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Effect of maximum size of aggregate and other factors on frost resistance of concrete.

Eddie C. Lau
University of Windsor

EFFECT OF MAXIMUM SIZE OF AGGREGATE AND OTHER FACTORS ON FROST RESISTANCE OF CONCRETE

A THESIS

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by

Eddie C. Lau

B.A.Sc., The University of Windsor, 1966.

Windsor, Ontario, Canada.

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APPROVED BY:

C. MacInnis

J. T. Kok

Alex Gnuff

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ABSTRACT

The introduction deals with the need to investigate the frost resistance of concrete under various exposure conditions. This is followed by a review of the theories relating to the mechanisms of frost damage in cement pastes. This leads to a discussion of factors affecting the frost resistance of concretes. Previous freezing and thawing studies beginning in the 1930's and continuing up to the present are then reviewed, and this brings out the aims of the Powers' method of investigation which was used in this programme of studies.

The experimental programme describes the use of 3" x 6" concrete specimens to determine the frost susceptibility during freezing by studying their length-change vs temperature patterns. A range of water-cement ratios from 0.45 to 0.60, each with three different maximum sizes of aggregates (3/4-in., 3/8-in. and 1/4-in.) was used. In order to simulate appropriate exposure conditions the specimens were conditioned to different degrees of saturation before being introduced into a freezing chamber. The main findings were:

(a) Low water-cement ratios increase the frost resistance of concrete.

(b) Large aggregate particles are more vulnerable to freezing damage.

(c) Critical degree of saturation is found to be dependent on the water-cement ratio of the paste and the size of aggregates used.

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1. INTRODUCTION

During the past 25 years many investigations have been carried out on the subject of durability of concrete under freezing and thawing exposure. The principal objective of much of this research has been the determination of comparative behavior of specimens of concrete made with various cements and aggregates, with various mix proportions, water-cement ratios, and air contents; cured in specific ways for various lengths of time; and subjected to various freezing and thawing tests. Some research has been of a fundamental nature, having as an object the determination of the conditions and mechanisms of deterioration and the role of air entrainment.

In view of the wide variety of concrete materials, mix proportions, curing procedures and test conditions employed, with a consequent wide variety of results obtained, it is not surprising that a considerable amount of uncertainty exists as to the meaning of much of the published results.

The methods currently used to test the frost resistance of concrete need to be re-examined critically in the light of present knowledge of the mechanisms of deterioration. It seems entirely possible that accelerated freezing and thawing tests could be devised which would result in the rapid destruction of air-entrained concrete which in nature would prove highly resistant.

Indeed, it may be questioned whether some of the high-speed tests now in use yield results from which valid predictions can be made of behavior under natural weathering conditions. It may not be essential that laboratory tests exactly reproduce natural processes, but many authorities think that it is important for the freezing rate to be slow, i. e., reasonably close to those obtaining in nature. The problem of using a slow freezing rate, of course, is that it then takes a very long time to perform enough cycles of freezing and thawing to induce appreciable deterioration. To overcome this problem, Powers (1955) suggested the use of a one-cycle freezing test involving length measurements during the freezing cycle to tell whether or not at any given time a specimen is vulnerable to frost action. "If it shrinks normally in the freezing range it is immune; if it dilates, it is not immune -- the process that eventually causes disintegration has begun". Powers (1955)

The purpose of this research project is to utilize the Powers' test to evaluate the effect of different maximum aggregate sizes on the frost resistance of concrete mixes at a variety of water-cement ratios and degrees of saturation. It is hoped that this in turn will provide data which could form a basis for the establishment of limiting water-cement ratios for different exposure conditions for concrete.

2. STRUCTURE OF HARDENED PORTLAND CEMENT PASTE

In order to understand the mechanisms of freezing and thawing within the paste, an understanding of the make-up of the Portland cement paste structure is essential.

In the parlance of the cement industry, a mixture of Portland cement and water is called cement paste; the chemical reactions of the components of Portland cement with water are spoken of collectively as cement hydration; hydration of cement causes the paste to harden and thus there is the term "hardened Portland cement paste".

Fresh cement paste is a network of particles of cement in water. The paste is plastic, and it normally remains thus for an hour or more, during which time it "bleeds", i.e., there is a small amount of sedimentation [Powers (1945)]. After this relative dormant period, the plastic mass sets and thereafter the apparent volume of the paste remains constant, except for microscopic but technically important variations caused by changes of temperature or moisture content, or by reactions with atmospheric CO_2.

Chemical reactions between components of cement and water produce new solid phases. One of them is crystalline calcium hydroxide and another, the predominant one, microscopically amorphous, is cement gel. Cement gel is composed of gel particles and interstices among those particles, called gel pores.

The structure of paste is not identical with the structure of gel. Space within the visible boundaries of a specimen of paste contains gel, crystals of calcium hydroxide, some minor components, residues of the original cement, and residues of the original water-filled spaces in the fresh paste. These residues of water-filled space exist in the hardened paste as interconnected channels or, if the structure is dense enough, as cavities interconnected only by gel pores. These residual submicroscopic spaces are called capillary pores, or capillary cavities.

Thus, two classes of pores within the boundaries of a body of paste are recognized: (1) gel pores, which are a characteristic feature of the structure of gel, and they vary from 0.000001 to 0.000008 mm in mean diameter, and (2) capillary pores or cavities, representing space not filled by gel or other solid componentns of the system. They are the original water-filled space which have not become filled with hydration products. These capillary space include a wide variety of "sizes" and "shapes" but perhaps can be considered to vary about 0.000008 to 0.013 mm in diamter, depending on the original w/c ratio and the degree of hydration of the cement.

Capillary porosity is greatest in a given paste when the paste is fresh. It is least when all the cement has become hydrated that can become hydrated under existing conditions.

At any given stage of hydration, capillary porosity depends on the original proportion of water in the paste, which is usually expressed as the ratio of water to cement in the original mixture.

The products from 1 cm^3 of cement requires a little more than 2 cm^3 of space. Therefore, the volume of water-filled space in fresh paste must exceed twice the absolute volume of cement, or some of the original cement must remain unhydrated. Cement gel can be only produced in water-filled capillary cavities, and when all those cavities become full, no further hydration of cement can occur. The degree to which the original water-filled space becomes filled with gel depends on how much of the cement has become hydrated and on the amount of water-filled space originally present. In other words, it depends on the w/c ratio of the paste and on the extent of hydration of the cement. Figure I illustrates how hydration products gradually reduce the amount of capillary space, and in some cases eliminate it.

It can be seen that hydration reduces the size and volume of the capillary space in the paste. If the original capillary space is low (water-cement ratio about 0.35 by weight), the bulk volume of the gel will be sufficient to fill this space and produce a paste free from capillary space. At high water-cement ratios, the gel volume is not sufficient to fill completely all the original water space in the paste, even after complete cement hydration, and pastes having

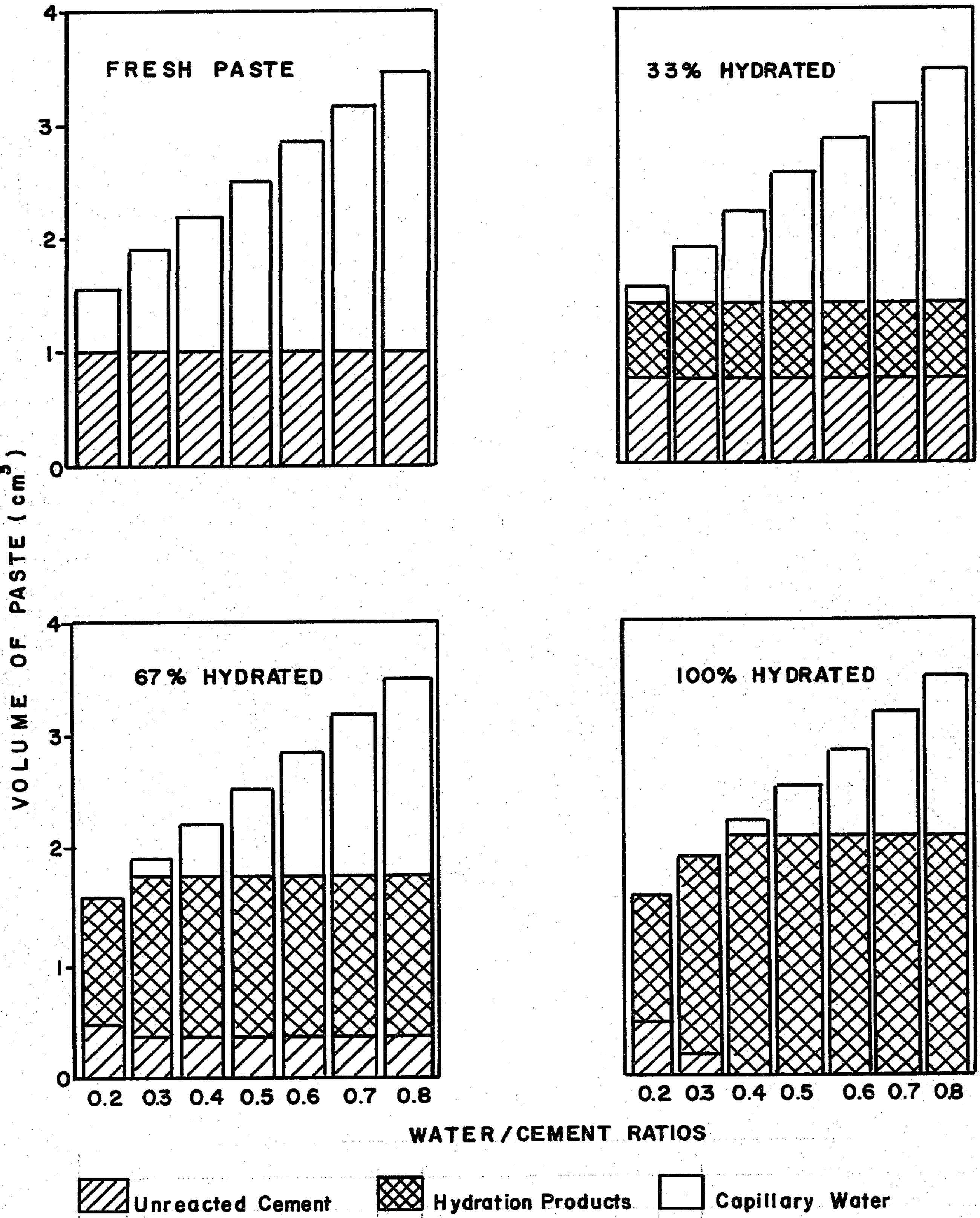

Figure I. Cement Paste of Various Stages of Hydration [Powers (1958)] relatively large volume of capillaries may be produced. The volume of the gel pores in each quantity of paste increases with continued hydration of the cement, whereas the volume of the capillary spaces decreases with hydration.

Water held in either gel or capillary pores does not behave as normal free water. The gel pores retain significant quantities of surface absorbed water and chemisorbed or hydrate water or both. Because the gel pores are so small, water contained in them is under relatively high surface tension and will not freeze under normal freezing temperatures. Capillary pores are many times larger and proportionately less of the capillary water is strongly absorbed on the pore walls, and it is therefore relatively more volatile than is gel water. These are the pores which lead to deterioration of cement because water can freeze in them.

3. MECHANISMS OF CONCRETE DETERIORATION

The mechanisms of concrete deterioration will become clearer by first considering two concepts: critical thickness and critical saturation. If a body of water-saturated hardened cement paste is extremely large -- that is, if it has no boundaries at all and no air voids -- all water that freezes must remain in the body and the body must increase in volume enough to accommodate the water-volume increase produced by freezing. Hence, the volume increase would be about 9 per cent of the volume of water that freezes. With a finite body, however, some of the excessive water-volume produced by freezing may escape from the body during freezing, and thus over-all dilation of the body will be less than it would have been had none of the excess been expelled. If the body of paste is a thin slab or a small particle, parts nearest "escape boundaries" (the surfaces through which excess water can be expelled) will not be directly damaged by freezing because all excess water can escape from those regions. If the body is sufficiently thick, inner parts will become dilated during freezing, and this will affect outer parts too; hence, the over-all effect of freezing in any given paste depends on thickness of the body. If the body is thinner than some critical limit, it can be frozen without damage.

If a body of paste is not saturated, the largest spaces tend to be empty while the smallest remain full. Some spaces will be partly full. If any given capillary space is 91.7 per cent full before it freezes, it should be exactly full after freezing (assuming 9 per cent volume expansion). Since it contains no excess water, it will not contribute to hydraulic pressure that may be generated by freezing in other fuller spaces. If it contains more than 91.7 per cent of its capacity, it must, of course, contribute to pressure; the more nearly full it is, the more it contributes. Therefore, for a given capillary space in hardened paste, 91.7 per cent is a critical degree of saturation.

If the paste as a whole is not saturated, water will not be uniformly distributed among the capillary spaces. The smaller spaces will tend to be fuller than the larger ones. Hence, freezing in a partially saturated paste may involve displacing water from smaller to larger spaces. Freezing in paste may produce some stress even when the over-all saturation coefficient is below the theoretical limit. Such stress is not likely to be destructive; in fact, indications are that a small loss of evaporable water enables a paste to withstand severe freezing. [Powers (1955)].

Freezing of water in a saturated paste causes paste to dilate destructively. The mechanisms involved are: (1) Hydraulic Pressure (2) Growth of Capillary Ice, and

(3) Osmotic Pressure.

3.1 Hydraulic Pressure

In a water soaked paste the capillary and gel pores are full or nearly full of water. Water can be caused to freeze in capillary pores, but it cannot freeze in gel pores. Gel pores apparently are too small to permit nucleation of ice crystals. When the temperature falls to a point where freezing should begin, ice crystals appear in the capillary pores. When the water begins to change to ice, the volume of water plus ice will exceed the original capactity of the pores because of 9 per cent increase in volume of water changing to ice. Therefore, the pore must dilate or the excess water must be expelled from it. Then hydraulic pressure is generated because the growing ice crystals displace unfrozen water, causing water to flow through the unfrozen parts of the body. The pressures that are developed during this process will depend upon the amount of freezable water, the rate of freezing, and the permeability of the surrounding material and the distance it must go to obtain relief. These pressure produce triaxial dilations of the paste, and if these hydraulic stresses remain below the strength of the concrete or the paste, they will rapidly be dissipated, but if they rise above the strength they will produce permanent damage. [Powers (1955)] .

The following table [Powers (1955)] gives the relation between degree of saturation and hydraulic pressure developed in freezing.

Degree of Saturation	Hydraulic Pressure Developed in Freezing (psi)
1.00	100
0.99	86
0.98	68
0.97	56
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----	---
0.917	0

3.2 Growth of Capillary Ice

When the body of paste contains few capillary cavities, ice begins to form at relatively few points, the resulting hydraulic pressure is too low to cause dilation. Once a body of ice has formed in a cavity, that ice acquires the ability to draw water from the surrounding unfrozen regions as soon as the temperature drops below the melting point of ice in the cavity. While water is being drawn from regions surrounding a body of capillary ice, the paste tends to shrink but water at the same time is moving into the cavity where it freezes and causes the ice crystal to grow. The over-all result is dilation because shrinkage is overcome by the growth of ice crystals.

3.3 Osmotic Pressure

The material bordering each capillary is cement gel containing gel pores and solution and ice cannot form in these pores because of their smallness. Freezing concentrates the solution in the capillary pores without producing an equal change in concentration in the gel pores. Thus freezing should immediately produce a tendency for the solute in the capillary water to diffuse into the region of lesser concentration, the contiguous gel water. At the same time gel water tends to diffuse into the concentrated solution in the capillary. While the concentration differential exists, a dilation tendency exists which, when opposed, will appear as osmotic pressure. This osmotic action also increases the hydraulic pressure in cement paste as freezable water is forced from the capillaries into the gel pores.

4. EFFECTS OF AIR ENTRAINMENT

Both hydraulic pressure and growth of ice crystals are related to the "degree of satuation" theory of frost damage. If the degree of satuation is below some critical proportion (about 91.7 per cent), there will ordinarily be present enough air-filled capillary space to accommodate the water displaced by the ice being formed. However, in the fine capillary structure of the cement paste, this space must be everywhere close to the points from which water is moving to avoid destructive pressure. Now the role of entrained air becomes evident.

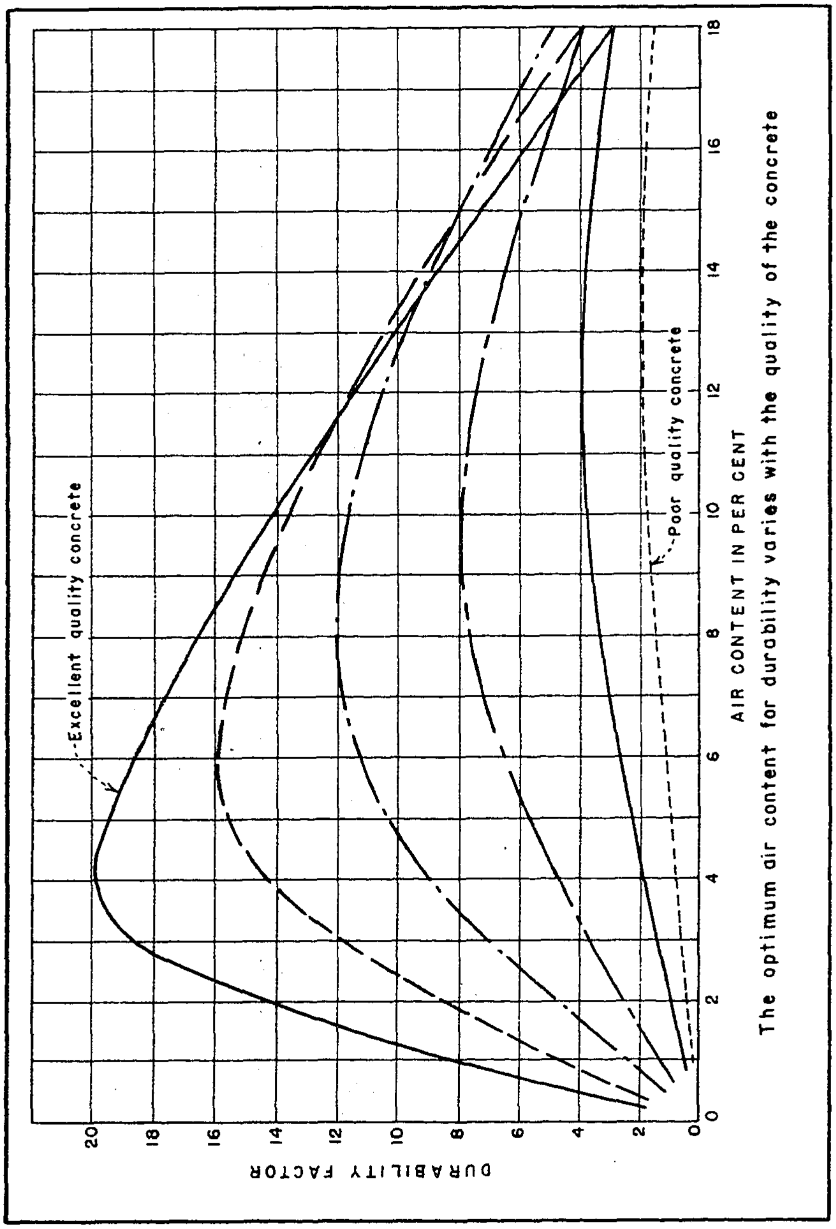
It is to provide in the hardened paste a multitude of air bubbles, ranging from 0.001 to 0.002 inch in diamter, separated from one another by only a few thousandths of an inch, so that excess water displaced during the freezing process has only a short distance to move before finding relief space. In other words, the air bubbles provide pressure-relief points, or "escape boundaries". The extruded water frozen in the air bubbles is able to extract additional water from the surrounding paste and thus prevent the growth of ice crystals in the paste. They not only simply serve as a buffering volume for the volume expansion of freezing water but also provide better possibilities for the out-flow of water. Usually these air bubbles are not filled with water or only partially, except under high vacuum and pressure. Being far larger than the capillary voids the entrained-air bubbles are available as points of pressure relief; moisture forced out of the capillary voids into the entrained-air bubbles during freezing is drawn back into the former by capillary forces during and after thawing. Because of the plastifying effect of these air pores already in fresh concrete, the same consistency and better workability are reached with a smaller quantity of mixing water. Thus a reduction in the quantity of mixing water reduces the capillary pore area of hardened concrete.

