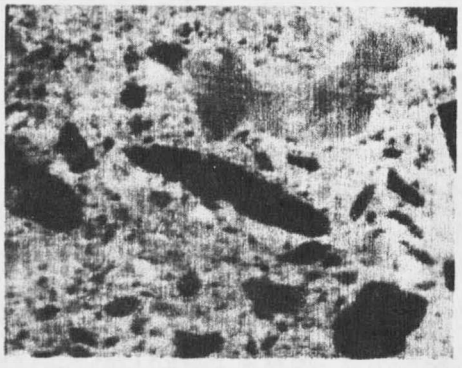


Fig. 11b Acid volcanic, probably dacite, white gel exudations along crack through center of particle. (No. 8 to 16 sieve size)

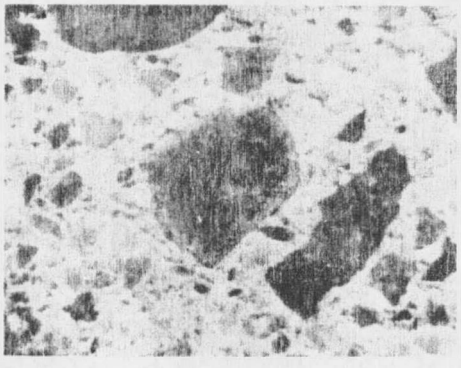


Fig. 11c Acid to intermediate volcanic light colored reaction rim and edge spalling. (No. 8 to 16 sieve size)

Figure 11 Reacted Particles, Aggregate No. 1-Bar No. 1H-3

the opal occurring in a highly chalcedonic fine grained structure being nearly rhyolitic. Acidic glassy fragments were also found im the thin section. The major portion of reacted particles observed in slabs cut from a mortar bar were identified as partly crystallized opal or volcanic glass. Photographs showing these particles may be found in Figure 12. The reacted particles shown in Figure 12 have essentially the same composition. However, the nature of the reaction has occurred in a different form for the particles in Figure 12a and 12b, than for the particles in Figure 12c and 12d. For the particles in Figure 12c and 12d, the reaction appears to have been internal, and the particles show no signs of reaction rims. In Figure 12a and 12b, the reaction appears to have proceeded imward from along the perimeter of the particles resulting in distinctive reaction rims. There is a possibility that the degree of crystallinity affects the manner in which a reacted particle is altered, since the particles in Figure 12a and 12b are partially crystallized opal, while particles in Figure 12c and 12d are apparently fully crystallized opal.

In aggregate No. 7, Table XI, the high percentage of acid to intermediate volcanic rocks is probably the source of reactivity found by the mortar bar and chemical tests. Thin section studies showed that these rocks contained a

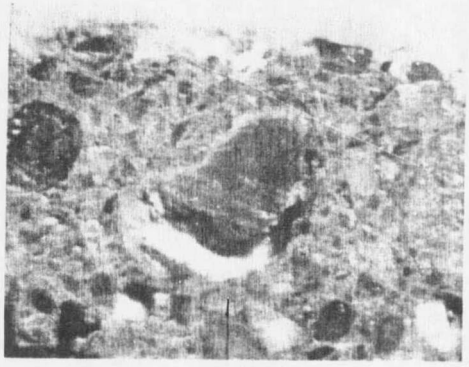


Fig. 12a Opal, partly crystallized (No. 4 to 8 sieve size)

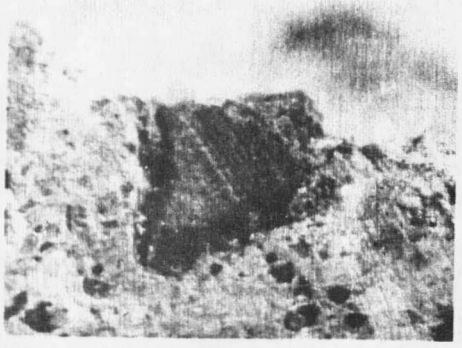


Fig. 12b Opal, partly crystallized (No. 4 to 8 sieve size)

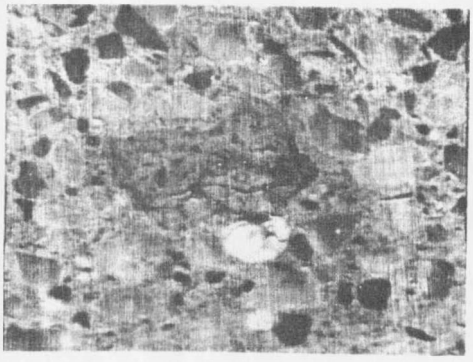


Fig. 12c Crystallized opal (No. 4 to 8 sieve size) White gel filled air pocket below particle

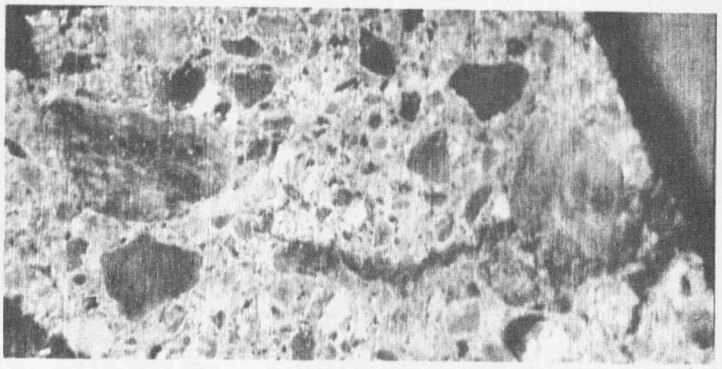


Fig. 12d Crystallized opal (left side of photo)(No. 4 to 8 sieve size) Apparent source of surface crack.

Figure 12 - Reacted Particles, Aggregate No. 4-Bar No. 4H-4

considerable amount of glassy material. Chalcedony chert and partly crystallized opal are also possible contributors to the reactivity. The most obviously reacted particles observed in cross-section specimens were found to be crystallized opal or chalcedony chert. Photographs showing these reacted particles may be found in Figure 13. Some zeolites present could be a source of additional alkalies.

In aggregate No. 9, Table XII, the acid to intermediate volcanic rocks were found to contain relatively small proportions of glassy material. There is a higher proportion of carbonate rocks and a lower proportion of granite rocks than in the other aggregates. Some dolomite found present could be a cause of interference in the chemical test. A correction of this possible interference would tend to indicate a more reactive aggregate than indicated. The mortar bar tests for this aggregate showed no signs of reactivity and cross-section specimens showed no gel deposits or reacted particles. It appears that the small proportion of reactive material found in this aggregate is not sufficient to give aggregate No. 9 a reactive classification.

TABLE XI

APPROXIMATE COMPOSITION OF AGGREGATE NO. 7

Approximate Composition (Per Cent)	Rock Type and Description
7	Granites and granite gneiss containing chiefly fledspars, quartz, biotite, and hornblende. Mostly fresh.
16	Hornblende gneisses, schists, and amphibolites. High proportion hornblende, feldspars. Some quartz and biotite.
4	Sandstone and quartzite, very high percentage quartz. Some sandstones contain ferromagnesian minerals. One piece has calcareous cement.
43	Intermediate and basic volcanics. Fine grained, some with plagioclase or pyroxene phenocrysts. Some weathering to produce iron oxide and clays, chlorite, and epidote, possibly minor zeolites. One piece contains small coatings of chalcedony and partly devitrified opal.
29	Acid to intermediate volcanic and shallow intrusive. Fine grained, some have phenocrysts of feldspar, biotite, some appear silicified. Some alteration of feldspars to clay. Some have epidote, chlorite, and/or zeolites in cavities. Considerably more variety of rock types than is present in "intermediate to basic" category. Some volcanics contain partly devitrified glass. At lease one (reddish) piece contains partly crystallized opal.
1	Chert, chiefly chalcedony and quartz.
100 Per Cent	

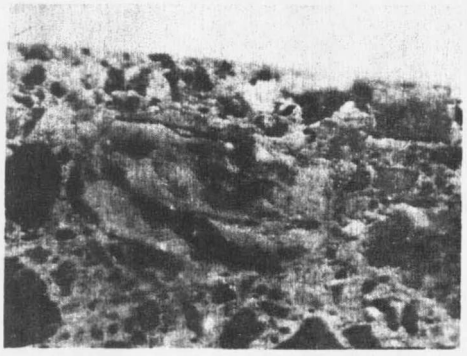


Fig. 13a Crystallized opal or chalcedonic chert. Suggests beginning stage of a future pop-out at edge of bar. (No. 4 to 8 sieve size)

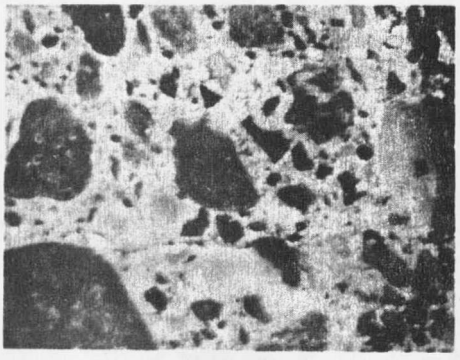


Fig. 13b Crystallized opal or chalcedonic chert. Light colored reaction rim. (No. 8 to 16 sieve size)

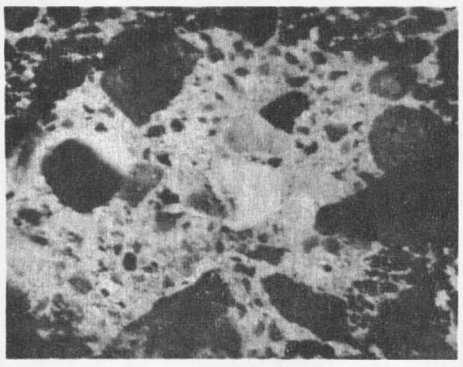


Figure 13c Crystallized opal or chalcedonic chert highly altered by the reaction (white area in photograph)(No. 8 to 16 sieve size) gel filled air void at tip of black arrow.

Figure 13 - Reacted Particles, Aggregate No. 7-Bar No. 7H-2

TABLE XII

APPROXIMATE COMPOSITION OF AGGREGATE NO. 9

Approximate Composition (Per Cent)	Rock Type and Description
5	Granite gneiss; feldspars, quartz, biotite.
24	Quartzite and siliceous sandstone. Non-calcareous cement except for one grain.
19	Limestone and dolomite, coarse to fine crystalline. Some dolomite partly silicified.
31	Intermediate to basic volcanic, some containing phenocrysts of hornblende, pyroxene, or plagioclase. Mostly fresh, but in places plagioclase partly altered.
16	Acid to intermediate volcanics, and shallow intrusives, considerable variety of types. Phenocrysts include feldspars, biotite, hornblende, possibly pyroxene. Some particles syenitic, Fresh to somewhat weathered. Feldspars weathers to clays. Some have calcareous coatings. In thin section a few pieces contain glass.
5	Chert, medium gray, fine quartz and chalcedony.
100 Per Cent	

TEST RESULTS OF MORTAR BARS CONTAINING LOW ALKALI CEMENTS AND POZZOLANS

The resulting mortar bar expansions were plotted for bars containing the low alkali cements and pozzolans, and are summarized for each aggregate source in Figures 14, 15, 16, 17, and 18. The curves used previously in the chapter, representing the high alkali cements tested with the natural graded aggregate and with the artificially graded aggregate were superimposed on these graphs for comparison purposes. All the curves in these figures are results of test bars stored under the standard 100°F storage conditions. With the exception of curves II and V, each curve represents an average of four bars unless otherwise indicated on the curve. The curves designated II and V represent an average of two bars.

The mortar bar expansions for the low alkali cement tests (curves designated I, II and V) for the six aggregates resulted in slight contractions or minus per cent expansion. The II and V bars stored in the standard cure room also resulted in slight contractions, but generally a little less than those under the standard 100°F storage. These bar's results are not shown in the Figures 14, 15, 16, 17 and 18, but may be found in the Appendix on pages 150 to 155.

The only essential difference in the mortar bar treatments for the curves designated I, II and V, and for the curve

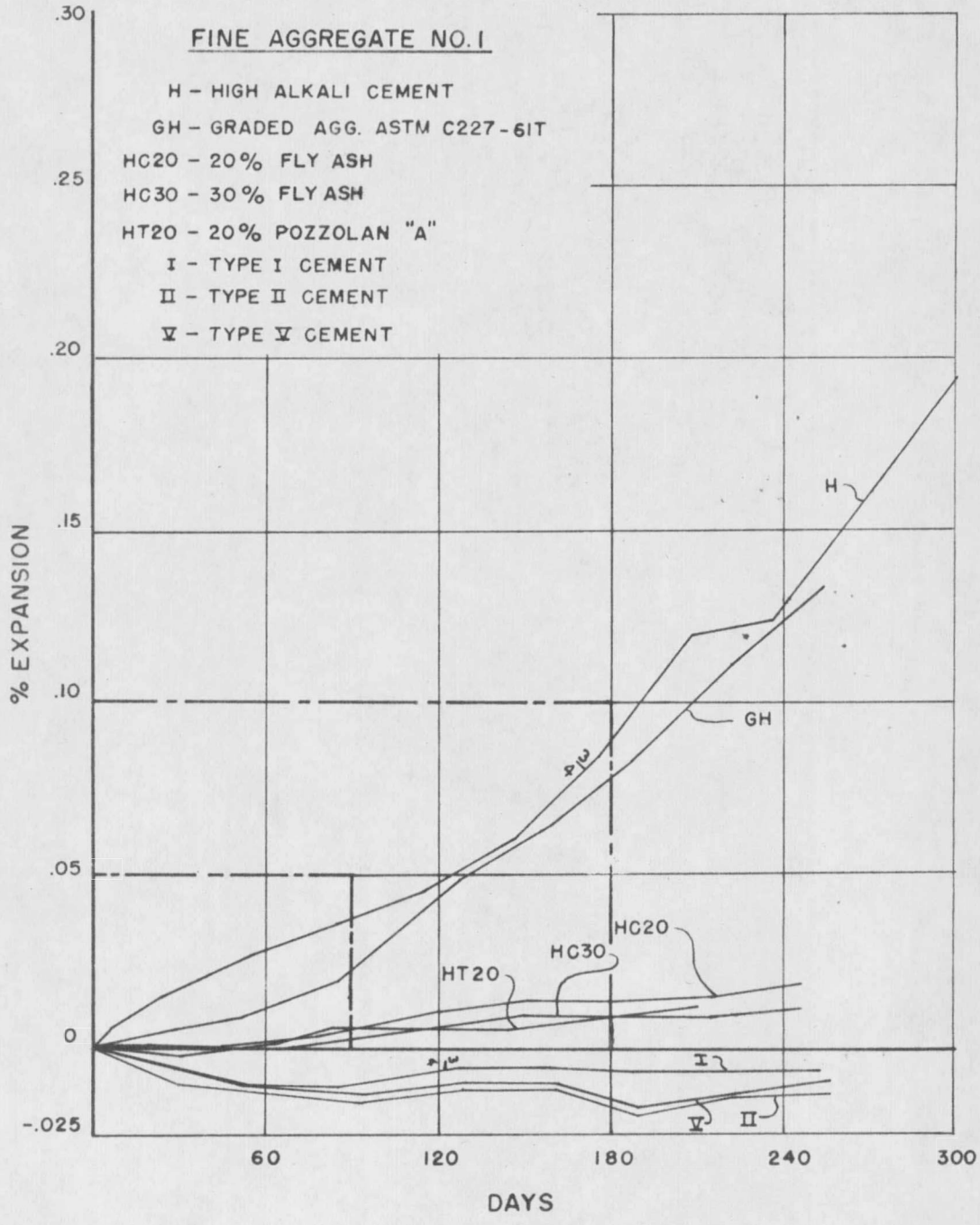


Figure 14 - Mortar Bar Results for Aggregate No. 1

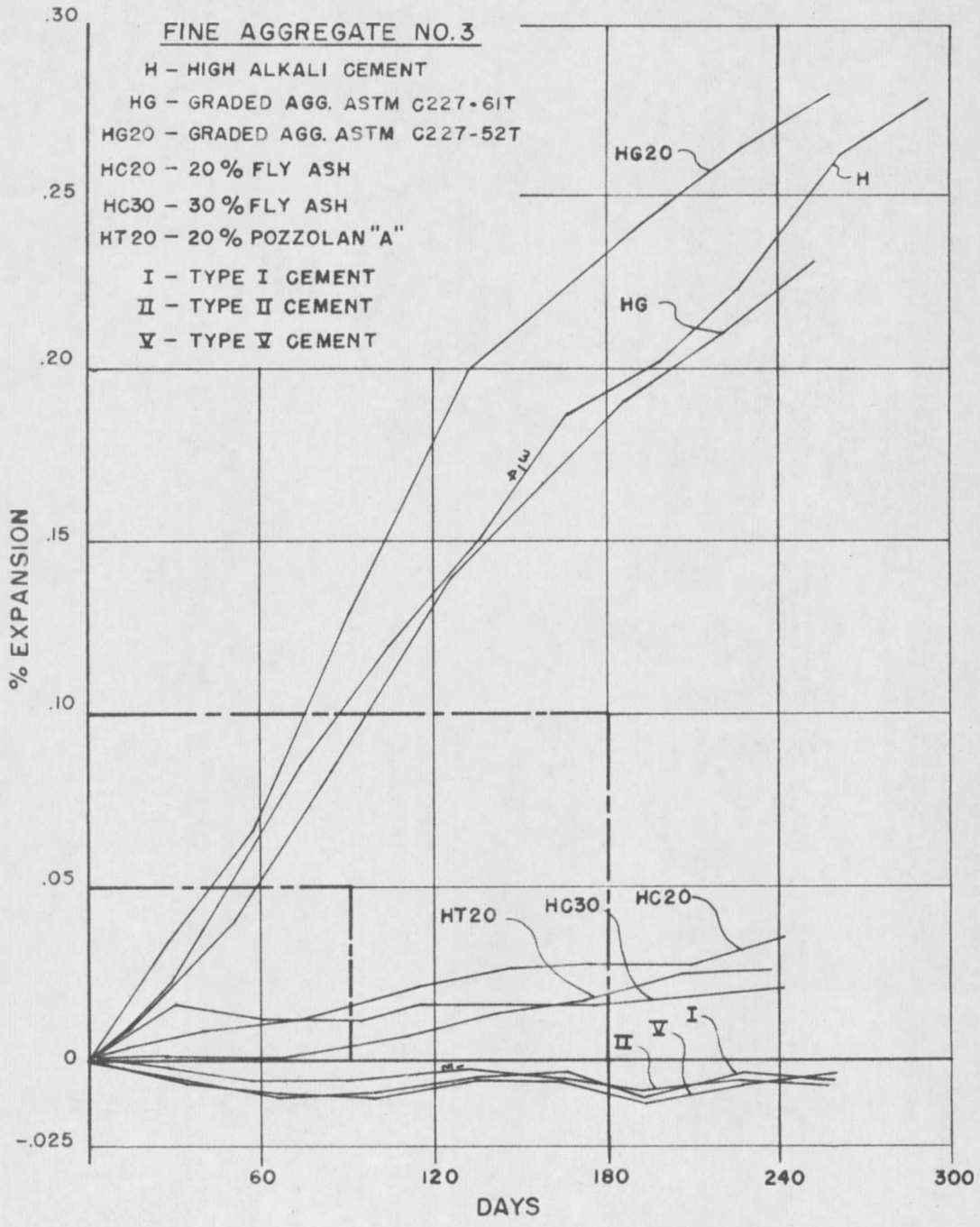


Figure 15 - Mortar Bar Results for Aggregate No. 3

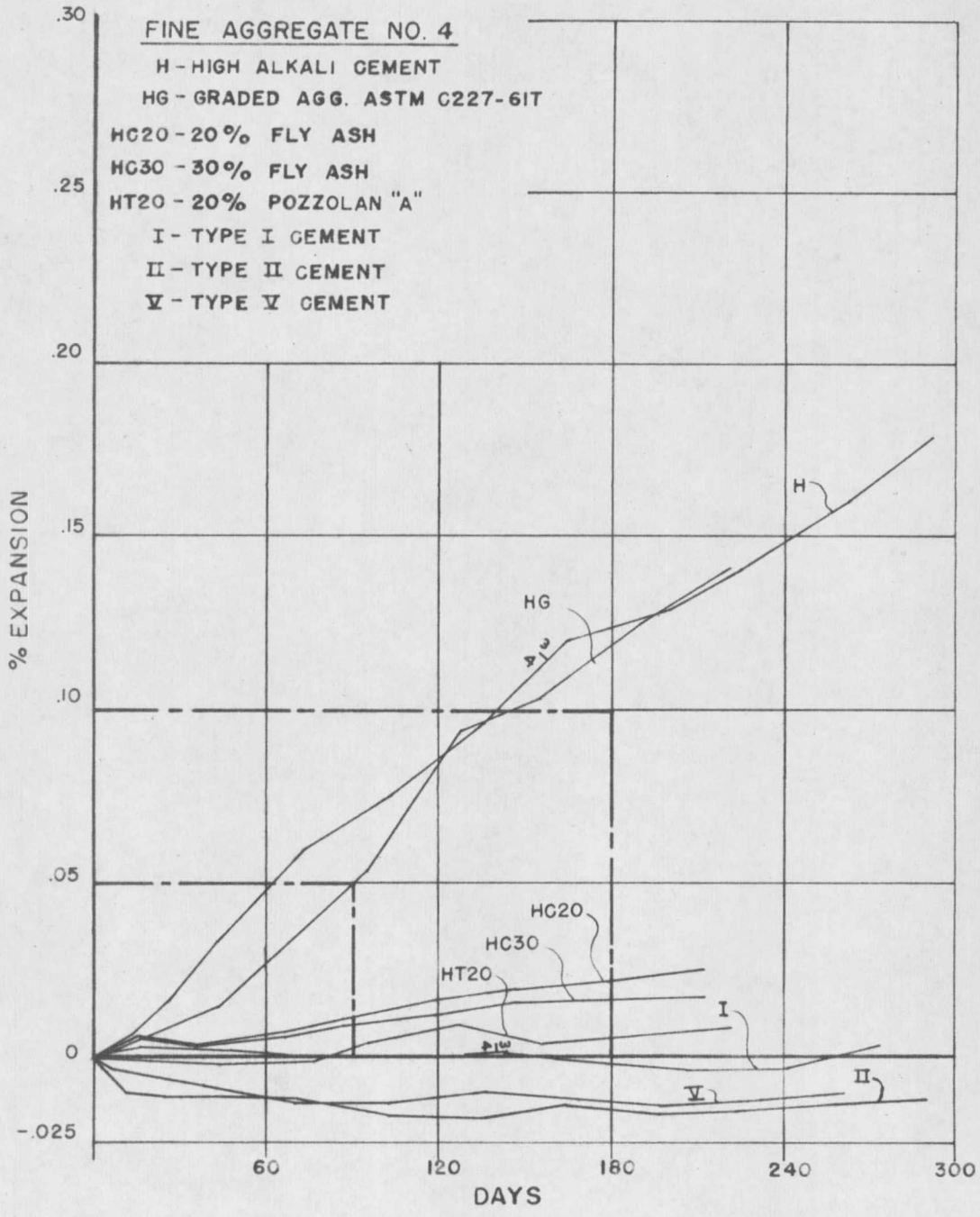


Figure 16 - Mortar Bar Results for Aggregate No. 4

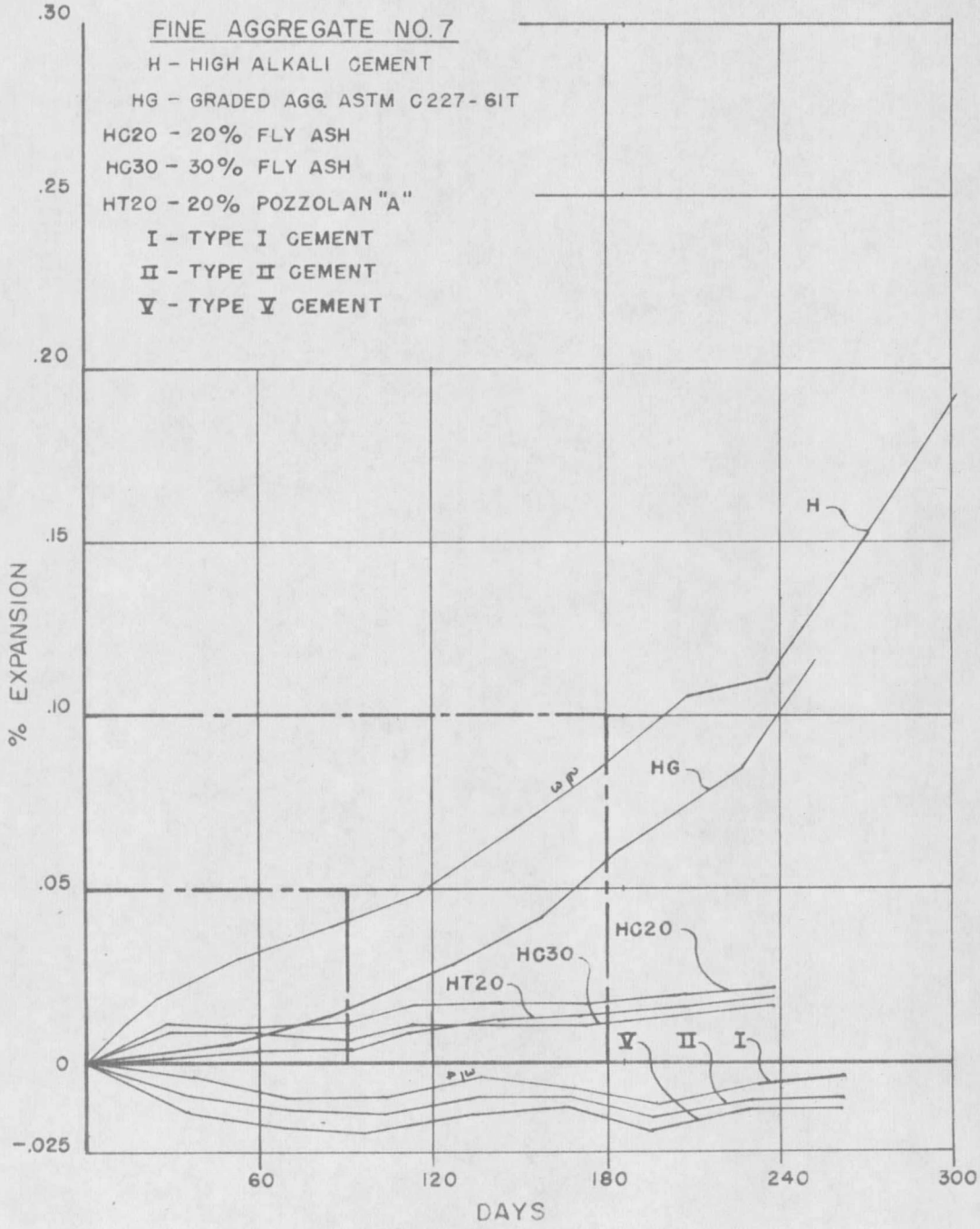
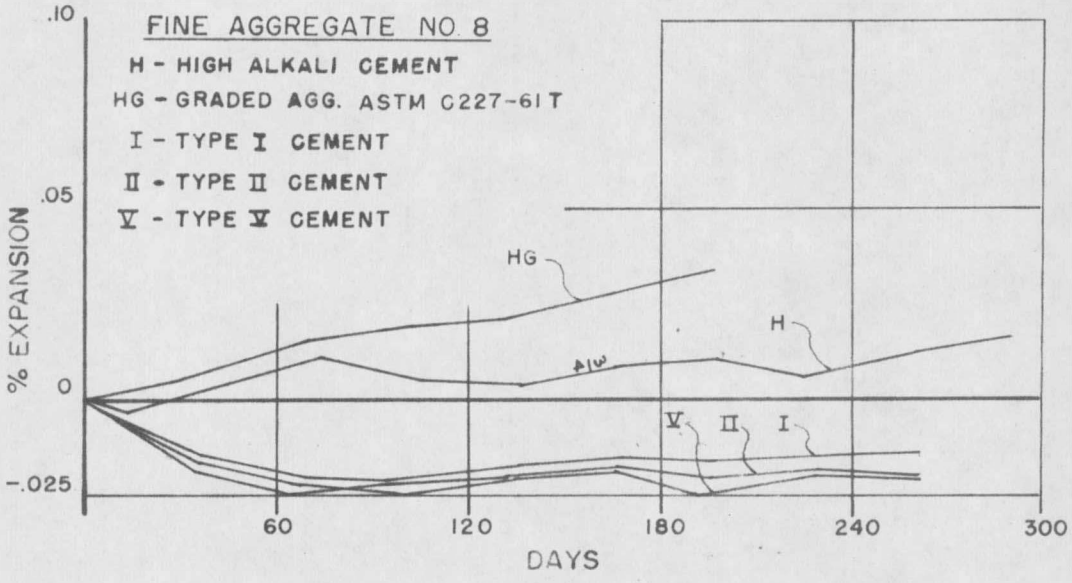


Figure 17 - Mortar Bar Results for Aggregate No. 7



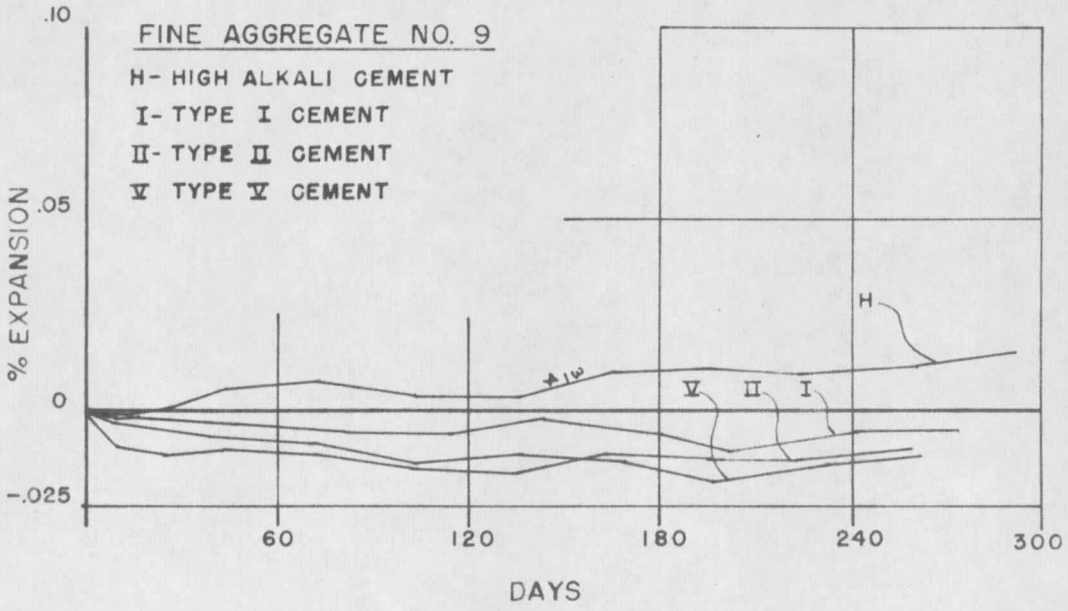


Figure 18 - Mortar Bar Results for Aggregates No. 8 and 9

designated H for each of these six aggregates is approximately 0.5 per cent (Na_2O equivalent) alkalies in the cements. The results indicate rather conclusively that a cement with 0.39 per cent total alkalies or less will prohibit any expansive reaction when used with the fine aggregate from these six sources. There was evidence, however, indicating that minor reactions had occurred with these low alkali cements, even though there were no significant expansions.

Figure 19 shows a mortar bar containing a naturally graded aggregate and Type I cement (0.39 per cent Na_2O equivalent alkalies) for each of the six aggregates. On the surface of bar 7I are two distinctive gel exudations (dried and white) along with minor gel spots (wet) not clearly distinguishable in the photograph. Similarly, on the surface of bar 1I are numerous small wet gel deposits (small dark spots in photograph). The deposits on bars 7I and 1I were materially the same type as shown for the bars containing high alkali cements in Figures 4, 5, and 6. Bar 4I did not show any signs of reactivity on the surface, however, a few reacted particles and gel filled air voids were found in cross-section specimens. Figure 20a shows a partially filled air void found in one of these cross-section specimens. The gel apparently came from a particle of crystallizing opal or volcanic glass that

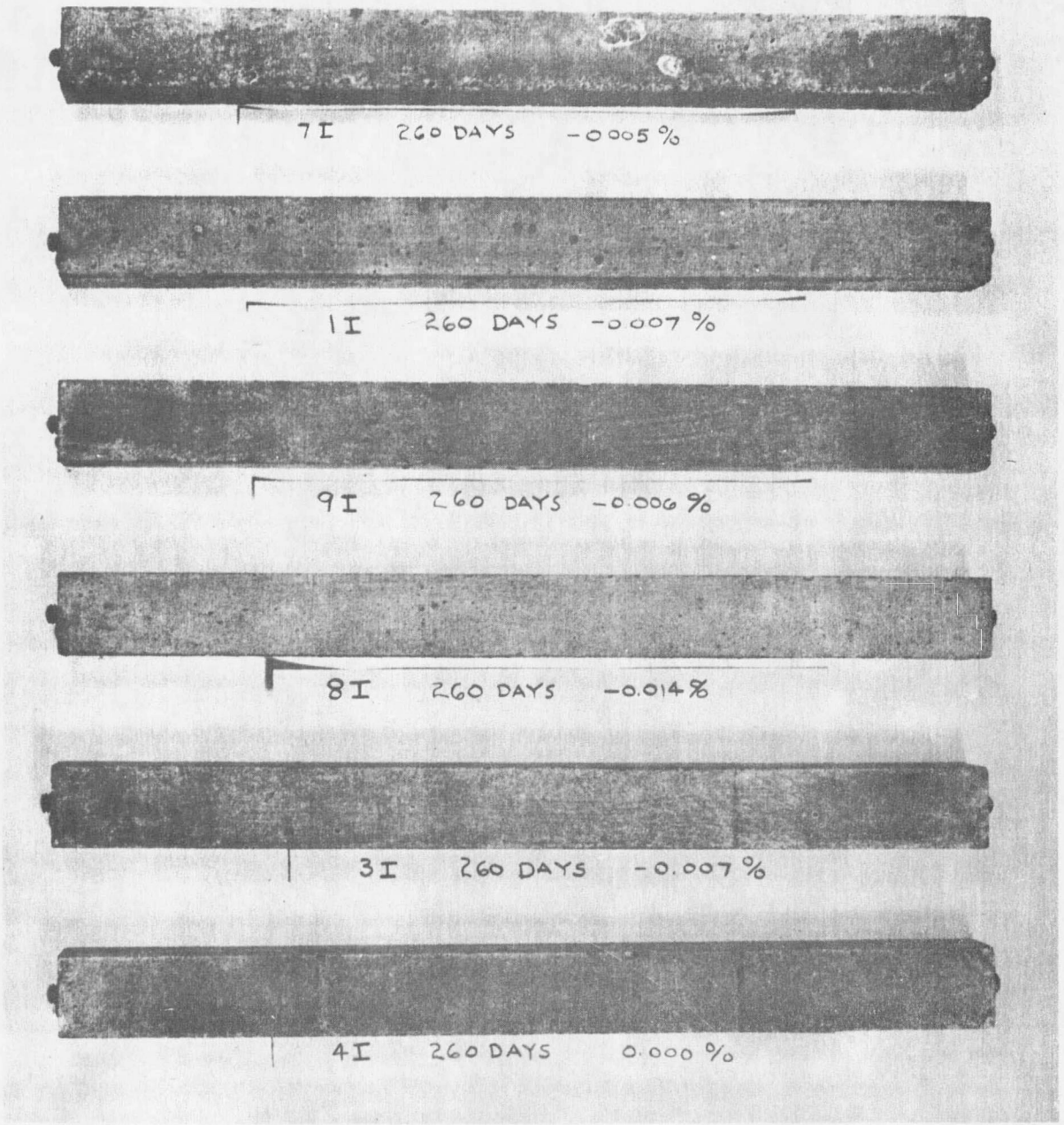


Figure 19 - Surface Appearance of Type I Cement Mortar Bars

is adjacent to the air void. The particle is the same color as the surrounding mortar and is not readily distinguishable in the photograph. Figure 20b is an air void half filled with silica gel. This cross-section specimen was taken from a bar made with aggregate No. 7 and Type I cement. The source of the gel is not known.

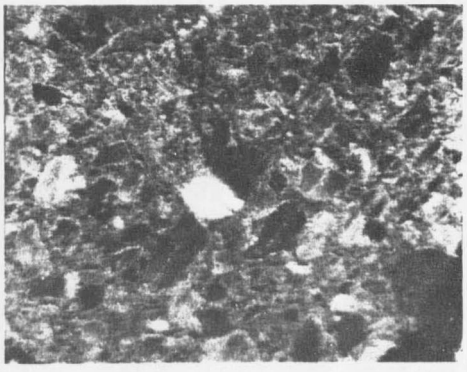


Fig. 20a Gel deposit (white area in center of photograph) Bar No. 4I-1

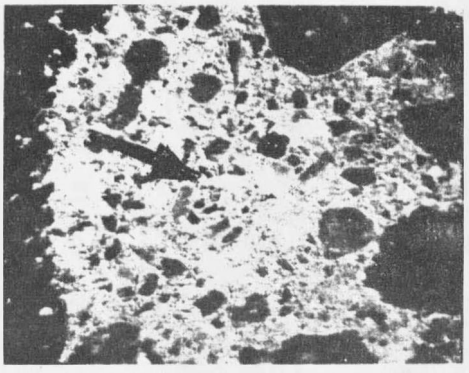


Fig. 20b Gel deposit (white area in center of photograph) Bar No. 7I-1

Figure 20 - Air Voids Partially Filled with Silica Gel-- Mortar bars were made with Type I cement (0.39 per cent total alkalies)

It should be mentioned that these cements with 0.39 per cent total alkalies or less demonstrated their ability to effectively prevent the expansive reaction when used with the known reactive aggregates Nos. 1, 3, 4 and 7. These test

results, however, did not establish that expansive reaction would be effectively prevented with these aggregates using 0.6 per cent total alkalies (the commonly accepted limits). In view of the results just presented, it would be difficult to predict what the effect of cements with 0.6 per cent total alkalies would be. This would be only 0.28 per cent total alkalies less than the 0.88 per cent total alkalies which produced the expansions represented by the curves designated H in Figures 14, 15, 16 and 17. It appears that if 0.6 per cent total alkalies were effective, the margin of safety would be unfavorably small.