The paste in non-air-entrained concrete may, and usually does, contain large natural air voids in sufficient total volume to contain the water displaced during the freezing process, yet such paste may be dilated and damaged by rapid freezing when saturated because the natural air voids are too far apart to be effective.

The necessity for using entrained air in concrete does not arise from a lack of space to accommodate the increase in water volume caused by freezing. All concretes contain at least one half of one per cent of air space, and this is more than enough to accommodate the increase in water volume produced by freezing of mature paste. The quantity of air required, ranging from 3% of the volume of concrete upwards, is that which supplies a sufficient number of bubbles per unit volume of paste to reduce the distances between bubble boundaries to an adequate low value, or in other words, the quantity necessary to a sufficient number of bubbles to divide the paste into very thin layers.

Figure 2 [Brewer (1948)] shows how durability varies with air content. An optimum air content is obtained for each concrete and this optimum varies with the quality of the concrete. High quality plain concrete is obtained by using good dry aggregate, good cement, and a low water-cement ratio and properly curing the concrete. Four percent air is sufficient for excellent quality concrete while as much as 12 percent air may be necessary to produce durable concrete from some poor quality materials. However, air contents of more than 8 percent (3/4-inch maximum sized aggregate) are not recommended because of detrimental effects to other properties of concrete.

Fig 2



The optimum air content for durability varies with the quality of the concrete

5. EFFECT OF WATER-CEMENT RATIO

Only the water in the capillaries may freeze. The capillary pores in concrete are formed by the excessive water which is a result of the relation of the total volume of mixing water to the chemically combined water and to the gel water subject to the adsorptive power. With sufficient long-time hydration, e.g., after 28 days, according to Wood 1964 , the chemically and physically combined water is said to be about 40 per cent of the cement water. That is, if a water-cement ratio below 0.40 by weight is used in concrete, the smaller number of capillaries in the paste would not be vulnerable to freezing deterioration. Portland-cement pastes of low water-cement ratio are more resistant to the build-up of hydraulic pressures and the growth of capillary ice simply because there are fewer capillaries in the paste.

The quantity of capillary pores in the paste depends on water-cement ratio. Since the volume of cement gel produced by hydrating the cement is approximately twice the volume of the cement, consequently the gel not only replaces the original cement minerals but also tends to fill the original water-filled space. Therefore, a well-cured low water-cement ratio paste will have smaller capillary volume, or smaller capillary sizes. The effects of these internal changs give rise to low permeability of the paste.

Table I [Powers, Copeland, Hayes and Mann, (1954)] shows the effects of age on permeability. The data pertain to a given paste at different stages of hydration. Notice that within a week the coefficient of permeability dropped to about one one-hundred-thousandth of its initial value.

The relationship for a series of pastes in which about 93% of the cement was hydrated is given in Figure 3. [Powers, Copeland, Hayes and Mann, (1954)] .

The permeability of a well-cured paste is reduced approximately a thousandfold by reduction in water-cement ratios from 0.8 to 0.4 by weight. This large reduction in permeability is due to the drastic reduction in capillary size and volume that accompanies the decrease in water-cement ratio. All of the capillary volume in fresh paste is capable of rapid transmission of water; this permeability rapidly decreases with hydration. The permeability of a paste of 0.8 water-cement ratio may decrease a thousandfold between the curing ages of 7 days and 1 year. Thus, there is a millionfold difference between the permeability of high-water-ratio paste at early ages and that of well-cured low-water-ratio paste.

The permeability of paste has an important bearing on the vulnerability of concrete to frost action. It determines the relative ease with which the cement paste and aggregates may become saturated. Sometimes engineers are concerned not only about the durability of the concrete were it to become critically saturated but more importantly about the length of time required for concrete to attain such a state of vulnerability to freezing when exposed to the wetting and freezing conditions of winter. Well-cured and low permeability concrete may require many months to attain a critical saturation and hence successfully pass through the freezing season.

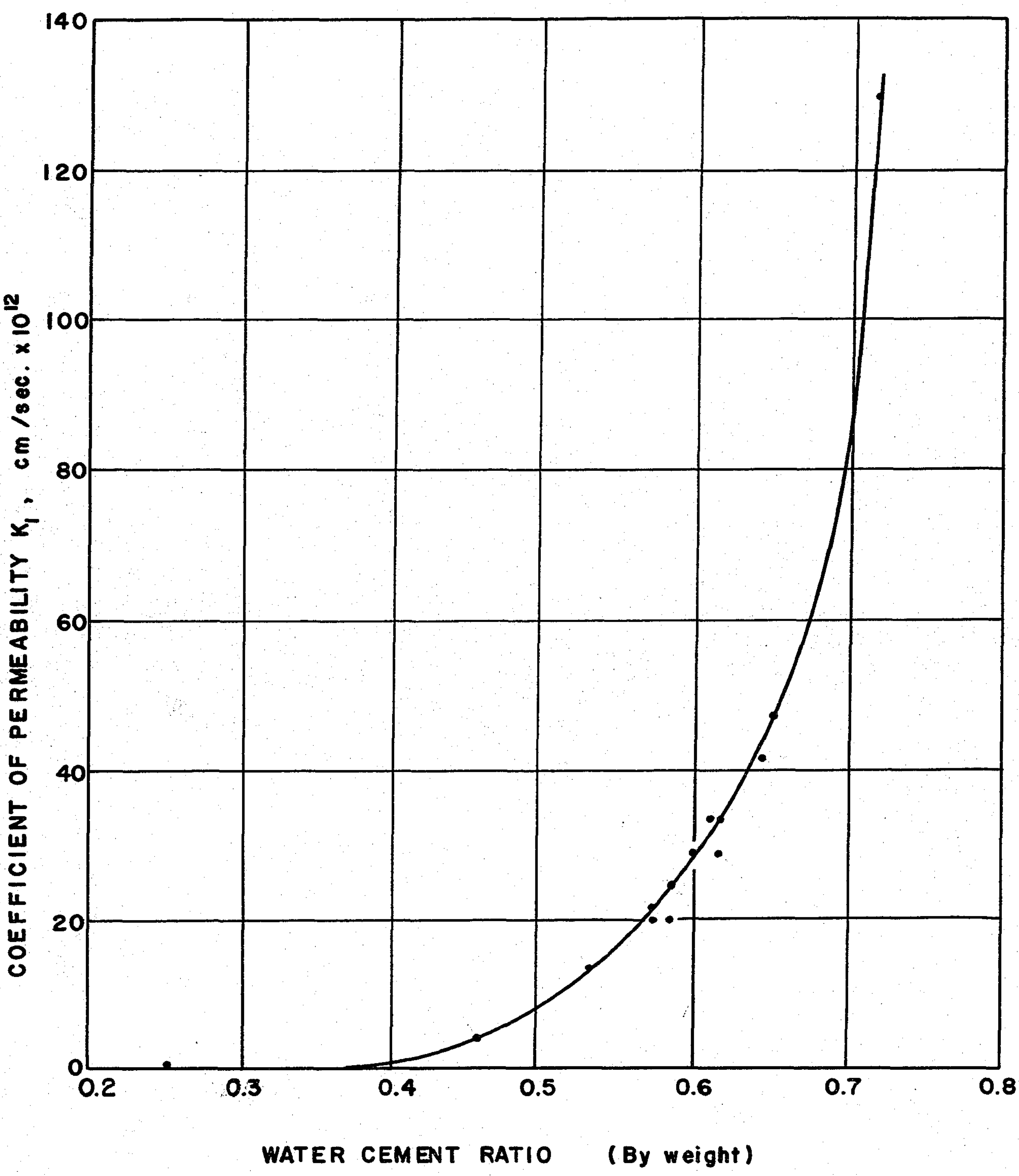


Figure 3. Relationship Between Coefficient of Permeability and Water-cement Ratio [Powers, Copeland, Hayes and Mann (1954)]

Table 1 - Reduction of Permeability By Cement Hydration [Powers, Copeland, Hayes and Mann (1954)]

Age	Permeability Coefficient K_1, cm/sec
fresh	2×10^{-4}
5 days	4×10^{-8}
6	1×10^{-8}
8	4×10^{-9}
13	5×10^{-10}
24	1×10^{-10}
Ultimate	0.6×10^{-10}

W/C = 0.70

6. EFFECTS OF AGGREGATES AND CRITICAL SIZE CONCEPT

The need for an understanding of the influence of aggregates on the resistance of concrete to freezing and thawing is becoming increasingly important. The durability of concretes depends on the rate at which the aggregates become critically saturated in the concrete and upon the different physical responses of the aggregates to freezing.

The general concepts of the frost resistance of cement paste are also applicable to aggregates. When saturated the resistance of aggregates to freezing depends upon the pore characteristics of the aggregates and the cement paste. As in the cement paste, the magnitude of the hydraulic pressure developed in aggregates depends upon their degree of saturation and the permeability and size of the aggregate particle. If the aggregate pores are not fully saturated, less water would need to be expelled during freezing and lower or negligible hydraulic pressures would result. If the pores are fully saturated, water will be expelled into the paste surrounding the aggregates and potentially destrutive hydraulic pressures may develop there as well as in the aggregates. Thus, the properties of paste, its permeability, air content, and porosity are also involved in the problem of aggregates durability. In addition, the paste can significantly influence the degree of saturation of the aggregates in concrete by limiting the ingress of water; the protection afforded in this manner depends upon the permeability and thickness of the paste or mortar cover separating the aggregate from the wet surface of the concrete.

The expelled water from the aggregate must find pressure-relief points before causing destruction of the paste. Relief-points are available if the paste is air-entrained. These air bubbles must be close enough to the aggregate because hydraulic pressure is a function of the travelled distances of the expelled water. It is for this reason that the use of entrained-air may be of benefit to the paste and the aggregate during freezing.

6.1 Thickness and Permeability of Mortar

It is reasonable to assume [Verbeck and Landgren (1960)] that the mortar cover transmits water by capillary tension in a manner approximating Darcy's Law for flow under hydrostatic pressure and therefore that the rate of flow would decrease as the thickness of the membrane increases, and that a highly permeable membrane would transmit water more rapidly than a membrane of low permeability.

The permeability of paste or mortar depends significantly upon the water-cement ratio and the degree of hydration of the cement as discussed earlier. For well hydrated pastes the permeability may be increased by as much as 100 fold as the water-cement ratio is increased from 0.40 to 0.70 by weight [Powers, Copeland, Hayes and Mann (1954)] . Such differences in permeability have a significant influence on the rate at which the mortar membrane will transmit water into an aggregate. That the permeability and thickness of the mortar cover does significantly affect the time required for an aggregate to become destructively saturated in concrete is demonstrated in Table 2.

Table 2. - Time Required for Destructive Saturation of Aggregate Depends upon the Permeability and Thickness of the Protective Mortar Cover. [Verbeck and Landgren (1960)] .

Mortar Cover		Days of Wetting Sustained Before Failure (Popout) at Various Thicknesses of Mortar Cover		
Water-Cement Ratio by Weight	Permeability K_1, cm/sec	1/8-in. Thick	1/4-in. Thick	3/8-in. Thick
0.70	3000×10^{-9}	111	879	792
0.45	1×10^{-9}	477	885	980

6.2 Critical Size Concept

If the degree of saturation of an aggregate is sufficiently high, say above 91 percent, so that the remaining air-filled pores cannot accommodate the 9 percent expansion of water during freezing, the water will be expelled into the paste surrounding the aggregate and hydraulic pressure is developed. The expelled water must travel a certain distance into the surrounding paste. The hydraulic pressure would increase as the distance increases. The expulsion distance depends significantly upon the aggregate size and the air content of the surrounding paste.

If the aggregate size is large, the freezing water must travel a relatively long distance before reaching the air-entrained surrounding paste (assuming the concrete is air-entrained). The hydraulic pressure increases as the travelled distance increases. The resulting pressure can be so high that even air-entrained paste would be damaged because of the relatively low permeability of the paste. Therefore, the advantageous effect of using a small maximum size of an aggregate in concrete on the required expulsion distance and potential destructive action appear obvious; the smaller the size, the shorter the expulsion distance, and lower the resulting hydraulic pressure.

7. DISCUSSION OF PREVIOUS FREEZE-THAW STUDIES

The possibility of using freezing-and-thawing tests on concrete as a means of studying the frost resistance has been recognized for many years; Jackson (1932), Lang (1938) and Campbell (1939) did similar work on the comparisions of freezing-and-thawing tests and field performance of various concrete aggregates. Specimens made with aggregate in question were considered to be acceptable if they did not show a reduction of flexural strength greater than 30 percent when subjected to 40 cycles of freezing and thawing.

The American Society for Testing and Materials published a symposium on freezing-and-thawing tests of concrete in 1946. Procedures and practices in the major U. S. laboratories were presented in detail, with many opinions regarding the interpretation of such tests. This series of papers is rich in useful information even today, but some items are particularly pertinent to a study of aggregate test methods. For example, a detailed procedure is given for testing concrete containing aggregate of uncertain quality. Some observations were: (a) high alkali cements should be avoided; (b) aggregate should be brought to field moisture conditions and carefully controlled; (c) the maximum particle size should not exceed one-third the minimum specimen dimension; (d) air content should be carefully controlled; (e) concrete expansion can be used as an indication of specimen deterioration; and (f) although freezing-and-thawing tests are useful for evaluating aggregate, much more must be known about their conduct and interpretation.

Several laboratory studies during the period 1948 to 1957 made particularly significant contributions to the problem of frost resistance of concrete by freezing-and-thawing tests. Some of the important points made which are pertinent to this project are: (a) Freezing-and-thawing tests should be evaluated in terms of the moisture conditions of the specimen [Sweet (1948)] ; (b) the limiting value for degree of saturation appeared to be ill defined, probably because of non-uniform water distribution [Blackburn (1949)] ; (c) A degree of saturation of less than 0.88 indicated a highly durable specimen and that low saturations could be conveniently obtained by air entrainment [Whiteside and Sweet (1950)] ; (d) largest particles were most subject to deterioration [Walker and McLaughlin (1956)] .

About 1950, the concept of using air entrainment as a means of making the paste matrix resistant to frost damage appears to have been firmly established. In addition, a basic theory of frost action had been presented by Powers.

Recent studies have made significant contributions or helped to summarize existing knowledge. Bloem (1963) noted the significance of particle size to durability and that drying between curing and testing greatly improved durability. The improved resistance appeared to be related to the locus of freezable water. Drying apparently removed water from the aggregates and subsequent soaking returned moisture to the paste phase where air voids provide a measure of frost resistance. Committee 201 of the American Concrete Institute published an extensive summary on concrete durability (1962). The most recent theories of Powers, Verbeck and Landgren, and others were used to evaluate current test methods. In summary, they state that "freezing-and-thawing tests probably provide the best measure of concrete durability but current tests are unable to measure durability with the certainty needed".

In 1955 T. C. Powers of the Portland Cement Association suggested a new method for testing the freezing-and-thawing resistance of concrete or aggregate. This method was based primarily on theoretical considerations relating to frost resistance of concrete developed over the period 1935-1950. Powers made rather detailed comments on procedural aspects of the test but did not publish any data confirming its applicability.

Powers prefaced his presentation of a new test rationale by a critical review of the existing procedures for freezing-and-thawing tests on concretes and noted several inconsistencies or weaknesses in them. For example, in the light of hydraulic pressure theory he felt that high and widely variable freezing rates tended to give a distorted picture of relative frost resistance rather than the hoped for simple acceleration of natural processes. That is, the mechanisms by which frost damage might occur at natural cooling rates, approximately 5 F per hour maximum, could not be correlated with those at rates of 10 to 100 F per hour, the high rates causing unrealistically high stress conditions. Considering the growth-of-capillary-ice theory, and perhaps the osmotic pressure theory, this rapid freezing could lead to an underestimate of natural freezing conditions where relatively long periods at low temperature are commonplace.

Because concrete has no intrinsic, measurable property of frost resistance, and because the contributory properties are numerous and difficult to evaluate quantitatively, Powers proposed to use volume change characteristics of concrete under controlled conditions as the basic test methodology. Specimens would be prepared and conditioned so as to similate field conditions and then be subjected to continual soaking with slow-rate freezing and periods at low temperature. According to Powers, concretes subject to frost damage should reach some critical saturation level, after which they would expand on freezing. Periodic measurements of dilation and temperature would permit identification of this critical point and the time required to reach it. Because of its theoretical background and its partial simulation of field conditions, it was hoped that the proposed procedure would yield data that could be interpreted in a meaningful fashion. It also would require only relatively simple and inexpensive equipment to handle sizeable test programs.

The California Division of Highways was first to report, in 1961, a practical application of the Powers Method [Trempen and Spellman (1961)]. They developed specimen preparation and conditioning methods, testing and measuring techniques, and performance criteria. The method was used to evaluate several aggregates for a major highway construction project. This highway appears to have performed well since the time of construction.

In the report Trempen and Spellman use the idealized cooling curves to illustrate the behavior of concrete specimens as shown in Fig 4. Curve 1 represents thermal contraction above the freezing point. The measured slope is not strictly proportional to the thermal

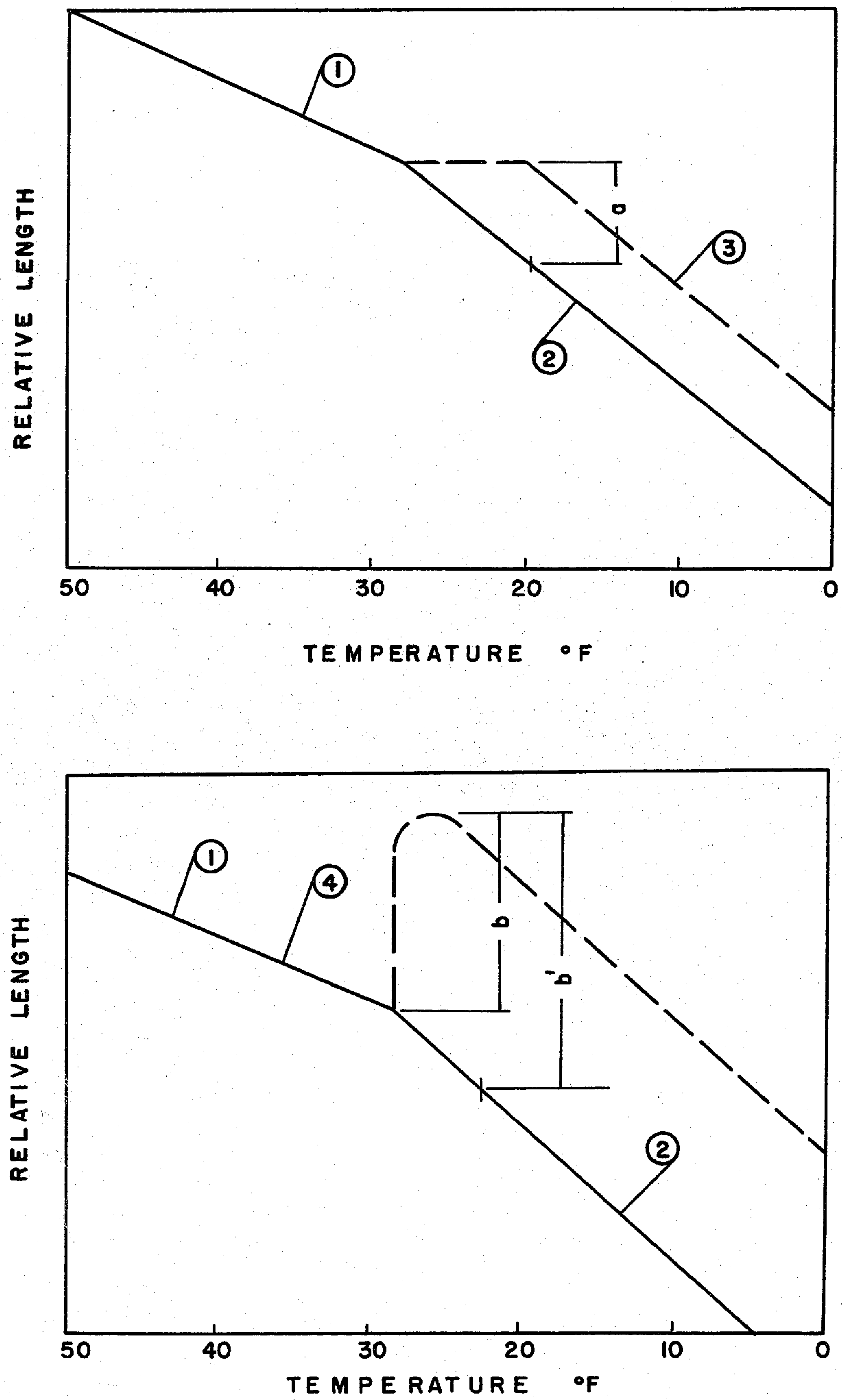


Figure 4. Idealized Cooling Curves [Tremper and Spellman (1961)]

coefficient for two reasons. The first is because the over-all thermal coefficient of the frame supporting the specimen is not zero. The second is because movement of water within the paste and aggregate does not have time to reach a complete equilibrium when the temperature is being lowered continually. Curve 2 represents the contraction after ice begins to form in the concrete. Ice crystals under progressive cooling, tend to attract moisture at the expense of that in the paste, causing the latter to shrink at a rate greater than that due to thermal contraction alone. The point of intersection of Curves 1 and 2 indicates the temperature at which ice begins to form. If experimental curves could be obtained with the precision of those shown in Fig. 4, the freezing point could be determined accurately.