The pozzolans were found to be effective in the mortar bar tests to prevent expansion when used with high alkali cement and each of aggregates Nos. 1, 3, 4 and 7.

The 30 per cent fly ash replacements (curves designated HC30 in Figures 14, 15, 16, and 17) caused less expansion than the 20 per cent fly ash replacements (HC20), while the 20 per cent pozzolan "A" replacements (HT20) produced generally less, or equal to, the amount of expansion caused by both percentages of fly ash replacements.

Figure 21 shows the surface appearance of the mortar bars made with the two percentages of fly ash replacements. The approximate amount of silica gel spots per unit area seem to agree with both the resulting expansions and the percentage

of pozzolan replacement.

Figure 22 shows the surface appearance of the mortar bars made with 20 per cent pozzolan "A". There appears to be less gel spots on the surface of these bars than the 30 per cent fly ash bars. The evidence found suggests that pozzolan "A" contains a relatively higher reactive silica than the fly ash. In addition, Table V, page 57 shows that pozzolan "A" contains 19 per cent more SiO_2 than fly ash.

It was noted that the pozzolans did not prevent surface pop-outs from occurring in aggregate No. 4, but did reduce the amount of pop-outs per mortar bar from what was observed on the bars containing aggregate No. 4 and high alkali cement.

Lerch (15) found that the effectiveness of a pozzolan depended on the degree of reactivity of the reactive material in the pozzolan, and that temperature made little difference for a highly reactive material. The favorable results obtained with these pozzolans under the standard mortar bar test are not conclusive evidence, but they do indicate potentially good additives which can only be justified by additional testing.

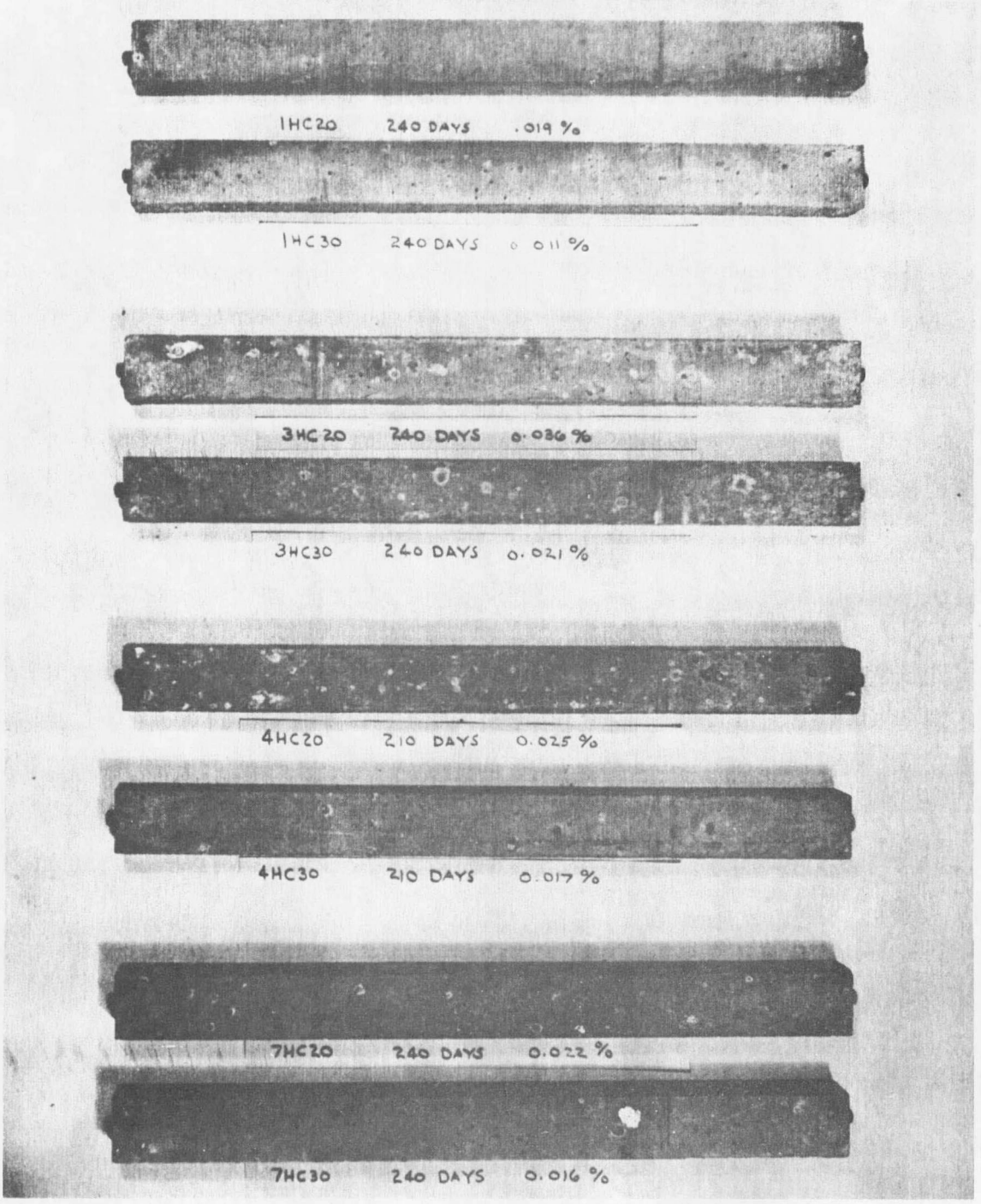


Figure 21 - Surface Appearance of Mortar Bars Containing Fly Ash

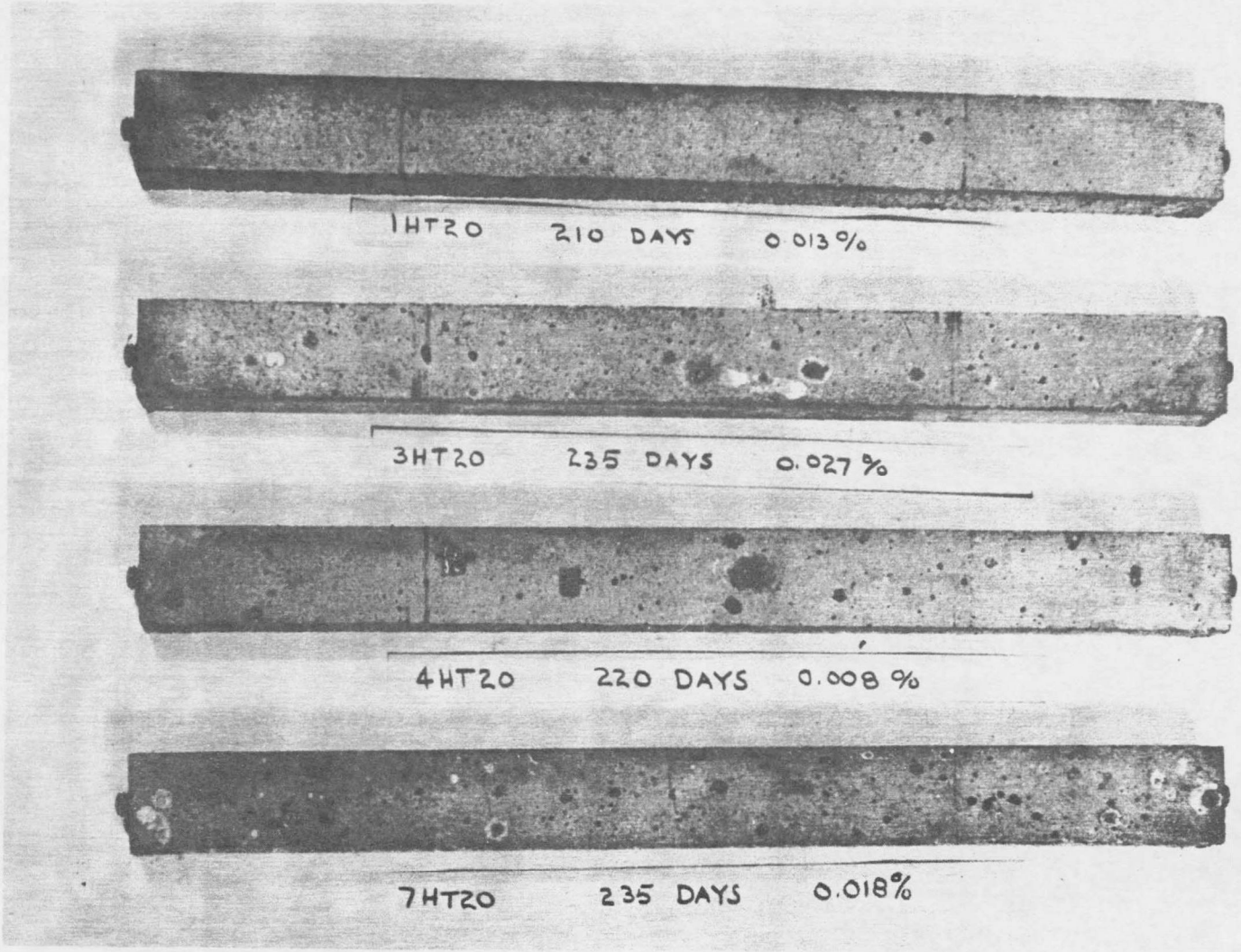


Figure 22 - Surface Appearance of Mortar Bars Containing Pozzolan "A"

CHAPTER V

SUMMARY AND CONCLUSIONS

Summary of Test Results

Table XIII presents a summary of the potential reactivity of the six aggregates found by the three tests methods.

The effectiveness of low alkali cements and pozzolans in preventing excessive mortar bar expansions are summarized in Table XIV.

TABLE XIII

REACTIVITY OF THE AGGREGATES WHEN USED WITH HIGH ALKALI CEMENT

Test Method	Agg. No. 1	Agg. No. 3	Agg. No. 4	Agg. No. 7	Agg. No. 8	Agg. No. 9
Mortar Bar	Border-line	Reactive	Reactive	Border-line	Non-reactive	Non-reactive
Chemical	Reactive	Highly Reactive	Reactive	Highly Reactive	Highly Reactive	Border-line
Petro-graphic	Very Possible	Reactive	Very Possible	Very Possible	Possible	Unlikely
CONCLU-SIONS	Reactive	Reactive	Reactive	Reactive	Possibly Reactive	Non-reactive

TABLE XIV

EFFECTIVENESS OF LOW ALKALI CEMENTS AND POZZOLANS IN COUNTERACTING EXCESSIVE MORTAR BAR EXPANSION

	Agg. No. 1	Agg. No. 3	Agg. No. 4	Agg. No. 7
Types I, II & V Cements 0.39% Total Alkalies or Less	Very Effective	Very Effective	Very Effective	Very Effective
RELATIVE EFFECTIVENESS OF POZZOLANIC ADDITIONS				
	Agg. No. 1	Agg. No. 3	Agg. No. 4	Agg. No. 7
Fly Ash-20%	Effective	Effective	Effective	Effective
Fly Ash-30%	Most Effective	Most Effective	Effective	Most Effective
Pozzolan "A" 20%	Effective	Effective	Most Effective	Effective

The reactive materials found present, and additional information concerning the nature of the aggregates are summarized for each aggregate as follows:

Aggregate No. 1: The reactive constituents are andesites and acid to intermediate volcanics with glass. This aggregate caused slight reactions, but no expansion in mortar bars containing the low

alkali cements.

Aggregate No. 3: The reactive constituents are rhyolites and trachytes with volcanic glass, opal opaline chert, chalcedonic chert, and some acid to intermediate volcanics with no glass. This aggregate has the highest degree of reactivity of the six aggregates tested. Slight reaction, but no expansion was encountered for mortar bars containing low alkali cements.

Aggregate No. 4: The reactive constituents are opal, partly crystallized opal, chalcedony, and possibly some acid volcanics. The opal rocks appear to be the major cause of mortar bar expansion. The opal caused a large amount of surface pop-outs, and this amount was reduced only slightly for mortar bars containing the pozzolans. The opal appears to react, but is not expansive when used in mortar bars with low alkali cements.

Aggregate No. 7: The reactive constituents are crystallized opal, chalcedonic chert, and possibly some acid to intermediate volcanics. Some zeolites were found present. This aggregate experiences some reaction, but is not expansive when used in mortar bars with low alkali cements.

Aggregate No. 8: The reactive constituents are possibly chalcedonic cherts, rhyolite and trachytes with volcanic glass and possibly some acid to intermediate volcanics without glass. The relatively high percentage of material passing the 200 sieve size in this aggregate can possibly cause pozzolanic action.

Aggregate No. 9: Some acid to intermediate volcanics with glass are probably reactive, but the amount appears to be small enough to avoid excessive expansion in mortar bars. The dolomite found present could cause a possible interference in the chemical test.

GENERAL CONCLUSIONS

The results obtained by the three test methods to deter-

mine the potential reactivity of an aggregate source clearly indicate that the true nature of the aggregate being tested cannot be concluded on the basis of one test method alone. The combined evidence obtained from the three test methods provided a basis to make relatively sound conclusions about the potential reactivity of the fine aggregates from aggregate sources Nos. 1, 3, 4, 7 and 9.

An apparent weakness in the tests was a consequence of the reactivity displayed by the basalt aggregate. The chemical tests indicated that aggregates Nos. 3 and 7 possessed a pessimum proportion. Fortunately, in the end results, the pessimum tests using the basalt aggregate were not actually necessary for these two aggregates, since the corresponding mortar bar test using the aggregates in their entirety did produce excessive expansions. The pessimum tests for aggregate No. 8 would probably have been more informative if the basalt had been inert, however, the pozzolanic action that appeared to be a possibility in this aggregate may have been the major cause for the questionable results obtained.

The pessimum tests were conducted using only two different percentages of inert aggregate replacements (50 and 25 per cent). Thus the aggregates were tested under three proportions; 100 per cent, 75 per cent, and 50 per cent. It

would have been desirable to lessen these percentage intervals and to cover the entire percentage range, however, storage space was not available for the series of mortar bars that would have been required.

The overall efficiency of the laboratory tests could have been improved had the sequence of testing been reversed; that is, if the chemical and petrographic tests results on the six aggregates were obtained first, many of the treatments used in the mortar bar test would not have been necessary. For example, this would have made more space available for a more thorough investigation into particular aggregates found by the chemical tests to have pessimum values.

RECOMMENDATIONS FOR FURTHER STUDY

More information is needed to evaluate the potential reactivity of aggregate source No. 8. This aggregate should be tested by the mortar bar method using artificially graded aggregate (eliminating material passing the 100 sieve size), and replacing the base aggregate with graded Ottawa sand in the percentages of 90, 80, 60, 40 and 20, by weight. The materials passing the 100 sieve size should be checked for their pozzolanic action. This could be done with the mortar bar method using the material in combination with Ottowa sand, 50 per cent or more Pyrex Glass, and high alkali cement.

A corresponding series of outdoor exposure specimens would be desirable for the six aggregate sources. These should include the coarse aggregate. The outdoor specimens should be rectangular prisms of suitable size fitted with gage points to enable measurements of length changes.

The fly ash and pozzolan "A" should also be included in the test series since their effectiveness showed considerable promise in the mortar bar tests.

APPENDIX

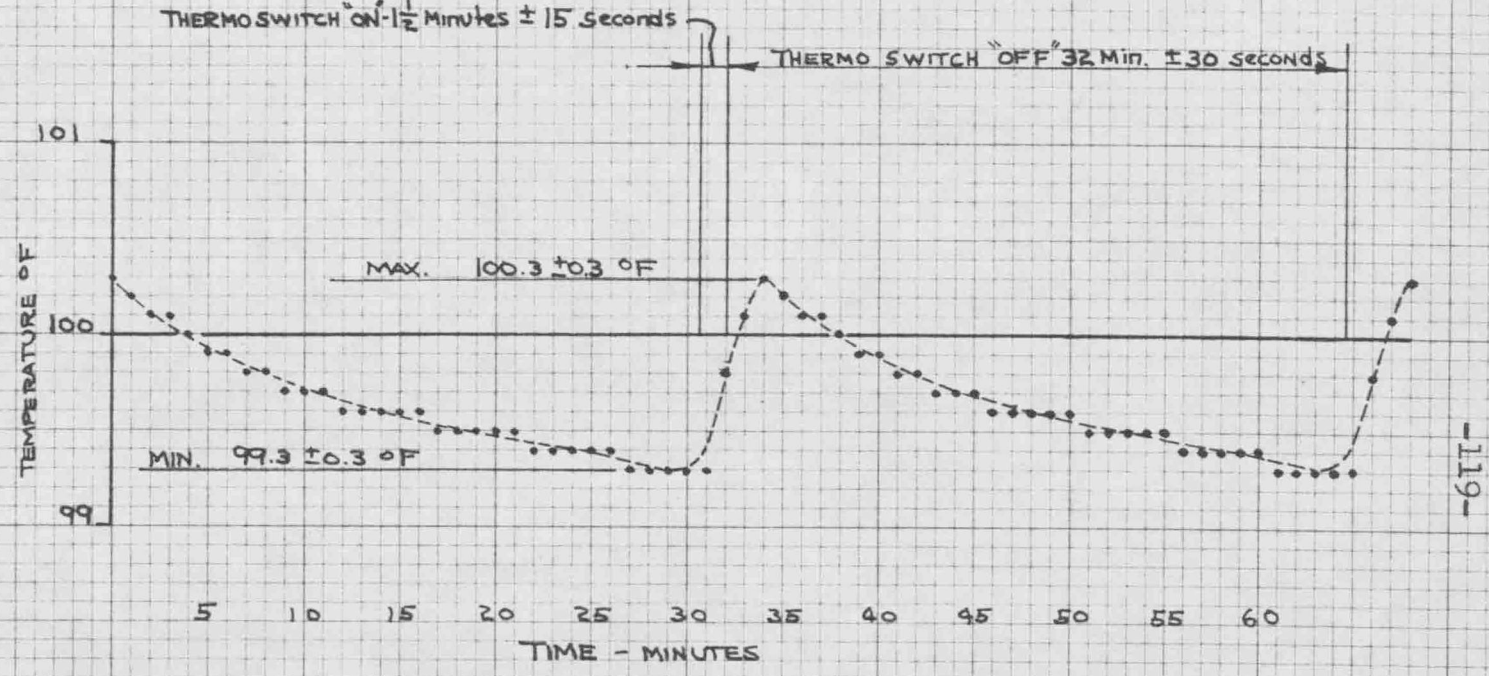


Figure 23 - GRAPH SHOWING TEMPERATURE FLUCTUATIONS in 100°F STORAGE CABINET

FINE AGGREGATE NO. 1

U.S. No.	Sample Weights	Per Cent	Per Cent Cumulative Weights
4	.3	.05	.05
6	24.2	3.98	4.03
8	40.1	6.60	10.63
12	47.1	7.58	18.21
16	40.6	6.77	24.98
20	61.0	10.05	35.03
30	67.6	11.12	46.15
40	71.9	11.81	57.96
50	85.3	14.00	71.96
70			
100	120.5	19.70	91.66
140	24.2	3.98	95.64
200	17.6	2.89	98.53
PASS 200	8.4	1.38	99.91
Totals	608.8	99.91	

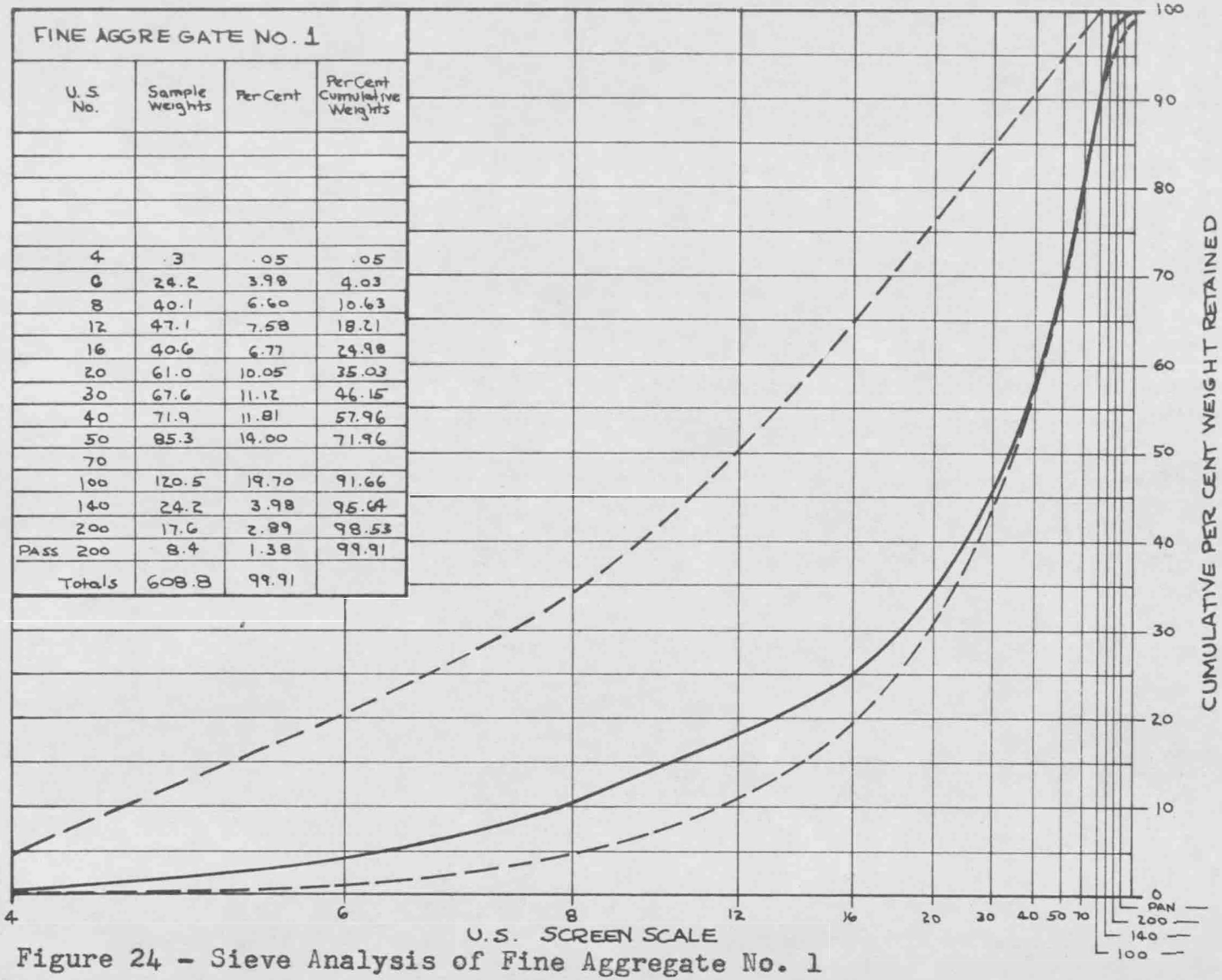


Figure 24 - Sieve Analysis of Fine Aggregate No. 1

FINE AGGREGATE NO. 3

U. S. No.	Sample Weights	Per Cent	Per Cent Cumulative Weights
4	18.9	2.78	2.78
6	85.6	12.99	15.77
8	61.7	9.34	25.11
12	58.2	8.83	33.94
16	35.1	5.33	39.27
20	40.6	6.15	45.42
30	36.7	5.56	50.98
40	56.3	8.58	59.56
57	103.3	15.65	75.21
70			
100	133.1	20.15	95.36
140	15.0	2.29	97.65
200	9.6	1.45	99.10
PASS 200	5.8	0.90	100.00
Totals	659.9		

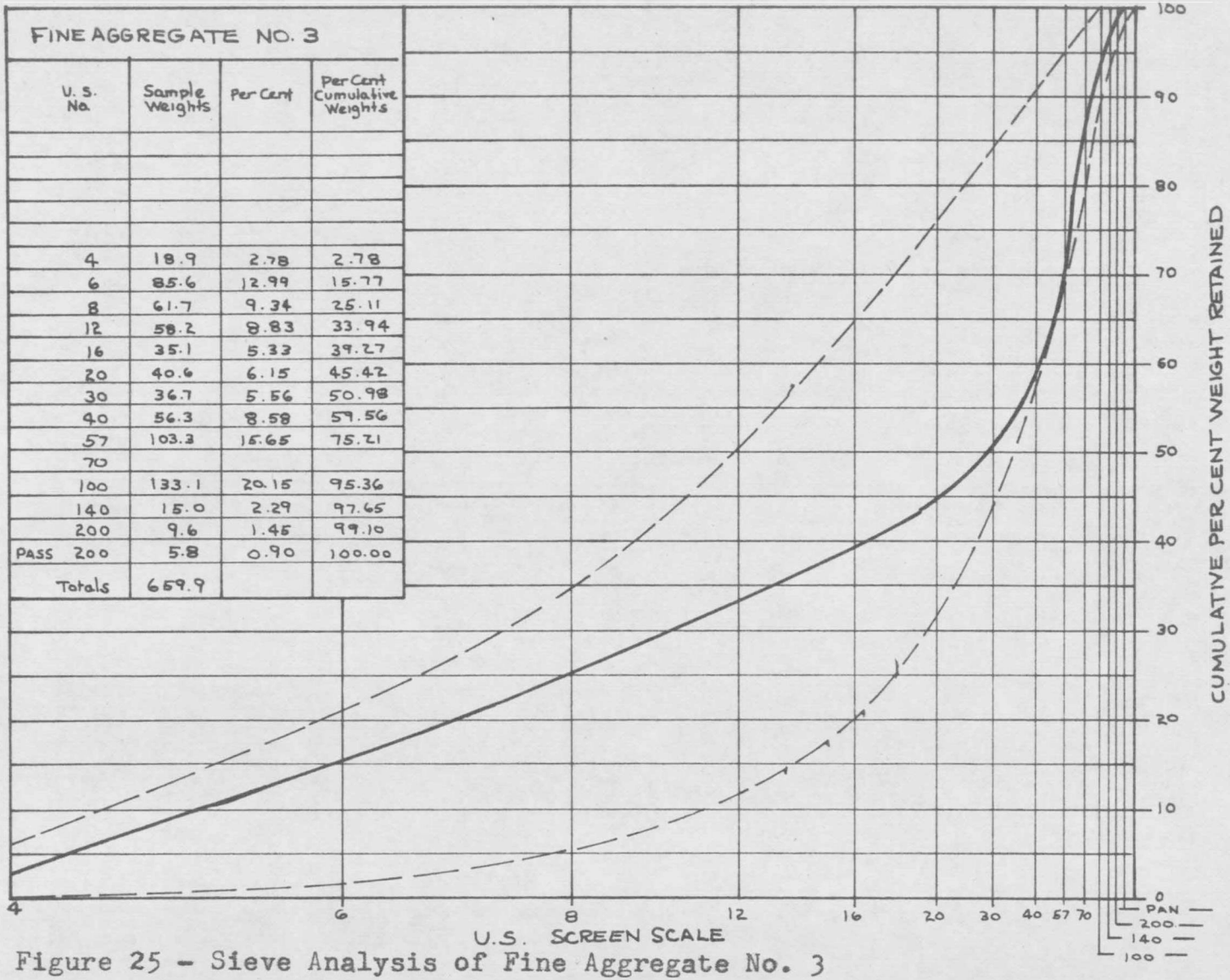


Figure 25 - Sieve Analysis of Fine Aggregate No. 3

FINE AGGREGATE NO. 4

U.S. No.	Sample Weights	Per Cent	Per Cent Cumulative Weights
4	0	0	0
6	56.5	9.48	9.48
8	47.1	7.90	17.38
12	41.3	6.94	24.32
16	48.9	8.20	32.52
20	75.9	12.70	45.22
30	108.6	18.20	63.42
40	85.2	14.30	77.72
50	53.2	8.95	86.67
70			
100	52.4	8.79	95.46
140	9.1	1.53	96.99
200	6.0	1.01	98.00
PASS 200	12.7	2.13	100.13
Totals	596.9	100.13	

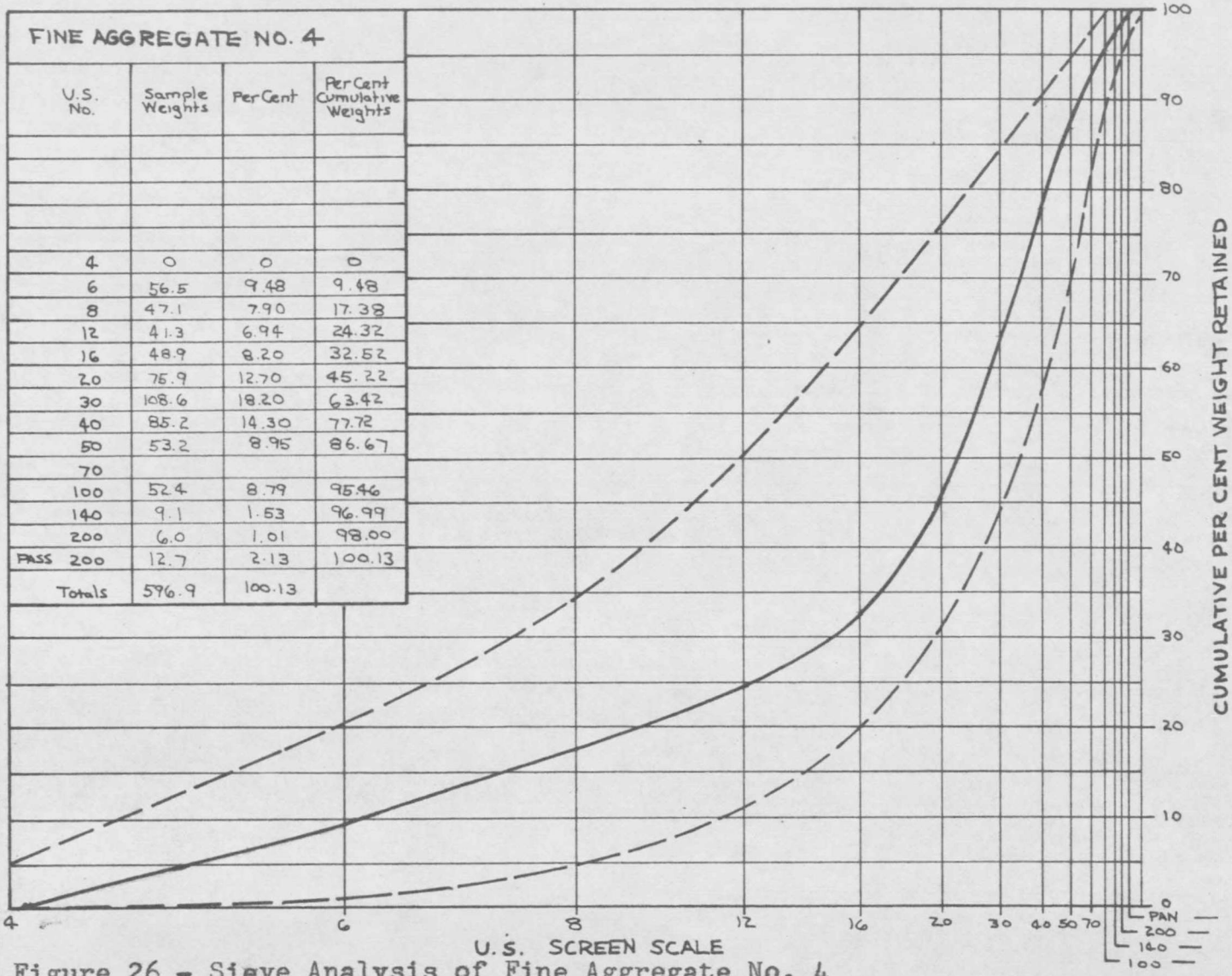


Figure 26 - Sieve Analysis of Fine Aggregate No. 4

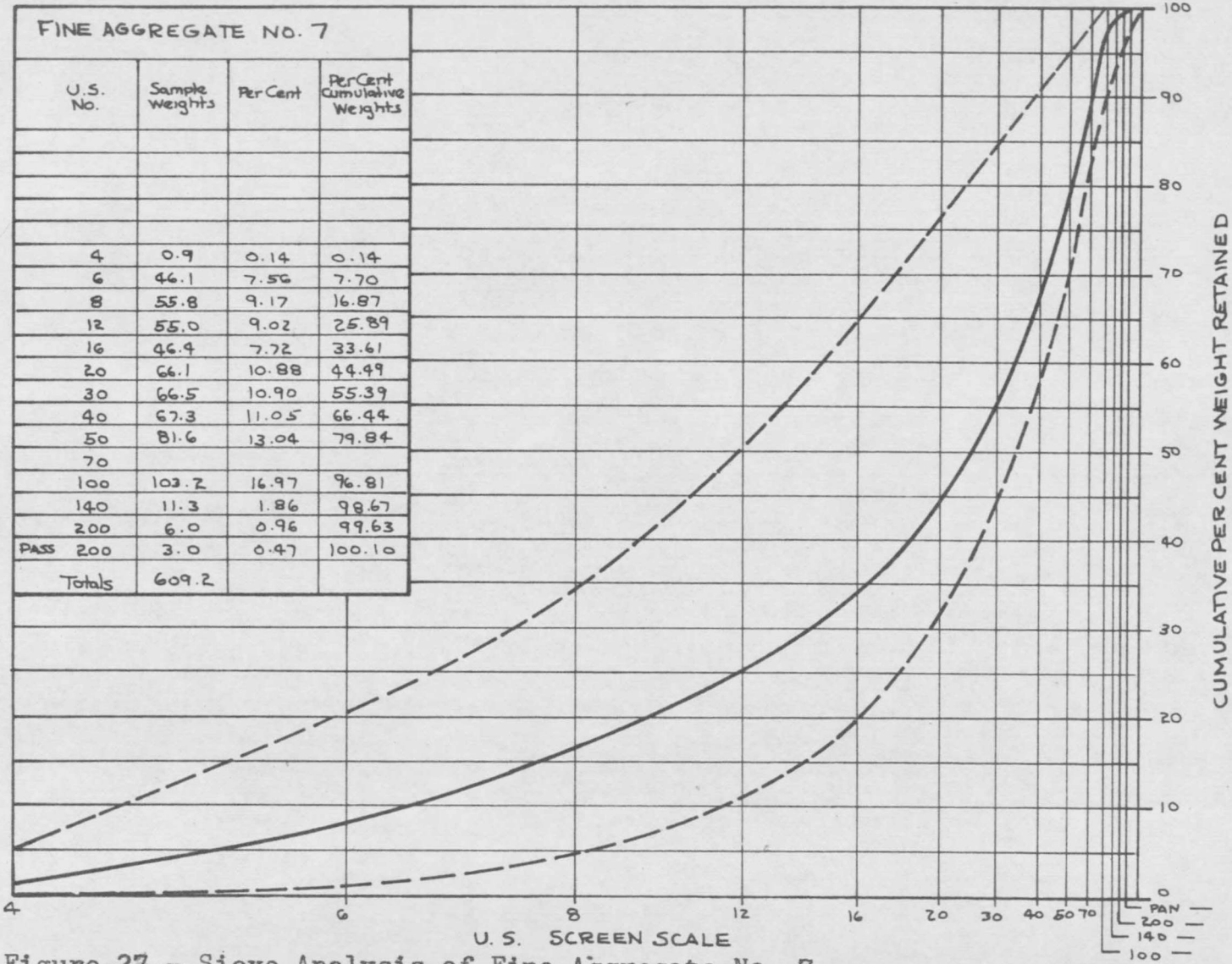


Figure 27 - Sieve Analysis of Fine Aggregate No. 7

FINE AGGREGATE NO. 8

U.S. No	Sample Weights	Per Cent	Per Cent Cumulative Weights
4	0	0	0
6	32.00	4.78	4.78
8	38.60	5.76	10.54
12	42.80	6.39	16.93
16	40.10	5.98	22.91
20	74.20	11.05	33.96
30	76.20	11.32	45.28
40	80.50	12.00	57.28
50	91.80	13.64	70.97
70			
100	109.3	16.30	87.27
140	21.3	3.18	90.45
200	23.1	3.44	93.89
PASS 200	40.9	6.09	99.98
Totals	670.8		