Curve 3 represents the type of result that has been obtained in certain instances. In this case, there is little or no change in length while the specimen is being cooled several degrees below its freezing point. Eventually the curve resumes a downward slope. Dilation has occurred as measured by the distance, a, which is the greatest distance between curves 3 and 2. Dilation of this type is extremely difficult to measure from the plotted curves obtained in the study. The most common type of curve that is obtained in the work when the concrete is not immune, is x represented by curve 4. Here there is an abrupt expansion at the freezing point.

The curve rounds quite sharply and then resumes a downward slope. The distance, b, is easily measured; however, it does not represent the entire dilation because of its nearly horizontal trend over a few degrees of cooling. The distance, b^1, represents the complete dilation but is difficult to measure in practice.

MacInnis (1962) applied the Powers test as a research tool to evaluate the frost resistance of cement grout mixtures for pre-stressed concrete. Air entrainment was found to be the most effective method of preventing expansion and cracking caused by freezing temperatures. The introduction of entrained air, even at a low percentage (5) in a mix of high water-cement ratio was effective in eliminating all but transitory expansions at all maturities tested. He concluded that water-cement ratio is next in importance to air-entrainment in providing frost protection for grouts. Provided a mix contained at least 5% entrained air a lower water-cement ratio seemed more effective than additional air in increasing frost resistance. He was also able to establish curing periods which would give frost resistance to grouts at various water-cement ratios.

Beaudoin (1966) worked on Powers' method to evaluate the limiting water-cement ratios for frost resistant mortars. His results showed that 0.58 water-cement ratio was the maximum for complete saturated mortar specimens which were air-entrained before dilation occurred. He also concluded that when pronounced expansion occurred, it did so for specimens 90% to 100% saturated, suggested that hydraulic pressure is the likely mechanism causing expansion. The results suggested 90% as the limiting degree of saturation; above this degree of saturation is danger of frost damage.

8. OUTLINE OF EXPERIMENTAL PROGRAM

The main purpose of this research program is to evaluate the effect of maximum aggregate size on the frost resistance of concrete mixes of various water-cement ratios and degrees of saturation -- where different degrees of saturation can be interpreted as representing different field exposure conditions. For example, hydraulic and waterfront structures probably have close to 100 percent saturation at the water-line, some highway pavement slabs can probably have degrees of saturation between 80 and 90%, while ordinary exposed structures such as buildings or portions of bridges probably have degrees of saturation between 50 and 70%.

A summary of the range of water-cement ratios, maximum aggregate sizes and degrees of saturation included in the program is as follows:

Water-Cement Ratios	Maximum Agg. Size	Degree of Saturation
0.60	3/4-in.,3/8-in., 1/4-in.	100, 90, 80 and 70
0.55	same	same
0.50	same	same
0.45	same	same

9. EQUIPMENT AND MATERIALS

(A) EQUIPMENT

Mixing Apparatus

A revolving drum type mixer of 2 cu. ft. capacity was used for mixing all concrete in this programme.

Specimen Moulds

Standard 3" x 6" cylindrical moulds were used.

Vacuum Tank and Pump

The vacuum tank was made of stainless steel with a one-inch thick plexiglas lid. Up to eight 3" x 6" cylindrical specimens could be placed in tank. A vacuum pump of an ultimate pressure of 1×10^{-4}mm Hg was used. A two-way valve connection was used as shown in fig.E1 to enable the vacuum tank to be evacuated of air before the introduction of water (see page 37).

Freezing Test Equipment

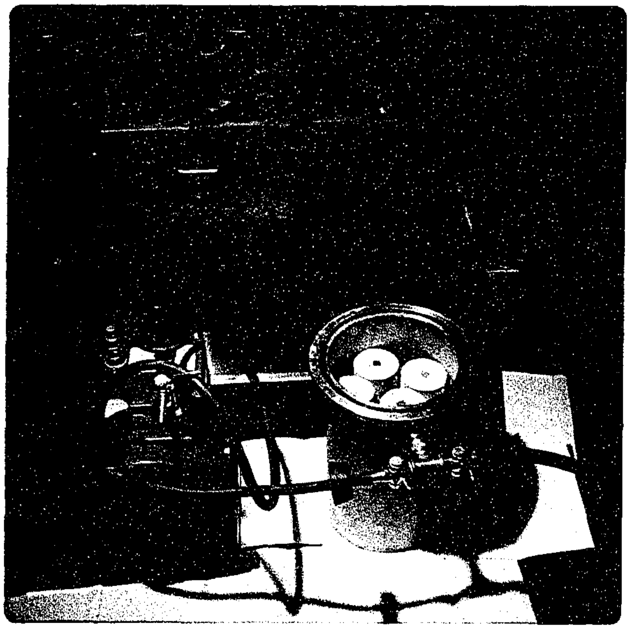
(a) Freezing chamber and Temperature Potentiometer

The temperature controlled(manual) freezing chamber used was a 5½ cu. ft. capacity (Lab-Line, model 166). A Leeds and Northrup temperature potentiometer calibrated to read directly in °F and °C, was used to measure the temperatures of both center and surface of the concrete specimen.

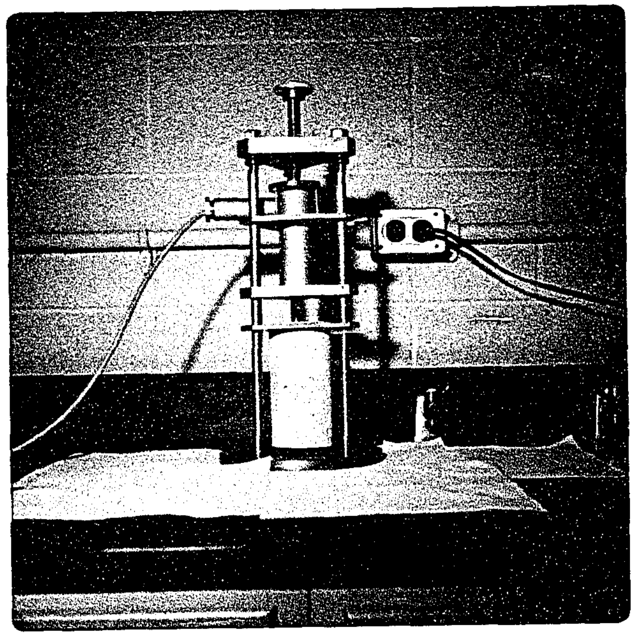
(b) Length Measuring Equipment

(1) Transmitter MDS 18 - Maihak transmitters

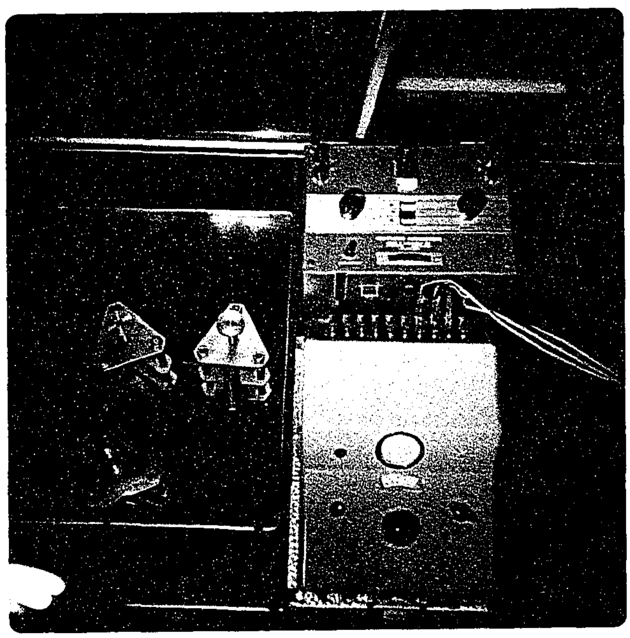
Fig E1



Vacuum Tank and Pump



Frame and Transmitter



Receiver, Temperature Potentiometer
and Freezing Chamber

were used to measure length change of specimens. The transmitter has the advantage of operating inside the freezing chamber without causing errors. It has negligible effect on cooling temperatures. The measuring range is 0 to 10mm. Each scale division in the Receiver is about 2.30×10^{-2}mm. (each transmitter has its own calibrated constant to the Receiver), but each scale can be further subdivided into tenths.

(ii) Receiver MDS - A picture of the Maihak Receiver is shown on page 37 .

(iii) Frame -- The frame was designed to support the transmitter vertically and firm. A picture is shown in Fig. E1 . Four of these were built. The vertical supports of the frame were made of Invar bars in an attempt to eliminate the effects of temperature on the frame as the termal coefficient of Invar is extremely small. A complete drawing of the frame is shown on Fig. E2 .

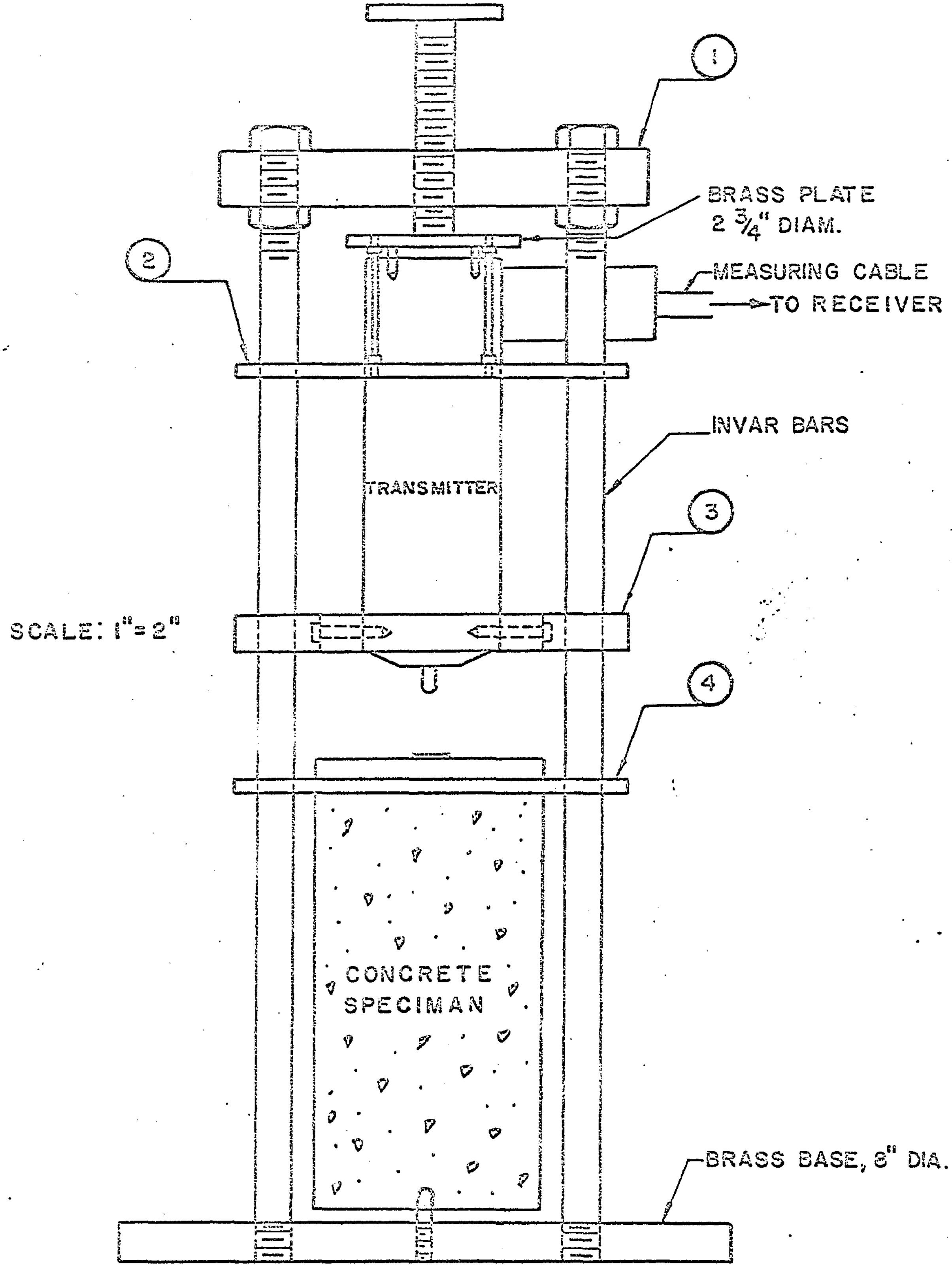
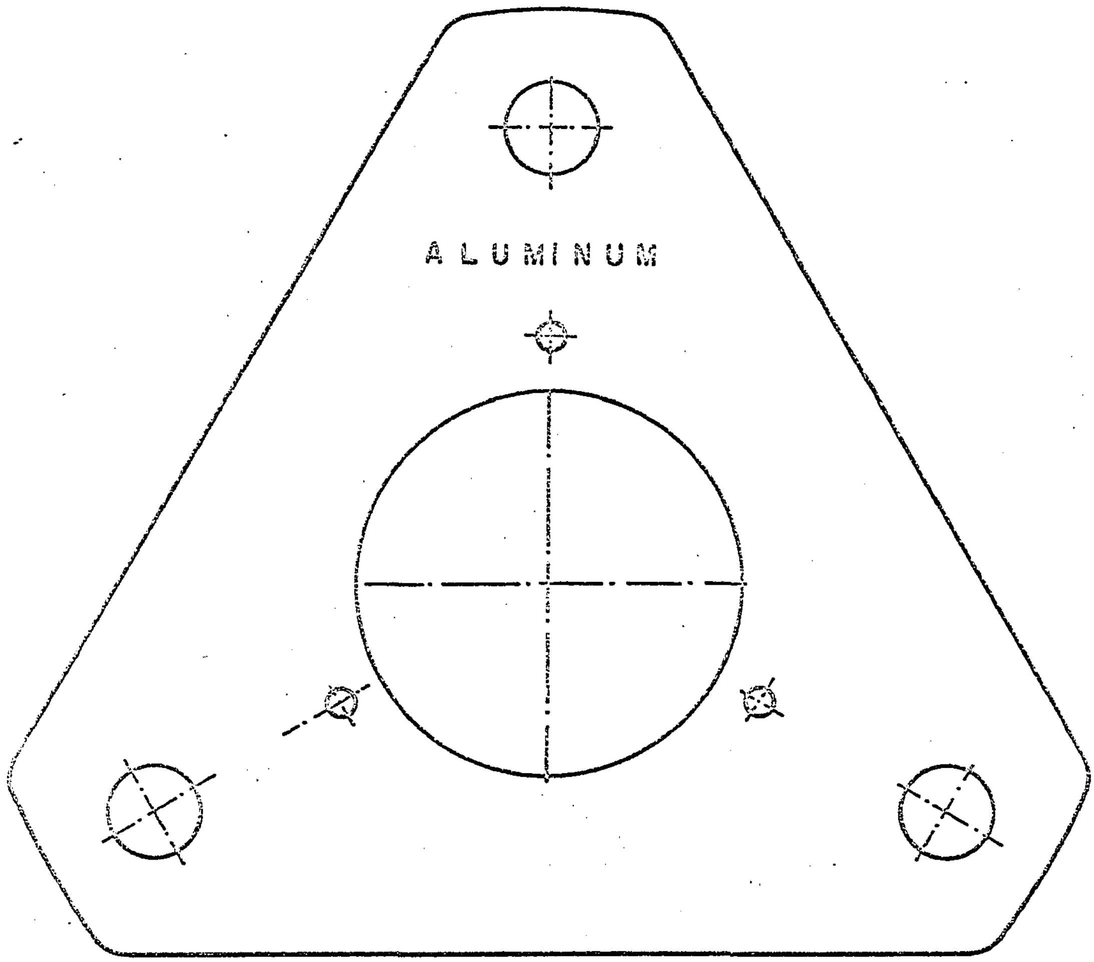
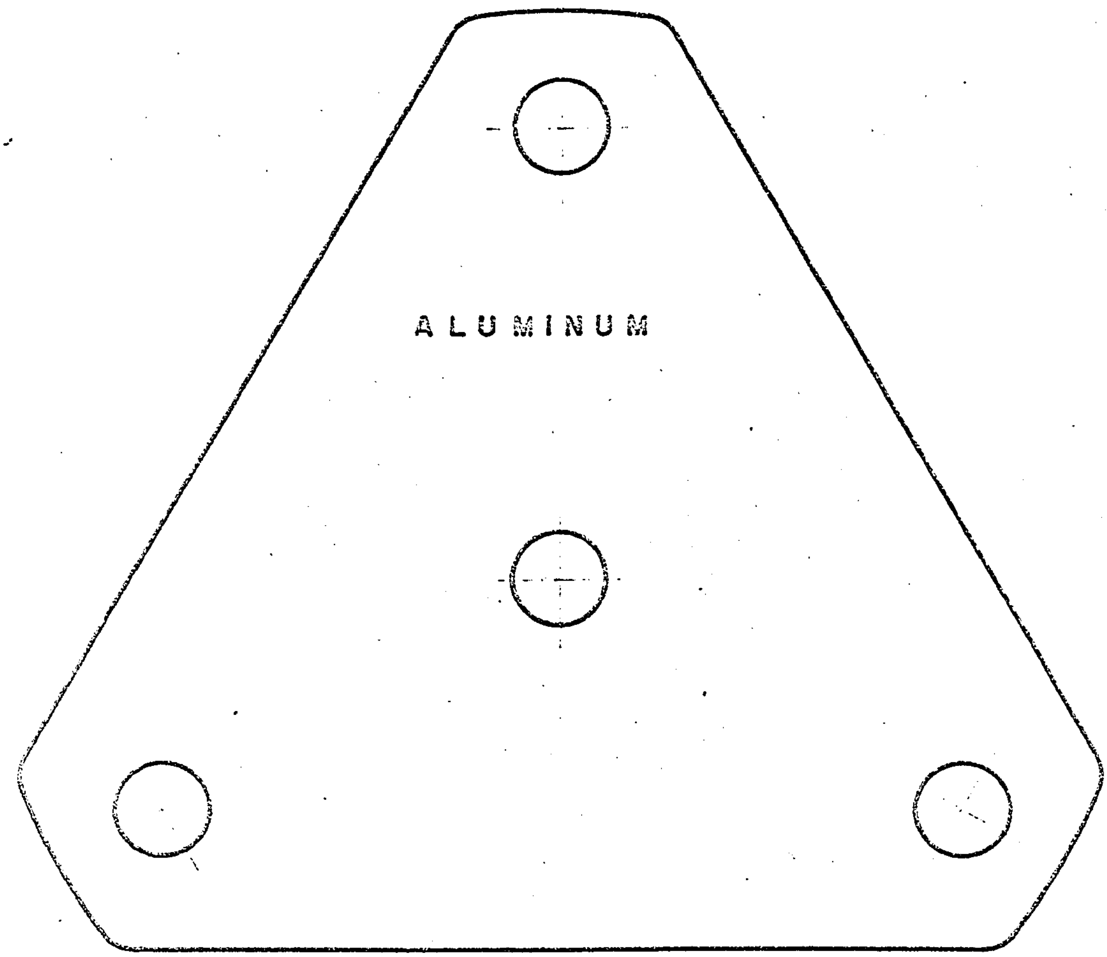


Fig. E2 - Supporting Frame for Concrete Specimen



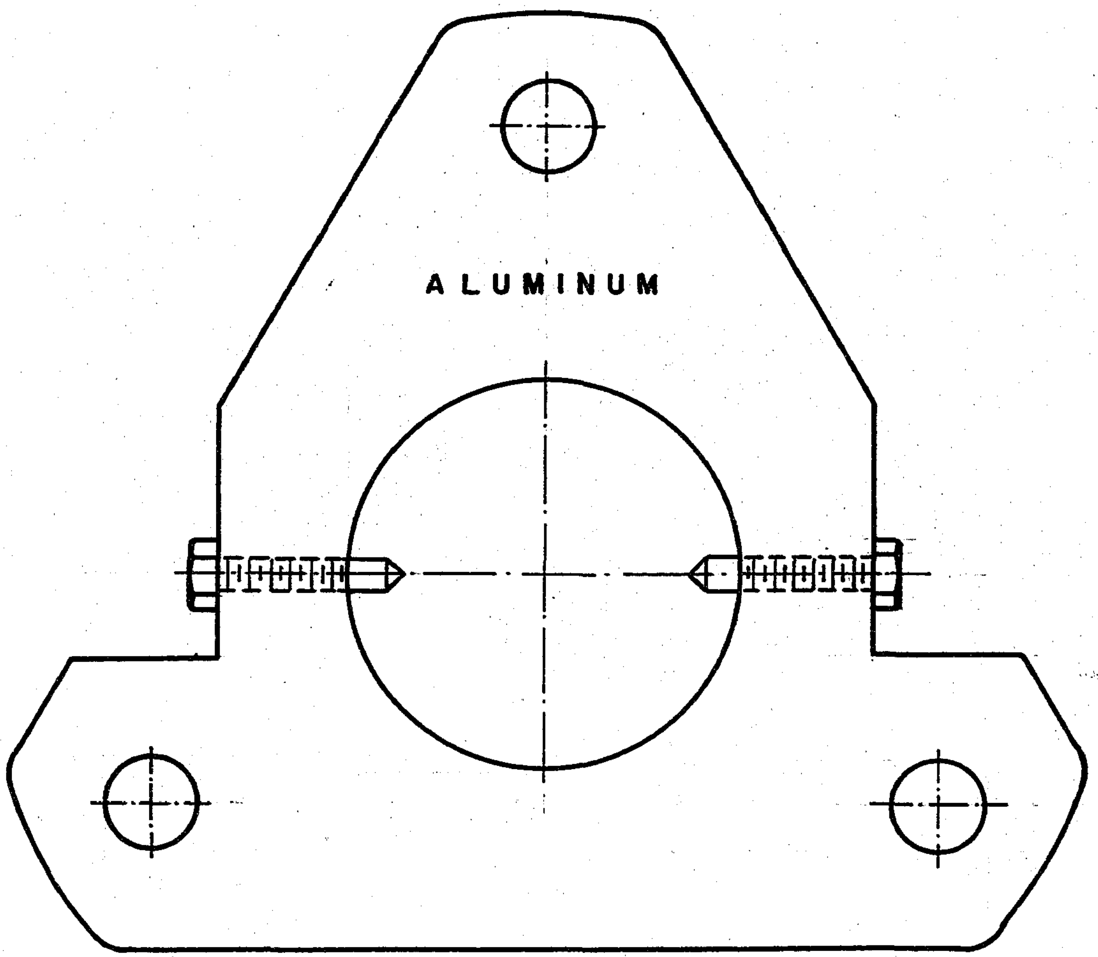
DRAWING No. 2

Fig. E2(a) - Detail of Guide Plate for Supporting Frame.



DRAWING No.1

Fig. E2(b) - Detail of Guide Plate for Supporting Frame.



DRAWING No. 3

Fig. E2 (c) Detail of Guide Plate for Supporting Frame

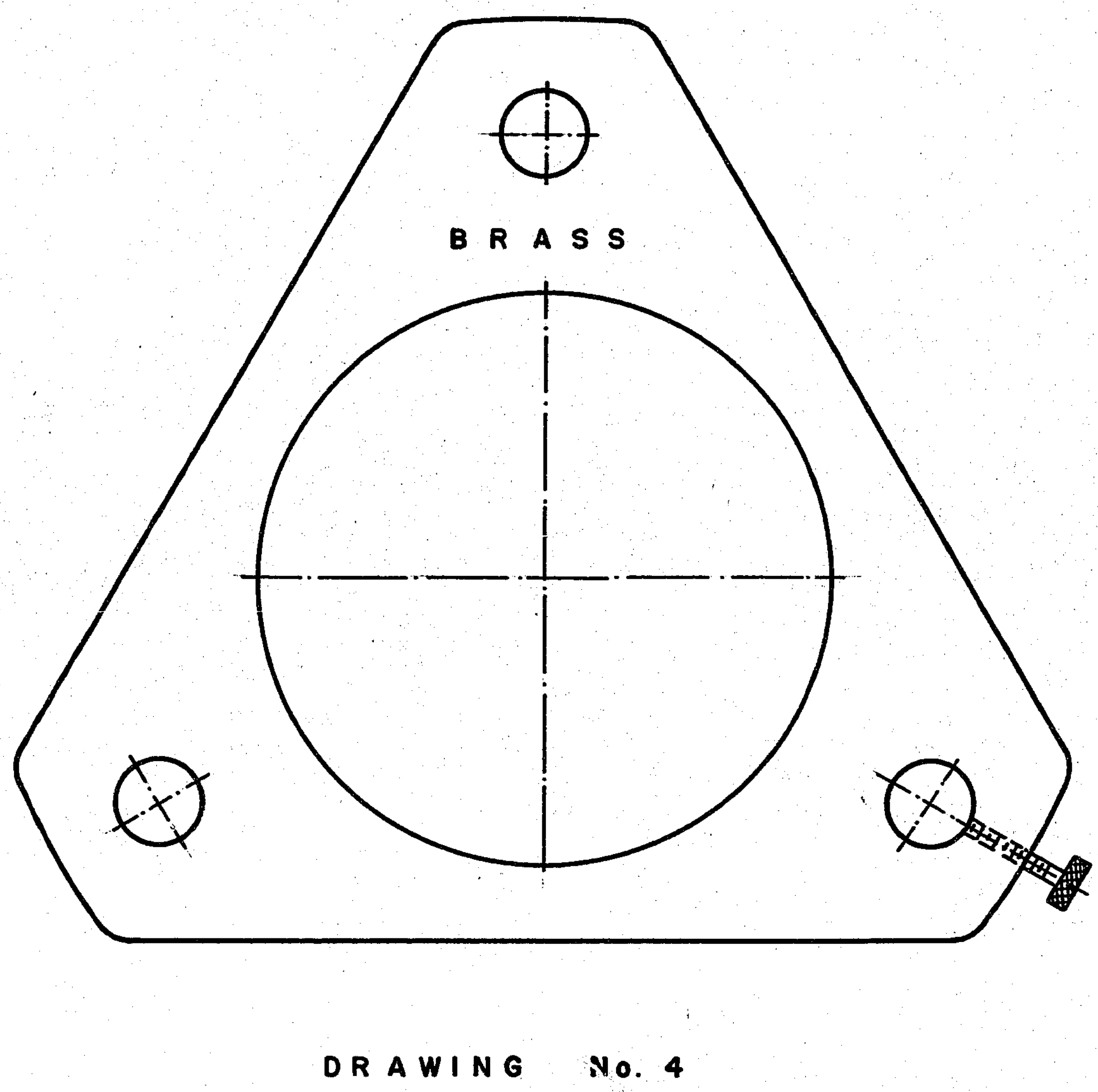


Fig. E2 (d) Detail of Guide Plate for Supporting Frame

(B) MATERIALS

Cement

Lake Ontario Type I Normal Portland Cement was used.

Coarse Aggregates

Dundas crushed dolomite aggregates of threee maximum sizes, 3/4-in., 3/8-in., and 1/4-in. were used. The sieve analyses for these materials are shown on table 3 . Specific gravity is 2.68 and the absorption by weight is 1.05 percent.

Sand

Paris sand meeting the A.S.T.M. requirements for concrete sand was employed. This sand is used by Ontario Hydro as a standard reference sand, and is known to be non-reactive. The grain size distribution for this sand is shown in figure E3 . Fineness modulus of sand is 2.68.

Air-Entraining Agent

Darex air-entraining agent was used in all mixes.

Table 3 SIEVE ANALYSES OF AGGREGATES

3/4-inch Aggregate

Sieve	Weight Retained (gms)	Accumulative Percentage Retained	Accumulative Percentage Passing
3/4"	0		
3/8"	1084	54.25	45.75
No.4	793	94.30	5.70
No.8	86	97.95	2.05
Pan	27	100	100
Total	2000		

3/8-inch Aggregate

Sieve	Weight Retained (gms)	Accumulative Percentage Retained	Accumulative Percentage Passing
3/8"	181	9.05	91.0
No.4	1342	76.15	23.85
No.8	301	91.12	8.88
No.16	158	99.1	0.90
Pan	18		
Total	2000		

1/4-inch Aggregate

Sieve	Weight Retained (gms)	Accumulative Percentage Retained	Accumulative Percentage Passing
3/8"	0		
No.4	286	14.3	85.7
No.8	1512	89.8	10.2
No.16	179	98.8	1.2
Pan	23	100	0
Total	2000		

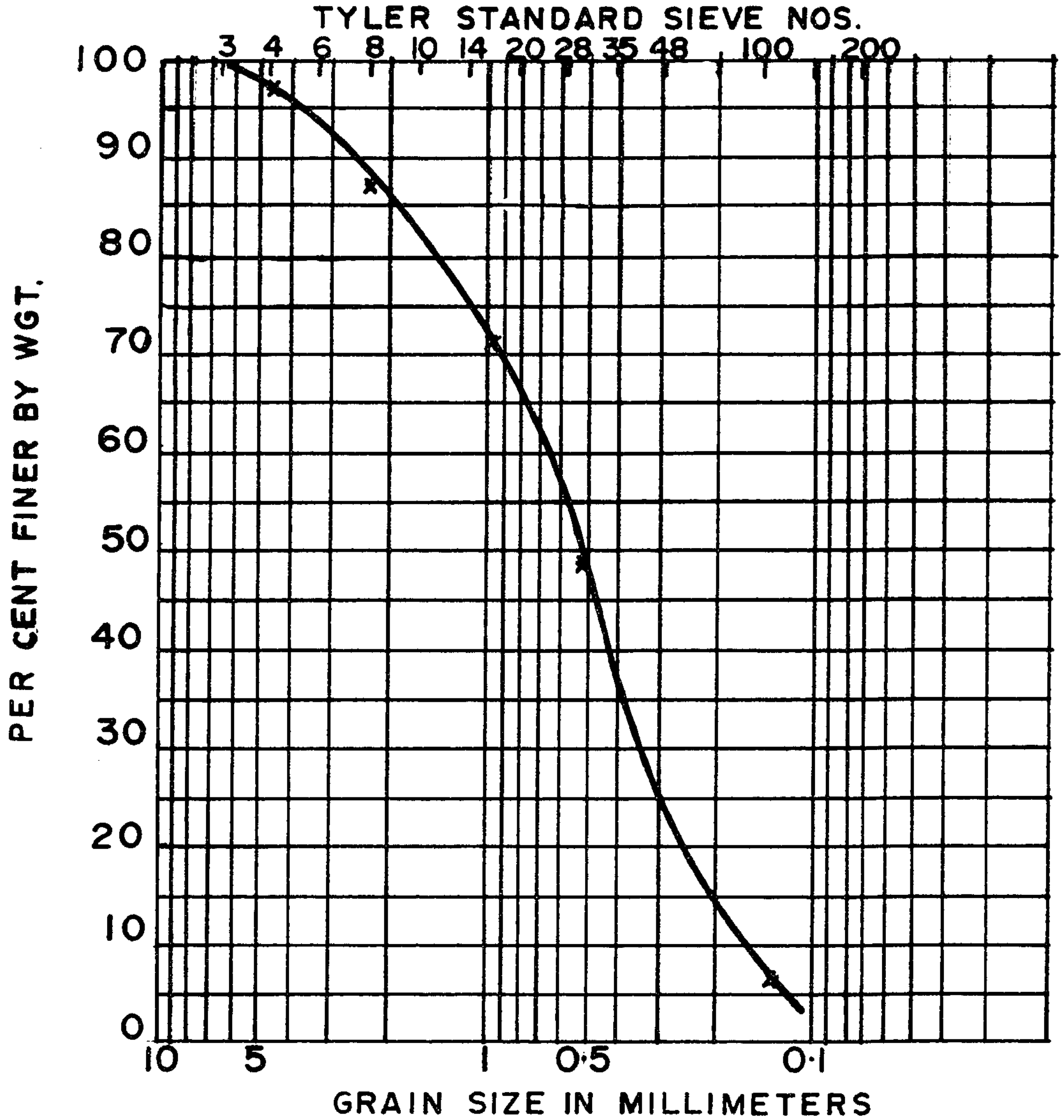


Fig. E3 **GRAIN SIZE DISTRIBUTION FOR PARIS SAND**

10. EXPERIMENTAL PROCEDURES

10.1 Mix Design

All concrete mixes were designed according to the American Concrete Institute Recommended Practice for Selecting Proportions for Concrete (ACI 505-54). All specimens were air-entrained. Air-entraining agent was gauged to produce an air content of 7% $\pm$ 0.5. A summary of all mix proportions is shown below:

Water-Cement Ratio	Cement Factor Sack/cu.yd.			Weight Proportions Cement:Sand:Coarse Agg.		
	3/4-in	3/8-in	1/4-in	3/4-in	3/8-in	1/4-in
0.60	5.71	6.52	6.90	1:2.88: 3.54	1:2.53: 2.34	1:2.73: 1.73
0.55	6.24	7.11	7.54	1:2.53: 3.24	1:2.25: 2.14	1:2.42: 1.58
0.50	6.85	7.82	8.28	1:1.84: 2.95	1:1.97: 1.95	1:2.13: 1.45
0.45	7.61	8.68	9.20	1:1.56: 2.66	1:1.69: 1.75	1:1.83: 1.31

10.2 Fabrication of Test Specimen

For each water-cement ratio and specified maximum aggregate size concrete, 24 specimens were cast from three similar batches. A total 288 specimens were made. A third of these wer used in preliminary work and trial-and-error tests. The air content was checked by a Techkote White air meter.

Immediately following the mixing, the test specimens (3-in. in diameter and 6-in. in height) were moulded. The cylindrical molds were filled vertically in three layers, and each layer was rolled 25 times with a bullet-nosed 1/2-in. diameter metal rod. They were then covered with wet burlaps and remained in the molds for 24 hours before removal.

After 24 hours in molds, all specimens were wet-cured in a water tank for 14 days. Then they were air-dried in the laboratory at 70° $\pm$ 2° F and 50 $\pm$ 5 percent relative humidity for at least 14 days and then vacuum saturated or partially saturated as described later in the paper.

During the drying period, a 1/2-in. square stainless steel plate was glued onto the top surface of the specimen. (The plate was available for the transmitter pin to sit on it in determining length changes). A 1/4-in. diameter by 1/2-in. deep hole was drilled at the bottom of the specimen.

10.3 Conditioning of Specimens to Appropriate Degree of Saturation

After considerable preliminary investigation, it was decided that the moisture condition of a specimen could be described best in terms of the amount of water in the specimen evaporable at 230° F, relative to the amount of water that the specimen could contain when saturated in vacuum for 24 hours and then immmersed in water for 60 days. This evaluation of moisture condition is termed "percentage of saturation and was determined in the following way.

For each water-cement ratio and specified size aggregate concrete, four trial specimens were saturated in a vacuum tank for 24 hours. Weights (W_i) at stages of 1 hour, 2 hours, 3 hours, 5 hours, 10 hours and 24 hours during this period were determined. Twenty-four hours later vacuum was released. They were then immersed in water for 60 days. Weights (W_i) at stages of 1 day, 3 days, 7 days, 14 days, 21 days, 28 days and 60 days during this period were determined. After 60 days the specimens were heated in an oven at 230° F for a period of 24 hours and weighed again.

Now let W_o be the oven-dry weight, W_s be the final weight at 60 days in water after 24 hour vacuum saturation. $W_s - W_o$ is equal to the total amount of water contained in the specimen. Let W_i be the weight of specimen at any stage from its air-dry condition to its final 60 days of water soaked period. Percentage of saturation is equal to

$$\frac{W_i - W_o}{W_s - W_o} \times 100$$

Values of degree of saturation and time required are then entered in a chart for each water-cement ratio and specified size aggregate concrete. (Table 4 to 8)

An approximate degree of saturation can be obtained from the chart when a desired value is required for actual testing of similar specimens. The required time for saturation is determined and the specimens are then conditioned until the required time is reached. After the specimens have been tested in the freezer they are placed in water for the remainder of the 60-day period, at the end of which period they are weighed, oven dried and reweighed. The exact degree of saturation for each specimen during test can then be computed using the above formula.

At the age of 60 days, all specimens were very reluctant to gain any water. Of course, if they were kept in water for another 6 months or more, they would probably have gained an additional small amount of water but that would not change their degree of saturation more than 2 or 3 percent. Therefore, 60 days soaking was arbitrarily taken for this project as representing close to 100% saturation.

10.4 Test Procedure

After the specimens had been conditioned to the desired degree of saturation, they were wiped and weighed (W_i). They were then sealed in polyethylene bags

TABLE 4. ESTIMATING DEGREE OF SATURATION

W/C = 0.50 to 0.45

Agg = 1/4 in.

Specimen Size = 3" x 6" cylinder

Wet Cured for 14 days

Conditioning	Time Required	Degree of Saturation %
Air Dried	15 to 30 days	52 to 62
Specimens Soaked in Vacuum Tank	1 hr.	60 to 70
	3 hr.	70 to 73
	9 hr.	74 to 76
	15 hr.	76 to 78
	24 hr.	79 to 82
Specimens Soaked in Water	1 day	87 to 91
	7 days	93 to 95
	14 days	96 ± 0.5
	28 days	97 ± 0.5
	60 days	100

TABLE .5. ESTIMATING DEGREE OF SATURATION

W/C = 0.60 to 0.55 | Specimen Size = 3" x 6" cylinder

Agg = 1/4 in. | Wet Cured for 14 days

Conditioning	Time Required	Degree of Saturation
Air Dried	14 to 70 days	35 to 44
Specimens Soaked in Vacuum Tank	1/4 hr.	46 to 52
	1 hr.	52 to 57
	3 hr.	58 to 62
	9 hr.	63 to 66
	15 hr.	67 to 69
	24 hr.	70 ± 3
Specimens Soaked in Water	1 day	85 ± 2
	7 days	91 ± 2
	14 days	95 ± 1
	21 days	96 ± 1
	28 days	98 ± 0.5
	60 days	100

TABLE .6. ESTIMATING DEGREE OF SATURATION

W/C = 0.50 to 0.45 Agg = 3/8 in.	Specimen Size = 3" x 6" cylinder Wet Cured for 14 days	
Conditioning	Time Required	Degree of Saturation %
Air Dried	14 to 30 days	44 to 52
Specimens soaked in Vacuum Tank	1/4 hr.	55 to 60
	1 hr.	60 to 64
	3 hr.	65 to 70
	9 hr.	71 to 74
	15 hr.	75 to 79
	24 hr.	80 ± 3
Specimens soaked in Water	1 day	88 ± 2
	7 days	91 ± 2
	14 days	94 ± 1
	21 days	96 ± 0.5
	28 days	97 ± 0.5
	60 days	100

TABLE 7. ESTIMATING DEGREE OF SATURATION

For: W/C = 0.50 to 0.45
Agg = 3/4 in.
W/C = 0.60 to 0.55
Agg = 3/8 in.