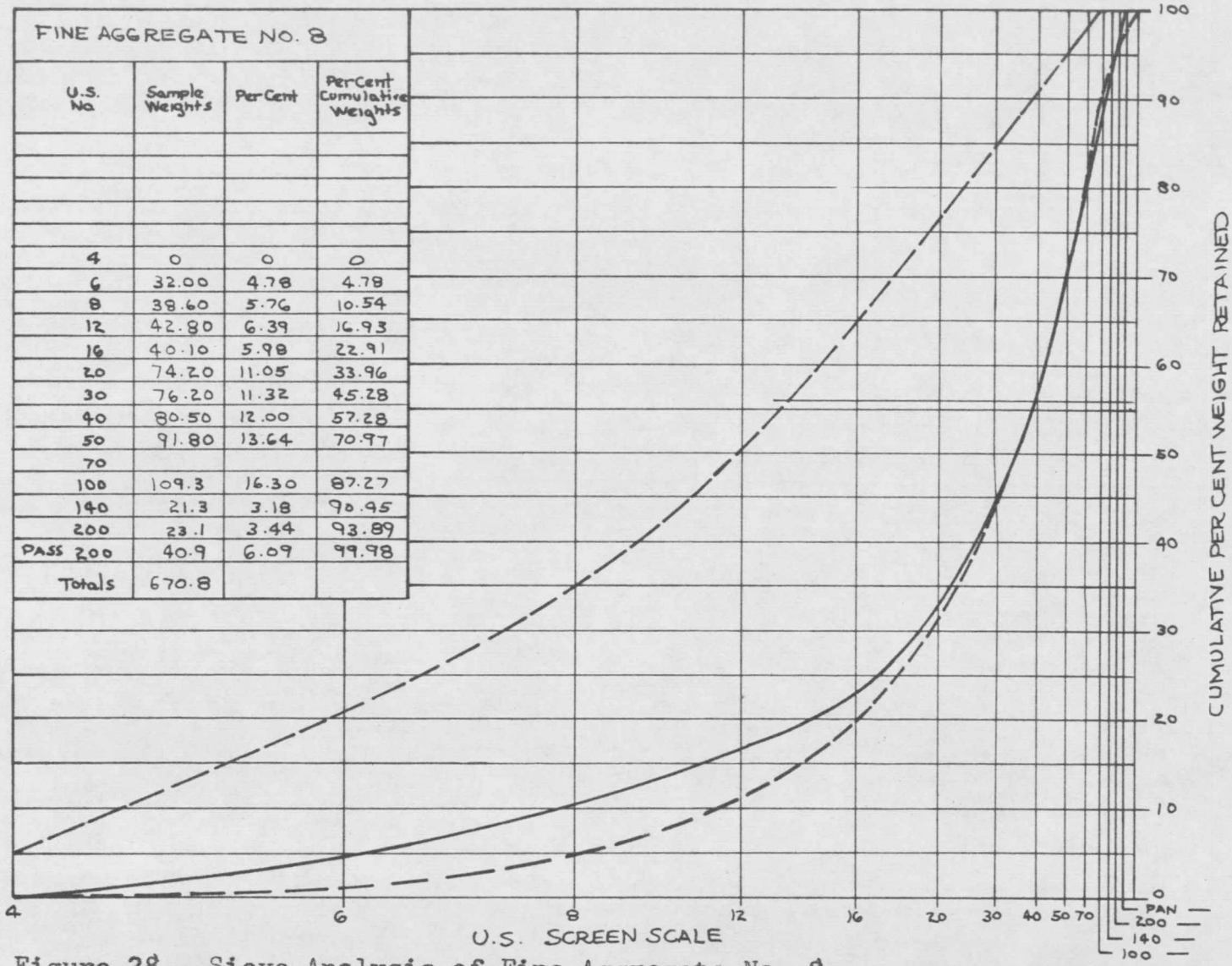


Figure 28 - Sieve Analysis of Fine Aggregate No. 8

FINE AGGREGATE NO. 9

U.S. NO.	Sample Weights	Per Cent	Per Cent Cumulative Weights
4	5.5	1.00	1.00
6	48.6	8.76	9.76
8	37.1	6.77	16.53
12	38.7	7.05	23.58
16	29.4	5.35	28.93
20	42.6	7.77	36.70
30	43.5	7.94	44.64
40	55.3	10.08	54.72
50	96.9	17.65	72.37
70			
100	122.7	22.35	94.72
140	13.7	2.50	97.22
200	9.9	1.81	99.03
PASS 200	5.3	0.97	100.00
Totals	549.2		

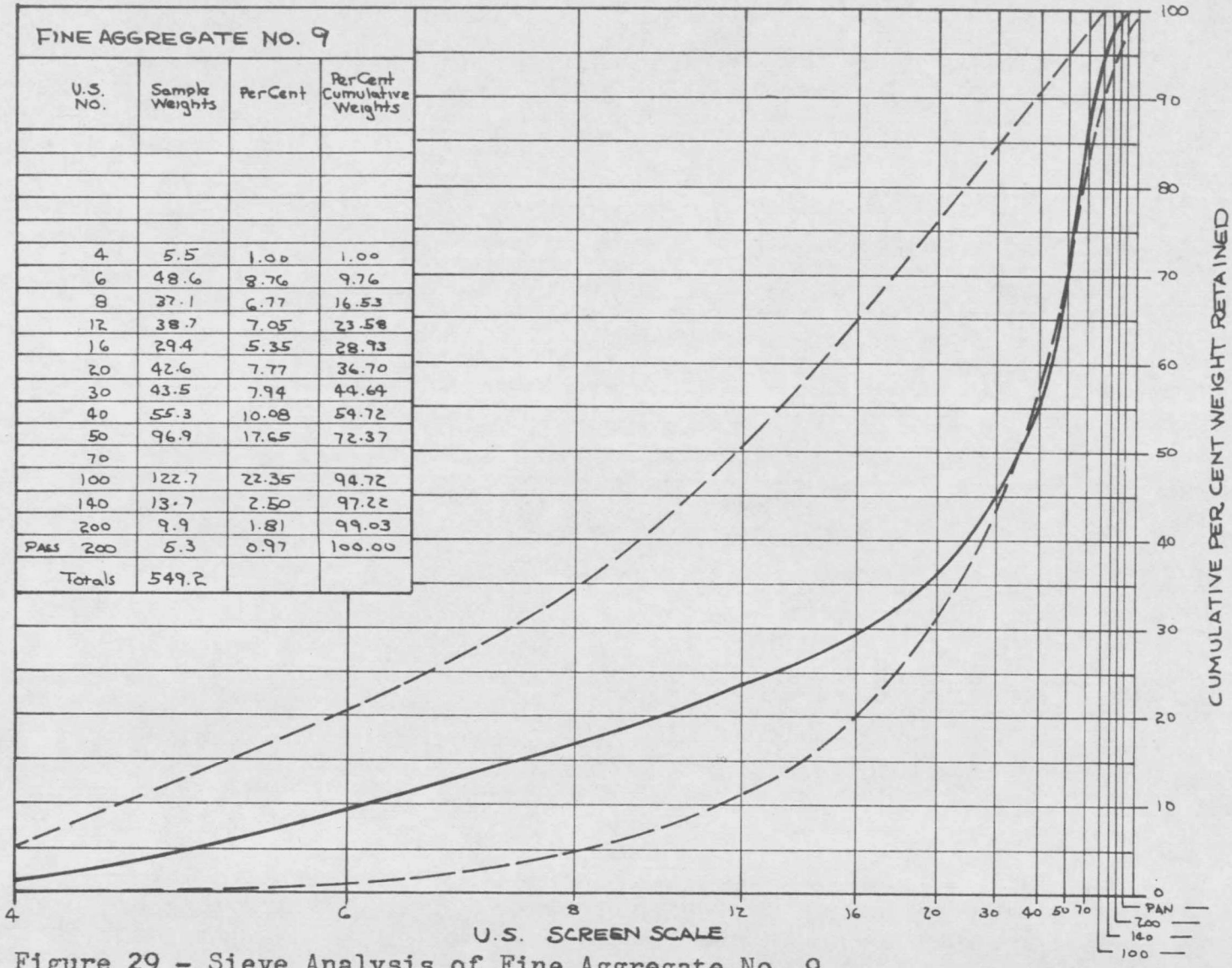


Figure 29 - Sieve Analysis of Fine Aggregate No. 9

TABLE XV

ASTM C289 - CHEMICAL TEST DATA

Agg. No.	Test Run	Dissolved Silica			Reduction in Alkalinity				
		C	V	Sc	V_2	V_3	V_1	N	Rc
1	1	0.265	2	265	15.7	----	20	0.0505	90.9
	2	0.250	2	250	15.9	----	20	0.0505	80.8
	3	0.265	2	265	15.8	----	20	0.0505	85.88
	Blank	0.000	2	---	----	17.5	20	0.0505	-----
	1	0.270	2	270	16.8	----	20	0.0484	58.14
	2	0.250	2	250	16.0	----	20	0.0484	96.90
	3	0.275	2	275	16.5	----	20	0.0484	72.67
	Blank	-----	2	---	----	18.0	20	0.0484	-----
3	1	0.374	3	250	17.0	----	20	0.0494	138
	2	0.355	3	237	17.1	----	20	0.0494	133
	3	0.345	3	230	17.1	----	20	0.0494	133
	Blank	-----	3	---	----	19.8	20	0.0494	-----
	1	0.355	3	237	17.1	----	20	0.0494	108
	2	0.355	3	237	17.0	----	20	0.0494	114
	3	0.320	3	213	16.3	----	20	0.0494	148
	Blank	-----	3	---	----	19.3	20	0.0494	-----
4	1	0.205	2	205	17.3	----	20	0.0505	55.55
	2	0.208	2	208	17.1	----	20	0.0505	65.65
	3	0.201	2	201	17.0	----	20	0.0505	70.70
	Blank	-----	-	---	----	18.4	20	0.0505	-----
	1	0.218	2	218	16.9	----	20	0.0505	65.65
	2	0.215	2	215	16.9	----	20	0.0505	65.65
	3	0.218	2	218	16.8	----	20	0.0505	70.70
	Blank	-----	-	---	----	18.2	20	0.0505	-----
7	1	0.33	1	660	16.9	----	20	0.5027	171
	2	0.30	1	600	16.8	----	20	0.5027	176
	3	0.28	1	560	16.7	----	20	0.5027	181
	Blank	----	-	---	----	20.3	20	0.5027	-----

TABLE XV (Continued)

Agg. No.	Test Run	Dissolved Silica			Reduction in Alkalinity				
		C	V	Sc	V_2	V_3	V_1	N	Rc
7	1	0.225	1	450	16.7	----	20	0.5027	191
	2	0.235	1	470	16.8	----	20	0.5027	186
	3	0.231	1	462	16.6	----	20	0.5027	196
	Blank	-----	-	---	----	20.5	20	0.5027	----
8	1	0.215	2	215	15.9	----	20	0.0505	126
	2	0.223	2	223	15.8	----	20	0.0505	131
	3	0.200	2	200	15.9	----	20	0.0505	126
	Blank	-----	-	---	----	18.4	20	0.0505	----
	1	0.175	2	175	16.4	----	20	0.0484	128
	2	0.185	2	185	16.5	----	20	0.0484	123.5
	3	0.175	2	175	15.5	----	20	0.0484	172.1
	Blank	-----	-	---	----	19.1	20	0.0484	----
9	1	0.300	3	200	16.5	----	20	0.0494	148
	2	0.300	3	200	16.3	----	20	0.0494	158
	3	0.270	3	180	15.8	----	20	0.0494	182
	Blank	-----	-	---	----	19.5	20	0.0494	----
	1	0.260	3	173	15.7	----	20	0.0505	161
	2	0.260	3	173	15.7	----	20	0.0505	161
	3	0.265	3	177	15.7	----	20	0.0505	161
	Blank	-----	-	---	----	18.9	20	0.0505	----
Basalt	1	0.158	1	316	16.4	----	20	0.0494	149
	2	0.162	1	324	16.4	----	20	0.0494	149
	3	0.150	1	300	16.2	----	20	0.0494	163
	Blank	-----	-	---	----	19.5	20	0.0494	----

Notes: Reduction in Alkalinity is taken to the phenolpthalein end point only.

TABLE XV (continued)

$$Sc = 20 \times \frac{100}{V} \times C$$

Sc = dissolved silica in millimoles per liter
C = dissolved silica in millimoles per liter as determined from photometer
V = milliliters of dilute solution used

$$Rc = \frac{20N}{V_1} (V_3 - V_2) \times 1{,}000$$

Rc = reduction in alkalinity in millimoles per liter
V_1 = milliliters of dilute solution used
V_3 = milliliters of HCL used to neutralize the blank
V_2 = milliliters of HCL used to neutralize the test sample
N = normality of HCL

TABLE XVI

PARTICLE COUNTS FOR FINE AGGREGATE NO. 3

CONSTITUENTS	Composition of Fractions on Sieves Shown Below											
	8		16		30		50		100		Passing 100	
	No.of Part.	Per Cent	No.of Part.	Per Cent	No.of Part.	Per Cent	No.of Part.	Per Cent	No.of Part.	Per Cent	No.of Part.	Per Cent
Quartz	---	----	---	----	150	48.4	100	33.0	108	36.4	125	42.1
Feldspar	---	----	---	----	63	20.3	77	25.4	72	24.2	47	15.8
Ferromags (amphibole & Pyroxene	---	----	---	----	4	1.3	5	1.6	14	4.7	13	4.4
Carbonates (mostly limestone)	---	----	2	0.7	1	0.3	---	----	---	----	---	----
Granitic	150	50.8	168	56.0	11	3.6	---	----	---	----	---	----
Sandstone	---	----	---	----	---	----	---	----	---	----	---	----
Siltstone & shale	2	0.7	1	0.3	---	----	---	----	---	----	---	----
Rhyolites & Trachytes	77	26.1	67	22.3	25	8.1	40	13.2	36	12.1	39	13.1
Andesites & Basalts	64	21.7	54	18.0	15	4.8	53	17.6	42	14.2	45	15.2
Chert	2	0.7	8	2.7	10	3.2	9	3.0	10	3.4	12	4.0
Rhyolite & Trachytes with Volcanic glass	---	----	---	----	---	----	3	1.0	5	1.7	3	1.0
Opal & Opaline Chert	---	----	---	----	---	----	11	3.6	1	0.3	3	1.0
Chalcedony & Chalcedonic Chert	---	----	---	----	31	10.0	5	1.6	9	3.0	10	3.4
TOTALS	295	100	300	100	310	100	303	100	297	100	297	100
Percentage of total fine aggregate		22.9		14.6		12.1		24.9		20.7		4.8

TABLE XVII

PARTICLE COUNTS FOR FINE AGGREGATE NO. 8

CONSTITUENTS	Composition of Fractions on Sieves Shown Below											
	8		16		30		50		100		Passing 100	
	No.of Part.	Per Cent	No.of Part.	Per Cent	No.of Part.	Per Cent	No.of Part.	Per Cent	No.of Part.	Per Cent	No.of Part.	Per Cent
Quartz	---	---	122	40.8	143	47.7	145	48.3	154	51.3	154	51.3
Feldspar	---	---	---	---	56	18.7	49	16.4	40	13.3	26	8.7
Ferromags (amphibole & Pyroxene)	---	---	5	1.7	---	---	21	7.0	20	6.7	8	2.7
Carbonates (mostly limestone)	63	20.9	41	13.7	35	11.7	30	10.0	20	6.7	28	9.3
Granitic	54	17.8	---	---	---	---	---	---	---	---	---	---
Sandstone	---	---	8	2.7	---	---	---	---	---	---	---	---
Siltstone & shale	159	52.7	92	30.7	19	6.3	---	---	---	---	---	---
Rhyolites & Trachytes	10	3.3	17	5.7	17	5.7	9	3.0	31	10.3	35	11.7
Andesite & Basalts	9	3.0	8	2.7	10	3.3	9	3.0	14	4.7	13	4.3
Chert	7	2.3	6	2.0	10	3.3	31	10.3	15	5.0	17	5.7
Rhyolite & Trachytes with Volcanic glass	---	---	---	---	---	---	---	---	3	1.0	9	3.0
Opal & Opaline Chert	---	---	---	---	---	---	---	---	---	---	---	---
Chalcedony & Chalcedonic Chert	---	---	---	---	10	3.3	6	2.0	3	1.0	10	3.3
TOTALS	302	100	299	100	300	100	300	100	300	100	300	100
Percentage of total fine aggregate		10.6		12.4		22.4		25.6		16.3		12.7

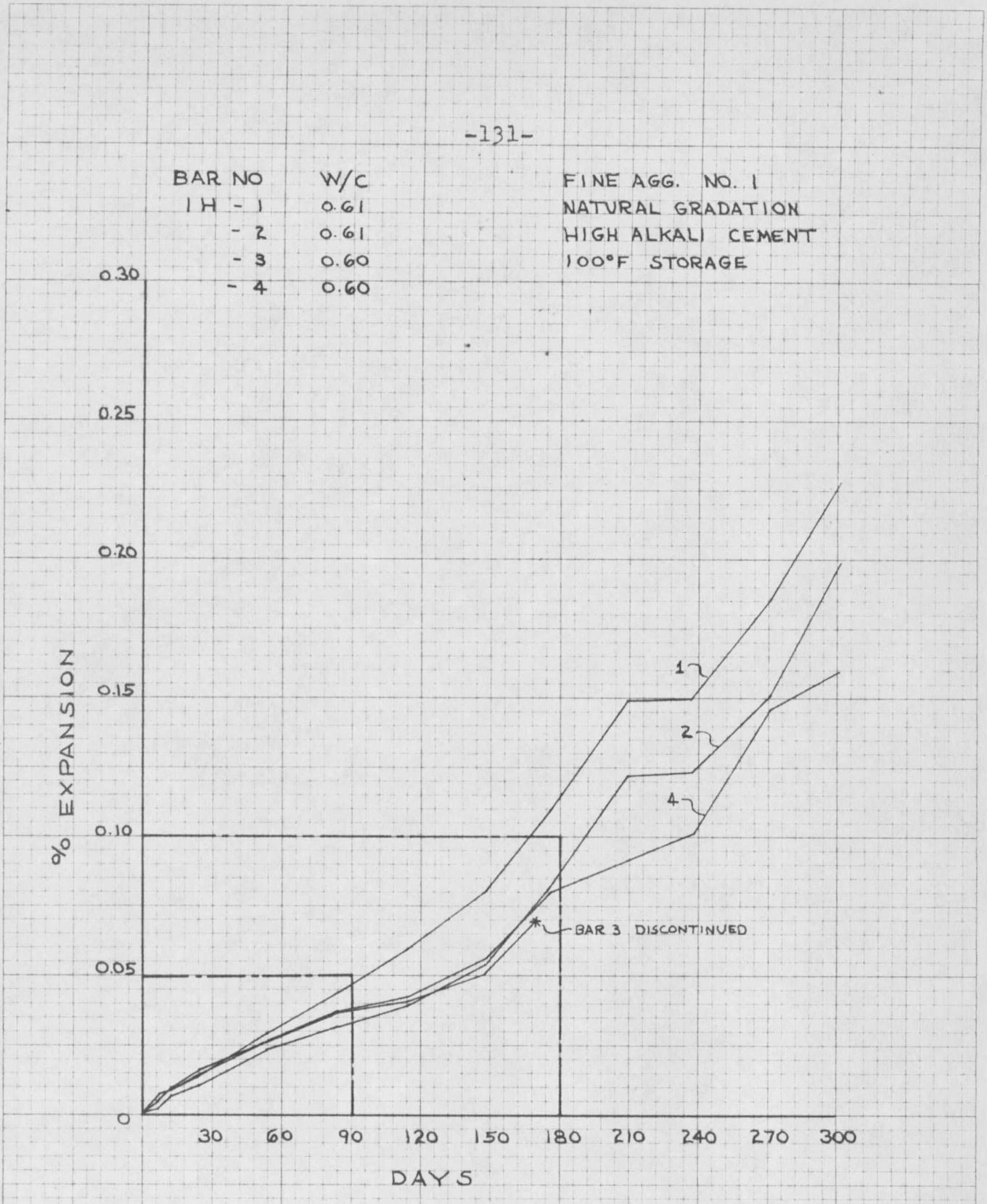


Figure 30 - Individual Mortar Bar Expansion Records

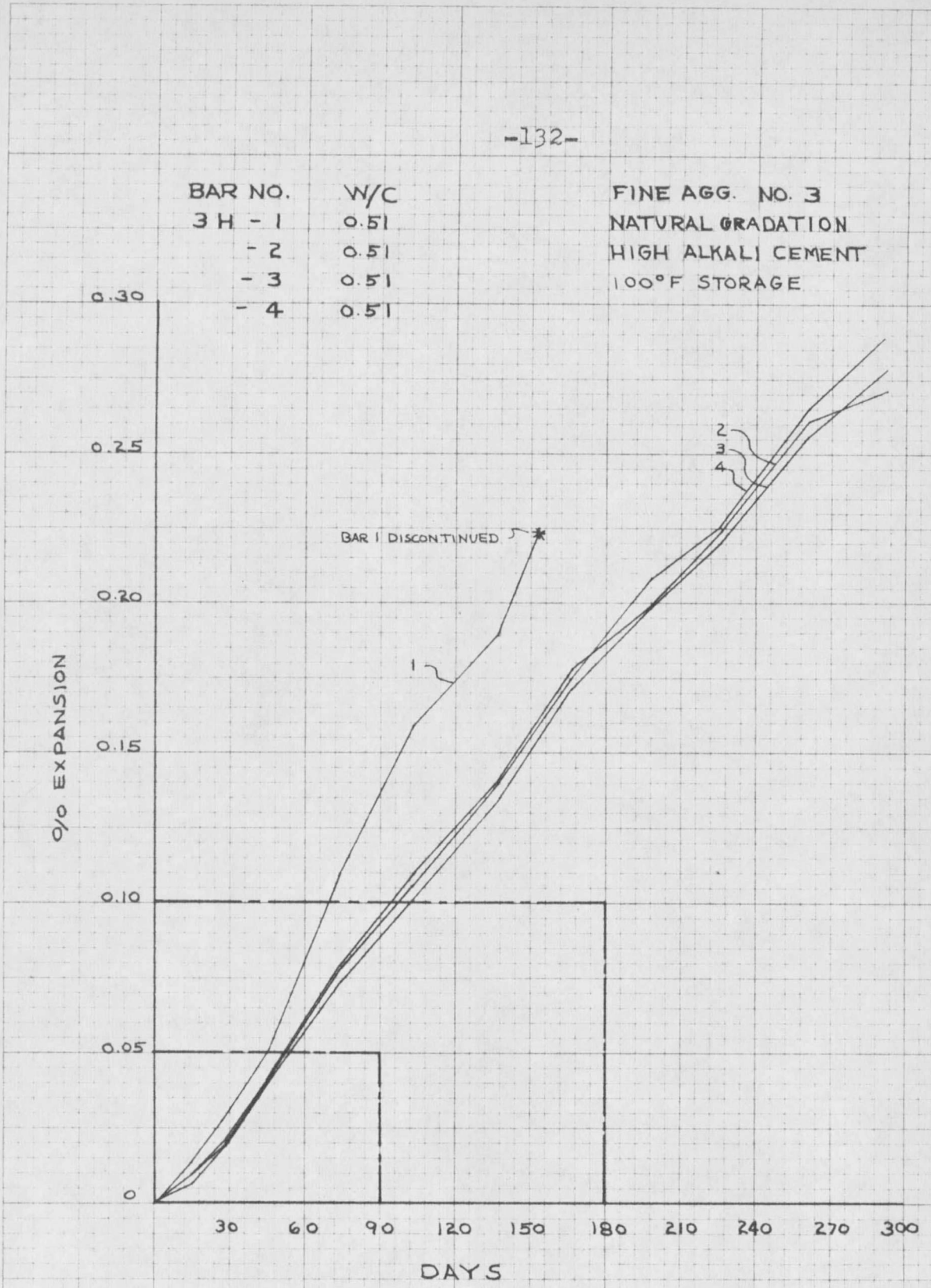


Figure 31 - Individual Mortar Bar Expansion Records

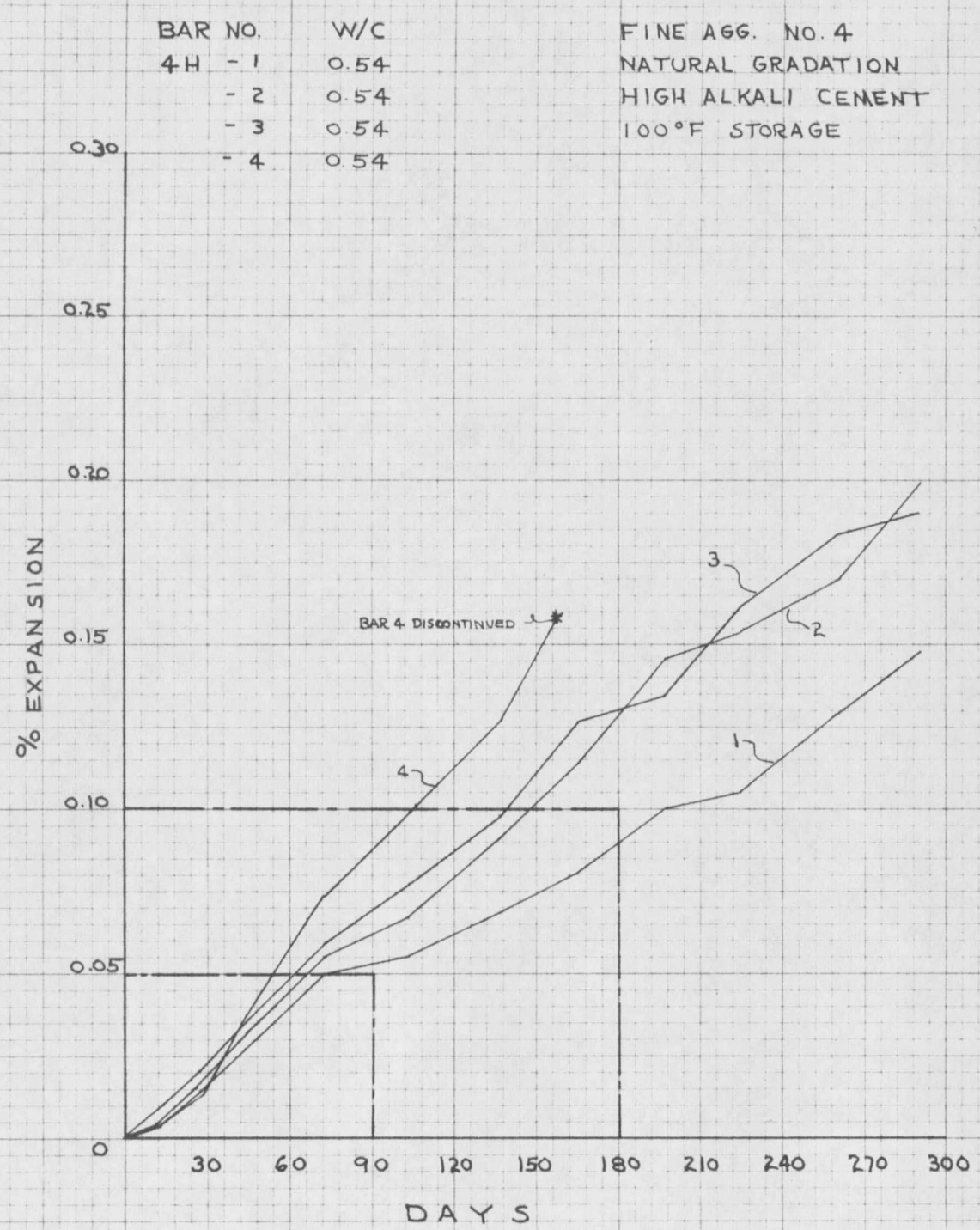


Figure 32 - Individual Mortar Bar Expansion Records

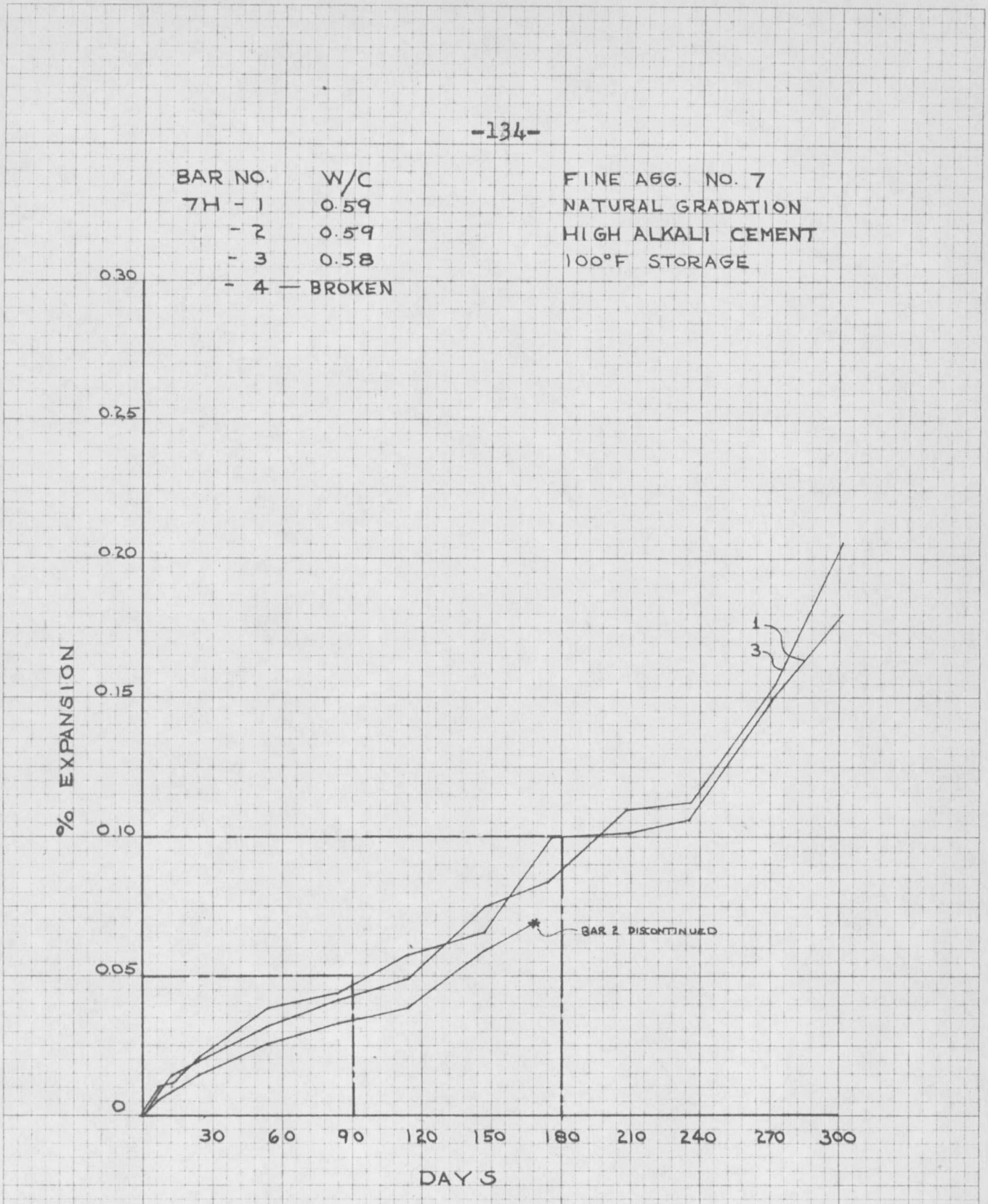
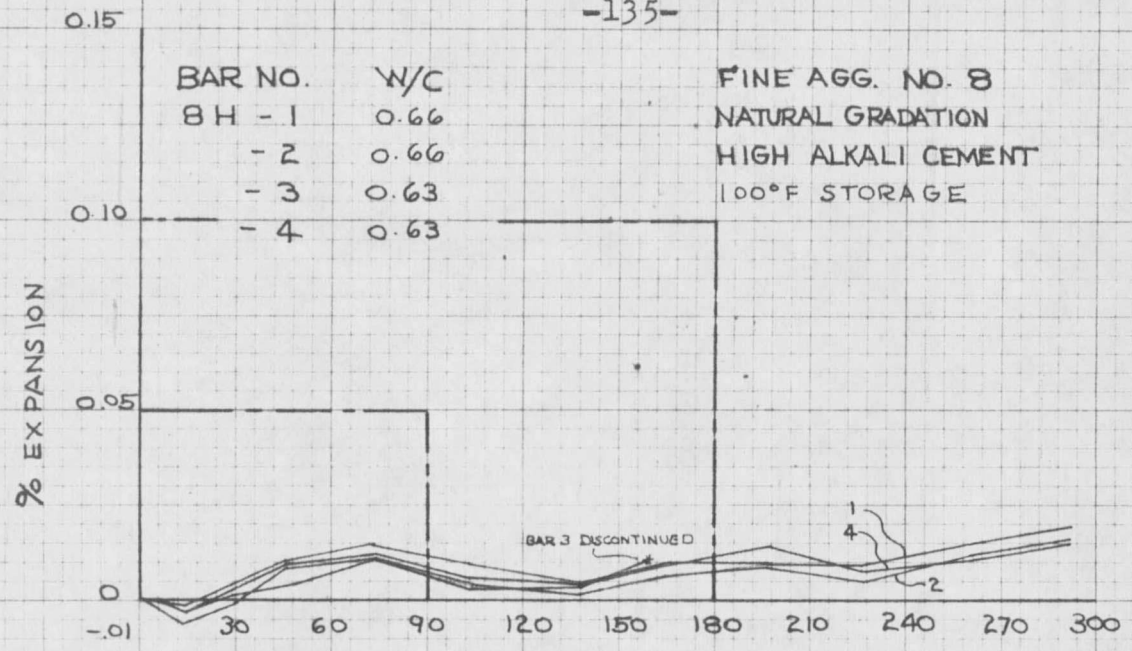


Figure 33 - Individual Mortar Bar Expansion Records



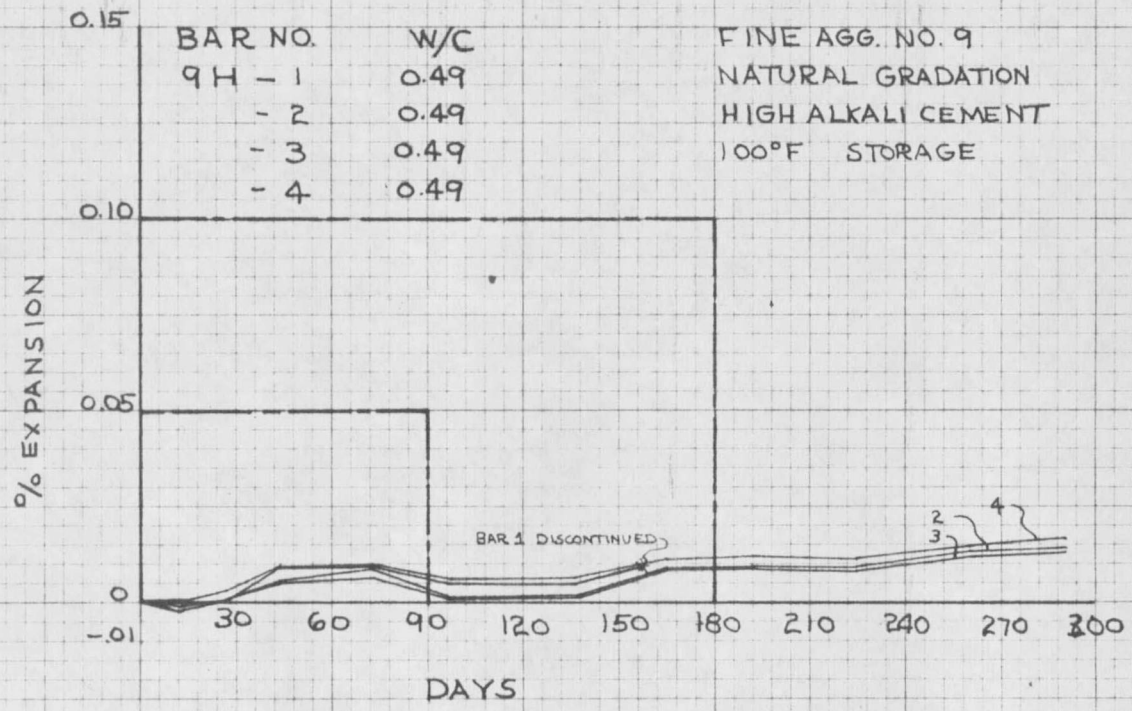
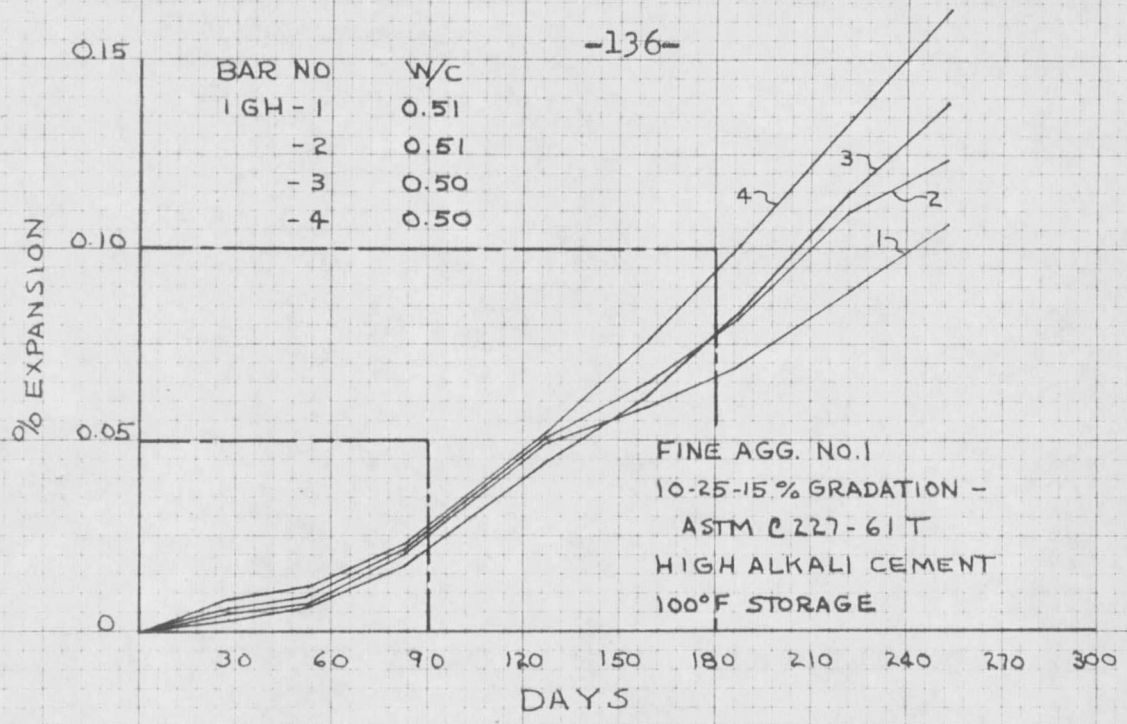