Specimen Size = 3" x 6" cylinder
Wet Cured for 14 days

Conditioning	Time Required	Degree of Saturation %
Air Dried	15 to 70 days	32 to 42
Specimens Soaked in Vacuum Tank	1/4 hr.	50 to 56
	1 hr.	53 to 57
	3 hr.	55 to 58
	9 hr.	59 to 61
	15 hr.	62 to 65
	24 hr.	66 to 70
Specimens Soaked in Water	1 day	82 to 86
	7 days	90 to 93
	14 days	95 ± 1
	21 days	96 ± 1
	28 days	97 ± 0.5
	60 days	100

TABLE .8. ESTIMATING DEGREE OF SATURATION

W/C = 0.60 to 0.55	Specimen Size = 3" x 6" cylinder
Agg = 3/4 in.	Wet cured for 14 days

Conditioning	Time Required	Degree of Saturation %
Air Dried	15 to 70 days	32 - 42
Specimens soaked in Vacuum Tank	1/4 hr.	50 to 58
	1 hr.	55 to 61
	3 hr.	62 to 65
	9 hr.	68 to 70
	15 hr.	70 to 73
	24 hr.	74 to 78
Specimens soaked in Water	1 day	87 to 90
	7 days	90 to 91
	14 days	95 ± 1
	21 days	97 ± 1
	28 days	98 ± 1
	60 days	100

to minimize drying during freezing and were placed on end in the measuring frames in the freezer.

Since all specimens in the freezer cooled at the same rate a dummy specimen with a thermocouple at the center and surface was used for temperature measurement. The average of these two temperatures was recorded as the temperature of the test specimens.

The initial temperature of the specimens was 70° F ± 2 and it was reduced to about 40° F during the overnight period. No length-change measurements were taken during this period. The purpose here was to obtain temperature equilibrium in the specimens. At 40° F, an initial length-change reading was taken and the temperature of the specimens was lowered at the rate of 5° F ± 0.5 per hour until the specimens were at 0° F. Readings were recorded hourly from 40° F to 0° F.

The specimens were removed from the freezer at 0° F. With polyethylene bags removed, the specimens were weighed (W_i). Normally there was only a negligible difference in weight before and after the specimens were tested in the freezer. In those cases where the difference was greater than 0.001 lb., the average value would be used.

Immediately following weighing, the specimens were kept in water for the remaining soaking period. At the end of the period (60 days), they were weighed (W_s) and then heated in an oven at 230° F for 24 hours and weighed again (W_o). The actual degree of saturation at the time of testing in the freezer was then computed.

11. DISCUSSIONS OF RESULTS

A complete summary of results is presented from Fig. 5 to 23. It is interesting to note that the results correlate reasonably well with the theories previously discussed, i.e., effects of maximum size of aggregate, water-cement ratio and degree of saturation.

11.1 Effect of Maximum Size of Aggregate

The effect of maximum size of aggregate is shown dramatically in Fig. 5 to 8. In Fig. 5 e.g., it can be seen that at a w/c ratio of 0.45 and 100% saturation only the mixes containing 3/4 in. maximum size aggregate exhibited expansion in the freezing test. In Fig. 6, at a water-cement ratio of 0.50 (and 100% saturation) the 3/4 in. aggregate mix exhibited very pronounced expansion, the 3/8 aggregate mix showed a minor amount of expansion while the 1/4 in. aggregate mix showed no expansion. In Fig. 7, at a water-cement ratio of 0.55 (and 100% saturation) both the 3/4 in. and 3/8 in. aggregate mixes show pronounced expansion while the 1/4 in. aggregate mix showed no expansion. In Fig. 8 at a water-cement ratio of 0.60 (and 100% saturation) all three mixes show significant expansion.

From the foregoing it can be seen that the frost resistance of concrete is significantly influenced by the maximum size of aggregate. The experimental results

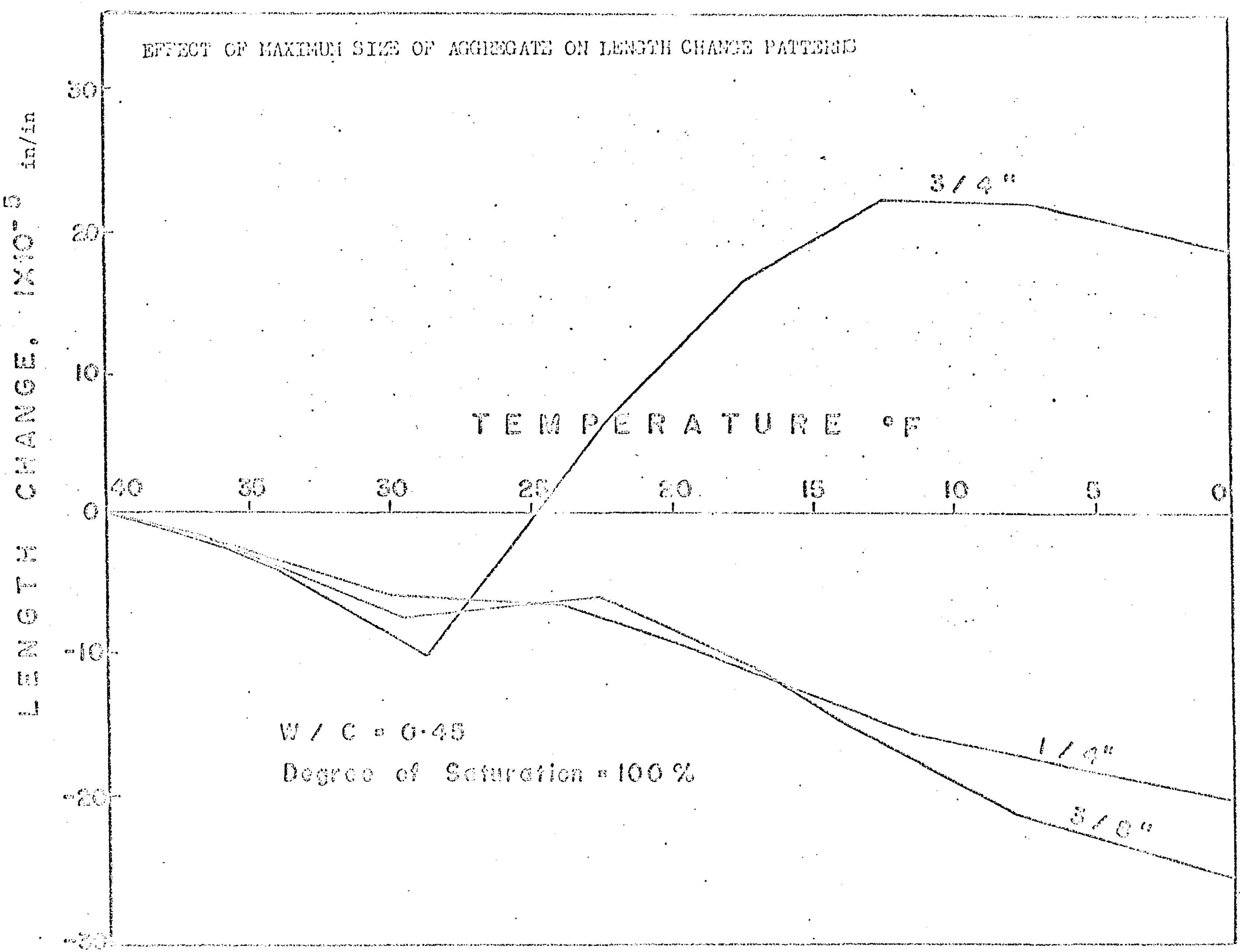


Fig 5

EFFECT OF MAXIMUM SIZE OF AGGREGATE ON LENGTH CHANGE PATTERNS

Fig. 6

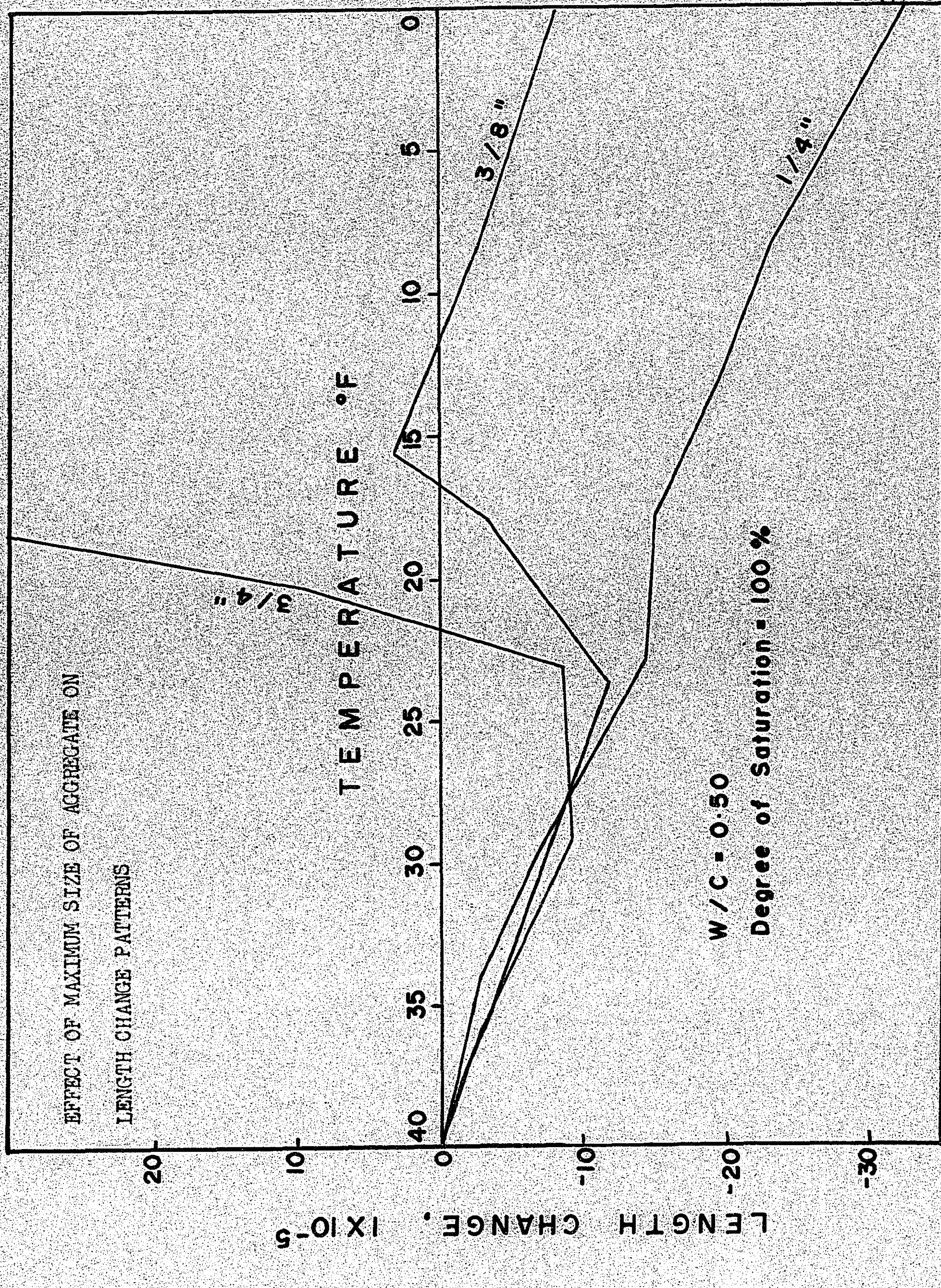
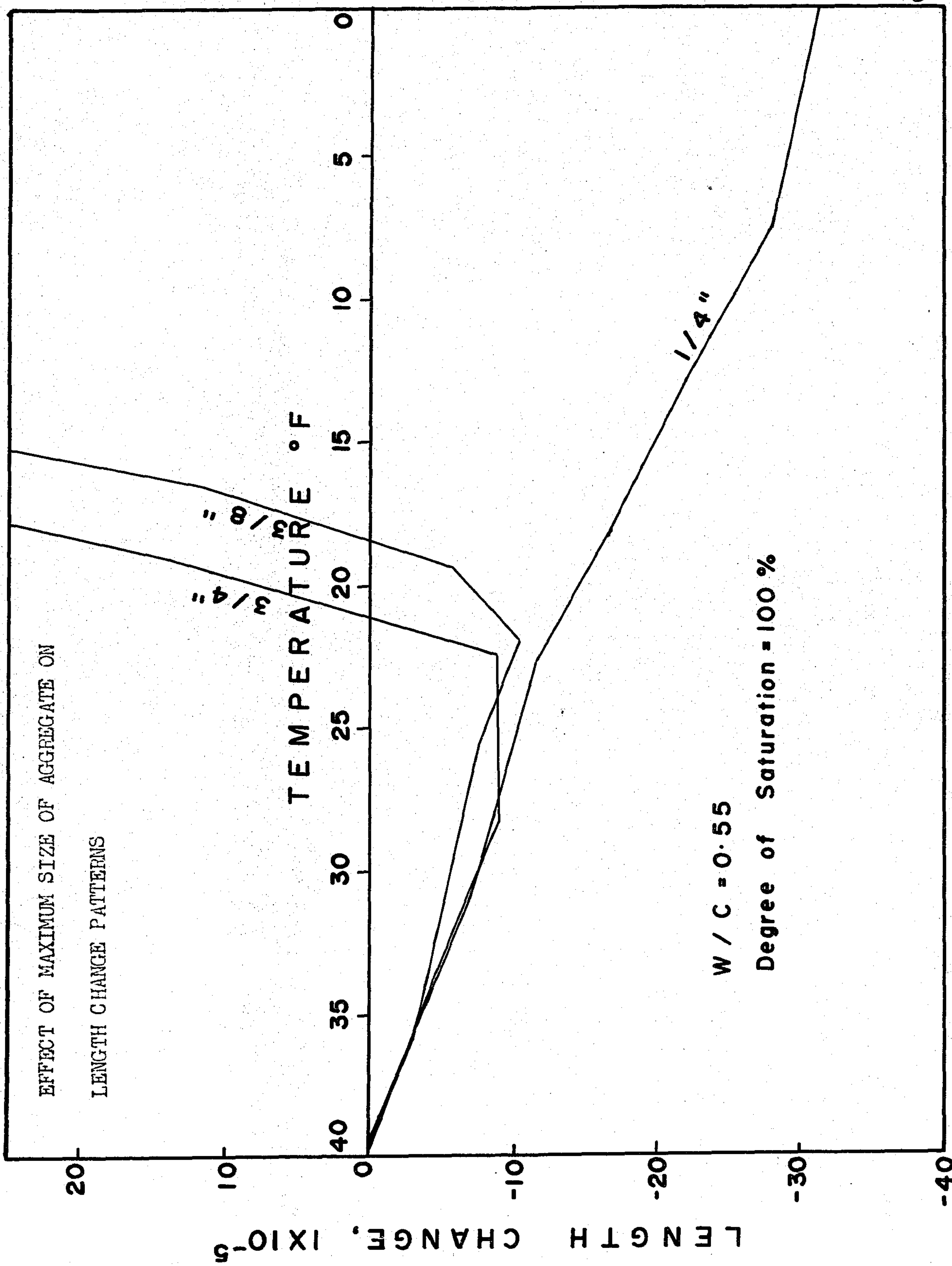
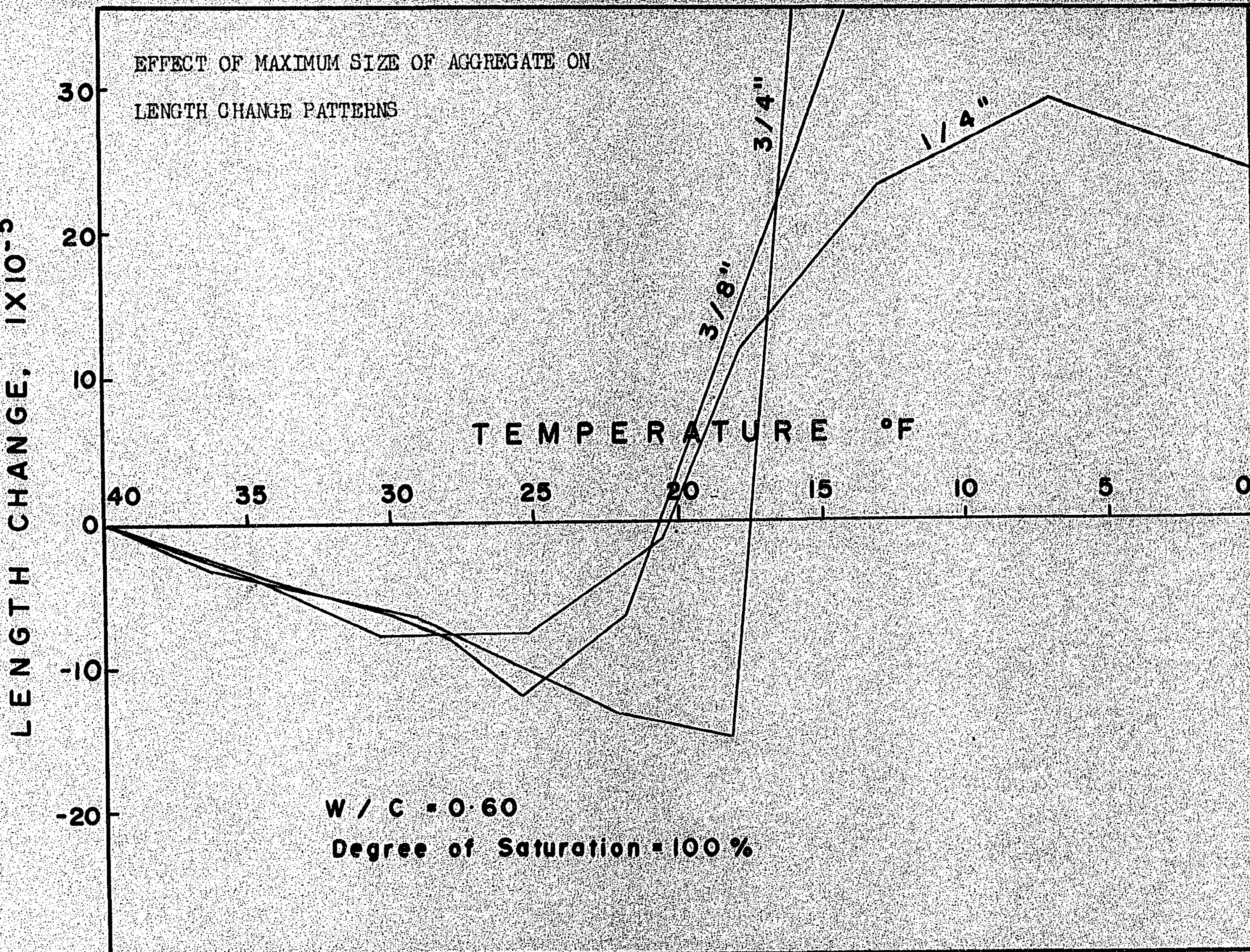

EFFECT OF MAXIMUM SIZE OF AGGREGATE ON
LENGTH CHANGE PATTERNS
TEMPERATURE °F
LENGTH CHANGE, 1X10⁻⁵
W/C = 0.50
Degree of Saturation = 100 %
3/8"
1/4"
3/4"
0
5
10
15
20
25
30
35
40
20
10
0
-10
-20
-30

Fig. 7



EFFECT OF MAXIMUM SIZE OF AGGREGATE ON
LENGTH CHANGE PATTERNS
TEMPERATURE °F
0
5
10
15
20
25
30
35
40
LENGTH CHANGE, 1X10-5
20
10
0
-10
-20
-30
-40
1/4"
3/8"
3/4"
W / C = 0·55
Degree of Saturation = 100 %

Fig. 8



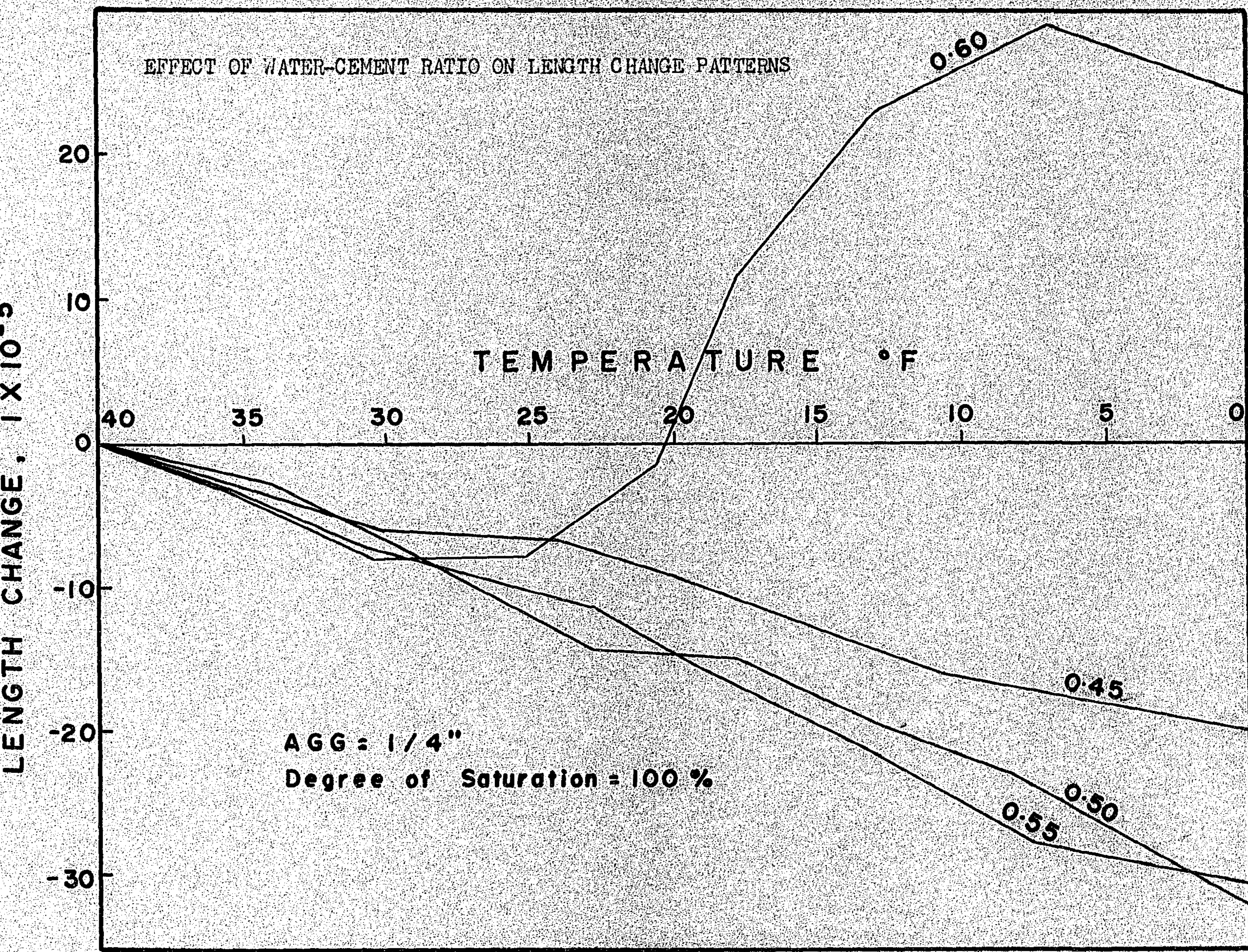
EFFECT OF MAXIMUM SIZE OF AGGREGATE ON
LENGTH CHANGE PATTERNS
LENGTH CHANGE, 1X10-5
30
20
10
0
-10
-20
TEMPERATURE °F
40
35
30
25
20
15
10
5
0
3/4"
3/8"
1/4"
W / C = 0·60
Degree of Saturation = 100 %

showed that the concrete specimens having smaller maximum size aggregate had higher frost resistance. This suggests that the larger aggregate particles produced higher internal hydraulic pressures when they were partially or completely saturated. The internal stresses were presumably the result of expelled water forced into the surrounding paste during freezing. The larger aggregate particles with longer expulsion distance produced higher stresses than that of the smaller particles with shorter expulsion distances.

11.2 Effect of Water-Cement Ratio

The effect of water-cement ratio on frost resistance will have been noted in Figures 5 to 8 already discussed, but is also shown in Figures 9 to 11. In Figure 9, it can be seen that with the 1/4 in. maximum aggregate size mix and 100% saturation only the mix of 0.60 water-cement ratio showed any expansion. In Figure 10, it can be seen that the 3/8 in. maximum size aggregate mixes (at 100% saturation) exhibited no expansion at water-cement ratio of 0.45, a slight expansion for the 0.50 water-cement ratio and increasing expansions for the higher water-cement ratios. Similarly in Figure 11, it can be seen that with the 3/4 in. maximum size aggregate mixes and 100% saturation all mixes of 0.60, 0.55, 0.50 and 0.45 water-cement ratios exhibited pronounced expansions.

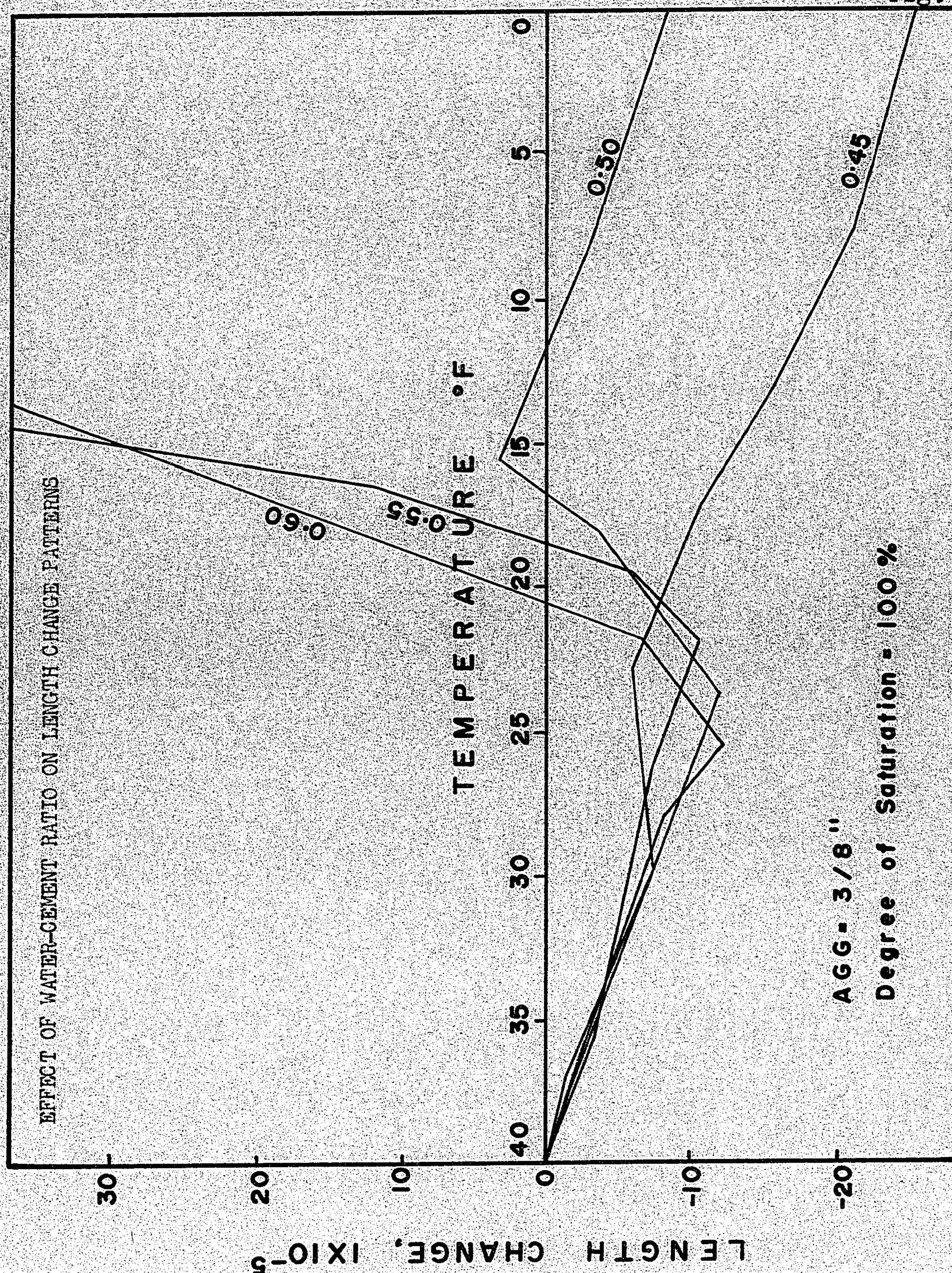
Fig. 9



EFFECT OF WATER-CEMENT RATIO ON LENGTH CHANGE PATTERNS
TEMPERATURE °F
40
35
30
25
20
15
10
5
0
LENGTH CHANGE, 1 X 10^-5
20
10
0
-10
-20
-30
0·60
0·45
0·50
0·55
AGG = 1/4"
Degree of Saturation = 100 %

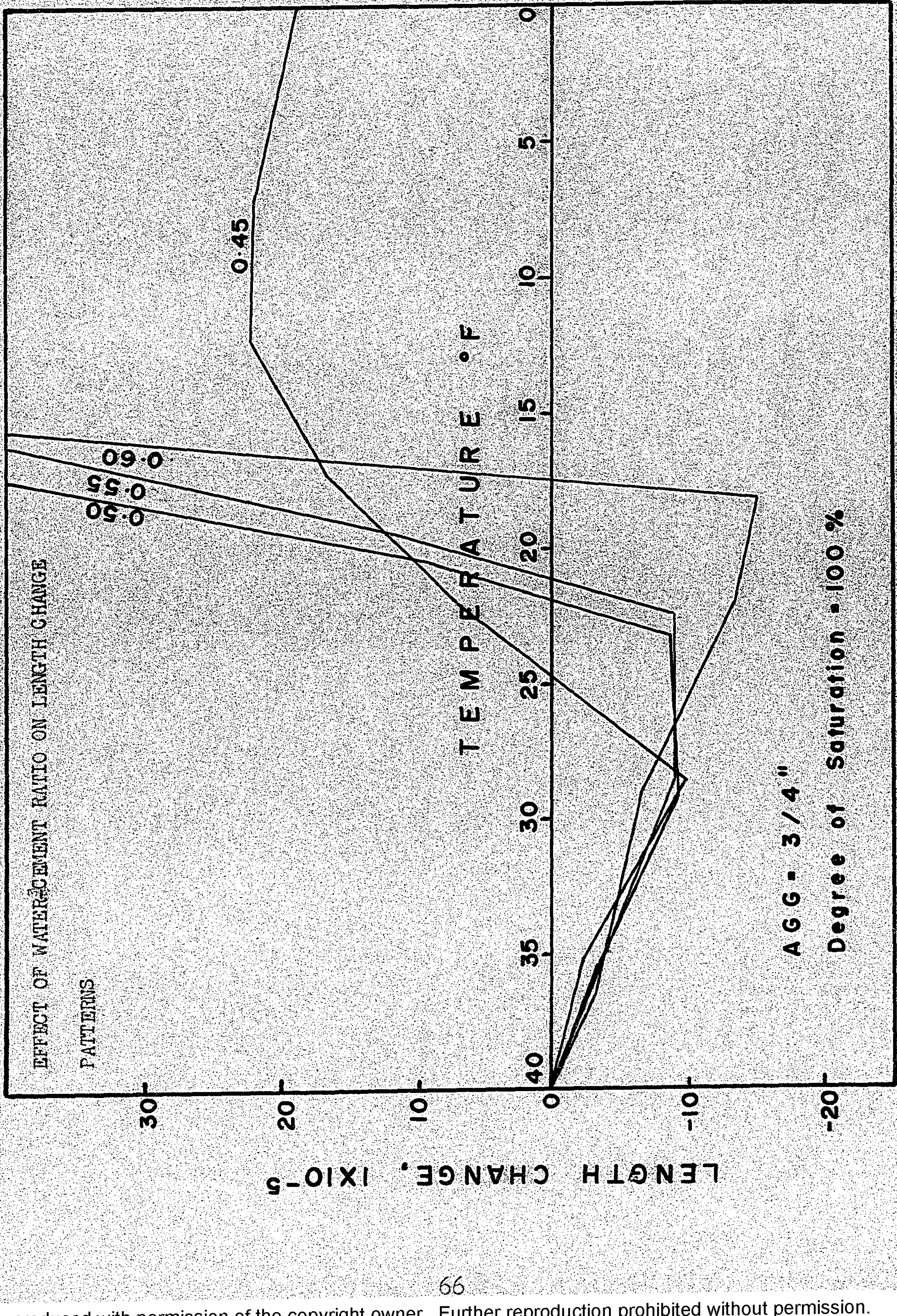
61

Fig. 10



EFFECT OF WATER-CEMENT RATIO ON LENGTH CHANGE PATTERNS

Fig. II


EFFECT OF WATER-CEMENT RATIO ON LENGTH CHANGE
PATTERNS
TEMPERATURE °F
0
5
10
15
20
25
30
35
40
LENGTH CHANGE, 1X10-5
30
20
10
0
-10
-20
0.45
0.50
0.55
0.60
AGG = 3/4"
Degree of Saturation = 100 %

It is seen that the frost resistance of concrete was higher the lower the water-cement ratio. The low water-cement paste not only limited the ingress of water (low permeability) but also limited the capillary volume produced. Even when 100% saturated the capillaries could only hold a relative smaller volume of water. Therefore, cement pastes of low water-cement ratio were more resistant to the build-up of hydraulic pressures and the growth of capillary ice simply because there were fewer capillaries in the pastes.

11.3 Effect of Degree of Saturation

The effect of degree of saturation is shown from Fig. 12 to 23. For those concrete specimens exhibiting expansions, expansions increased with increasing degree of saturation. A typical example is shown on Fig. 15. With water-cement ratio of 0.60 and having 1/4-in. maximum size aggregate, no expansion exhibited at 75.5% degree of saturation. At 85.4% saturation the concret showed a minor amount of expansion. At 92.6% saturation expansions were increased and at 100% saturation the concrete showed pronounced expansions.

Theoretically no expansion should exhibit if the degree of saturation is below 91%. However, many of the concrete specimens did show expansions even though they were protected by air-entrainment. An example is shown on Figure 19. With water-cement ratio of 0.60 and having 3/8-in. maximum size aggregate, the mix exhibited expansions at 88.9% saturation or even lower. The expansions could be accounted for by a non-uniform distribution of water in the concrete specimens, i.e, certain regions of the specimens might be more than 91% saturated while the average saturation was below this value.

In summary it can be seen that there is no one limiting water-cement ratio for concrete that will assure no expansions during a freezing cycle, because degree of saturation and the maximum size of aggregate are parameters that also influence frost resistance.

Fig. 12

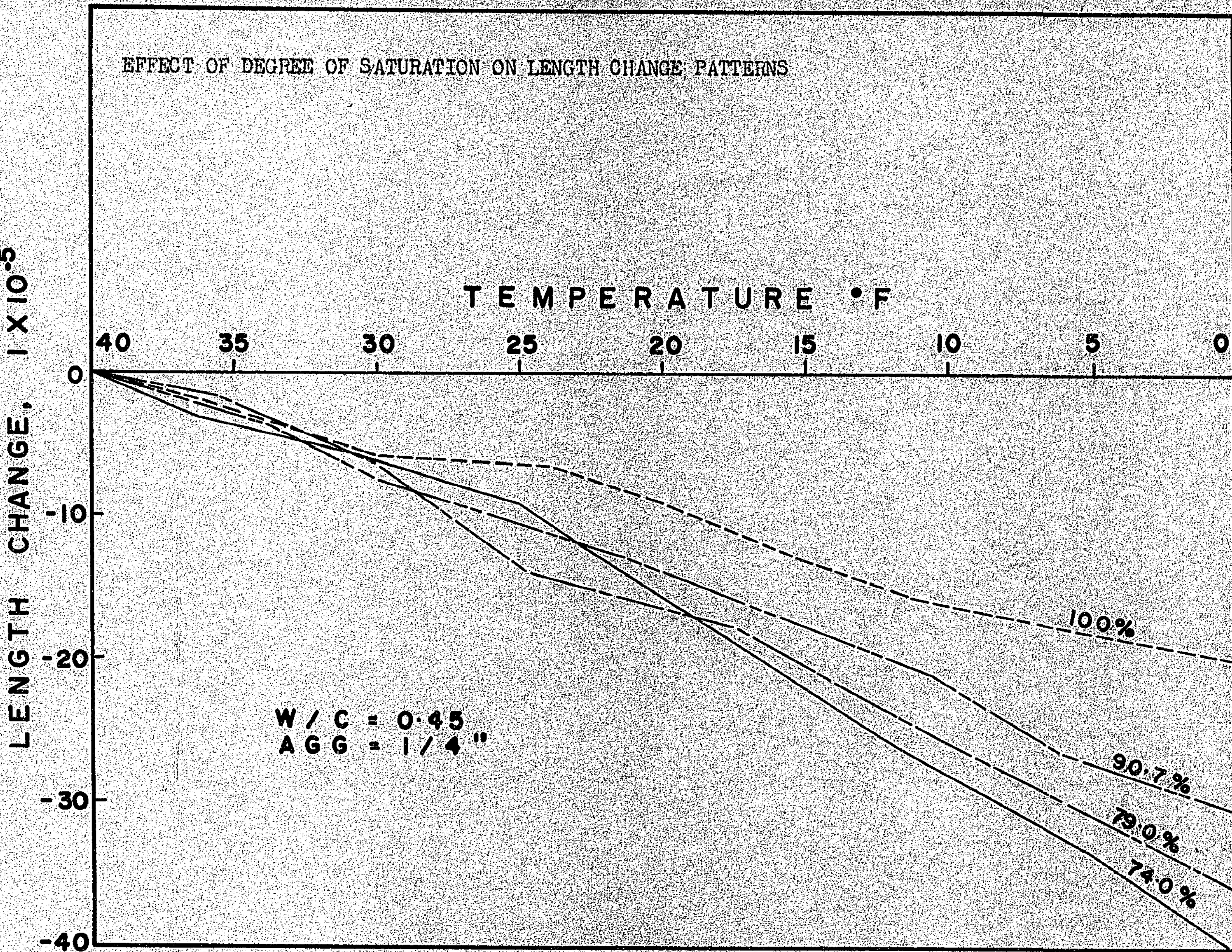
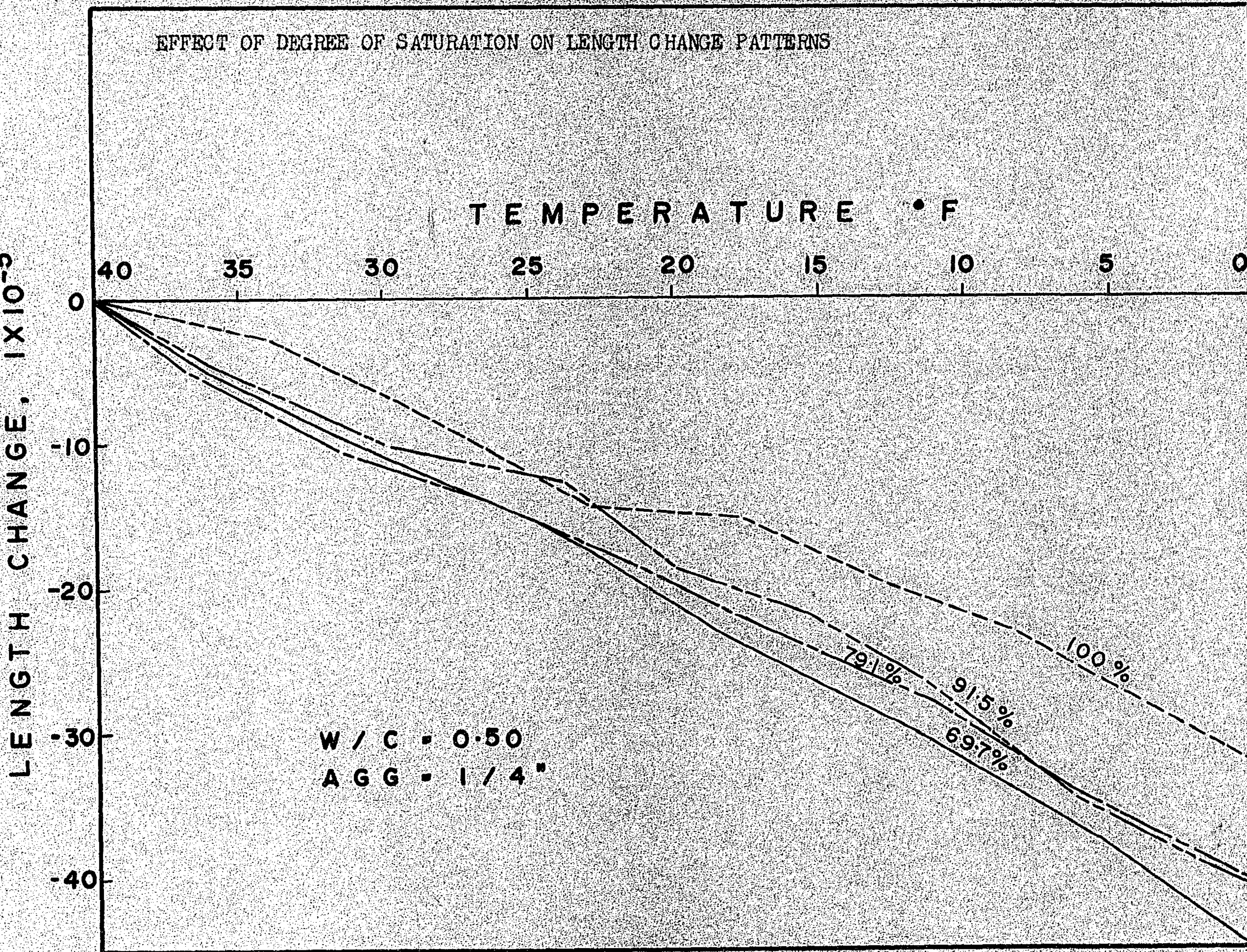