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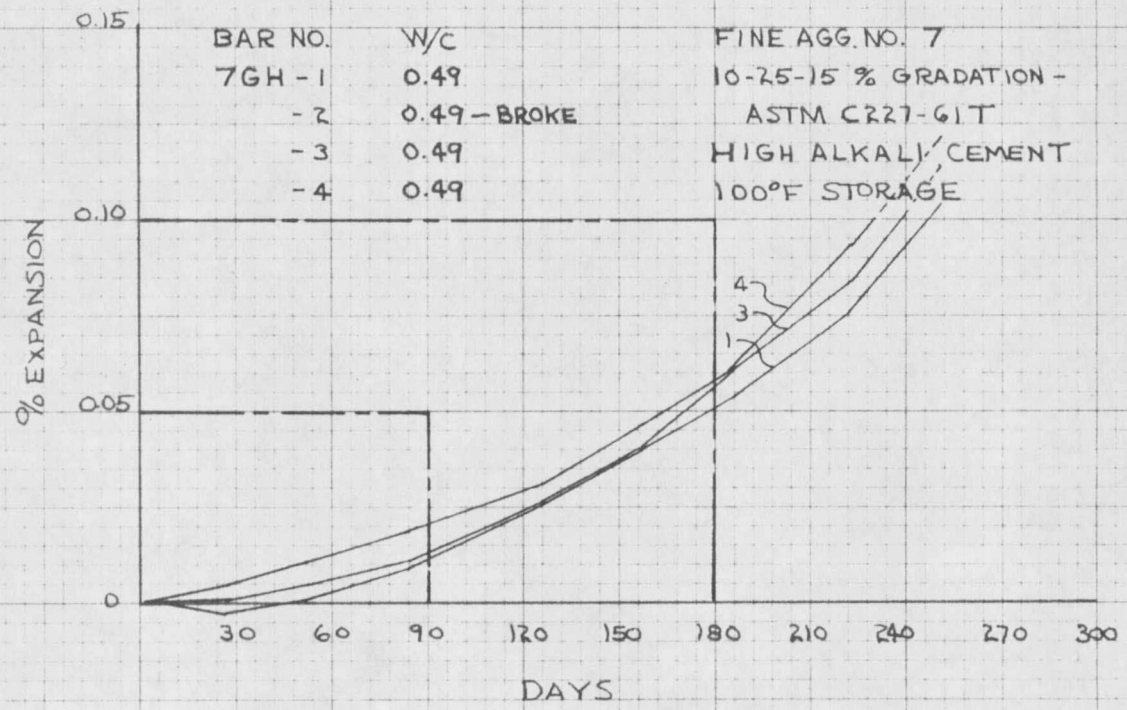


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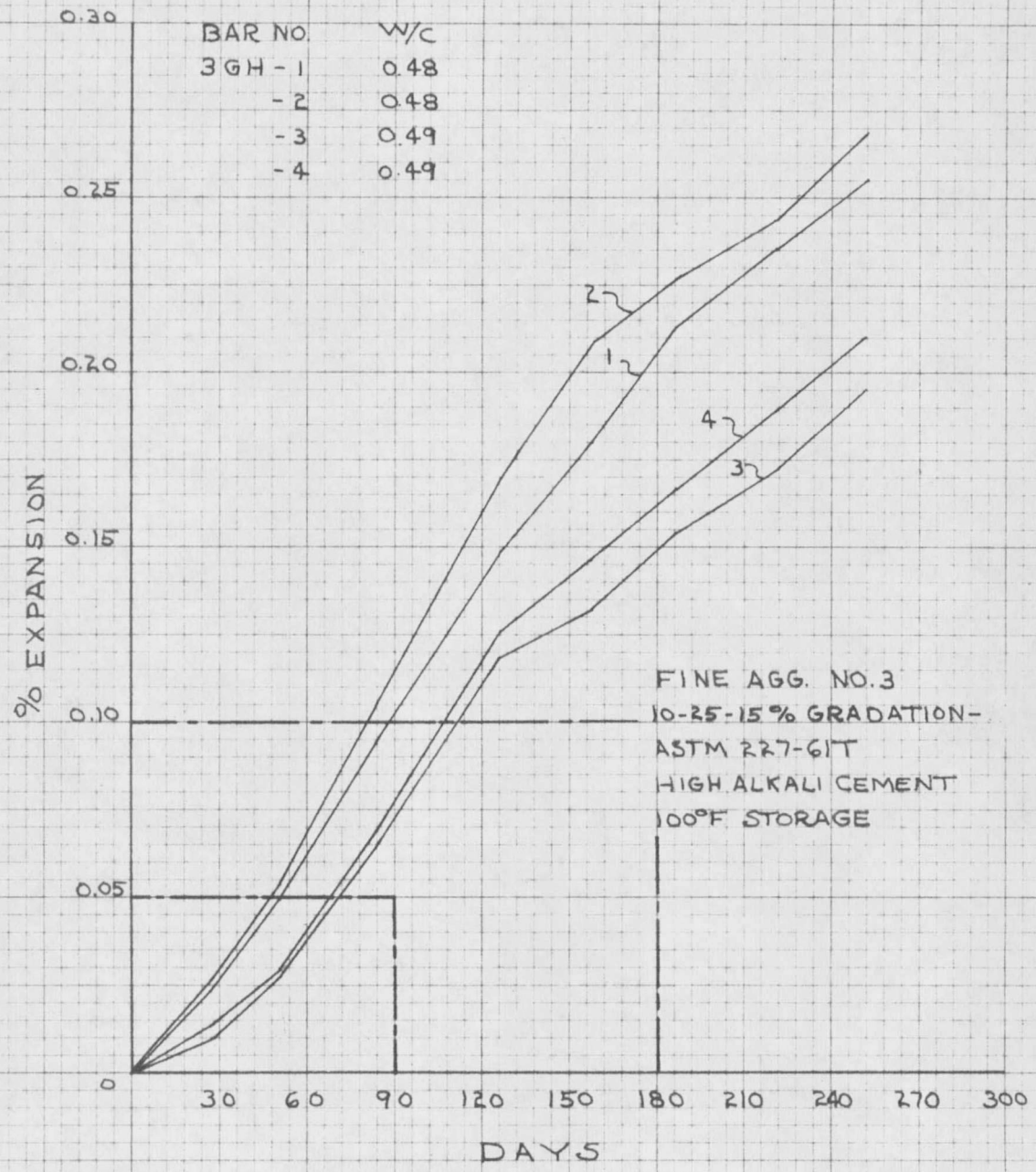


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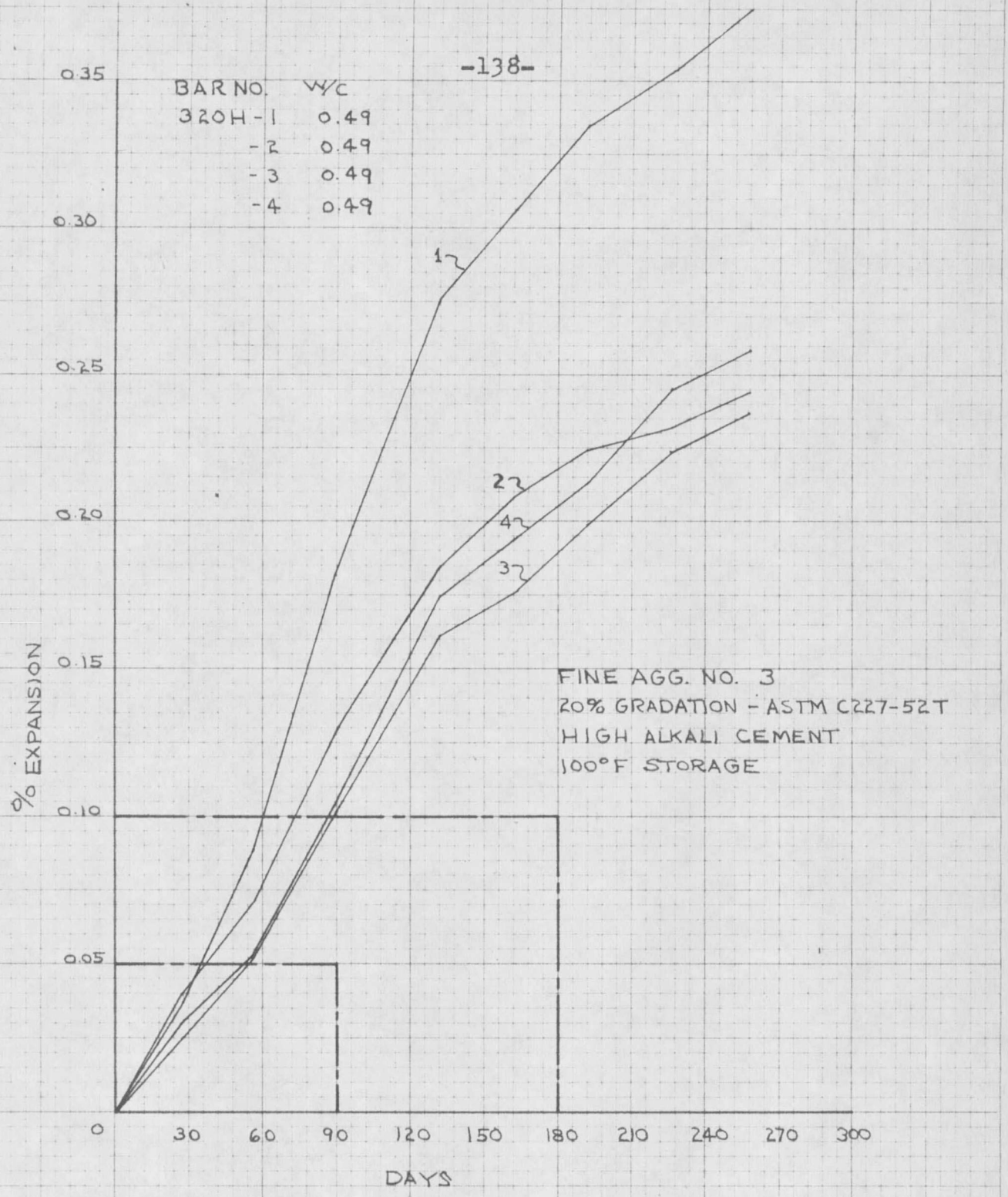


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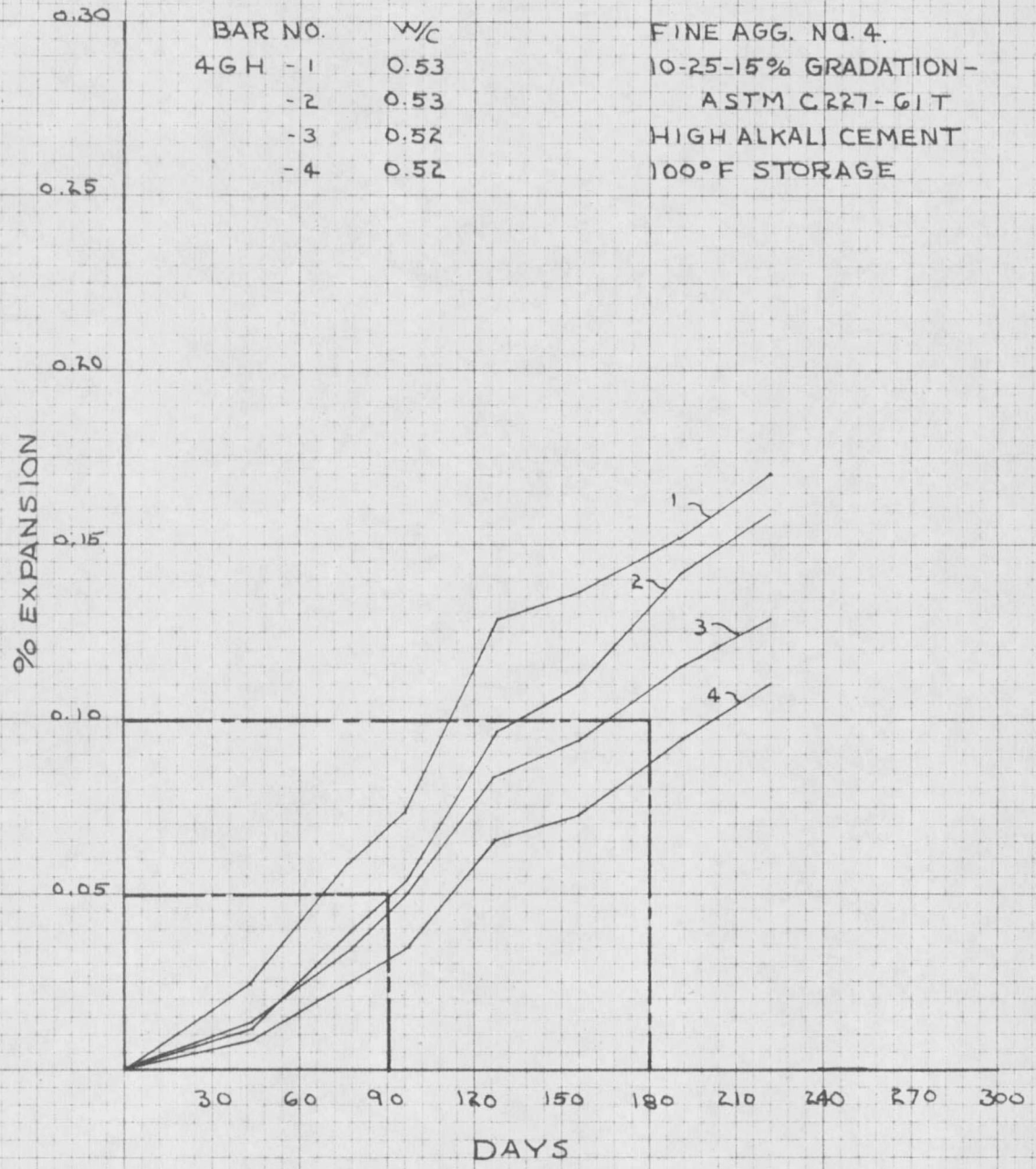


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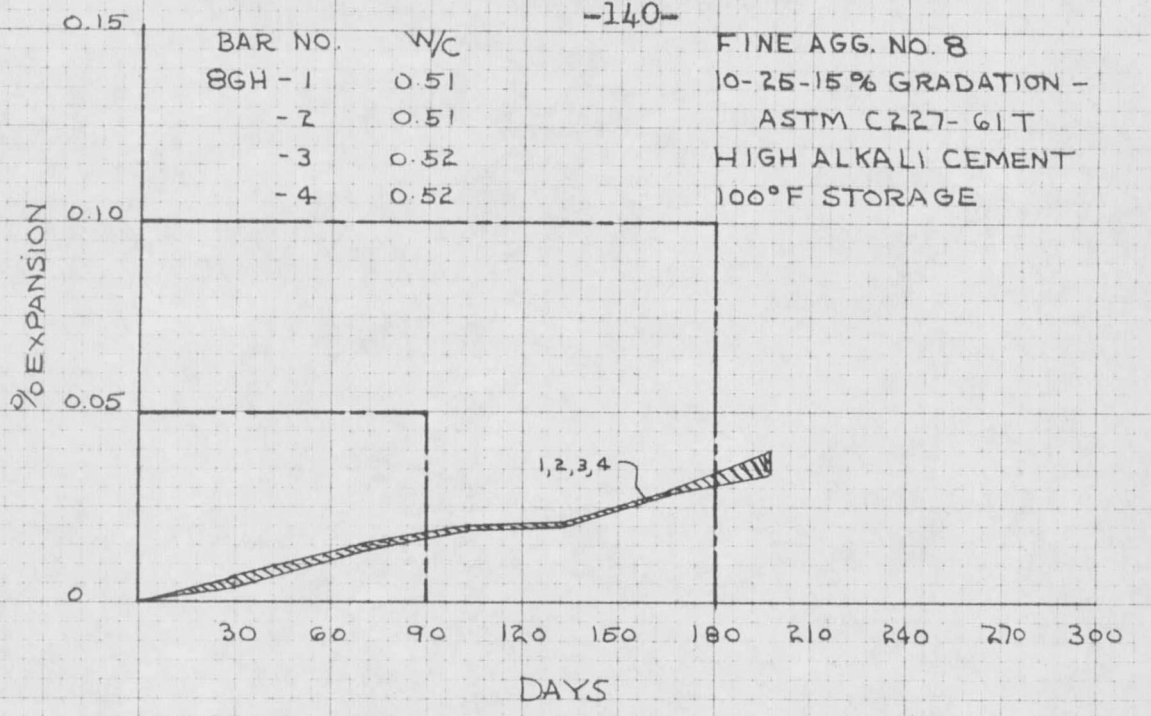
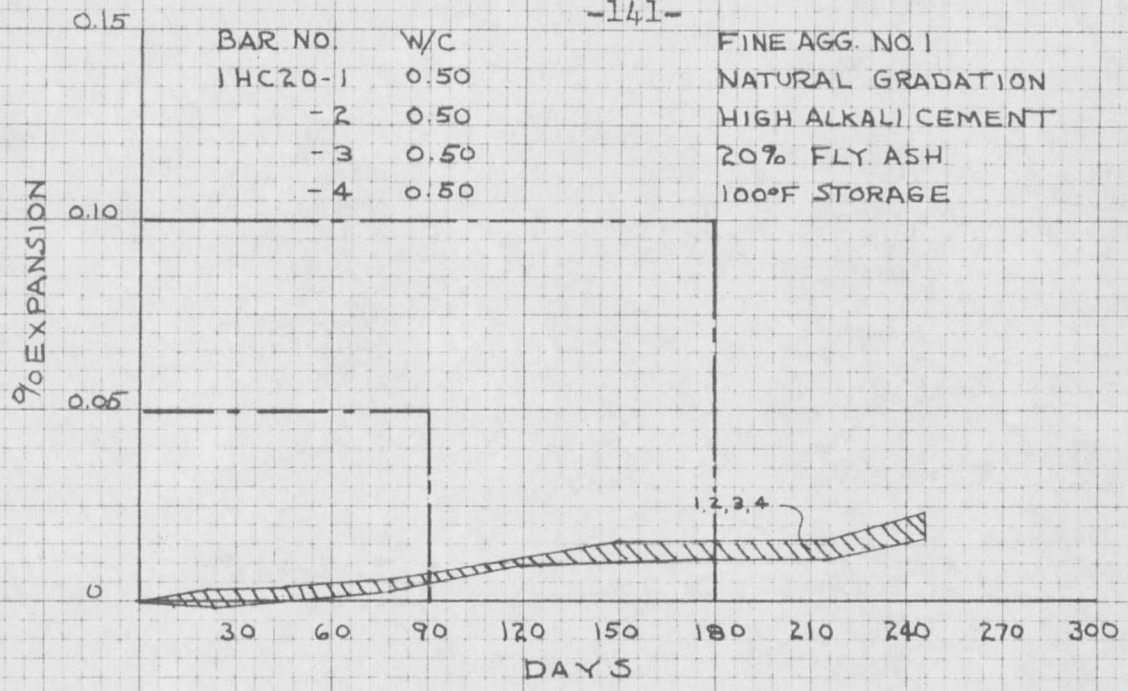


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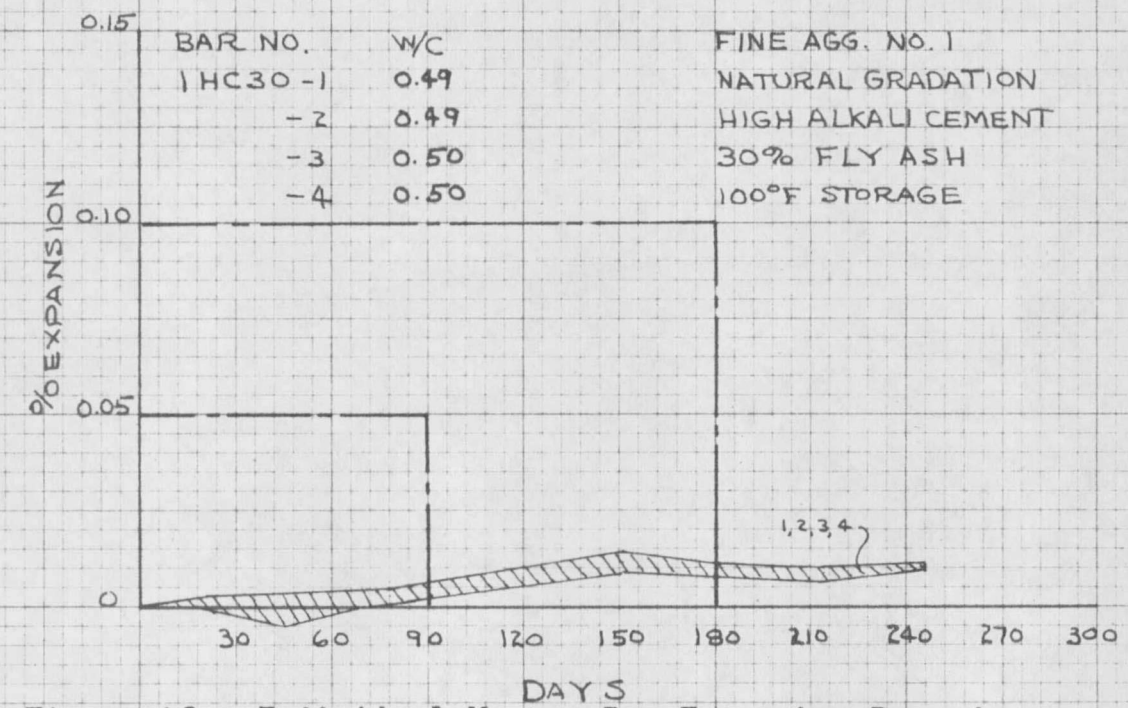
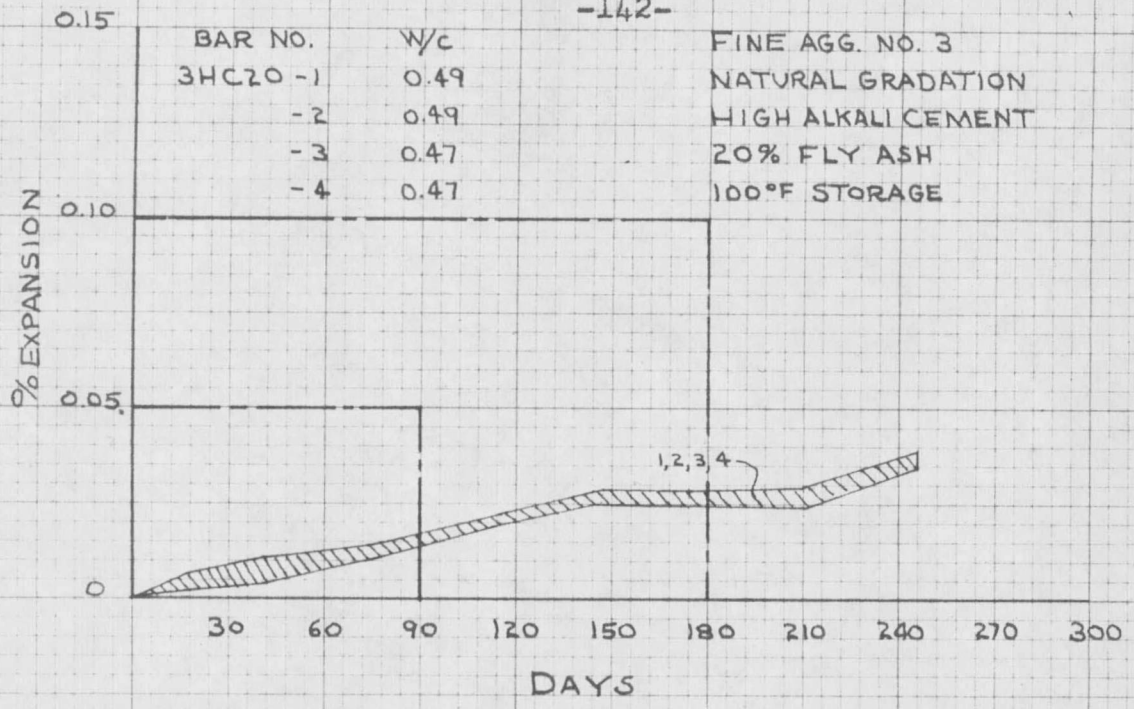


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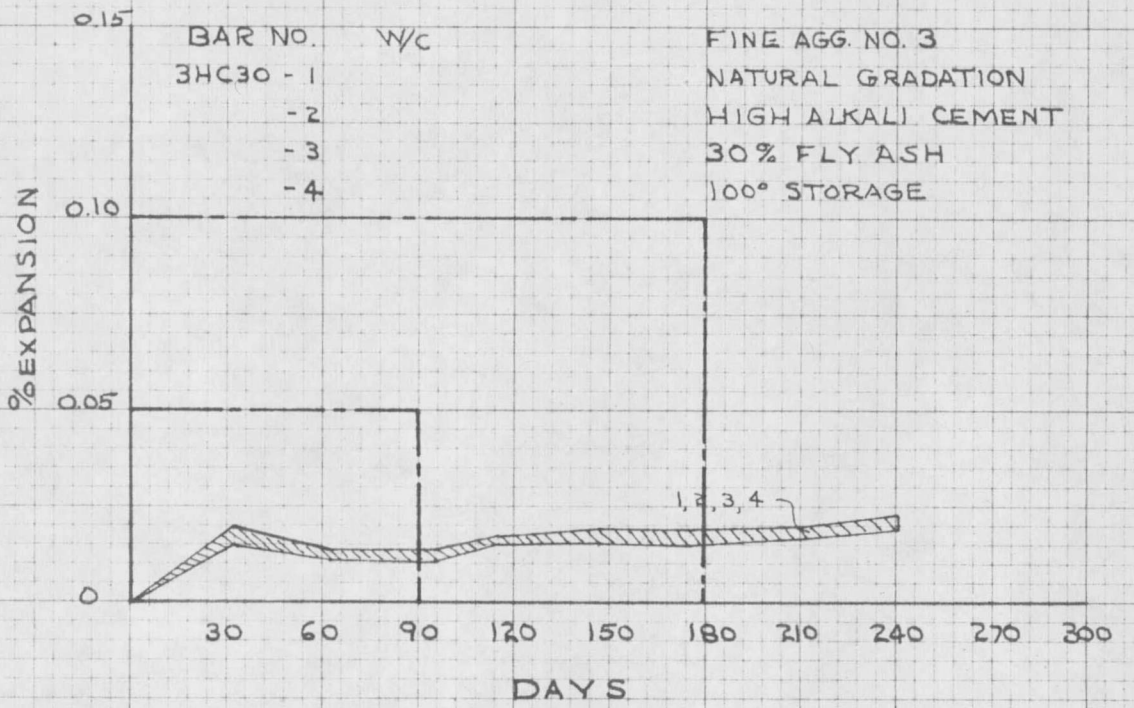
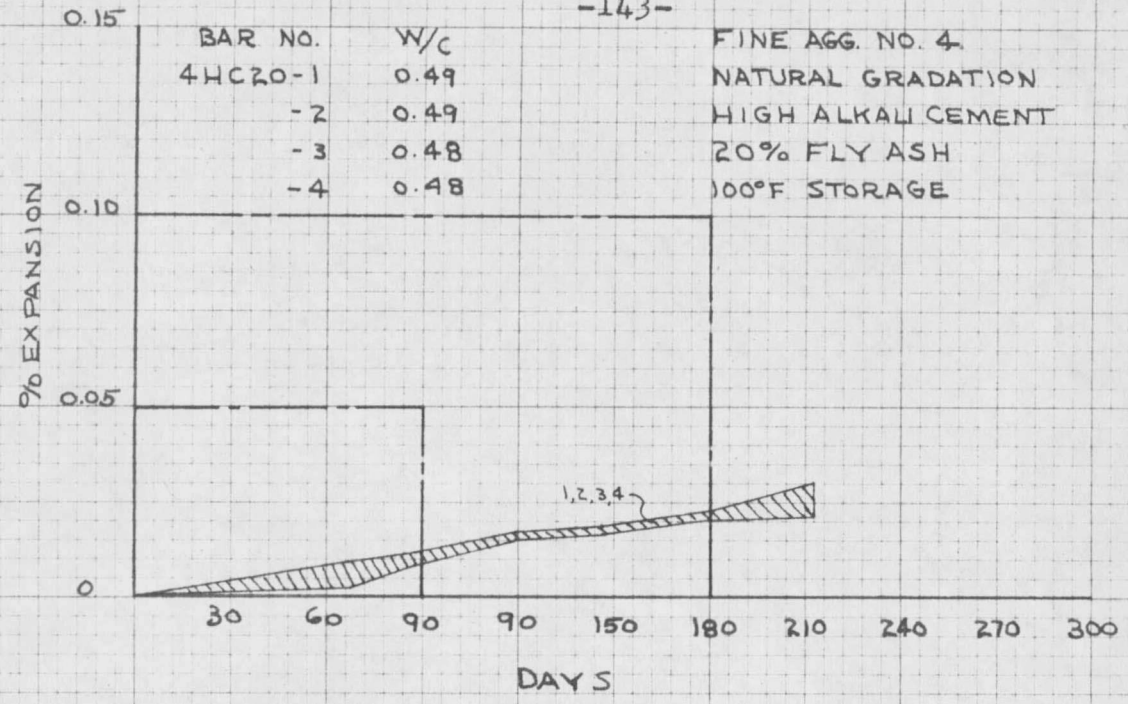


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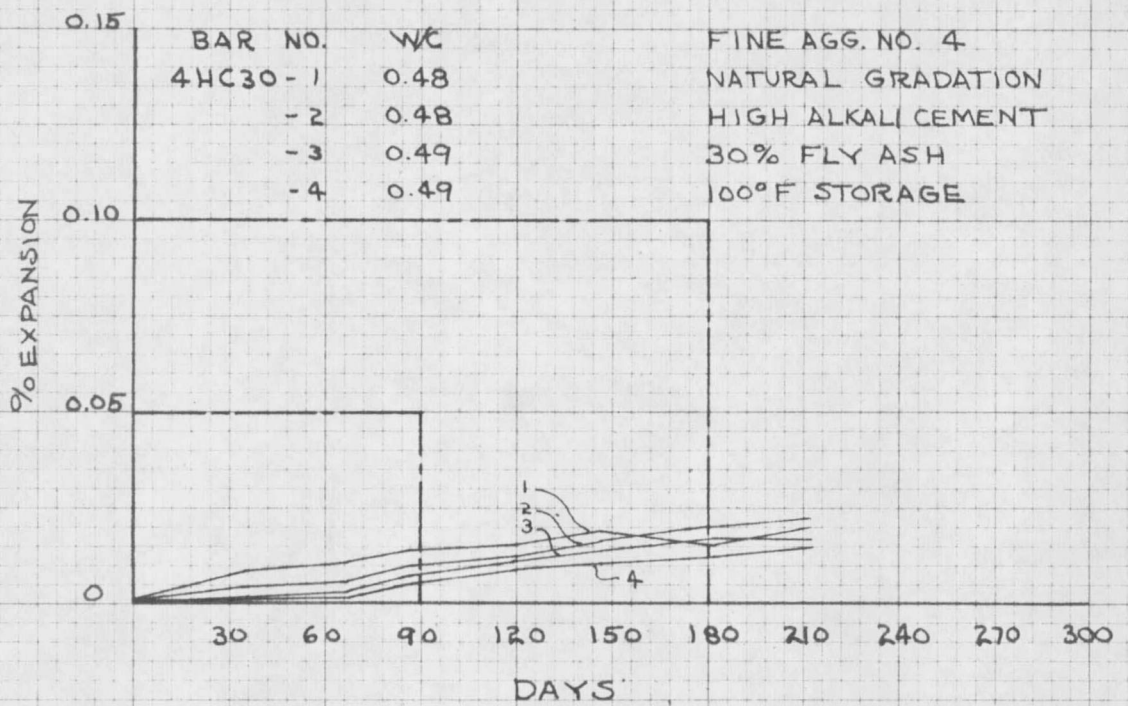
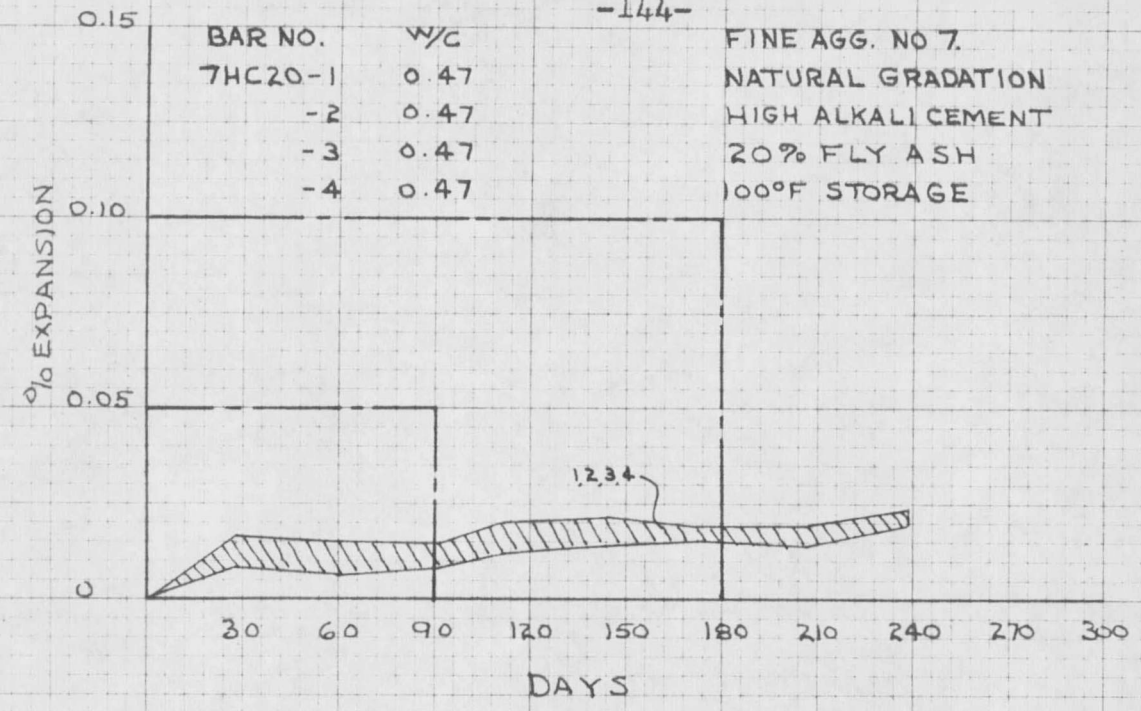


Figure 42 - Individual Mortar Bar Expansion Records



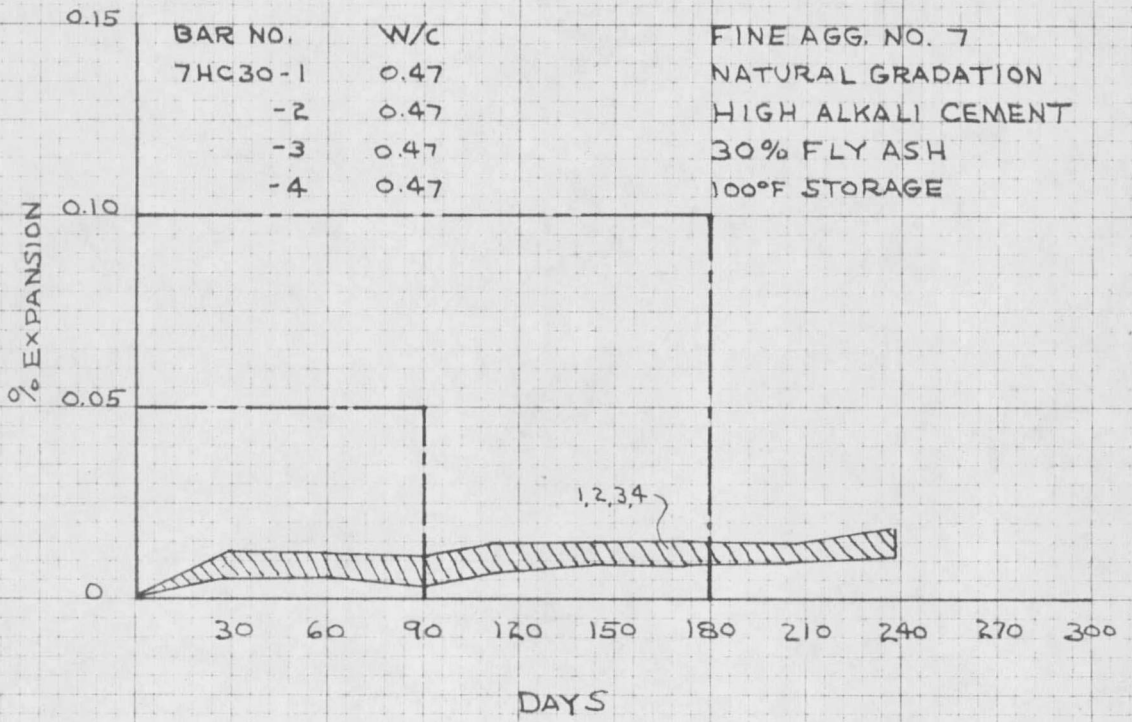
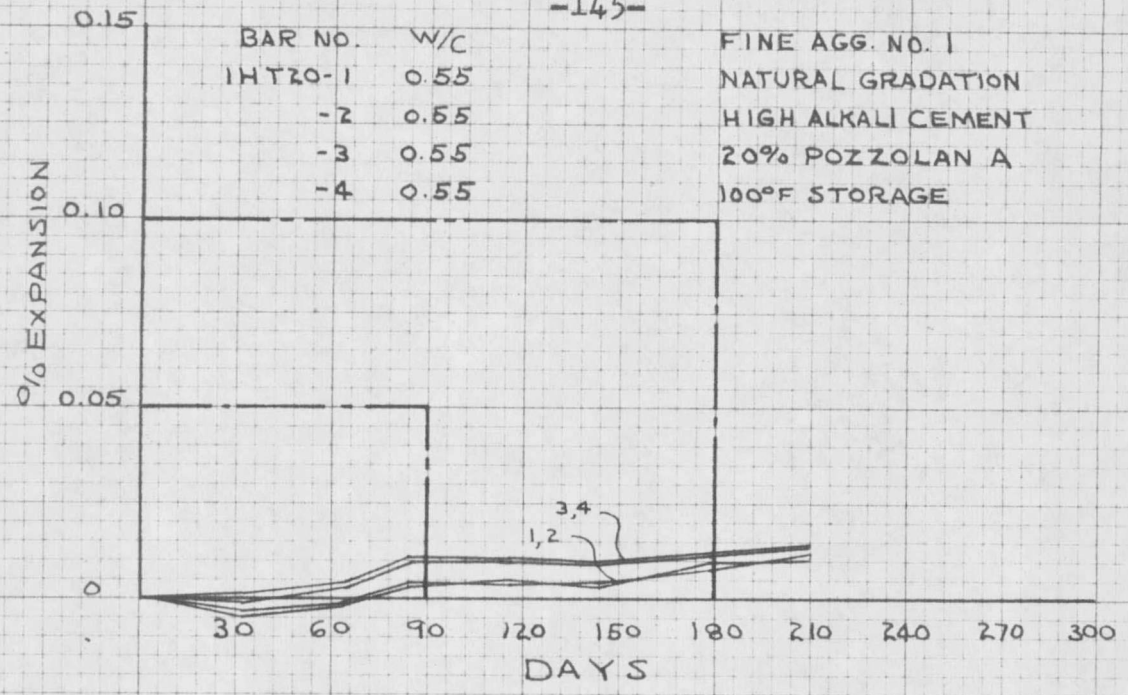


Figure 43 - Individual Mortar Bar Expansion Records



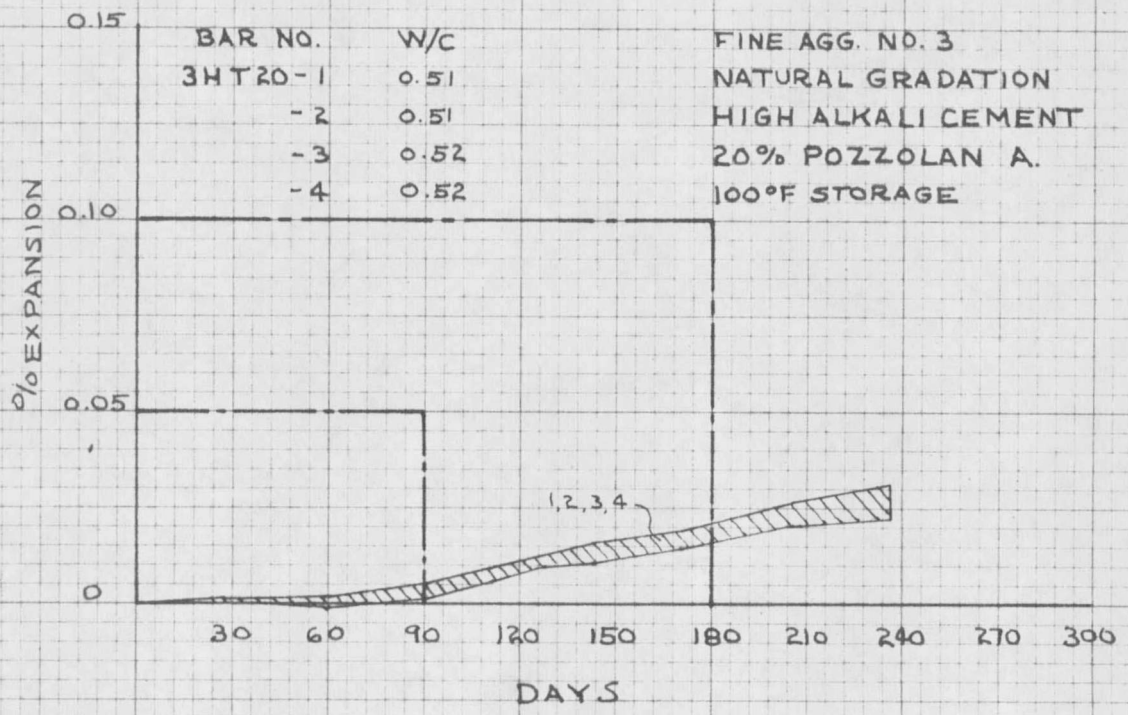
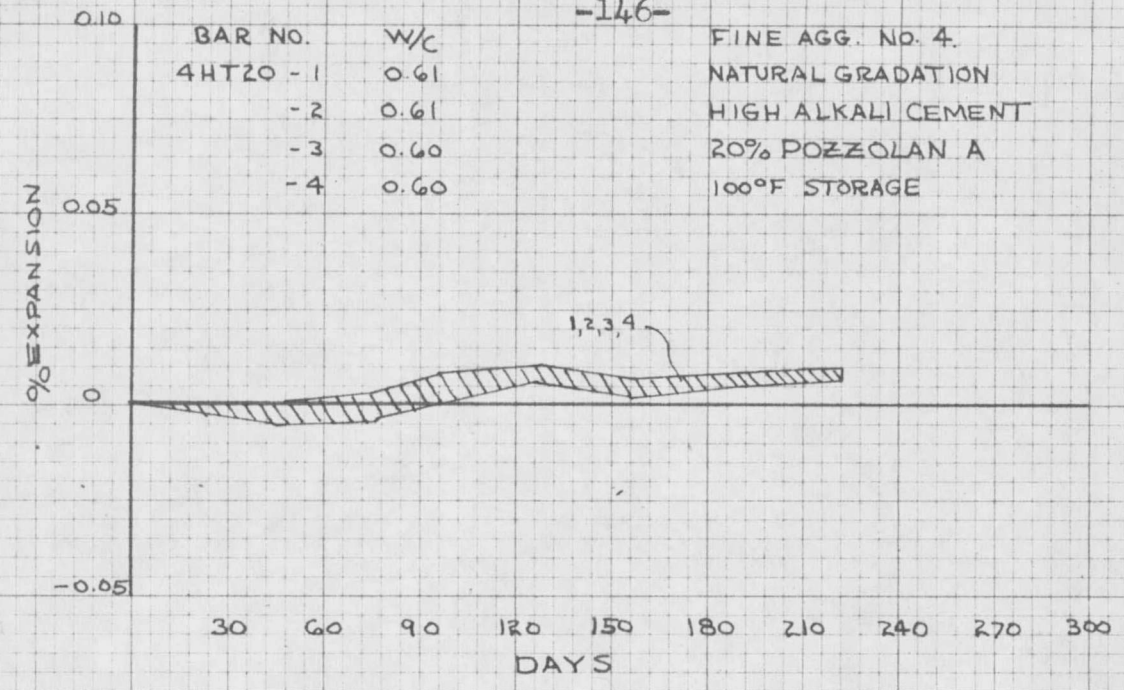


Figure 44 - Individual Mortar Bar Expansion Records



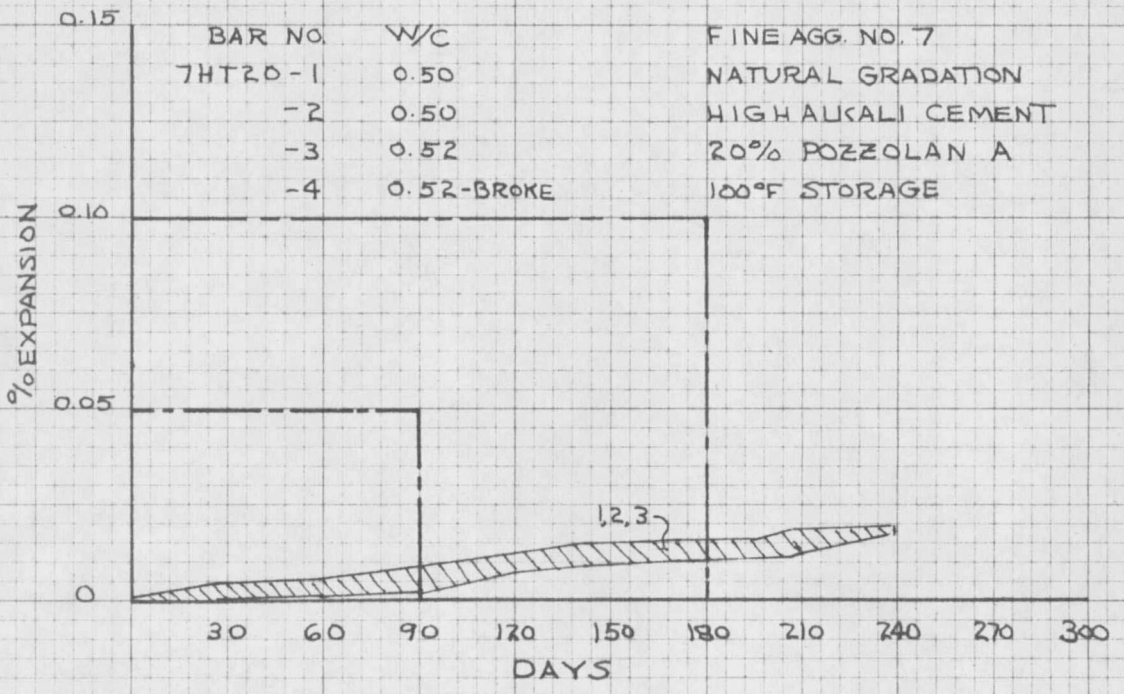
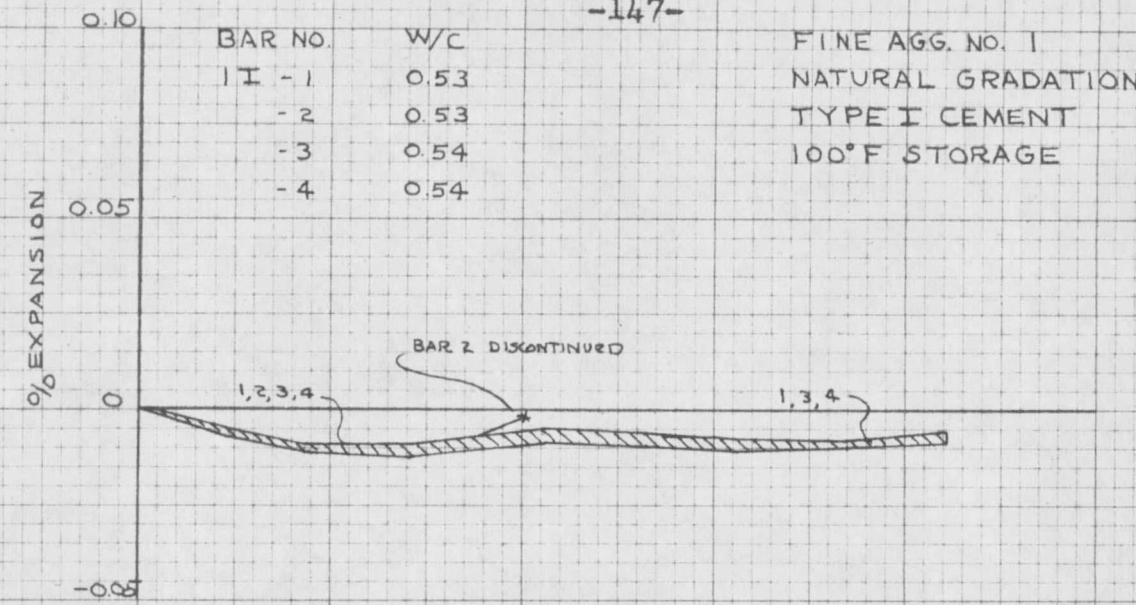


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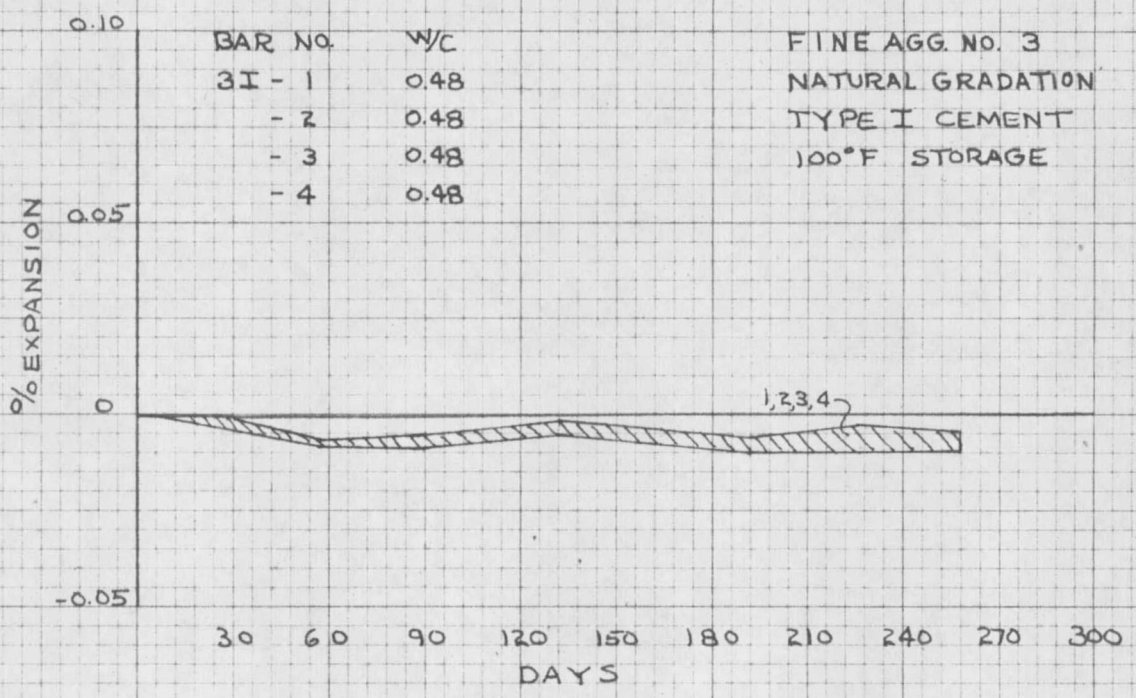
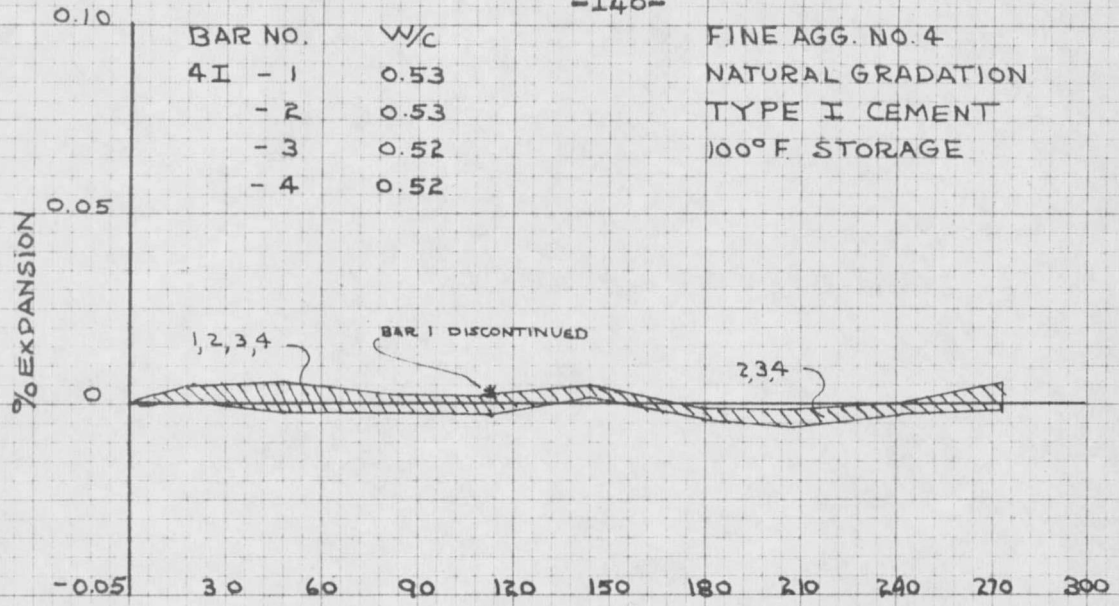


Figure 46 - Individual Mortar Bar Expansion Records



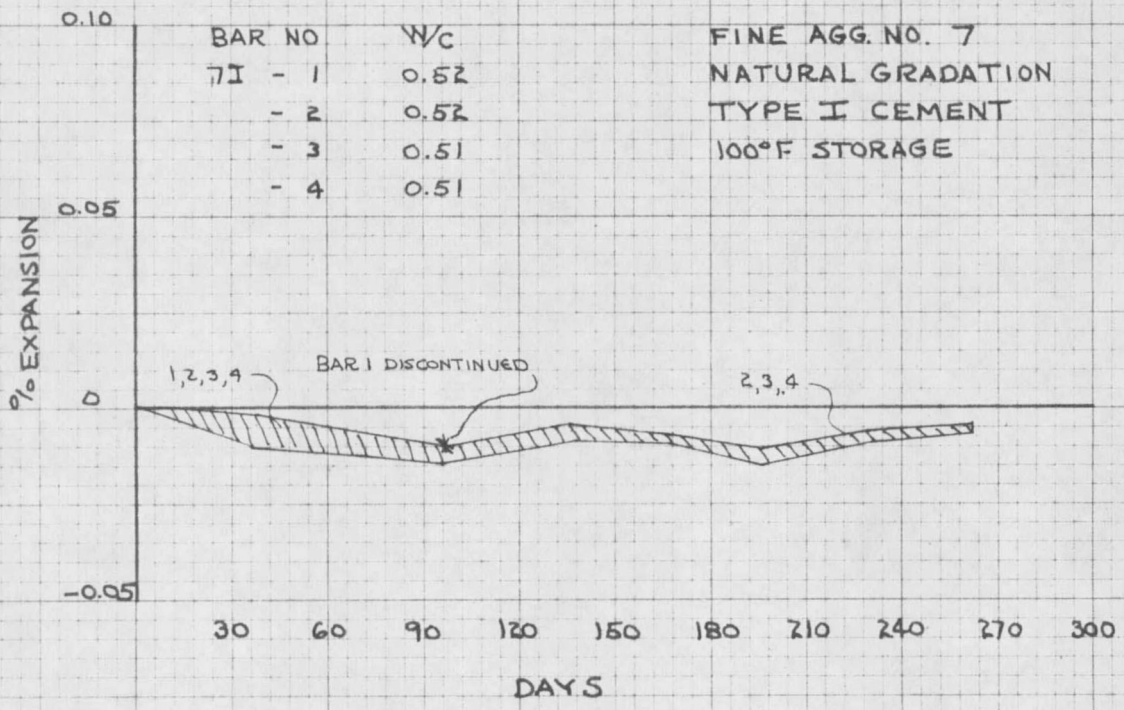


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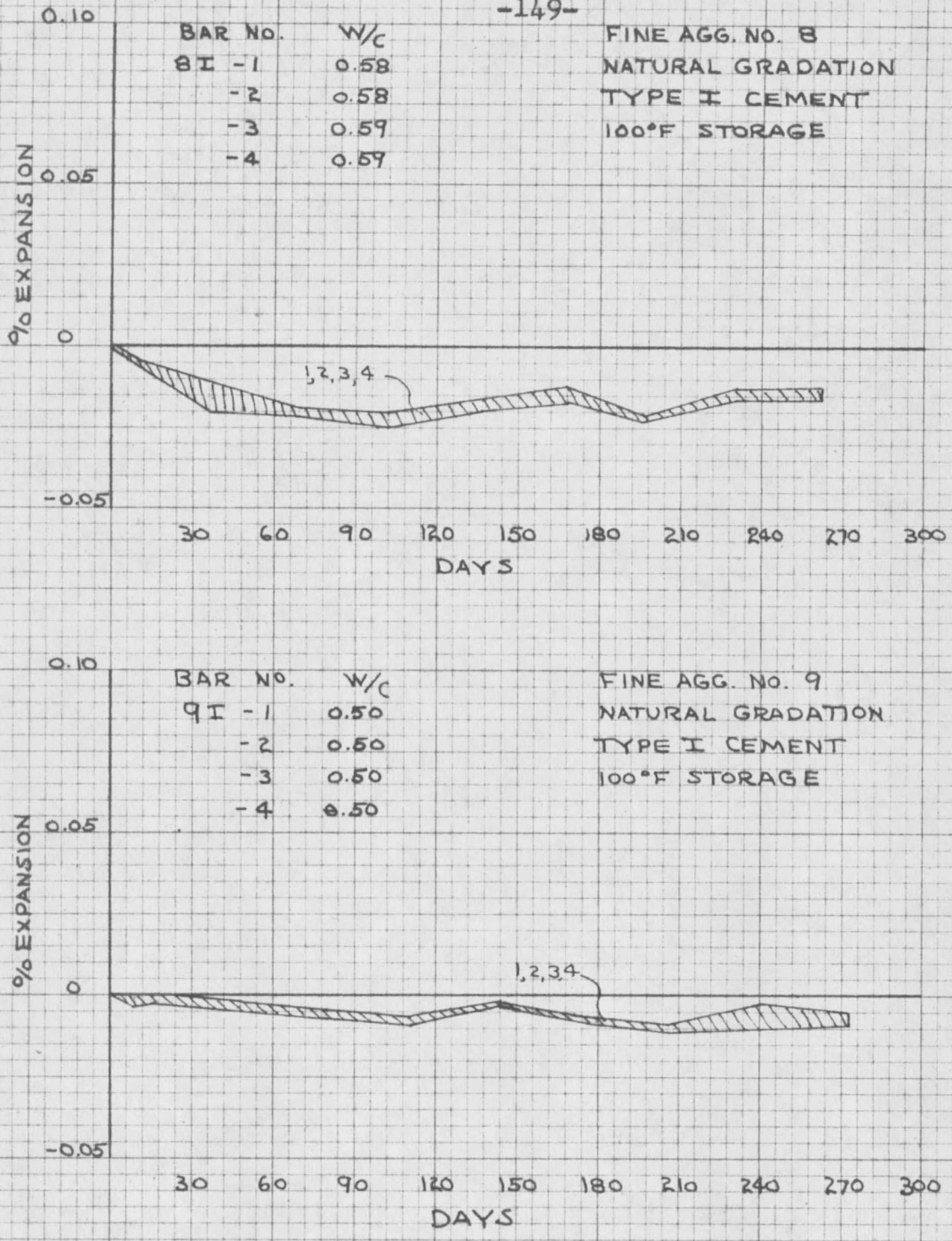


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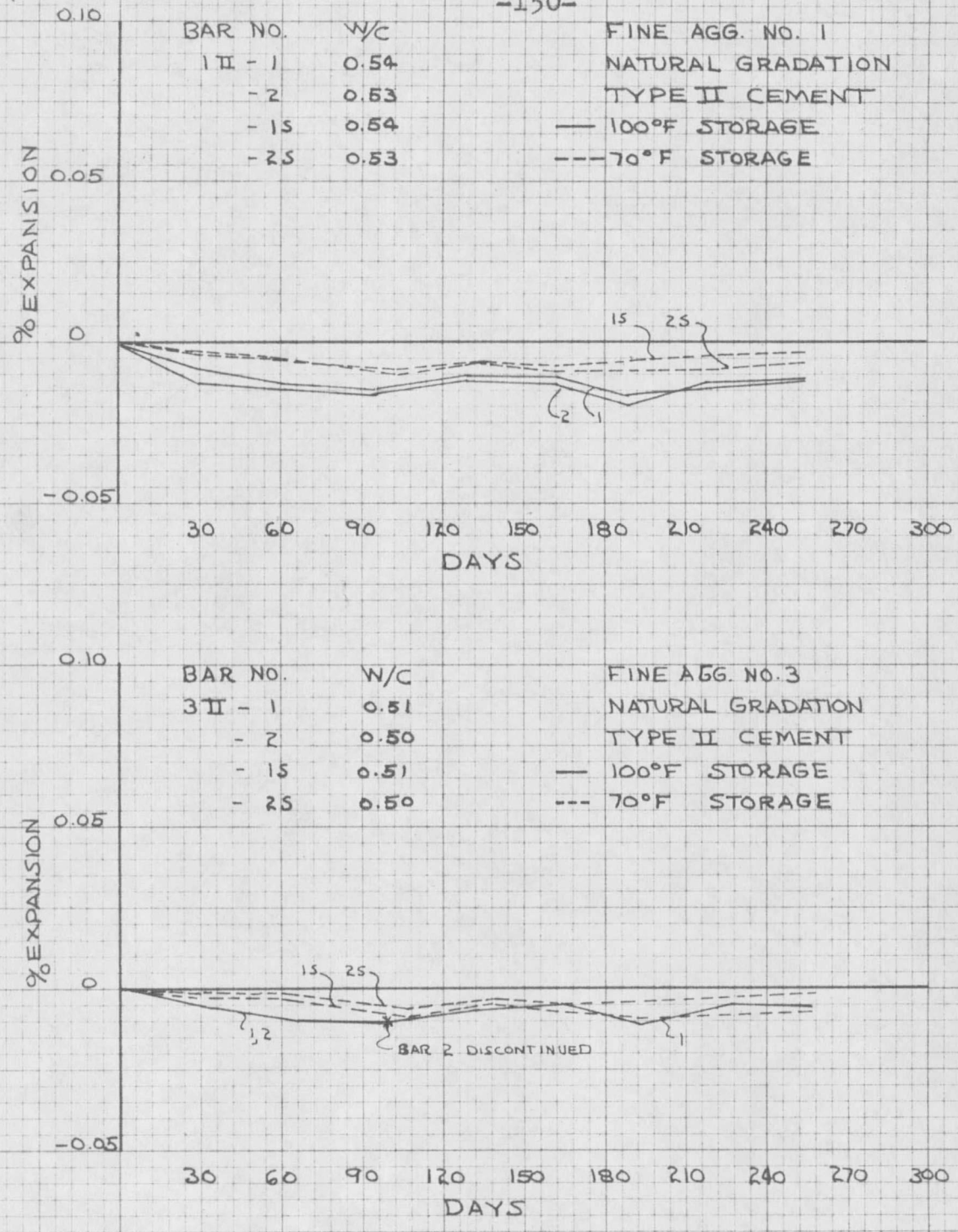


Figure 49 - Individual Mortar Bar Expansion Records

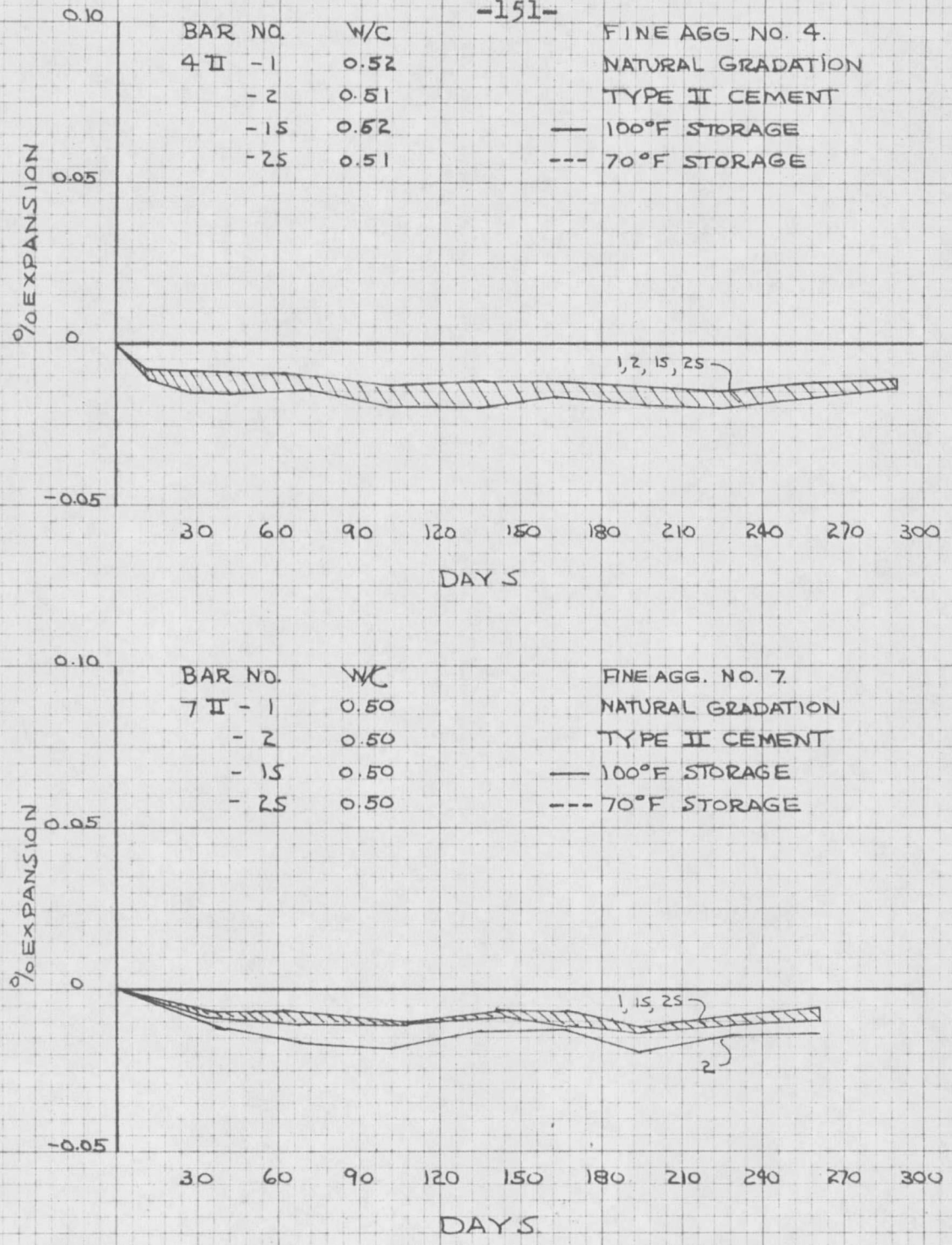


Figure 50 - Individual Mortar Bar Expansion Records

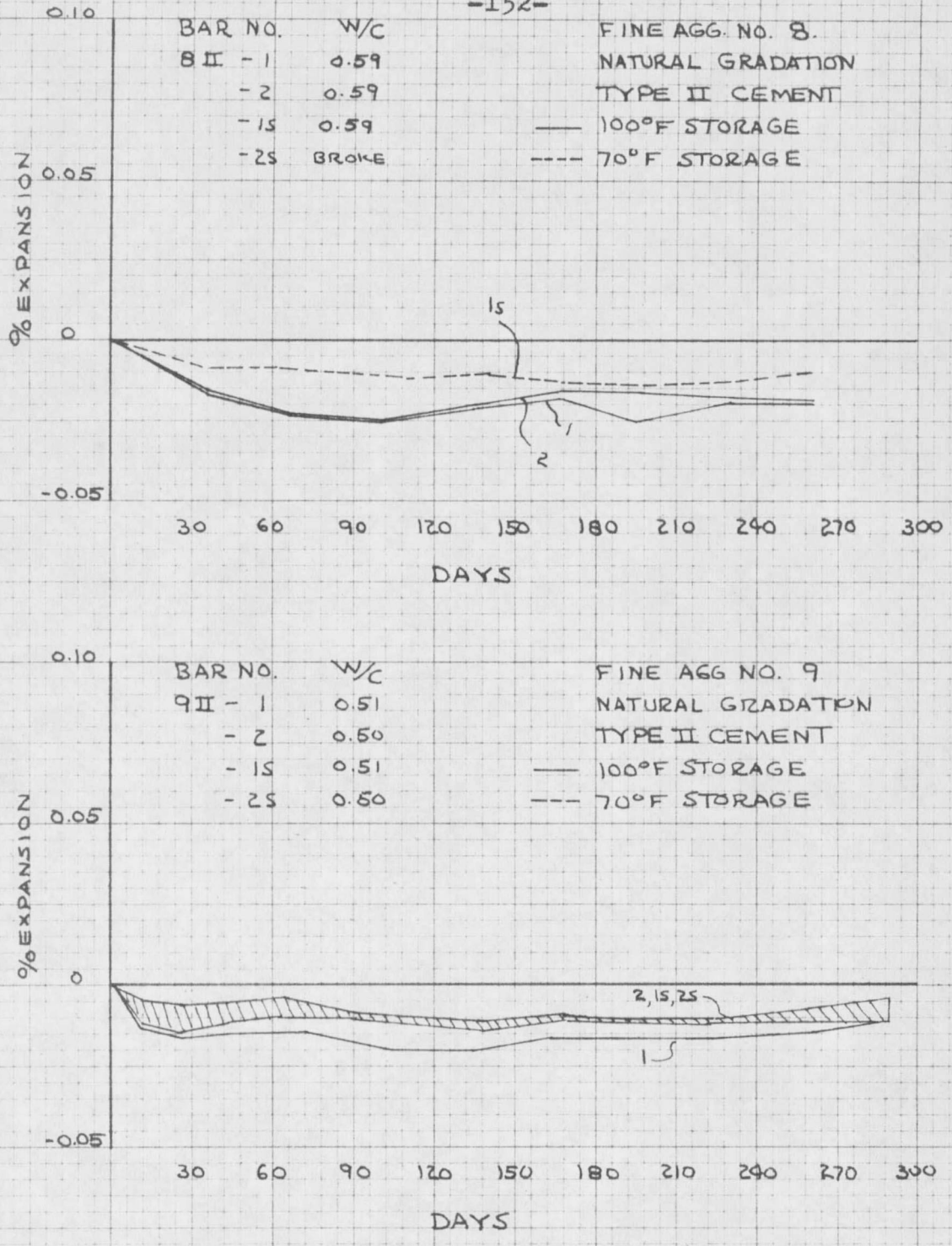


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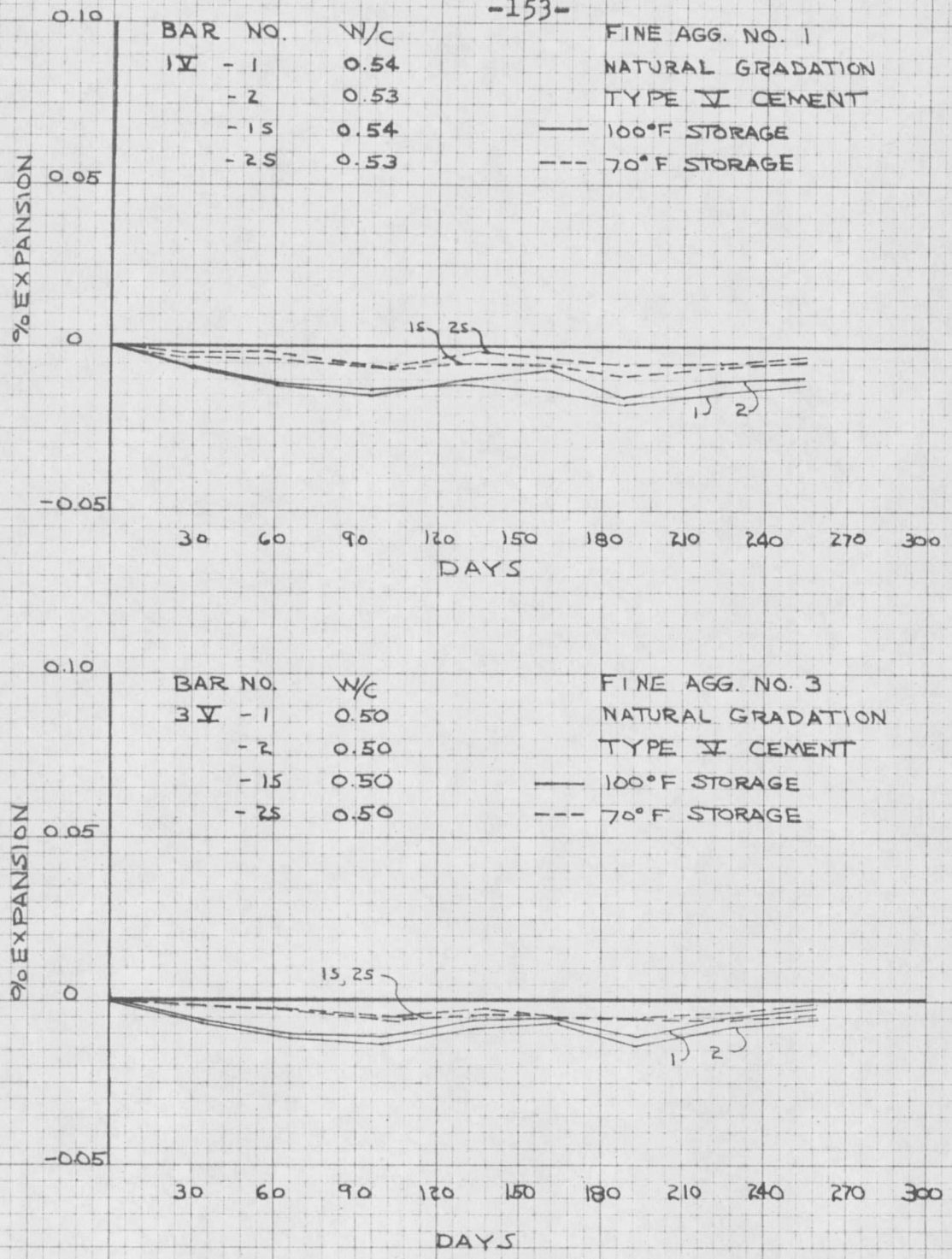
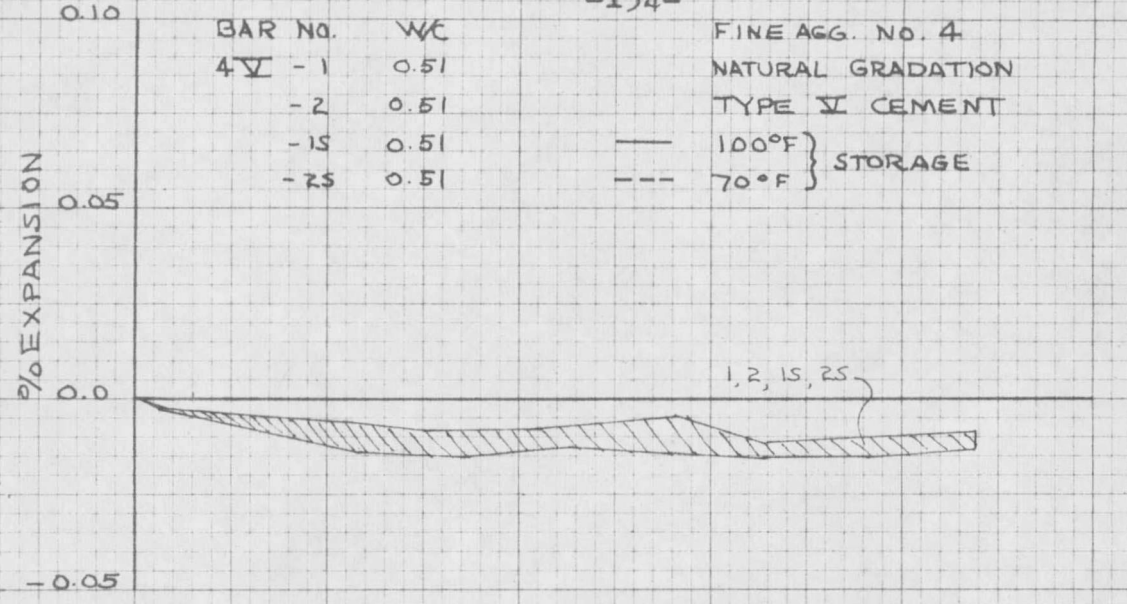