EFFECT OF DEGREE OF SATURATION ON LENGTH CHANGE PATTERNS
TEMPERATURE °F
40
35
30
25
20
15
10
5
0
LENGTH CHANGE, I X 10^-5
0
-10
-20
-30
-40
100%
90·7%
79·0%
74·0%
W / C = 0·45
AGG = 1 / 4"

Fig. 13



EFFECT OF DEGREE OF SATURATION ON LENGTH CHANGE PATTERNS

EFFECT OF DEGREE OF SATURATION ON LENGTH CHANGE PATTERNS

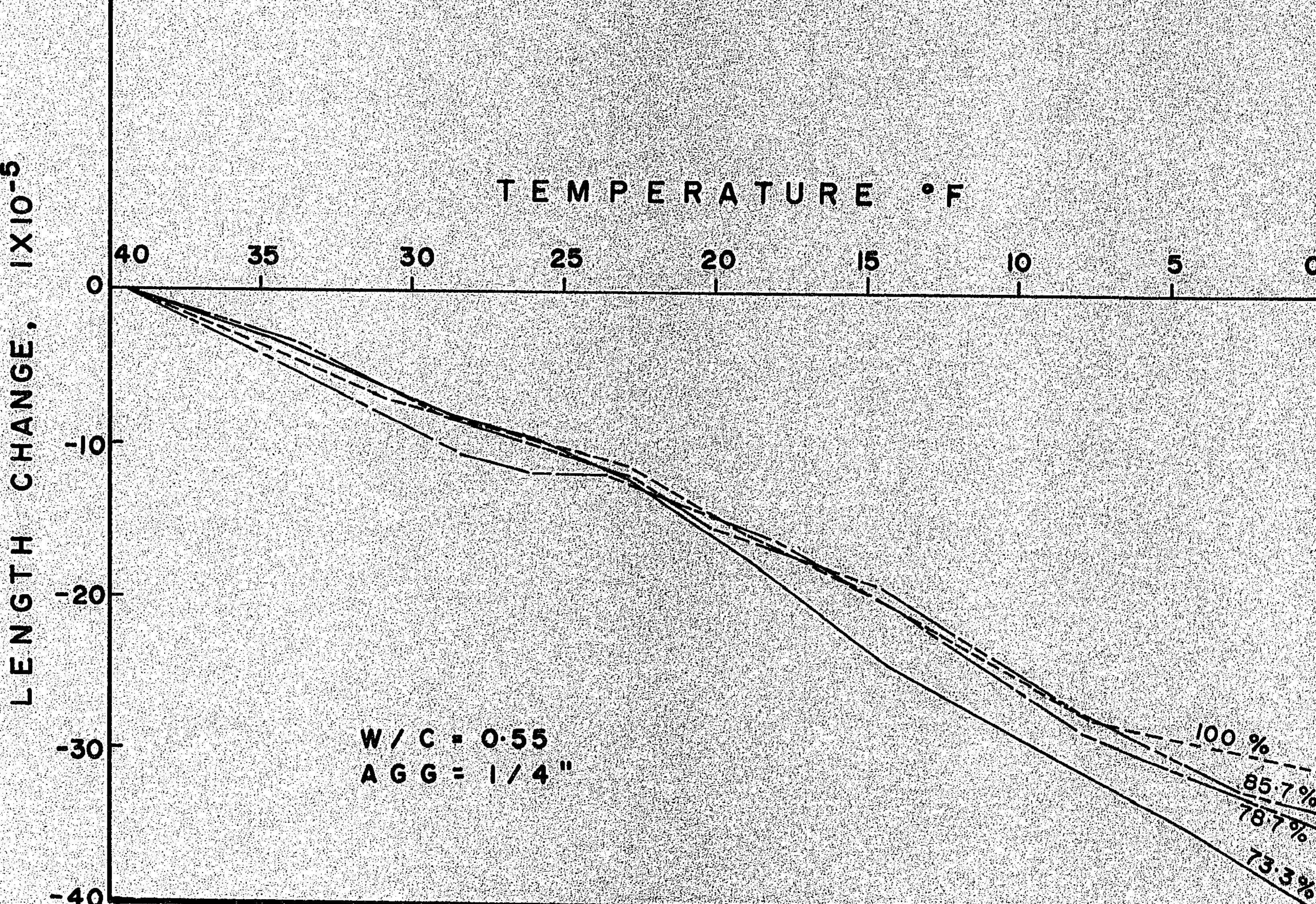
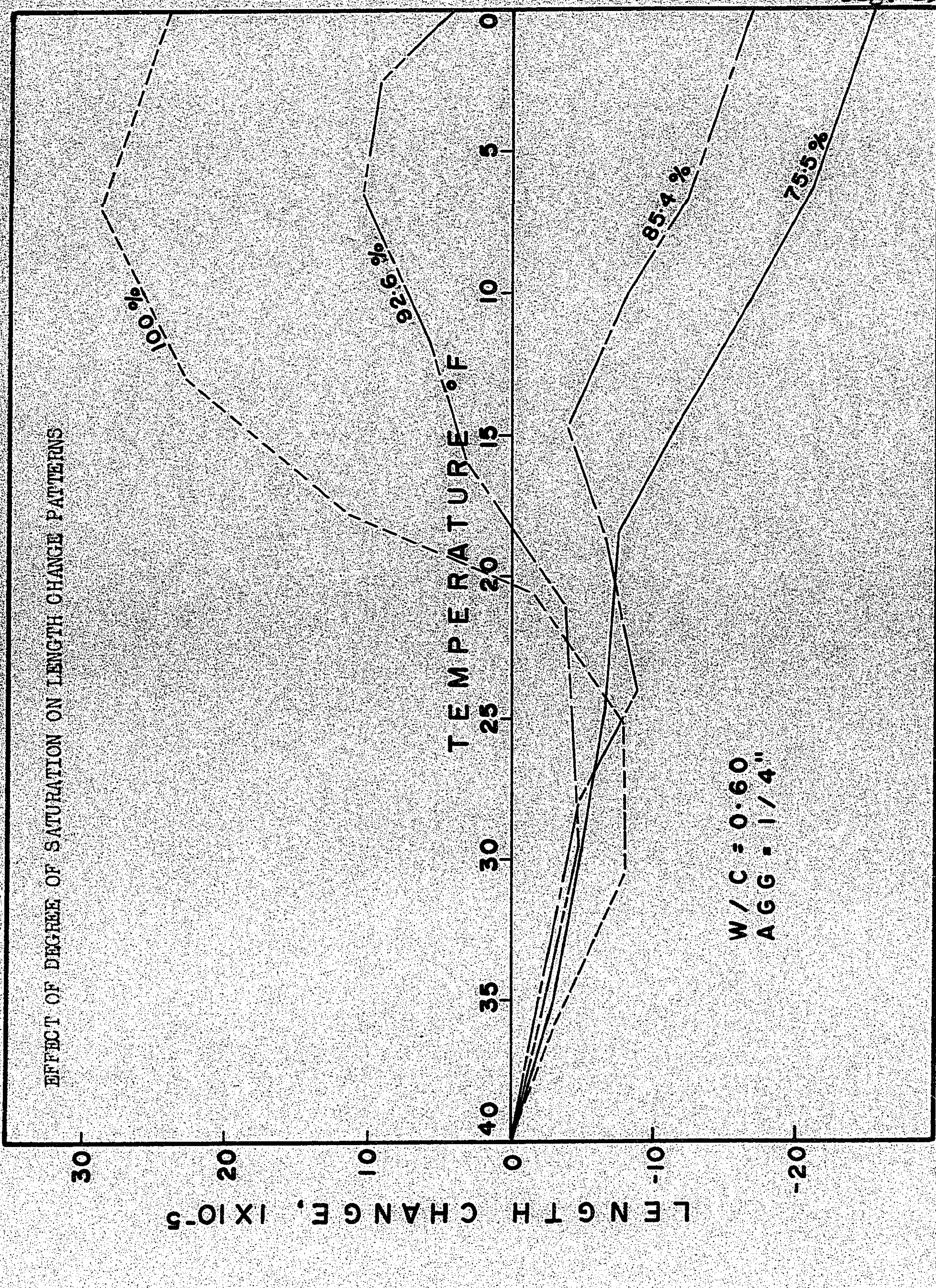


Fig. 14

Fig. 15



EFFECT OF DEGREE OF SATURATION ON LENGTH CHANGE PATTERNS
100 %
92.6 %
85.4 %
75.5 %
W / C = 0.60
AGG = 1/4"
TEMPERATURE °F
0
5
10
15
20
25
30
35
40
LENGTH CHANGE, 1X10-5
30
20
10
0
-10
-20

Fig. 16

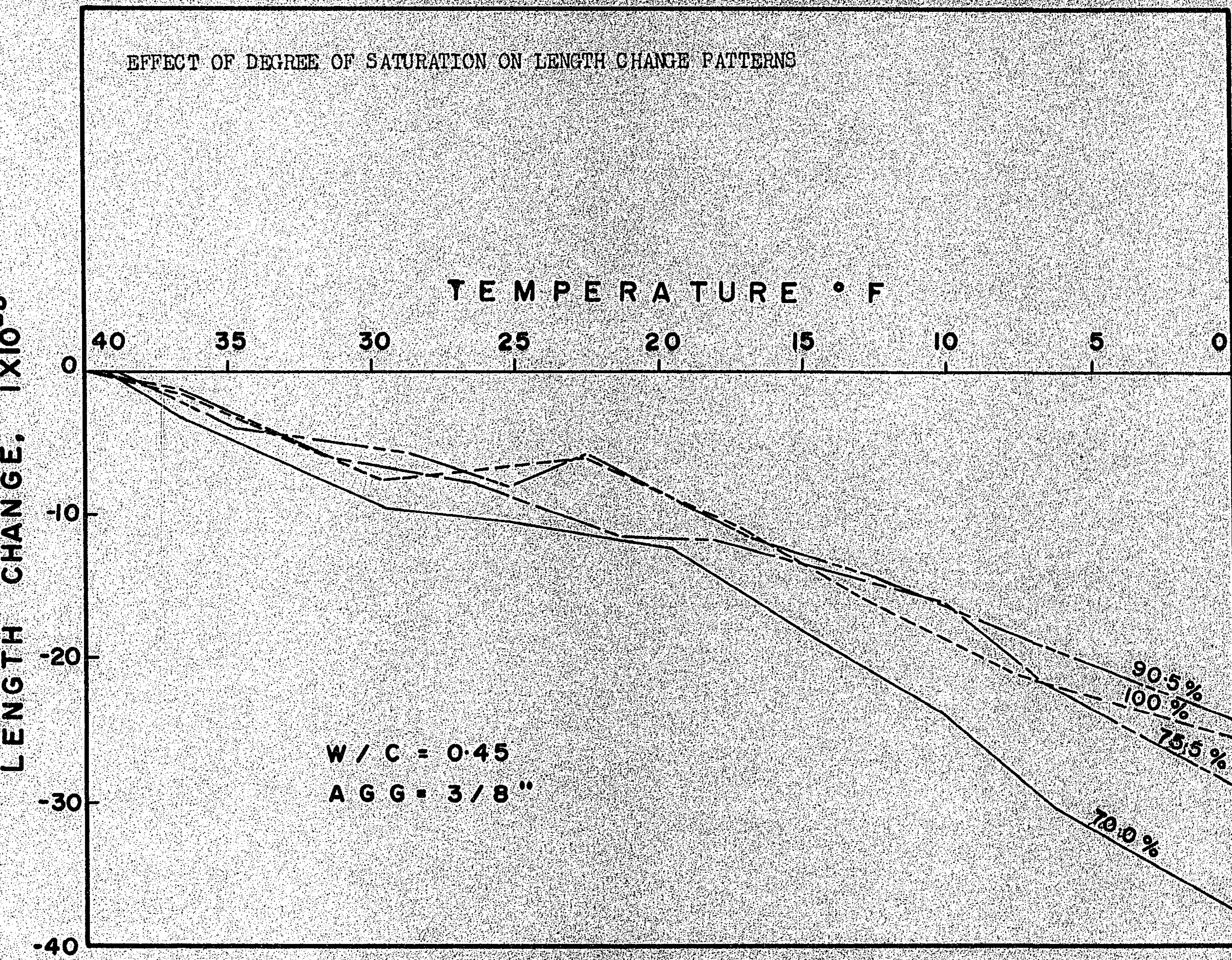
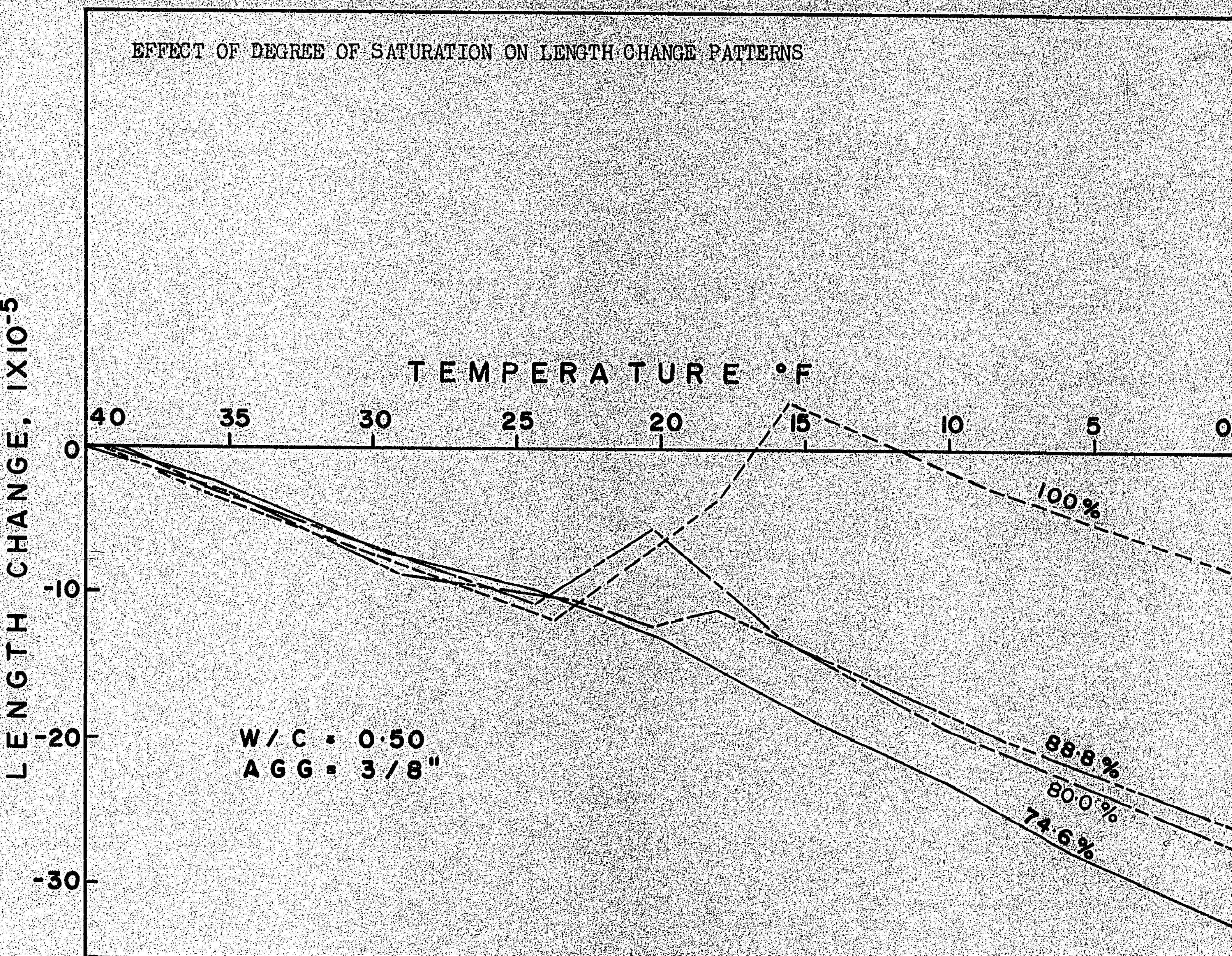
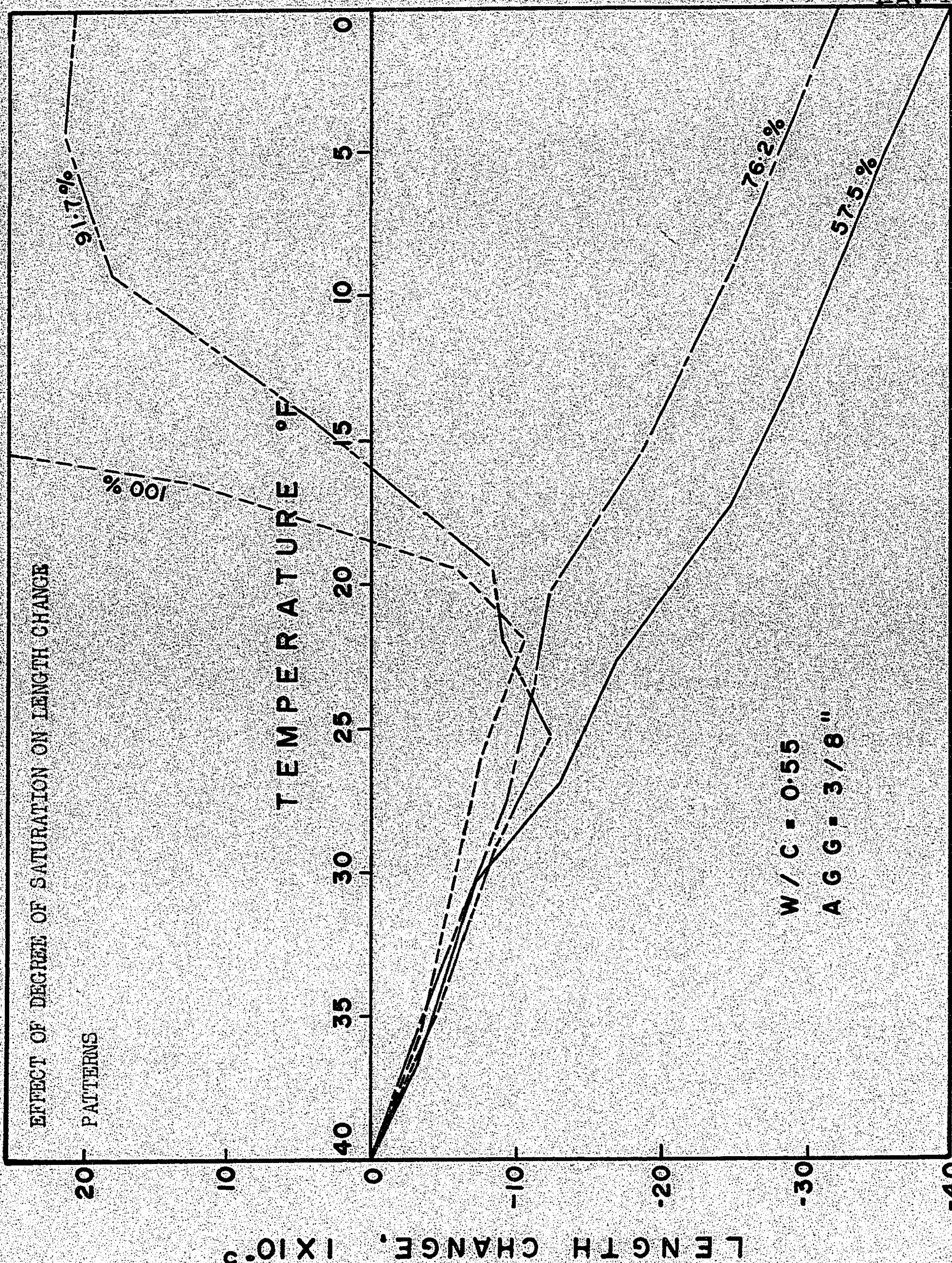