Figure 52 - Individual Mortar Bar Expansion Records



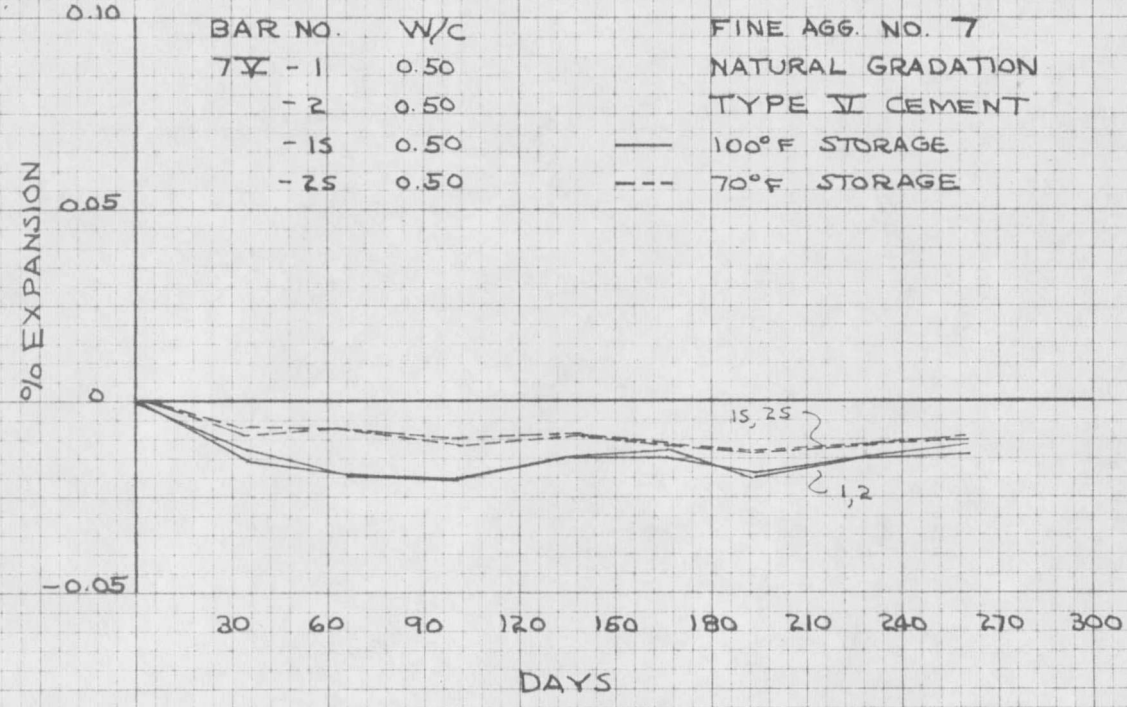
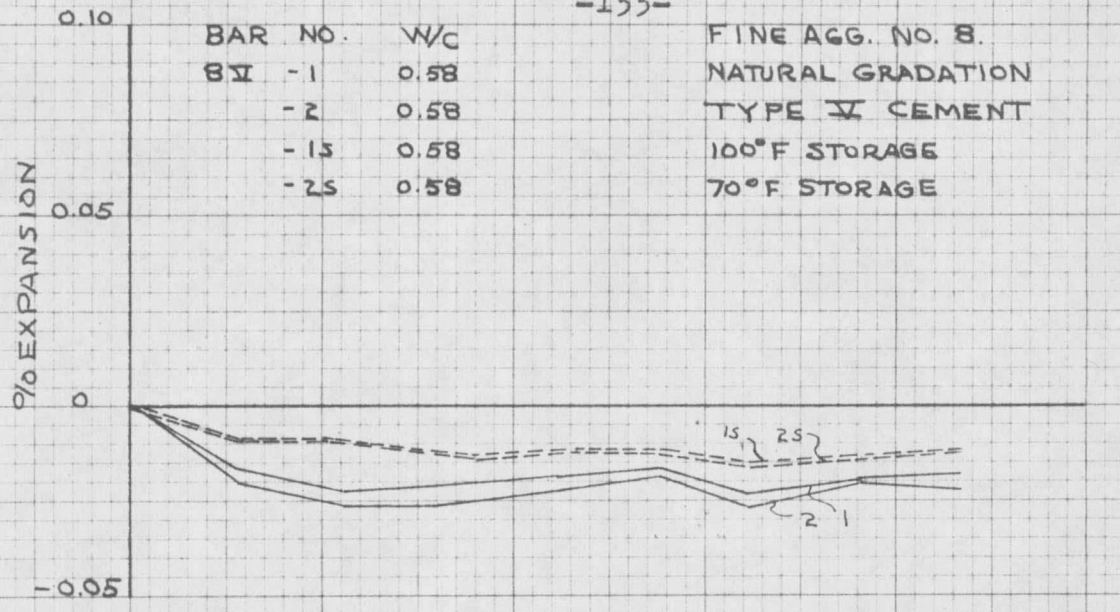


Figure 53 - Individual Mortar Bar Expansion Records



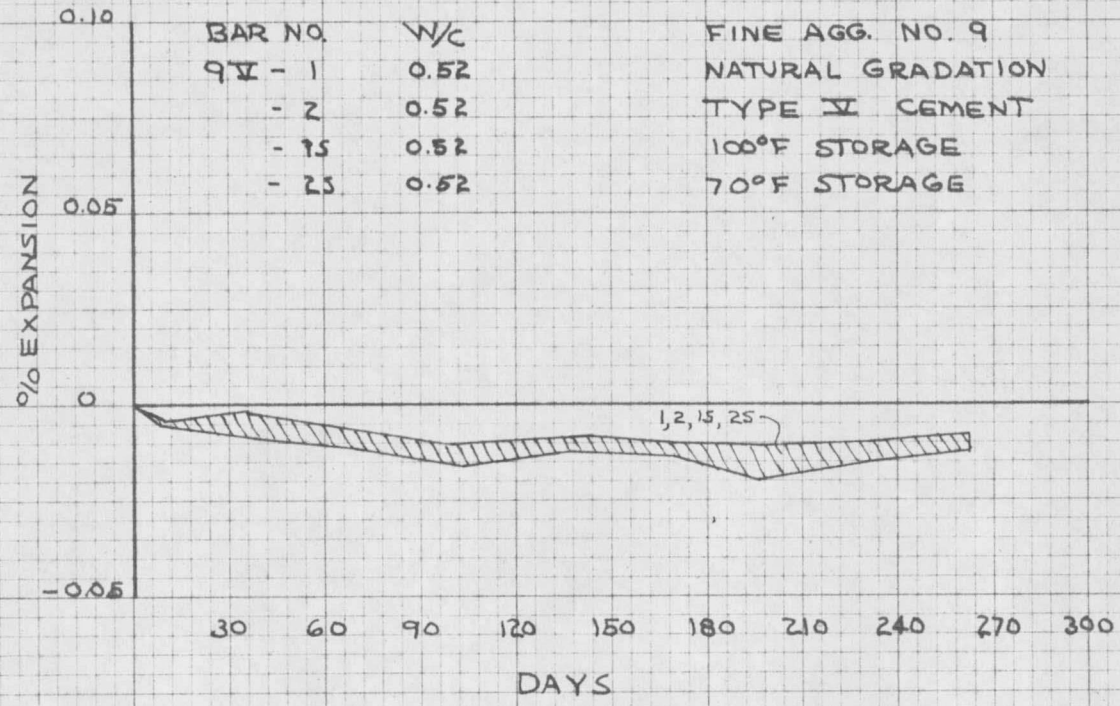
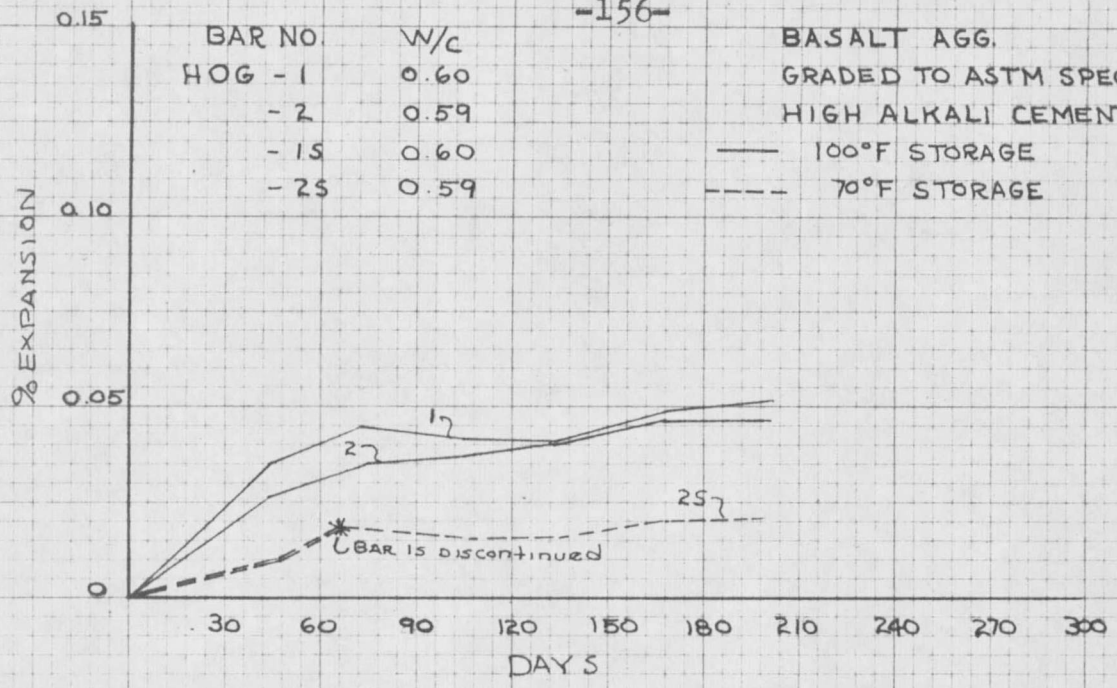


Figure 54 - Individual Mortar Bar Expansion Records



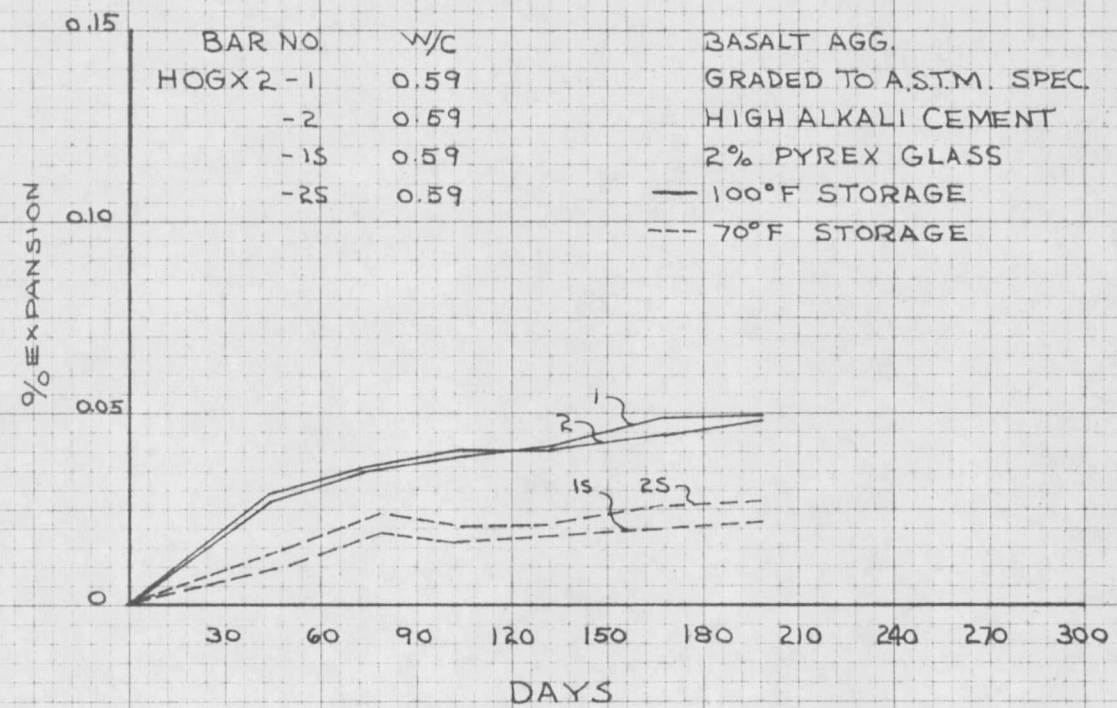
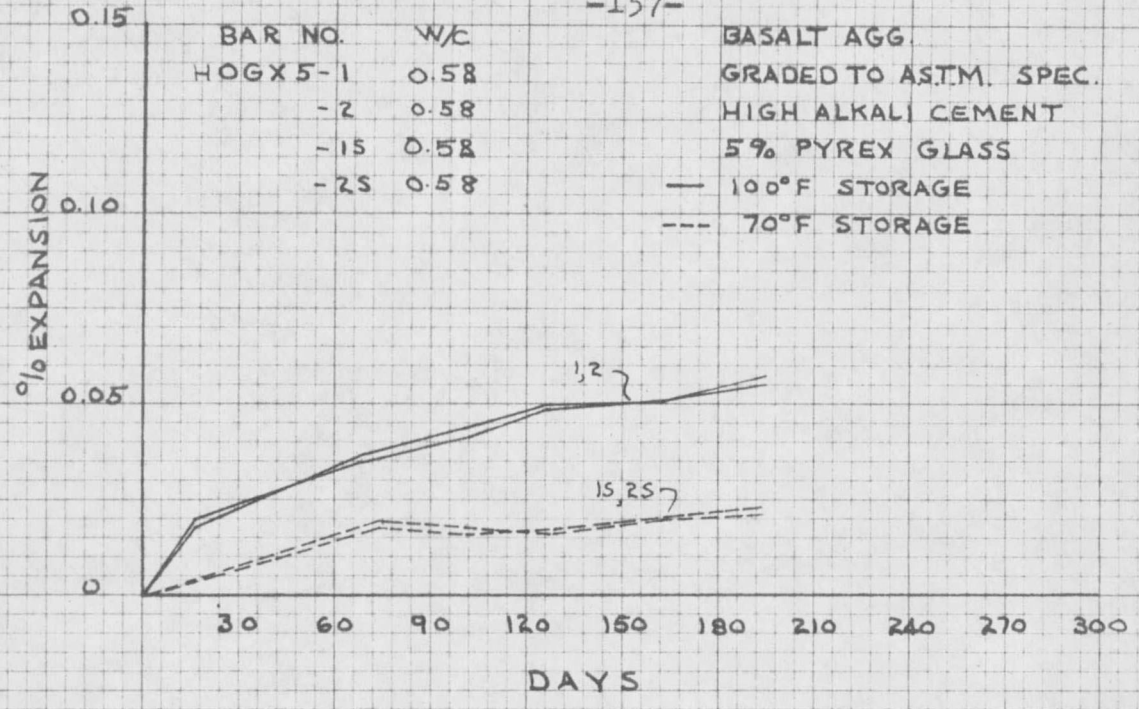


Figure 55 - Individual Mortar Bar Expansion Records



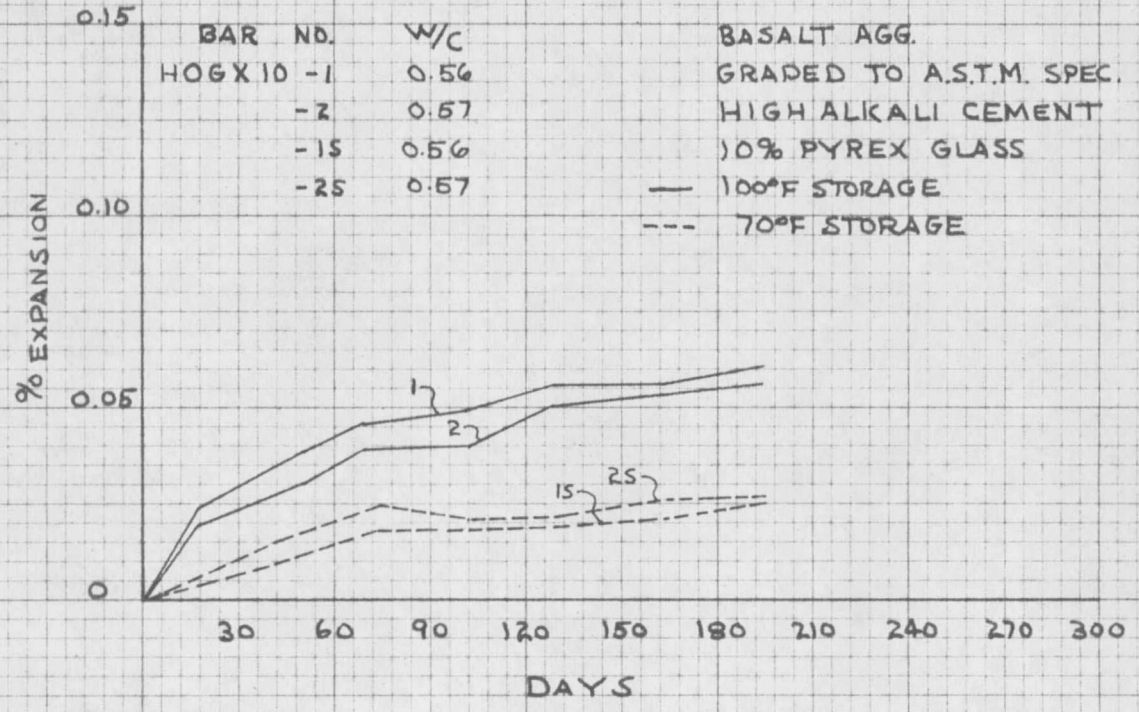
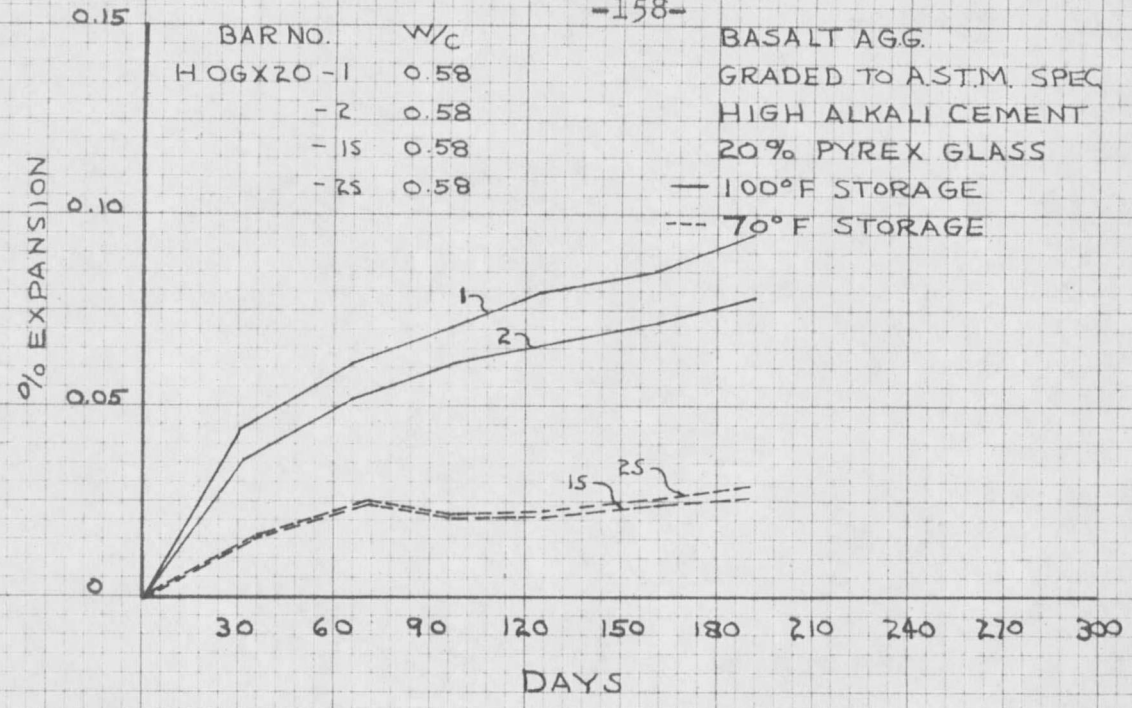


Figure 56 - Individual Mortar Bar Expansion Records



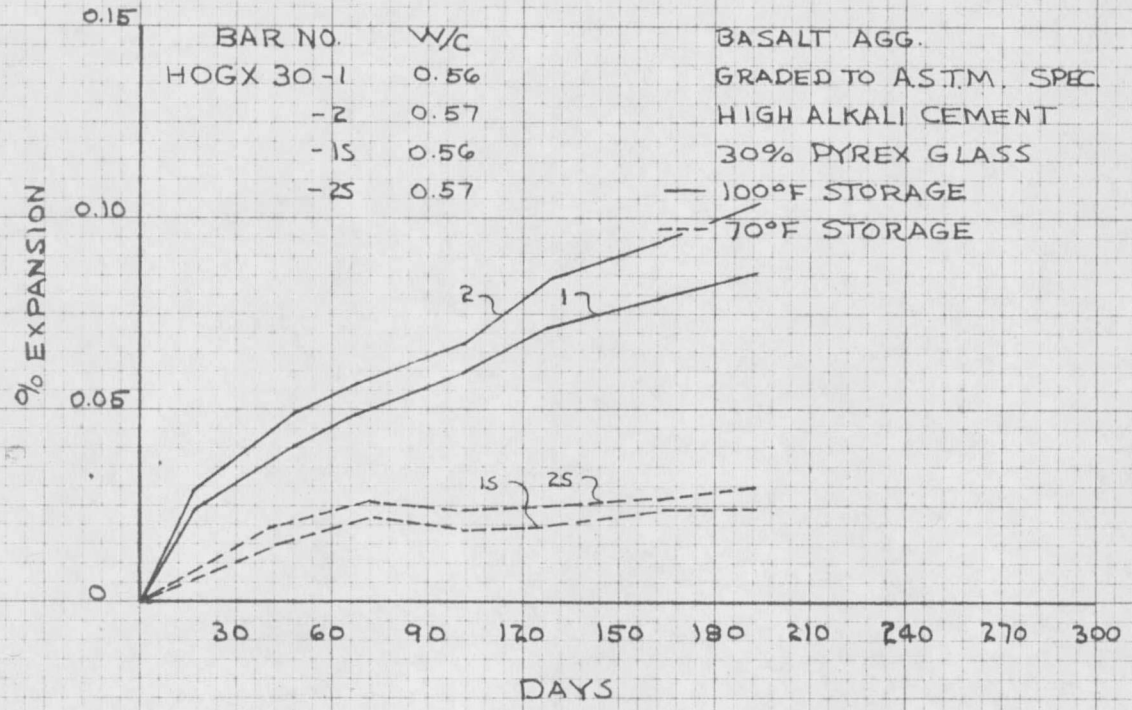


Figure 57 - Individual Mortar Bar Expansion Records

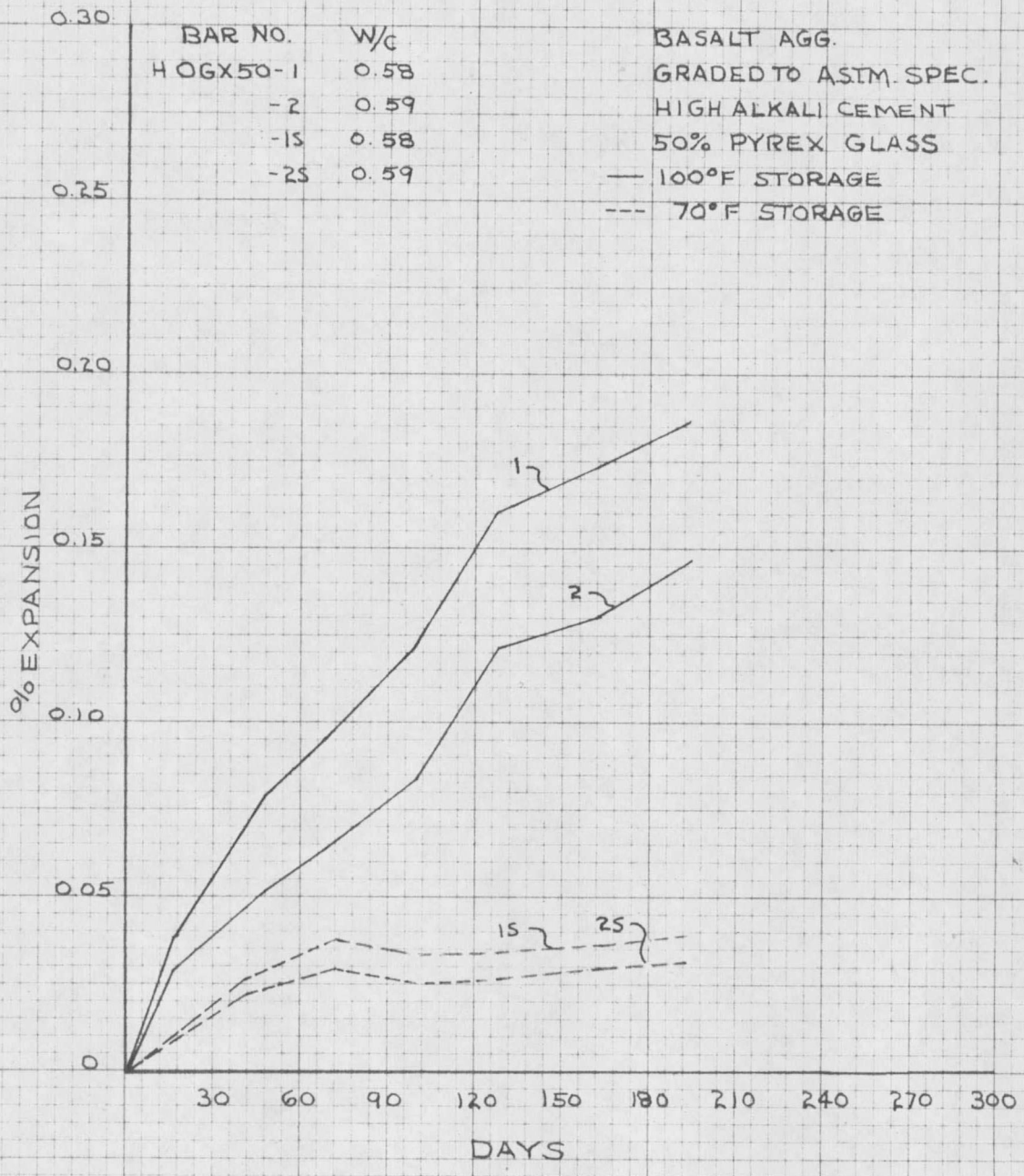
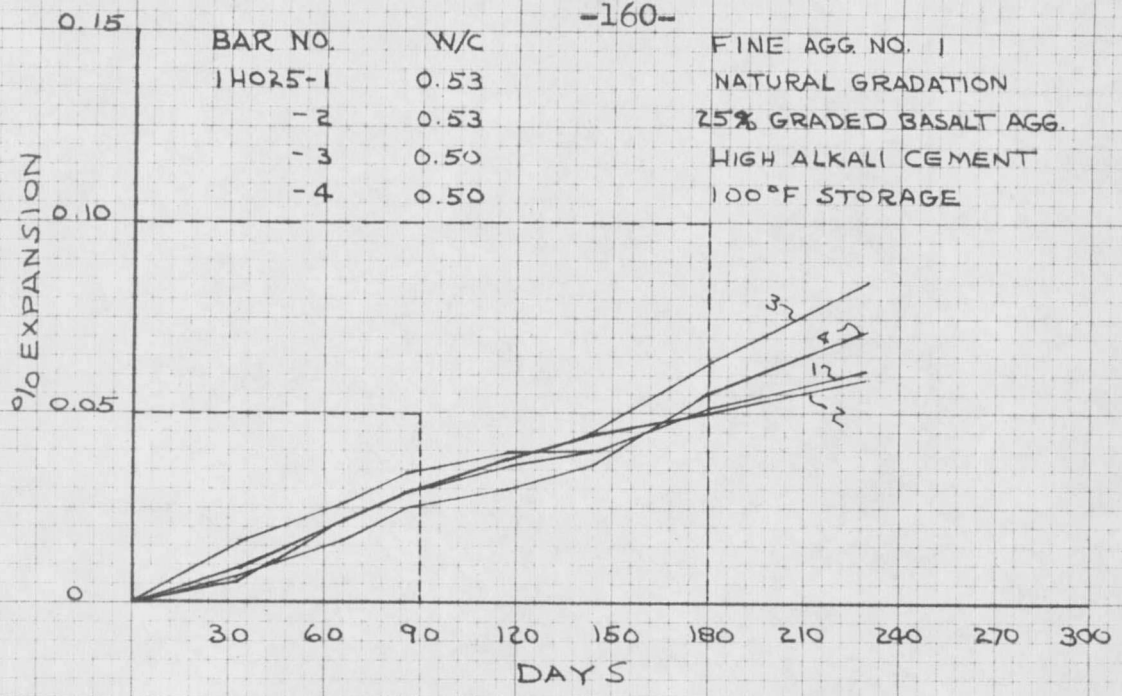


Figure 58 - Individual Mortar Bar Expansion Records



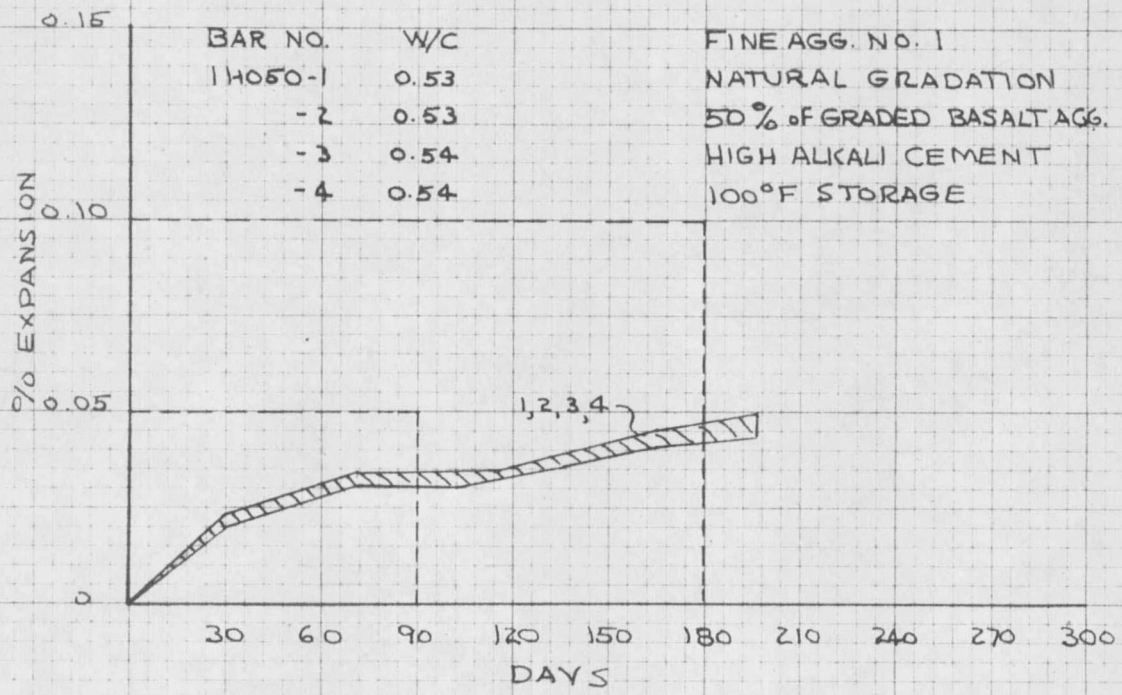
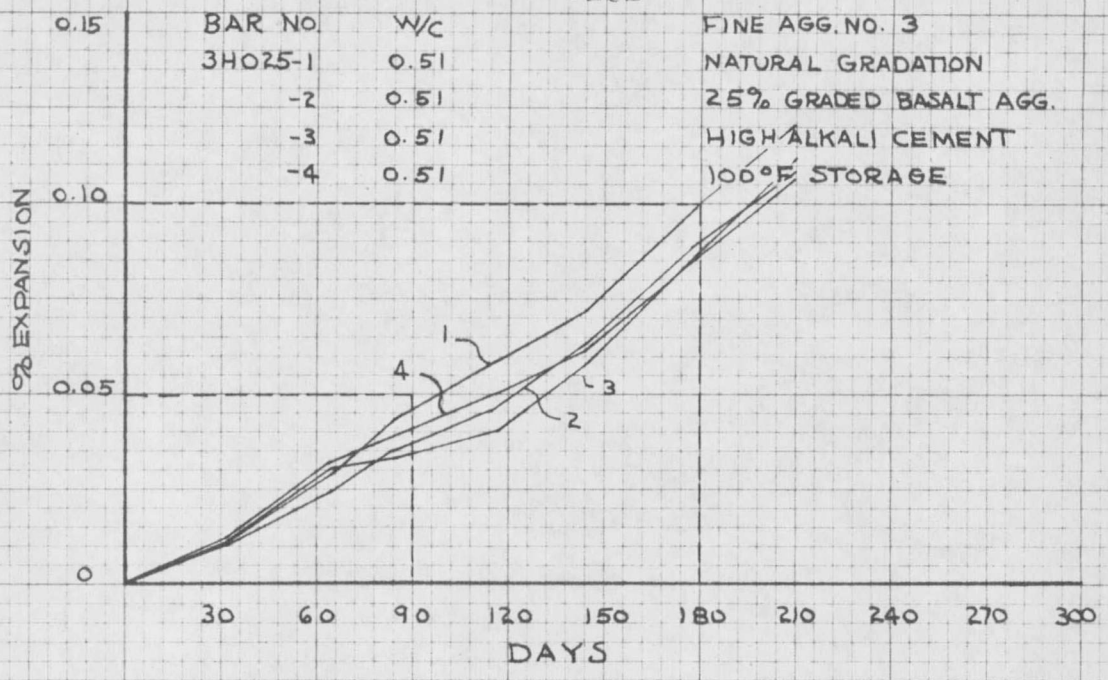


Figure 59 - Individual Mortar Bar Expansion Records



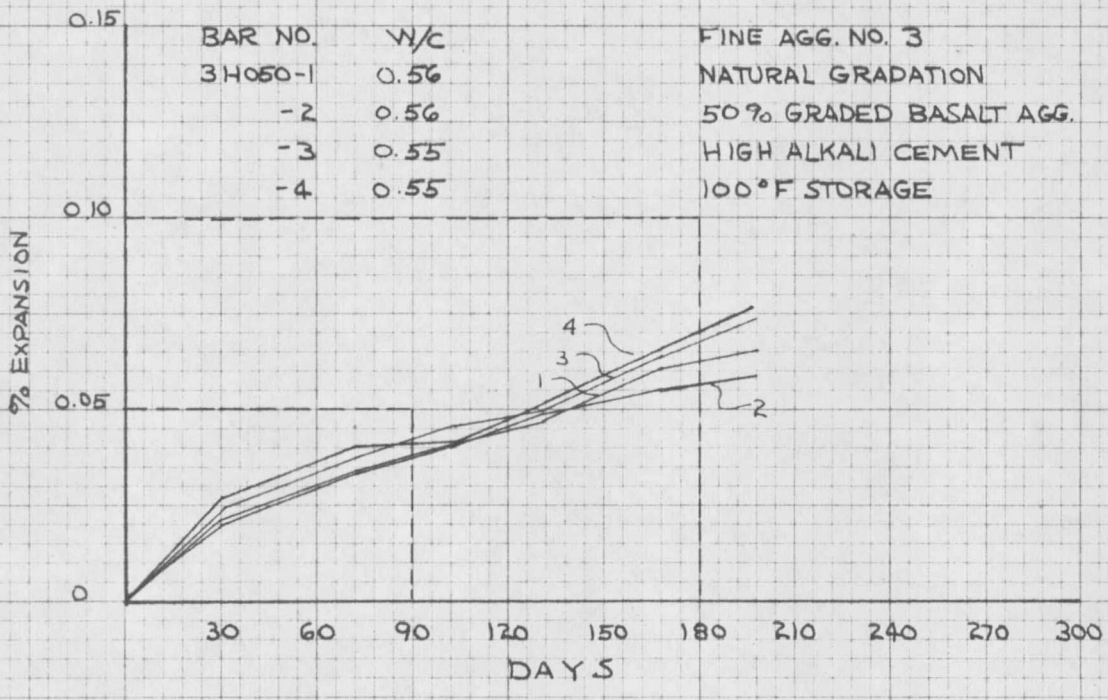
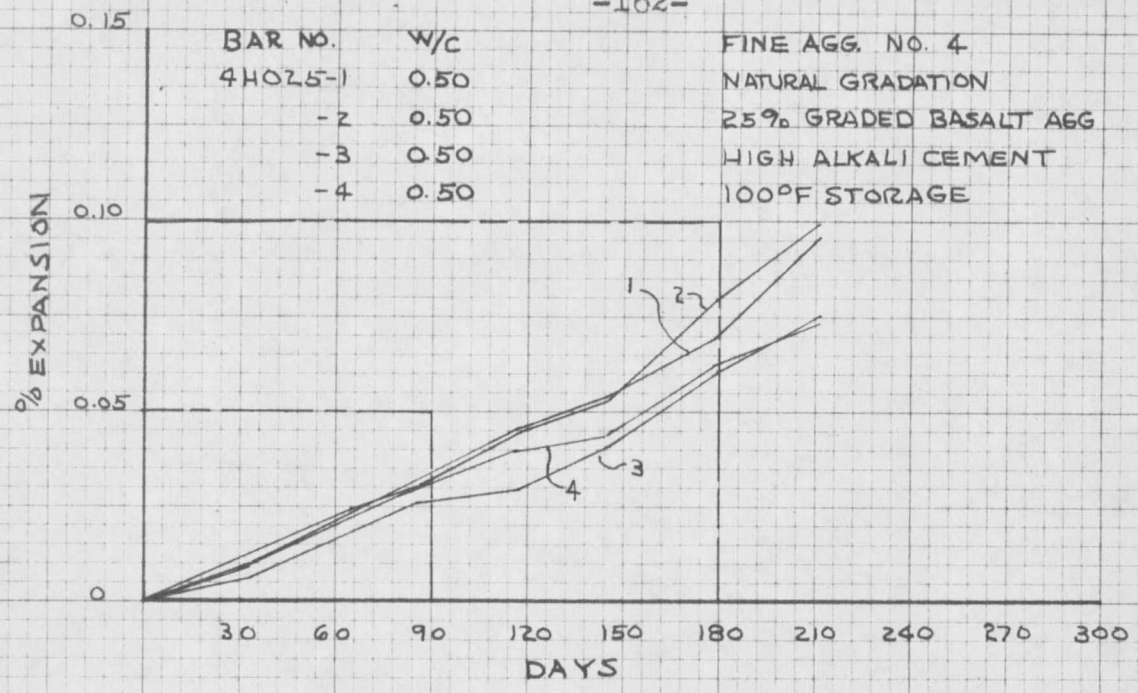


Figure 60 - Individual Mortar Bar Expansion Records



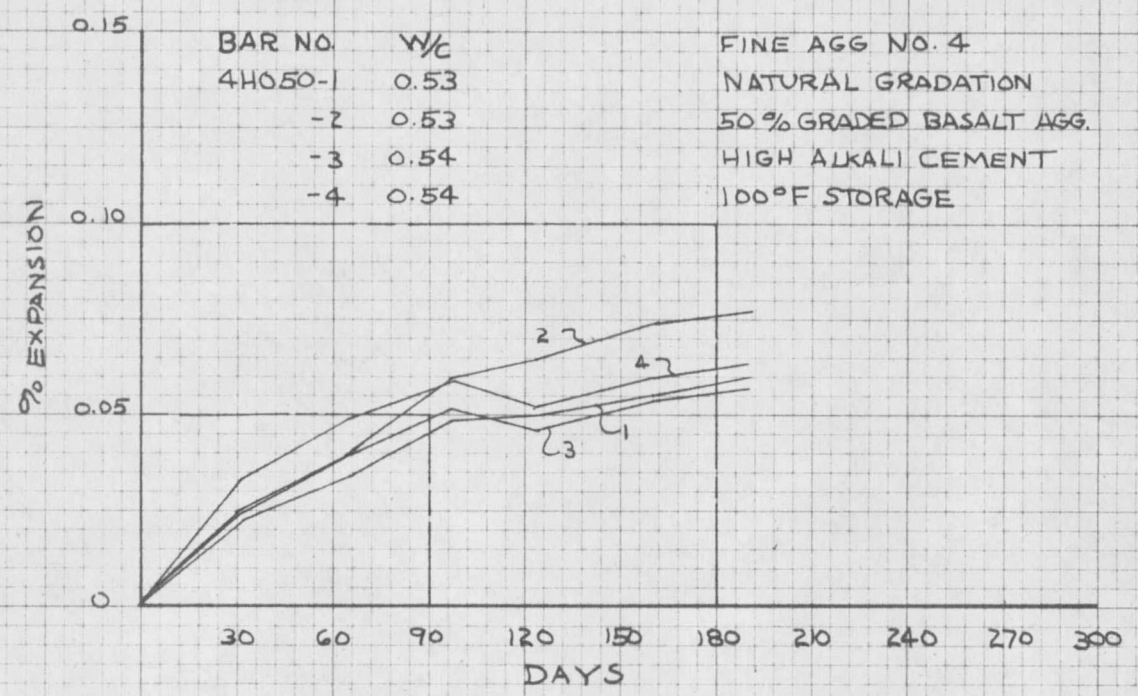
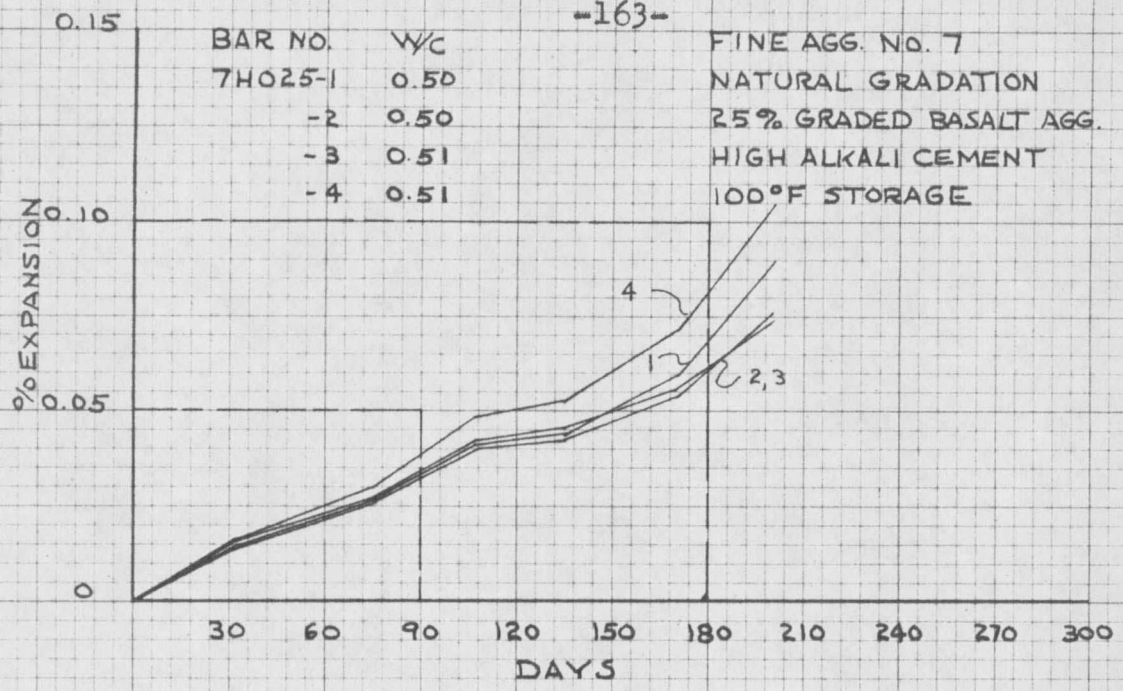


Figure 61 - Individual Mortar Bar Expansion Records



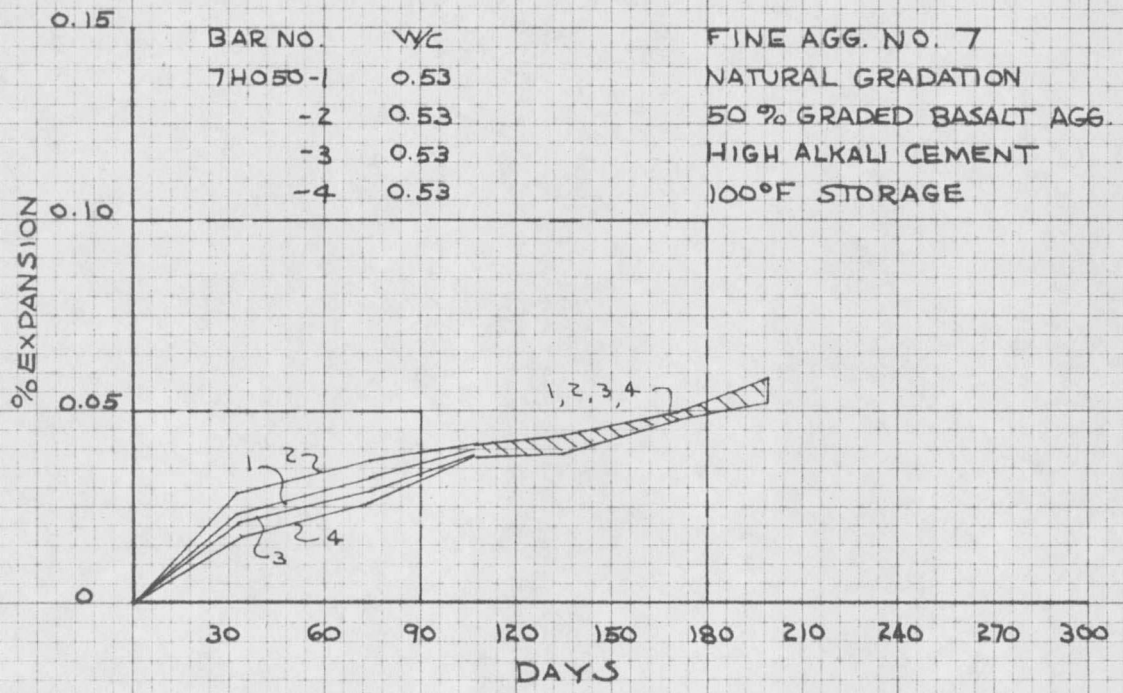
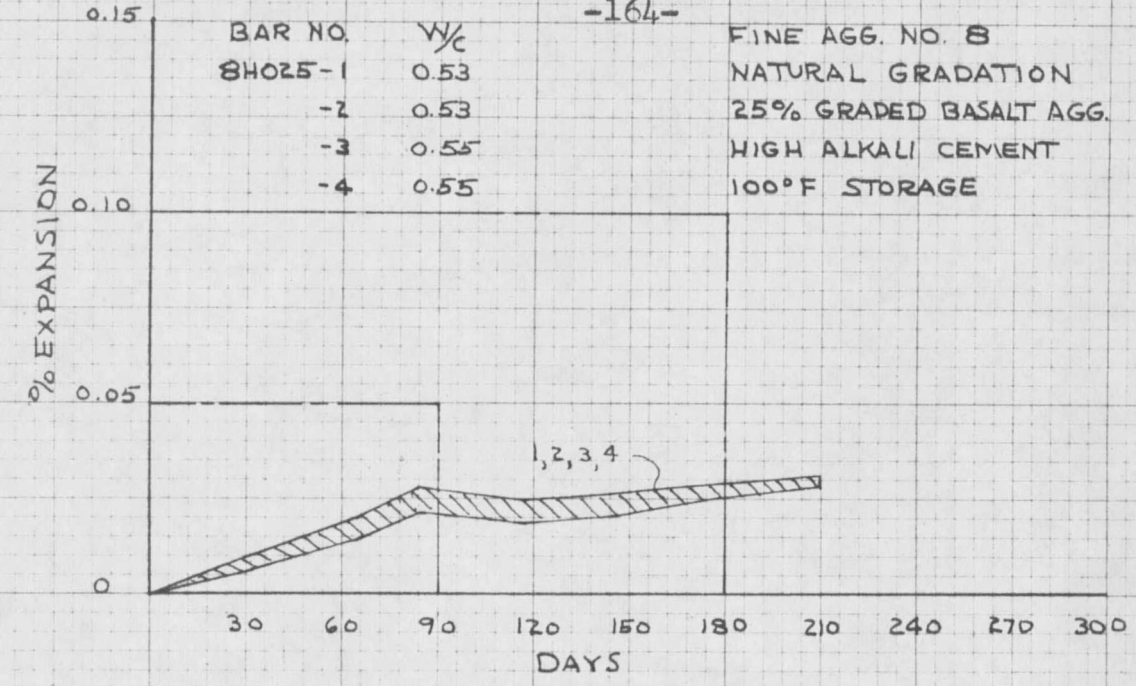


Figure 62 - Individual Mortar Bar Expansion Records



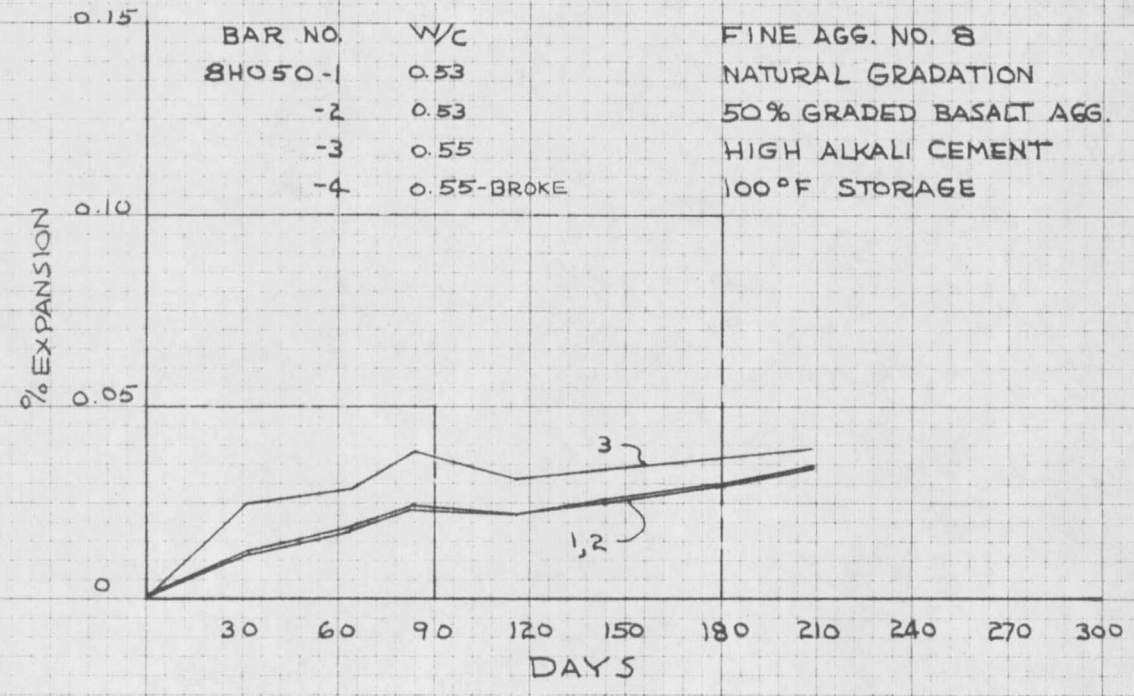
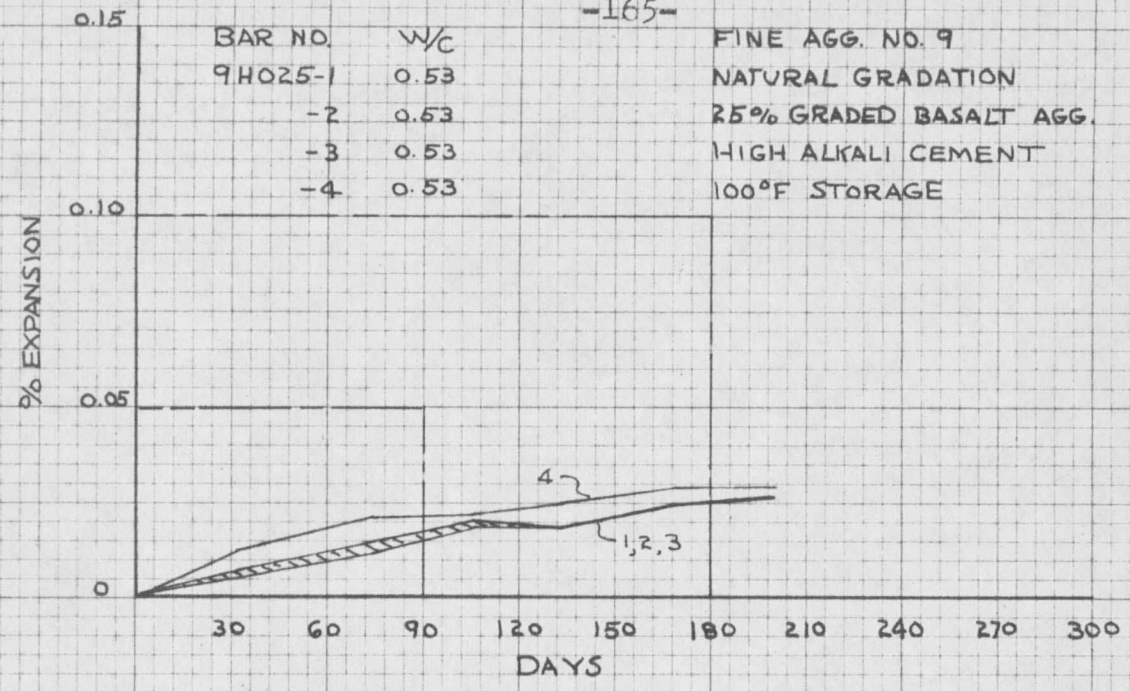


Figure 63 - Individual Mortar Bar Expansion Records



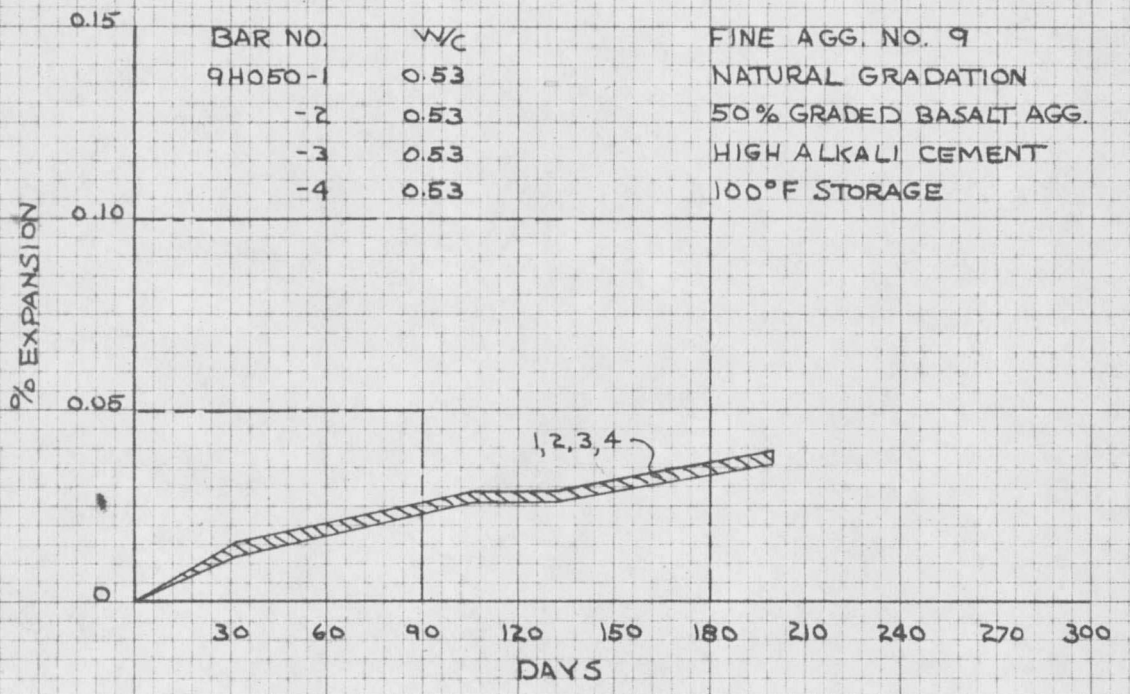
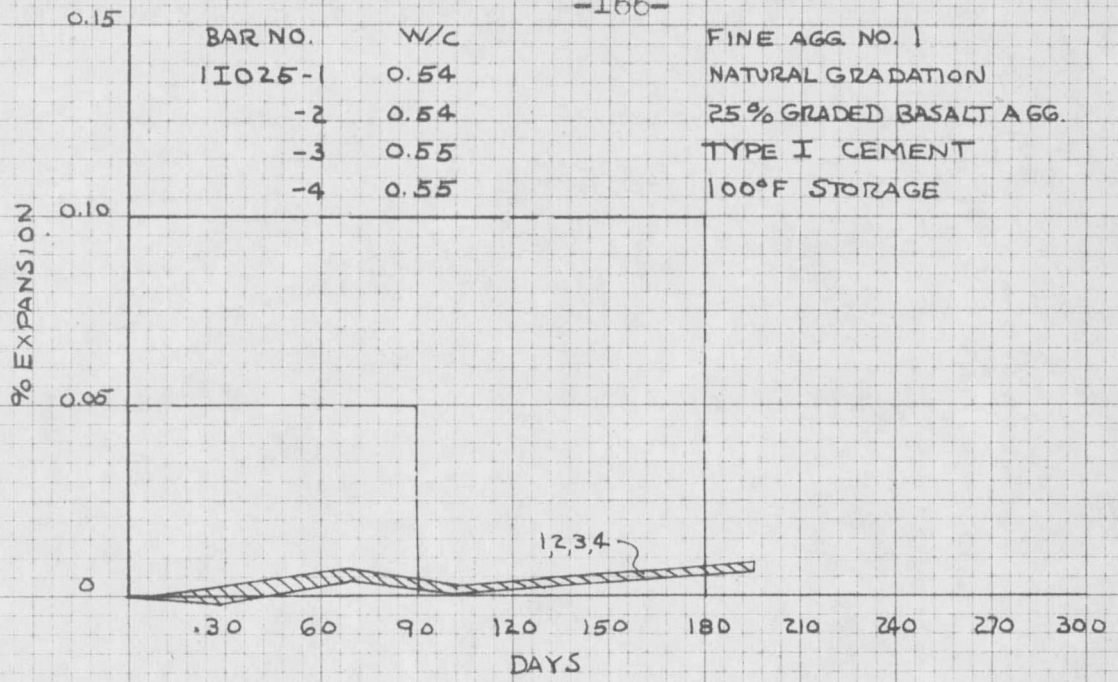


Figure 64 - Individual Mortar Bar Expansion Records



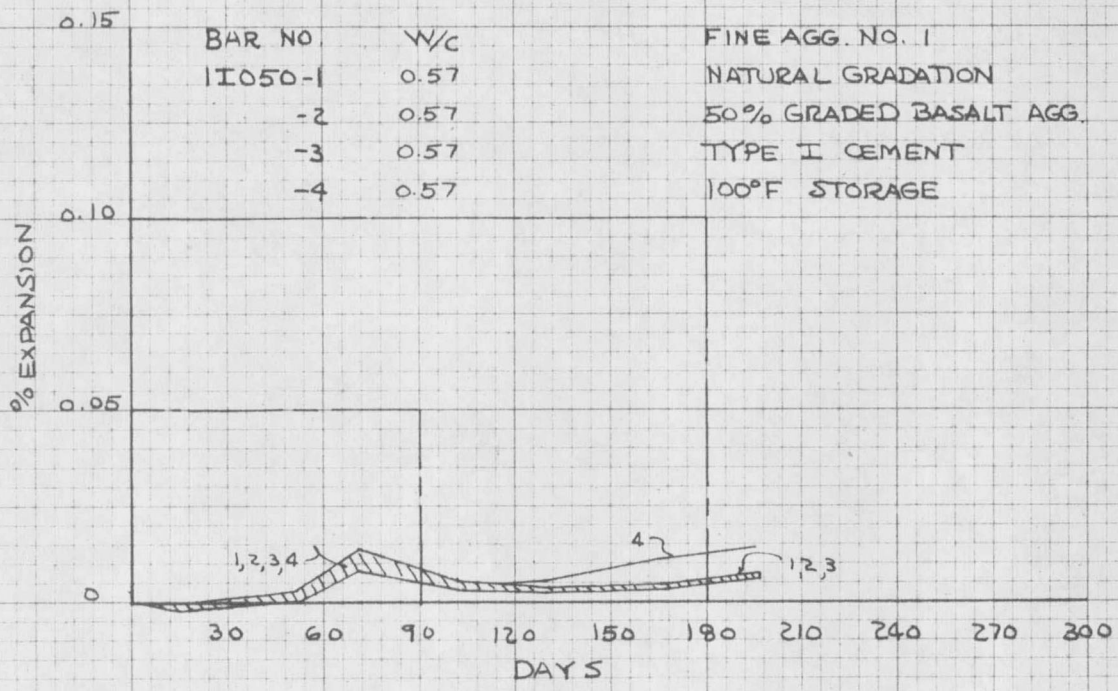
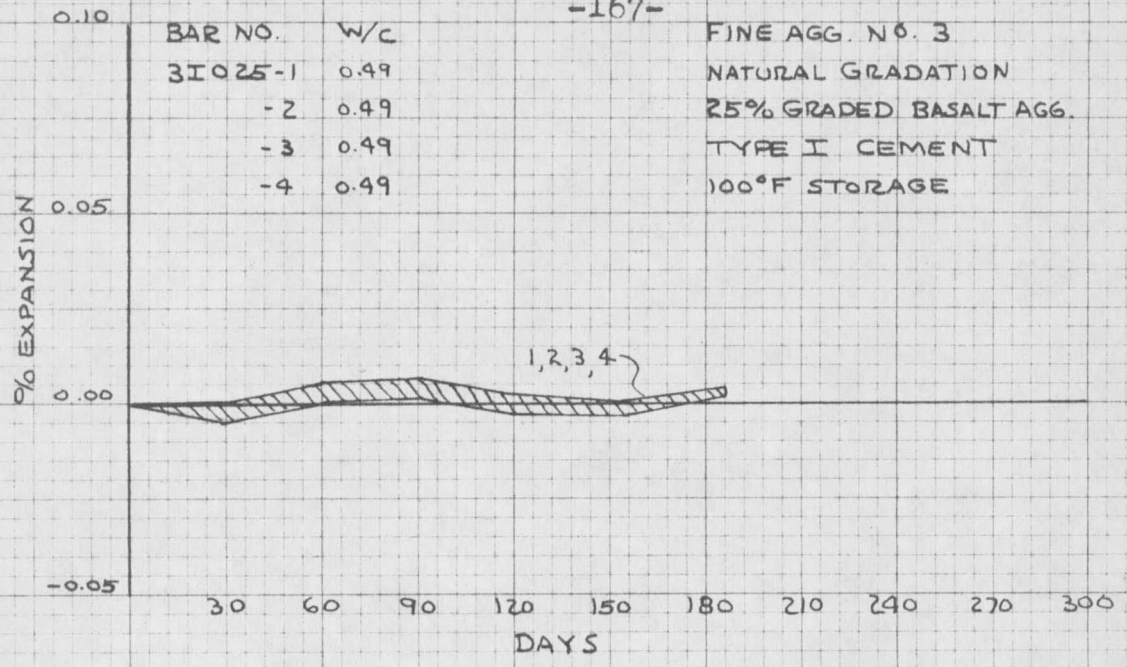


Figure 65 - Individual Mortar Bar Expansion Records



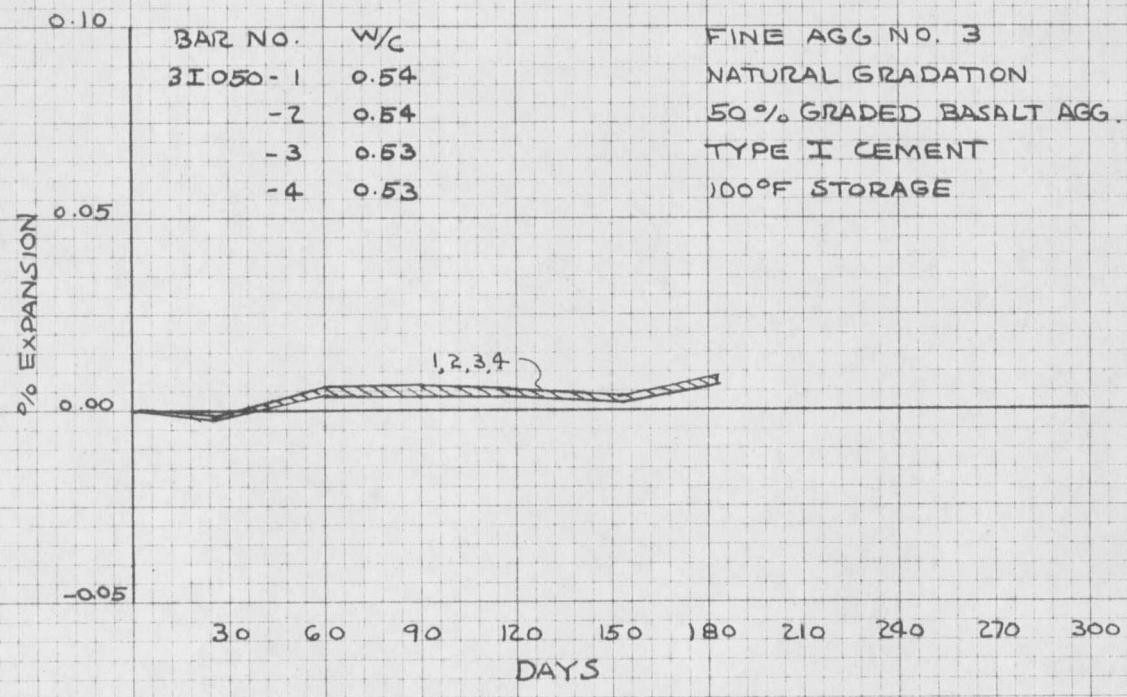
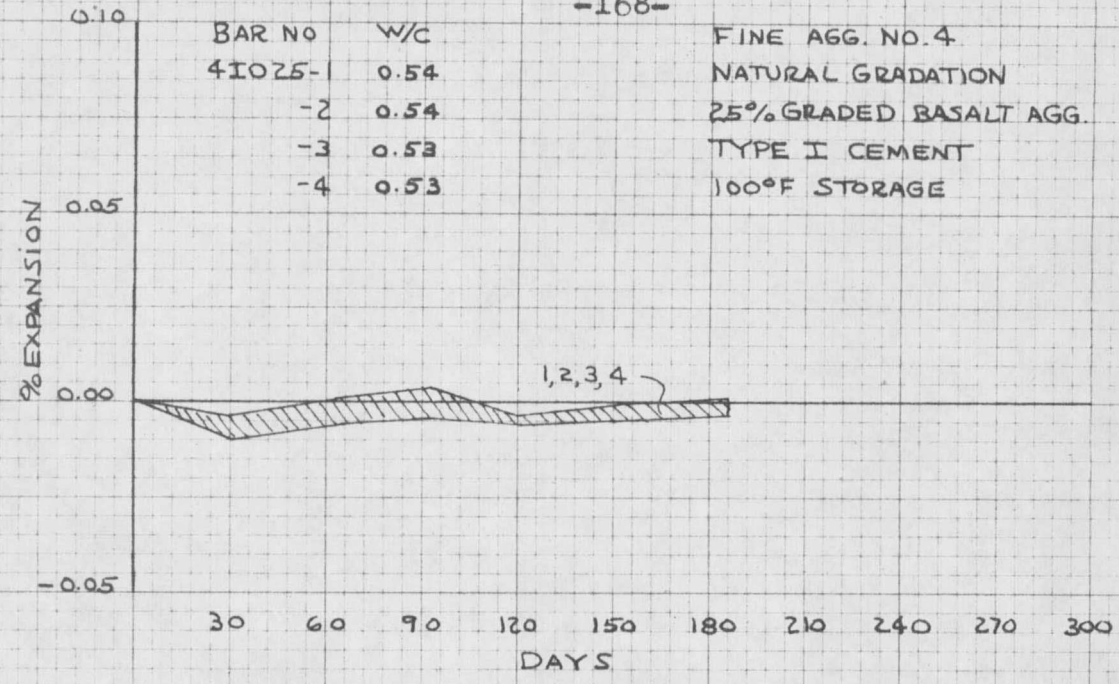


Figure 66 - Individual Mortar Bar Expansion Records



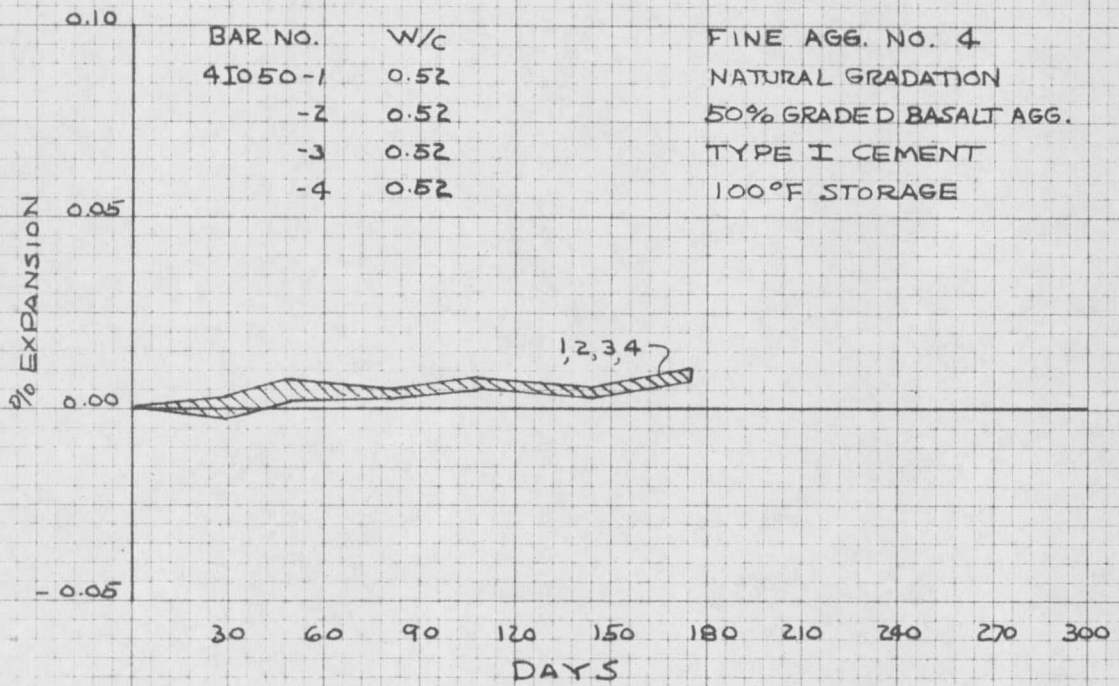
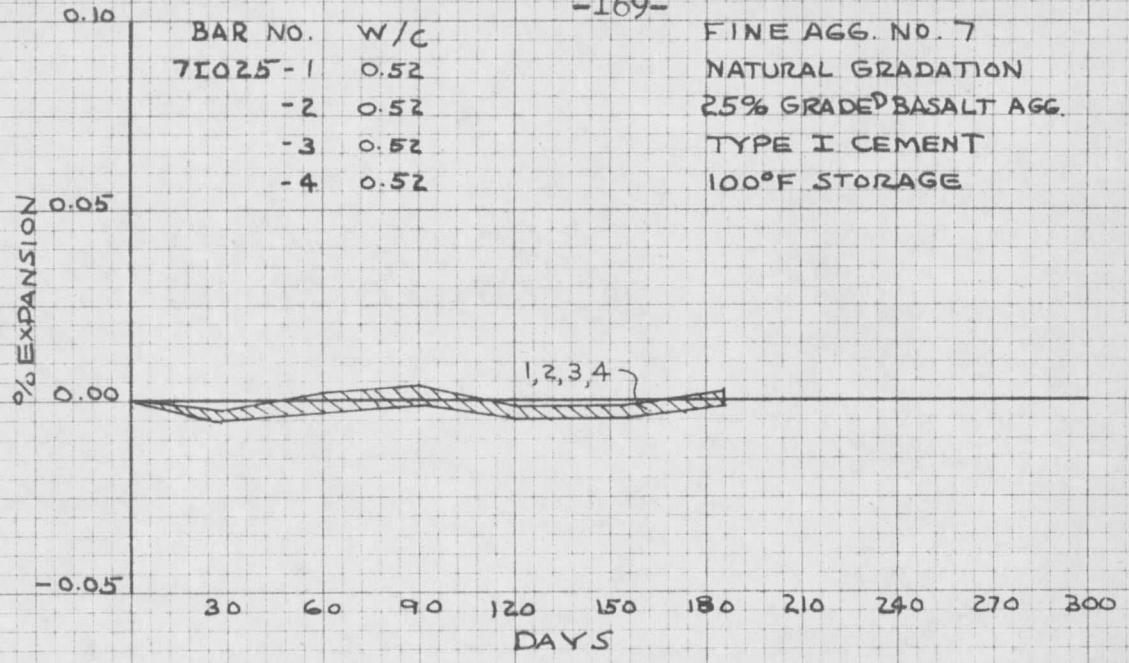


Figure 67 - Individual Mortar Bar Expansion Records



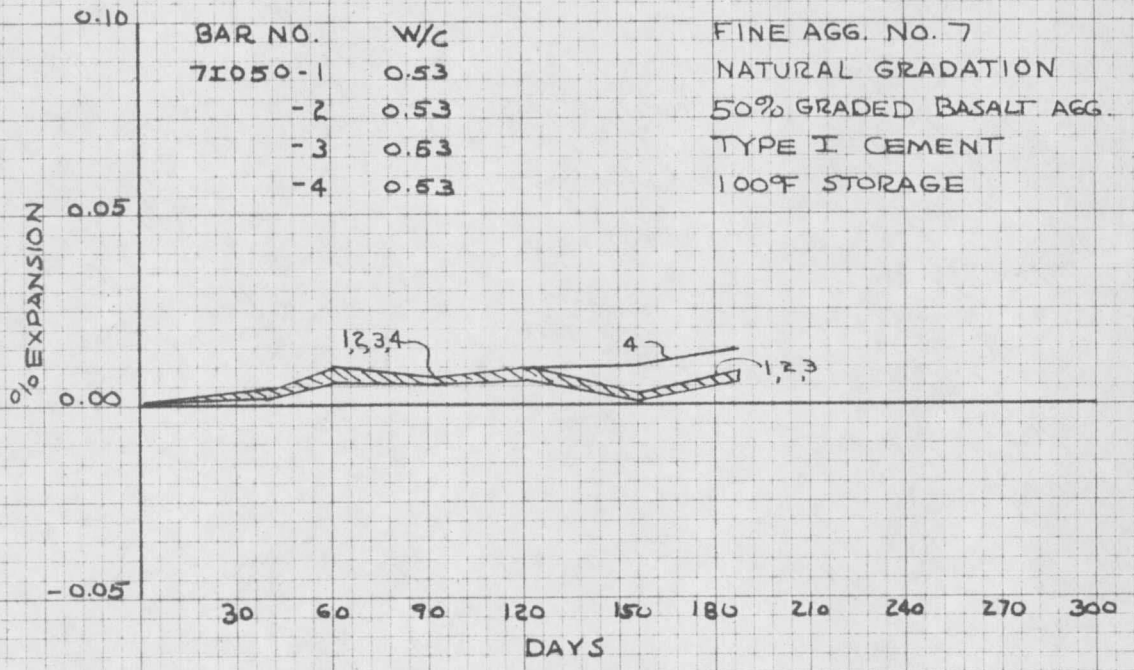
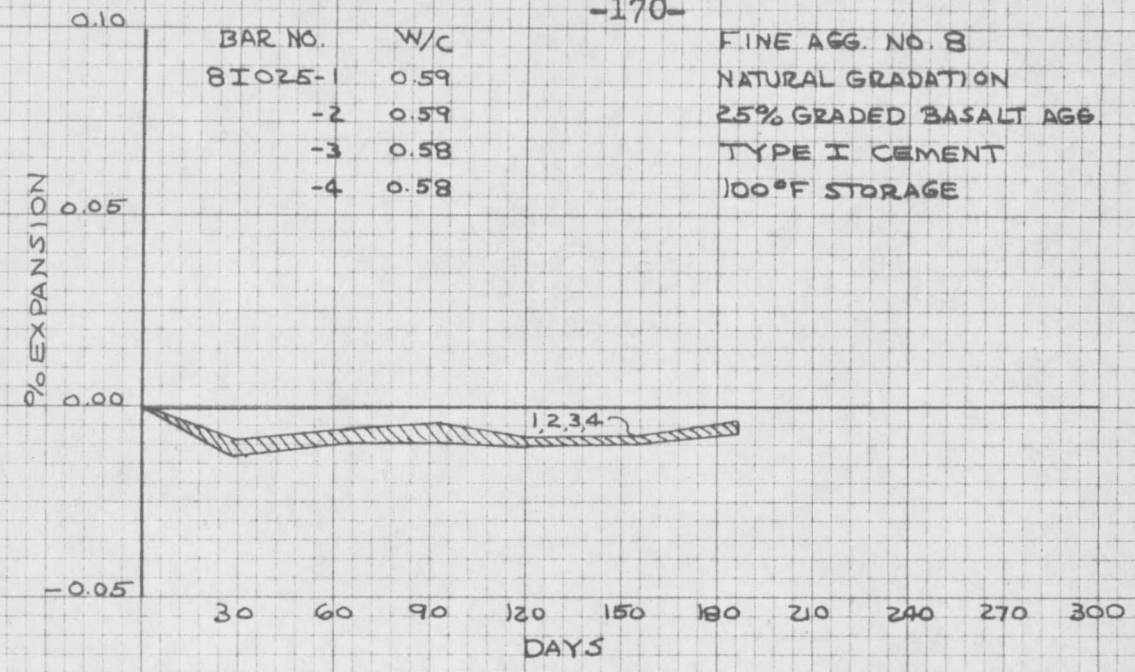


Figure 68 - Individual Mortar Bar Expansion Records



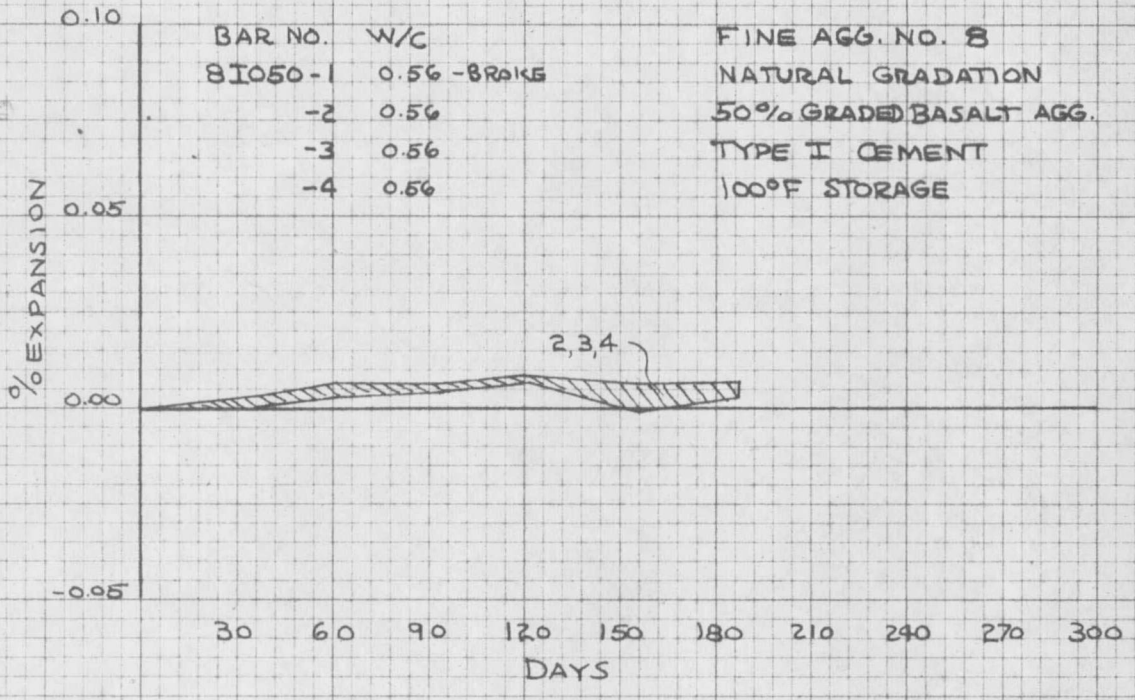
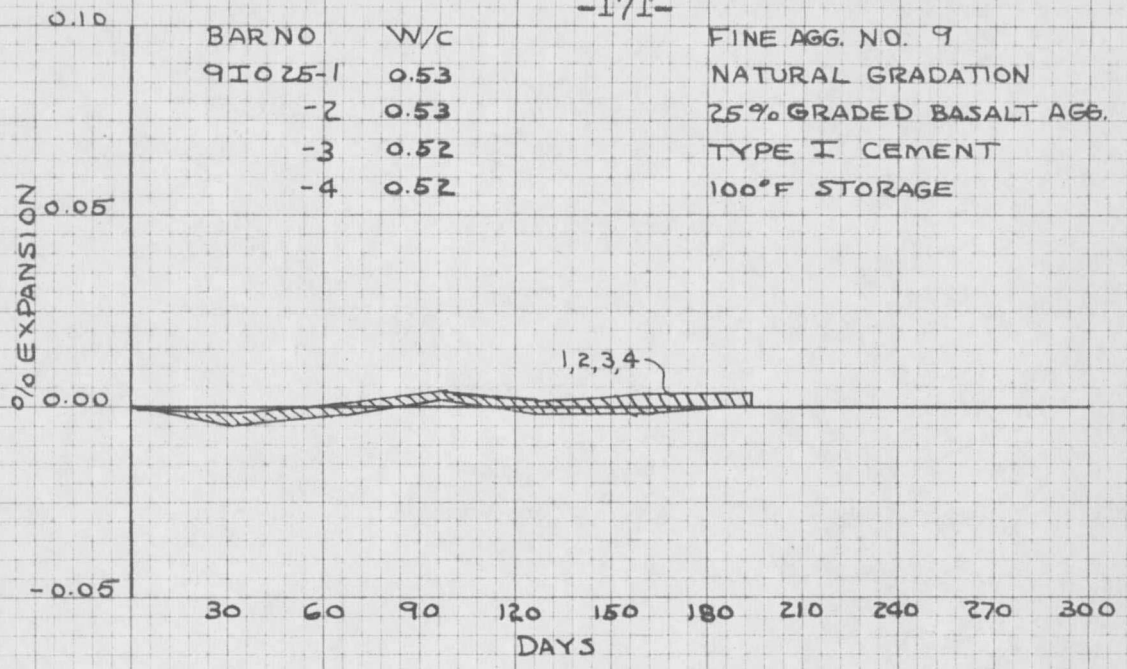


Figure 69 - Individual Mortar Bar Expansion Records



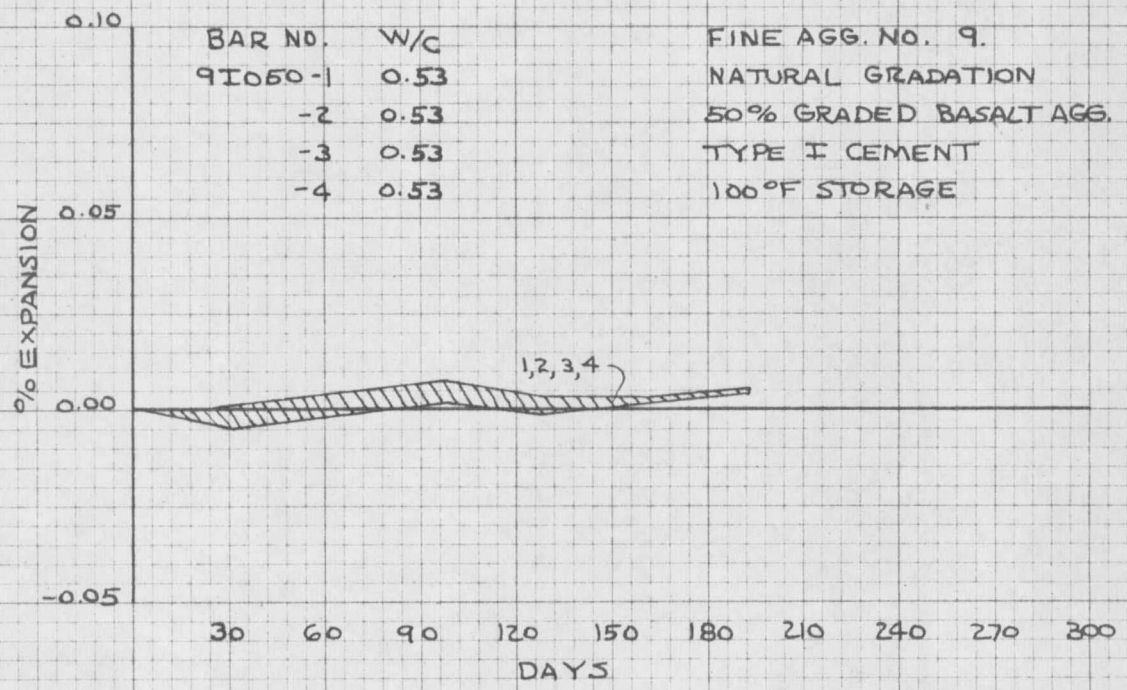
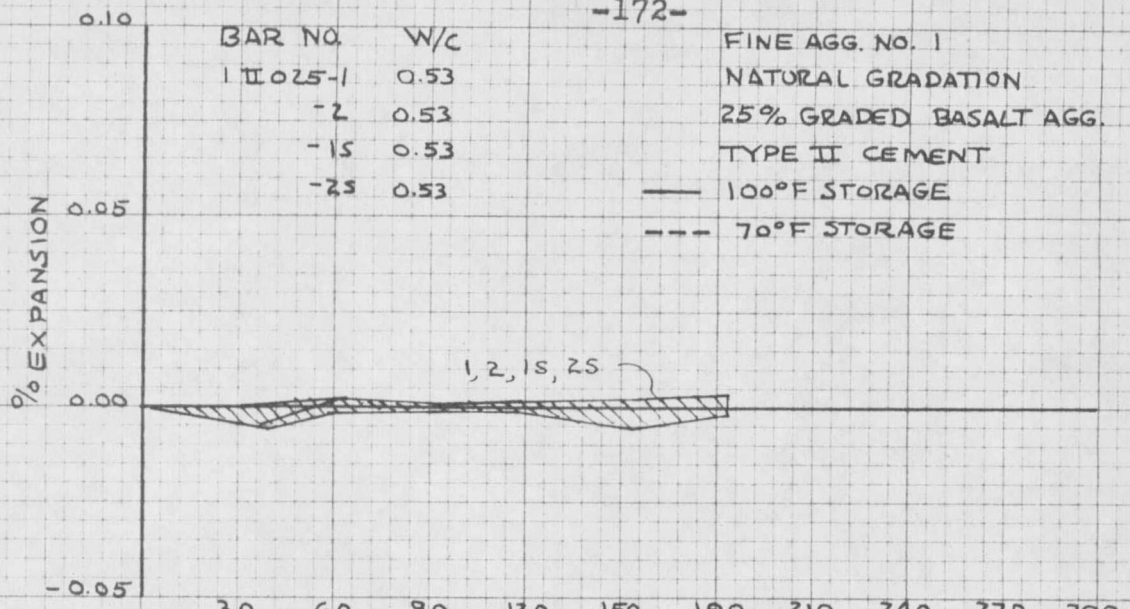


Figure 70 - Individual Mortar Bar Expansion Records



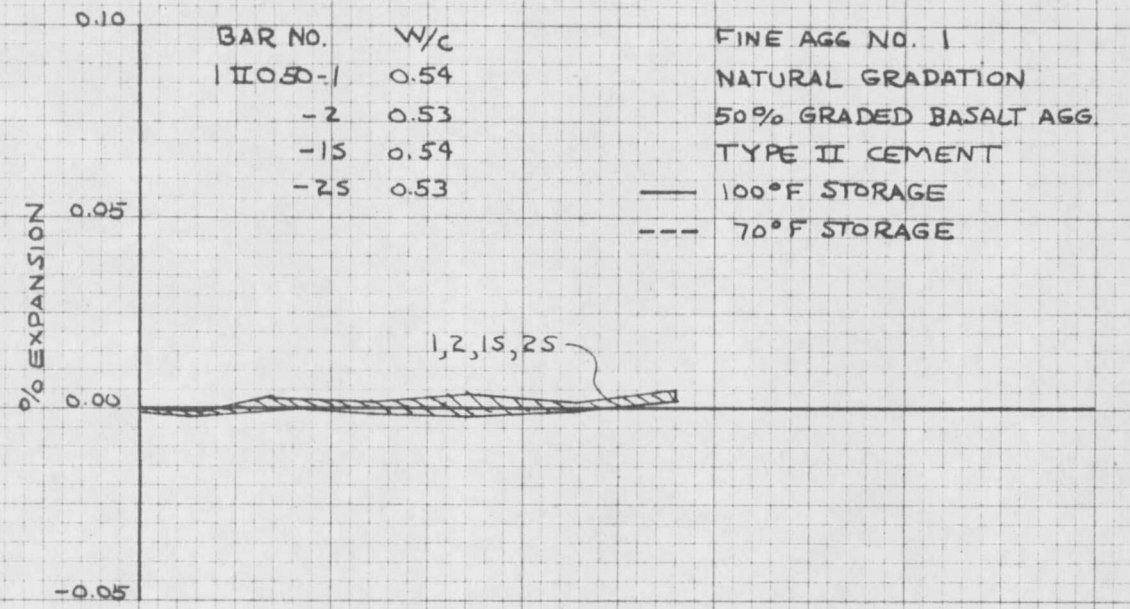
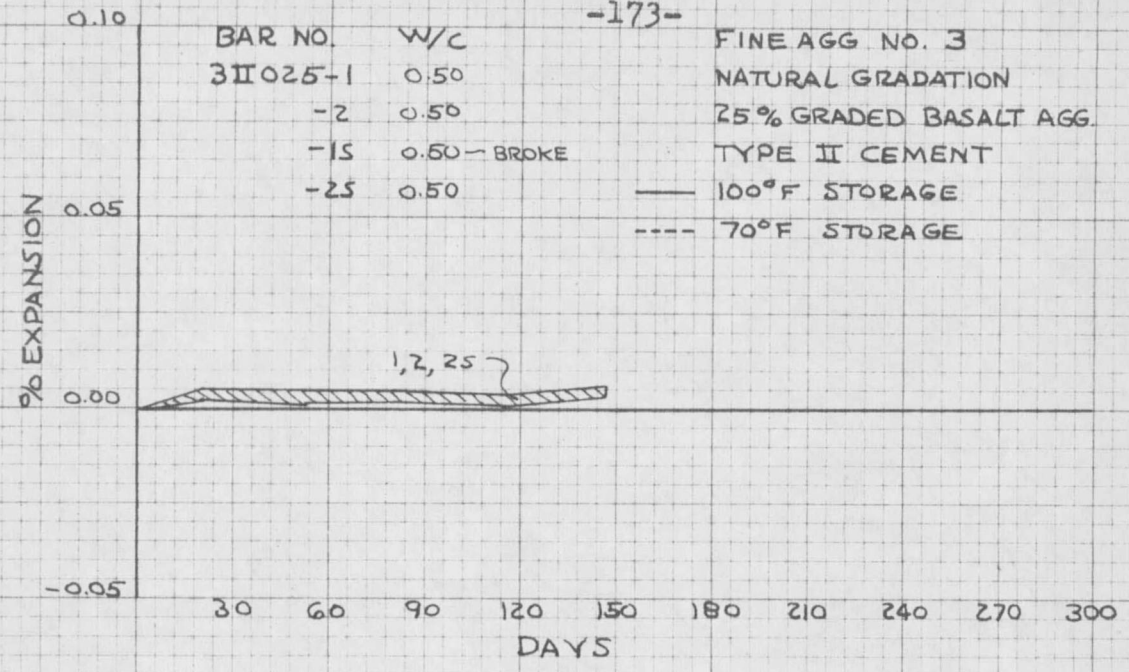


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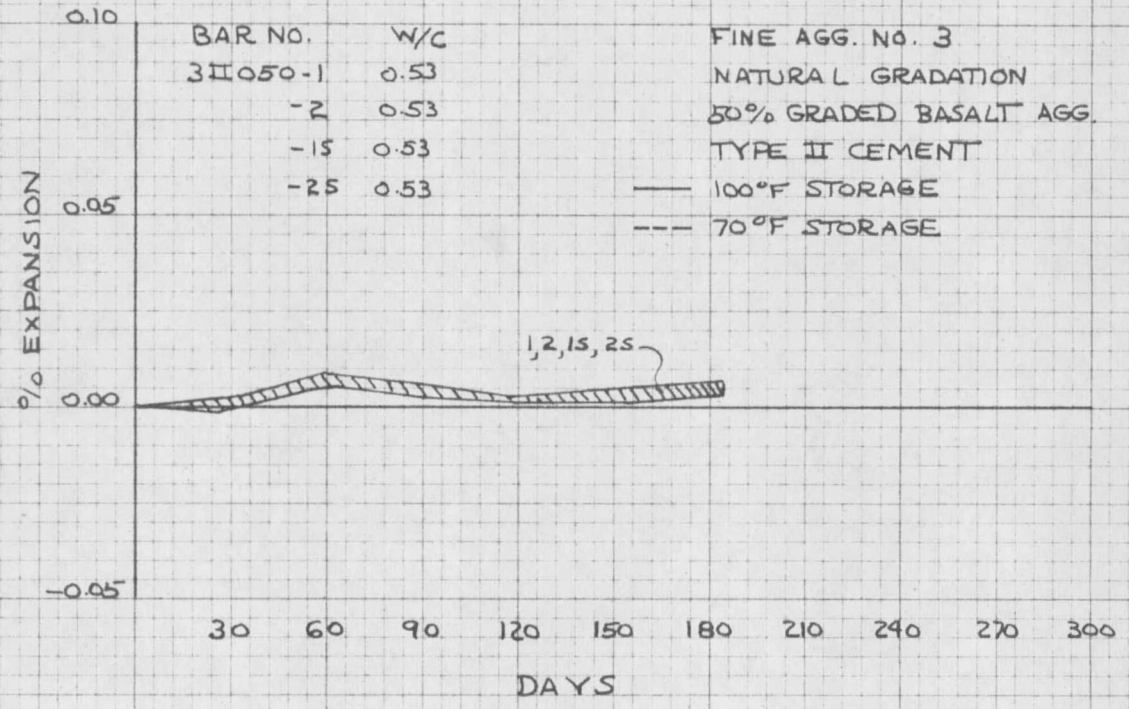
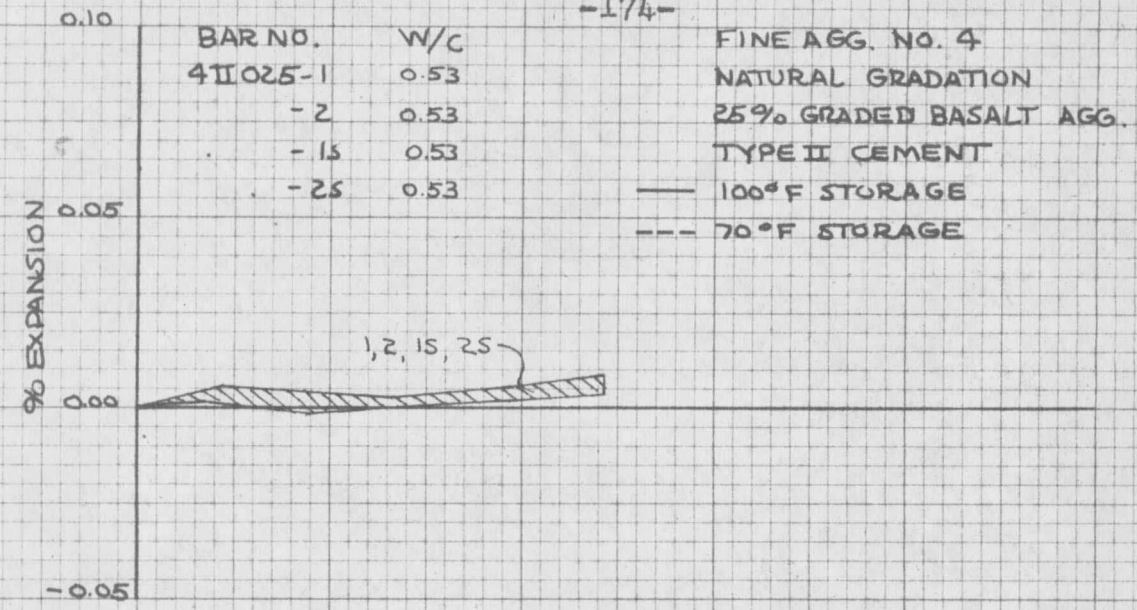


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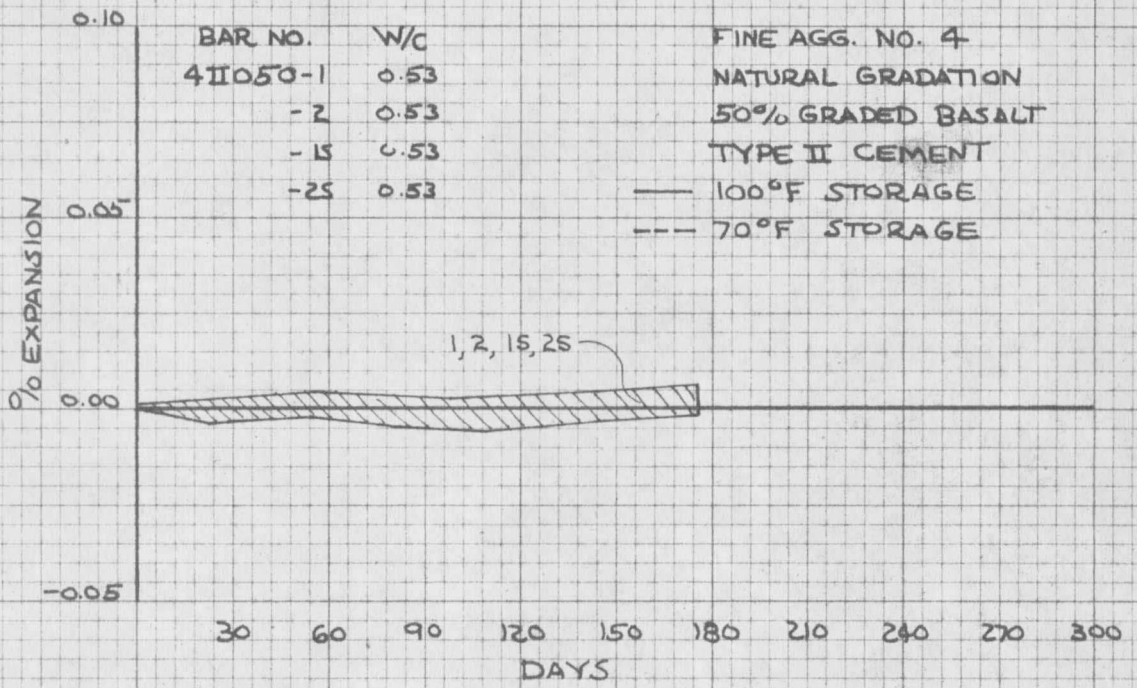


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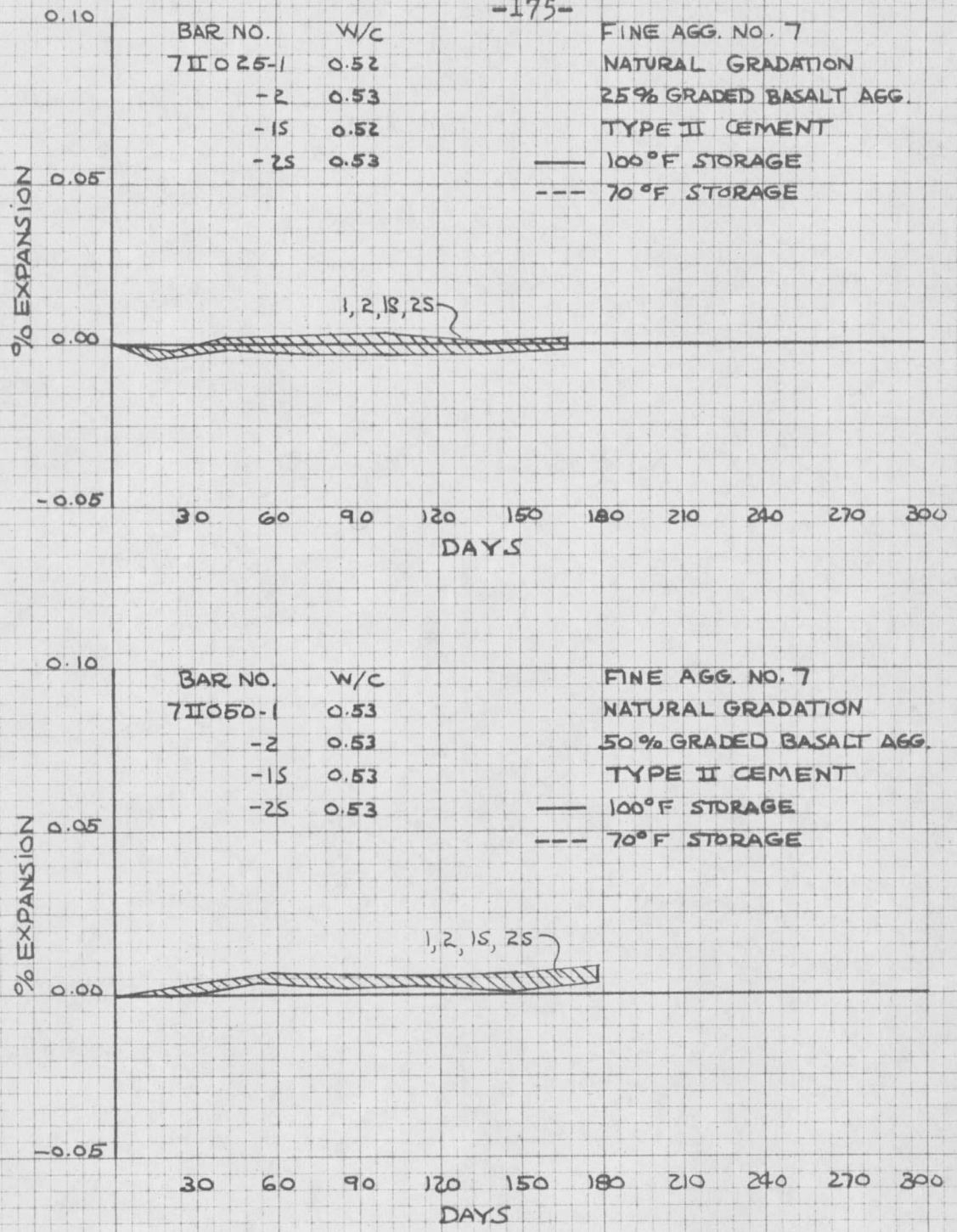
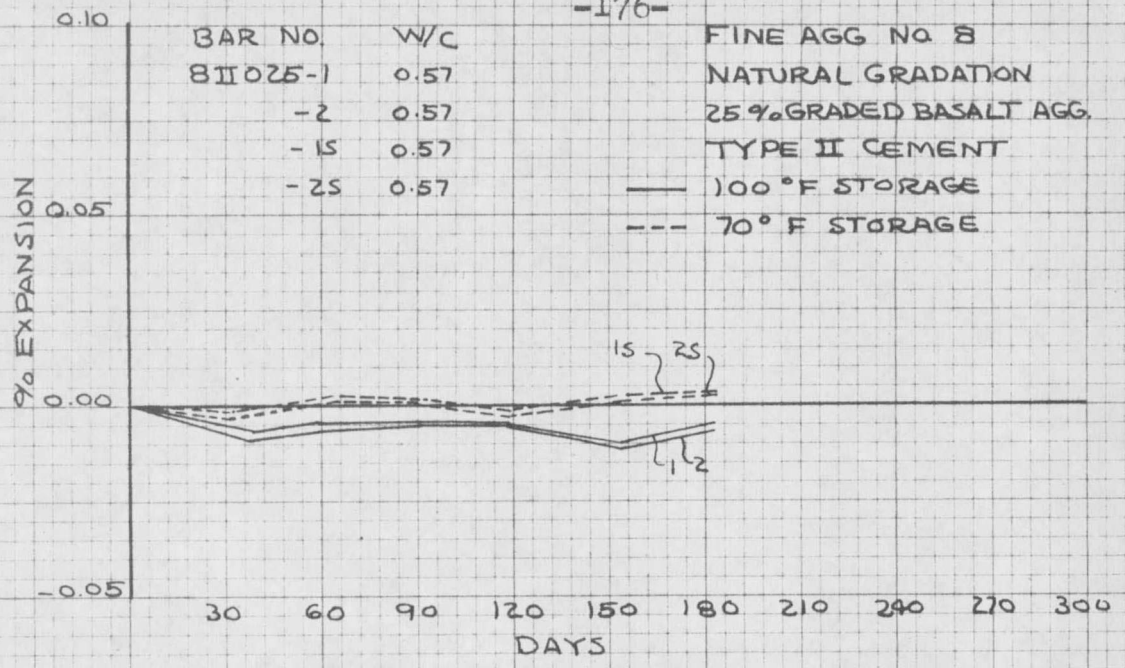


Figure 74 - Individual Mortar Bar Expansion Records



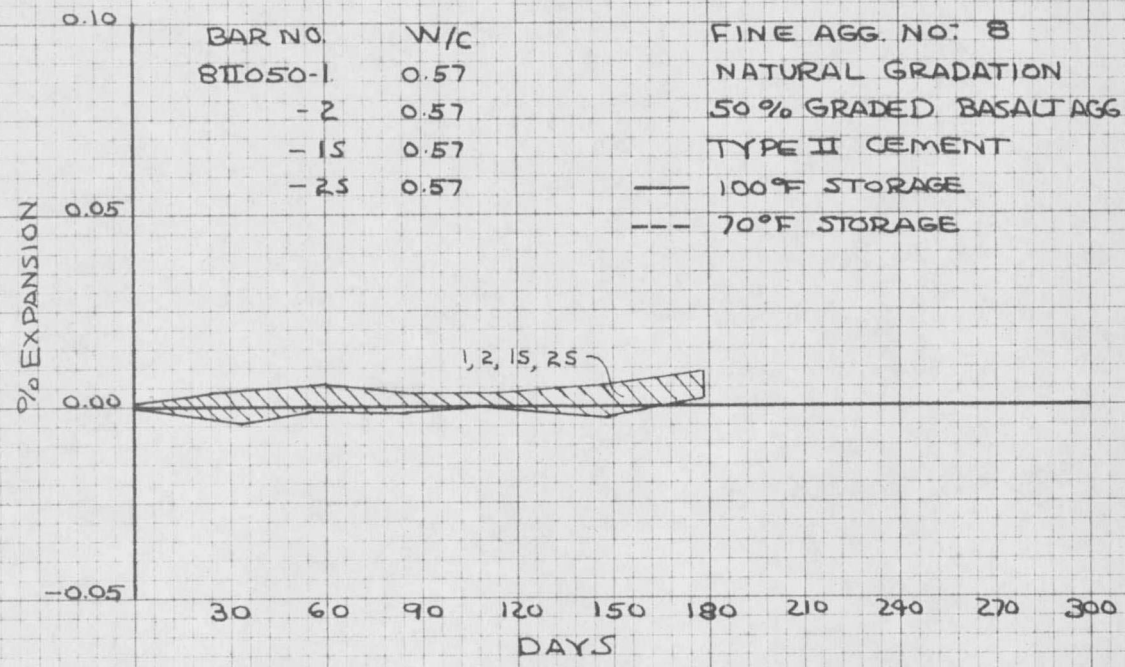
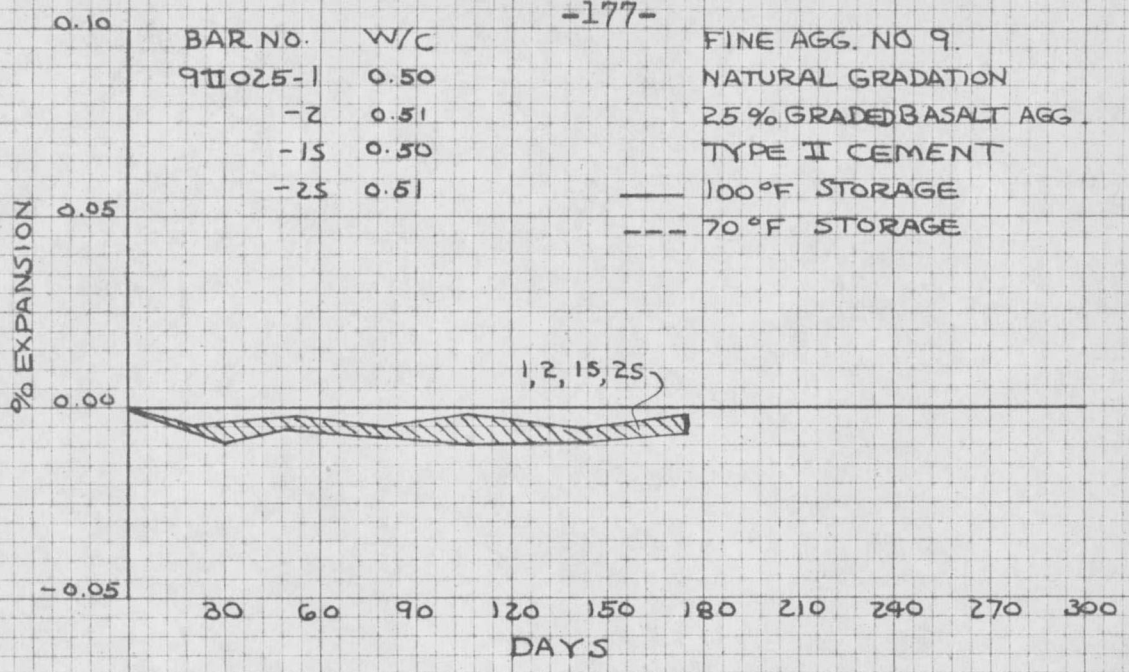


Figure 75 - Individual Mortar Bar Expansion Records



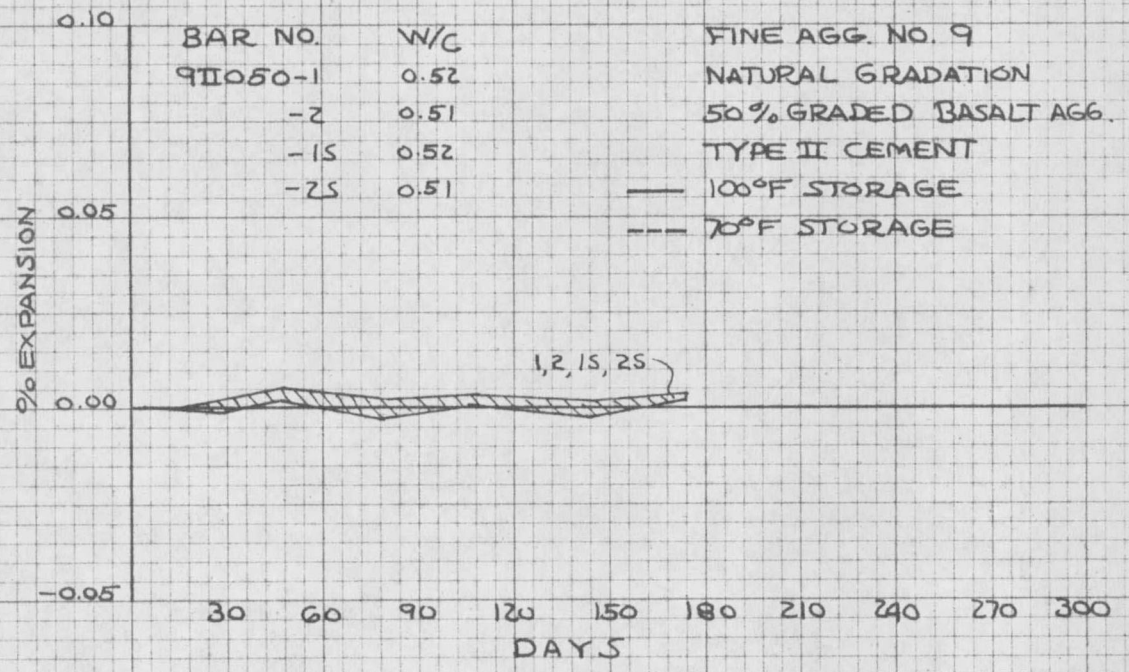


Figure 76 - Individual Mortar Bar Expansion Records

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