EFFECT OF DEGREE OF SATURATION ON LENGTH CHANGE PATTERNS
TEMPERATURE °F
40
35
30
25
20
15
10
5
0
LENGTH CHANGE, 1X10⁻⁵
0
-10
-20
-30
-40
90.5 %
100 %
75.5 %
70.0 %
W / C = 0.45
A G G = 3/8"

Fig. 17



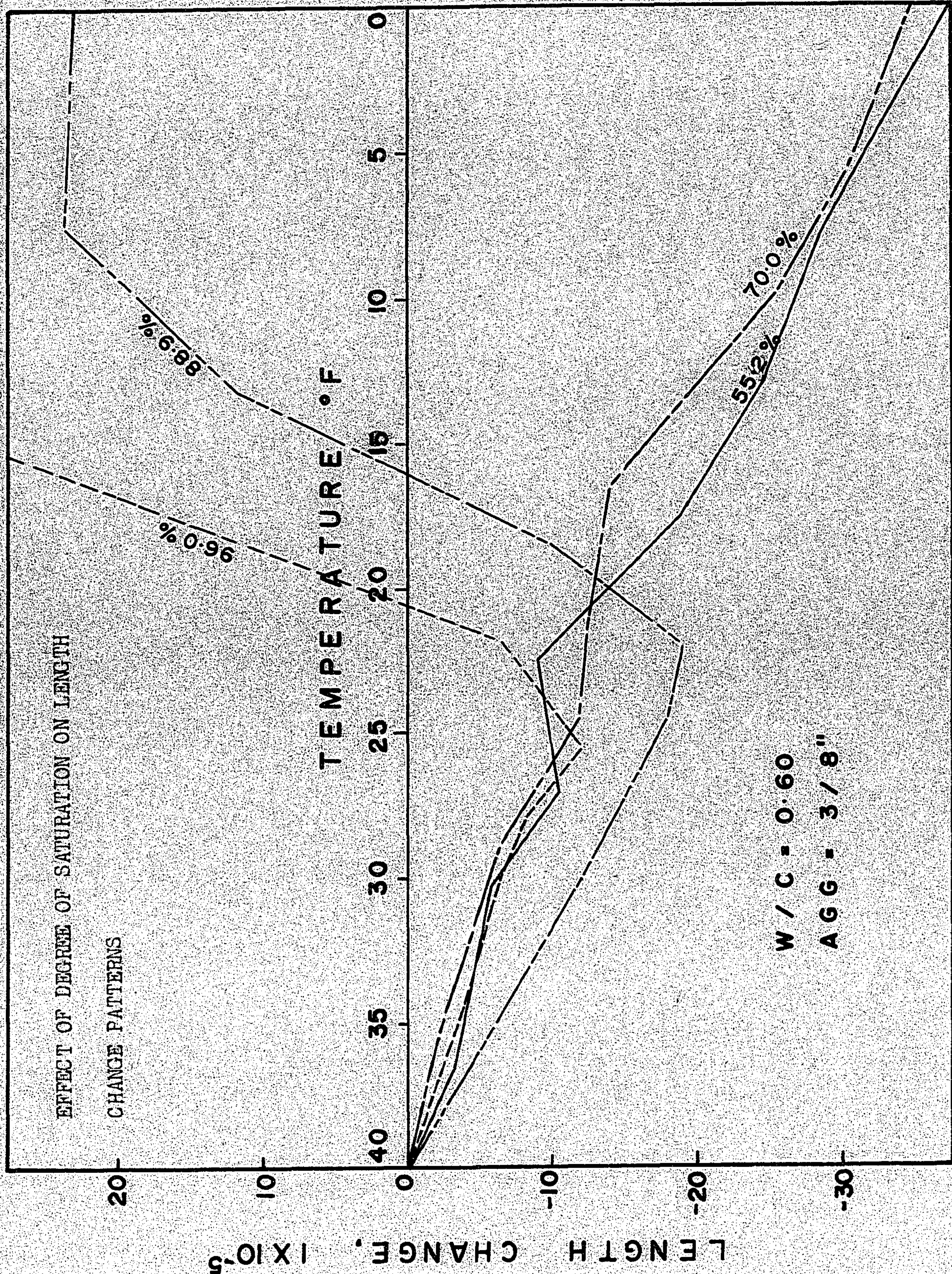
EFFECT OF DEGREE OF SATURATION ON LENGTH CHANGE PATTERNS
TEMPERATURE °F
40
35
30
25
20
15
10
5
0
LENGTH CHANGE, 1X10-5
0
-10
-20
-30
100%
88·8%
80·0%
74·6%
W/C = 0·50
AGG = 3/8"

Fig. 18



EFFECT OF DEGREE OF SATURATION ON LENGTH CHANGE PATTERNS

Fig. 19



EFFECT OF DEGREE OF SATURATION ON LENGTH
CHANGE PATTERNS
TEMPERATURE °F
LENGTH CHANGE, I X 10^-5
88.9 %
96.0 %
70.0 %
55.2 %
W / C = 0.60
AGG = 3 / 8"
0
5
10
15
20
25
30
35
40
20
10
0
-10
-20
-30

Fig. 20

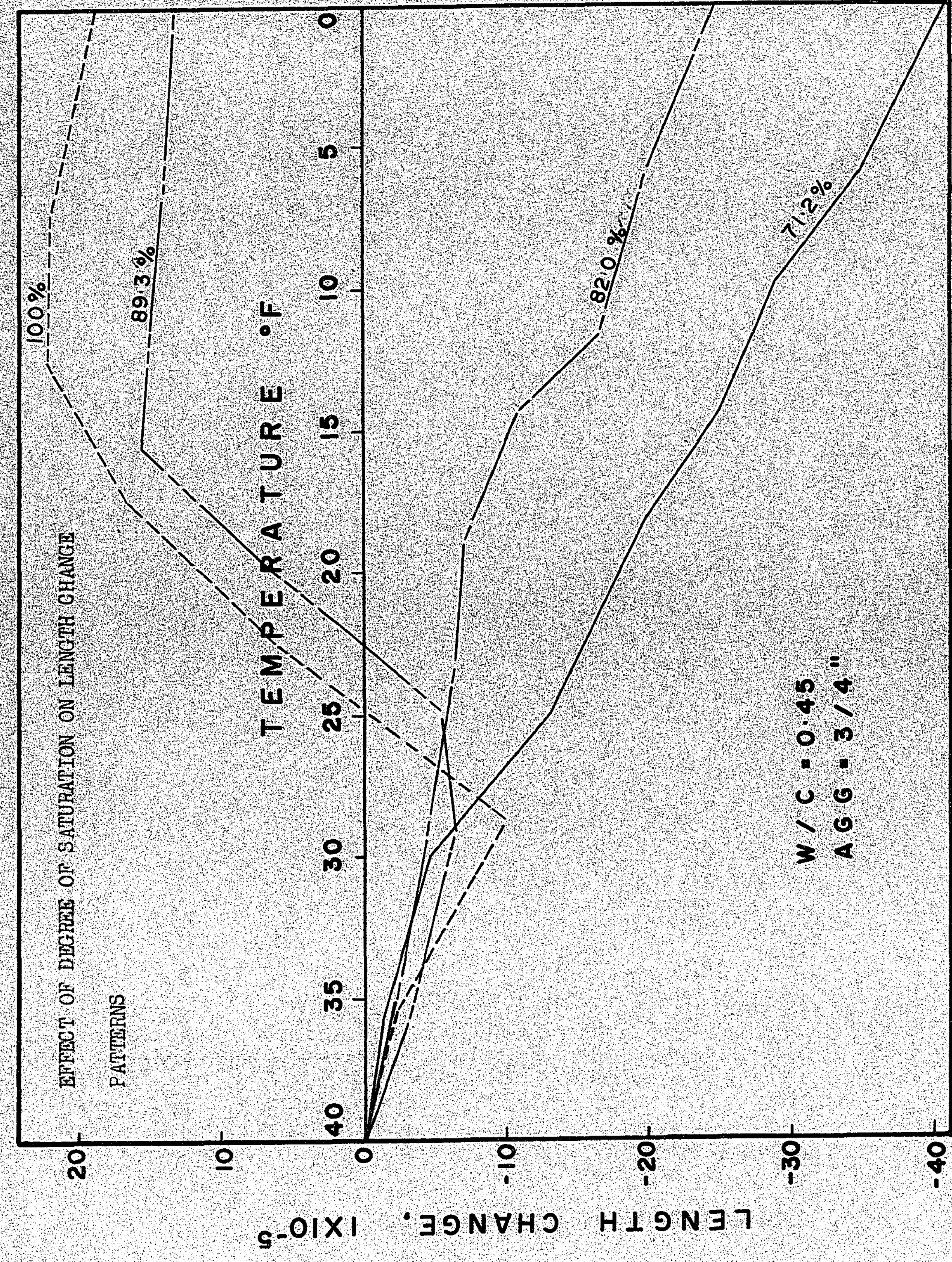

EFFECT OF DEGREE OF SATURATION ON LENGTH CHANGE
PATTERNS
TEMPERATURE °F
LENGTH CHANGE, 1X10^-5
W/C = 0.45
AGG = 3/4"
100%
89.3%
82.0%
71.2%
0
5
10
15
20
25
30
35
40
20
10
0
-10
-20
-30
-40

Fig. 21

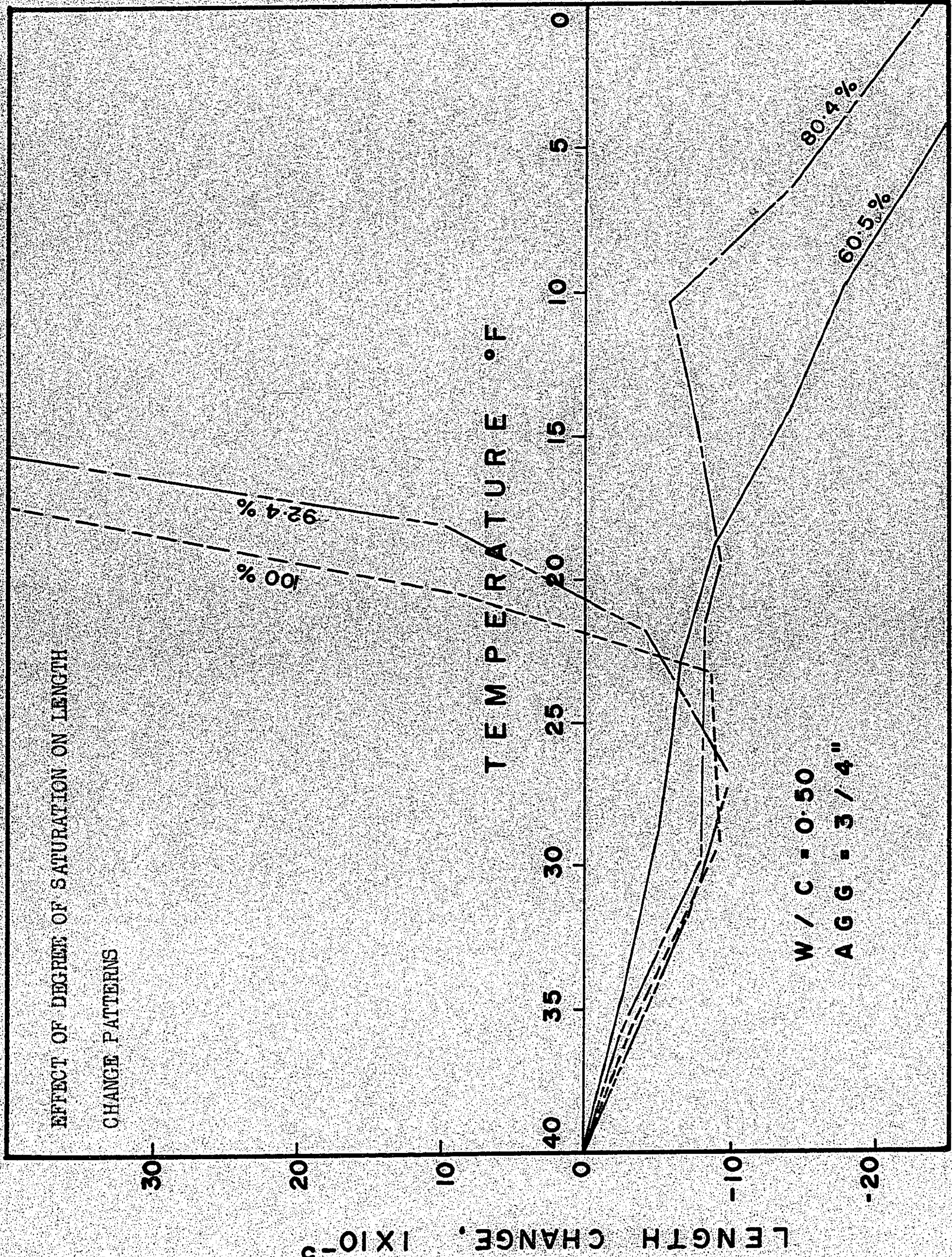

EFFECT OF DEGREE OF SATURATION ON LENGTH
CHANGE PATTERNS
TEMPERATURE °F
0
5
10
15
20
25
30
35
40
LENGTH CHANGE, 1X10⁻⁵
30
20
10
0
-10
-20
80·4 %
60·5 %
92·4 %
100 %
W / C = 0·50
AGG = 3 / 4"

Fig. 22

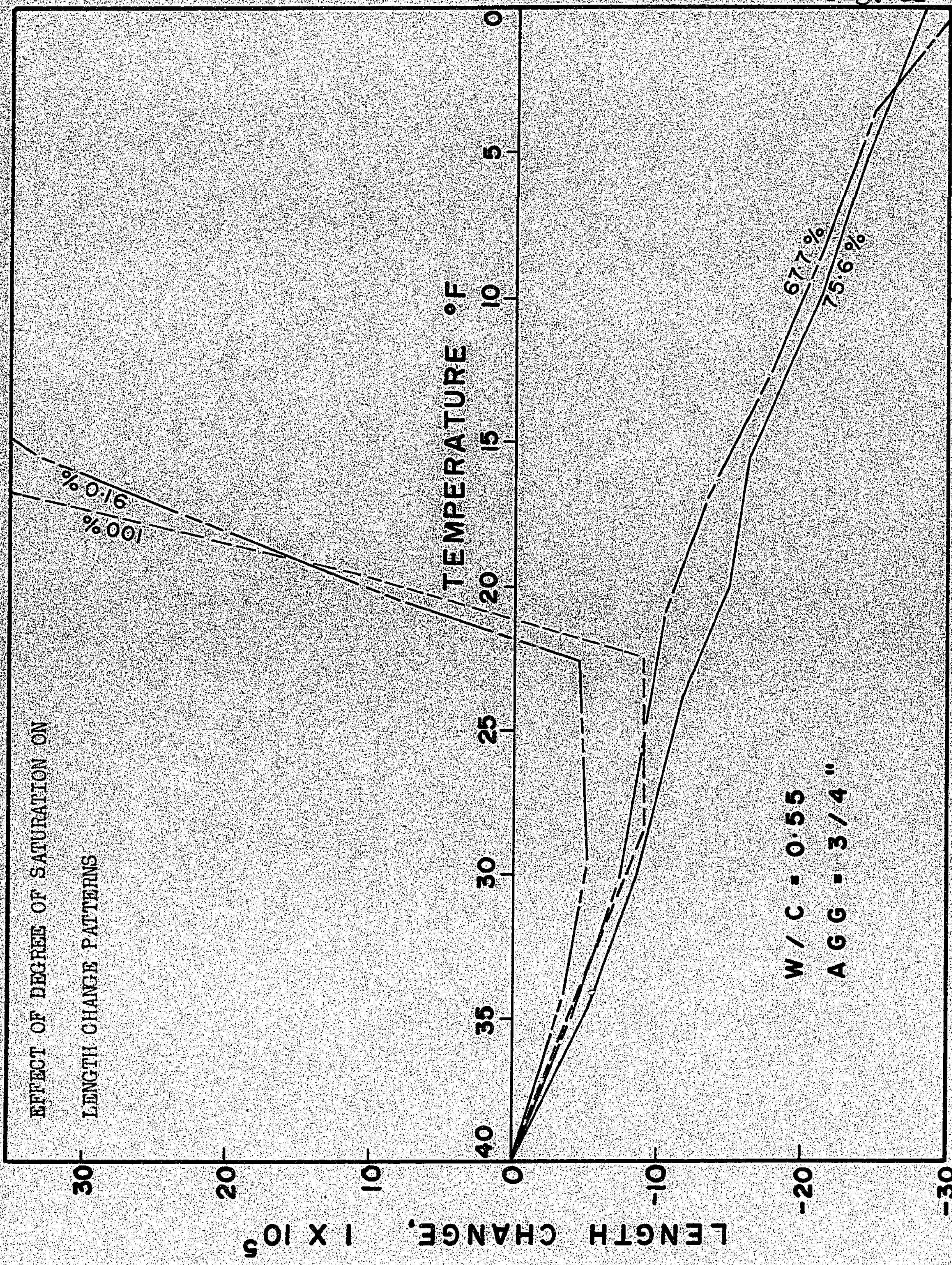
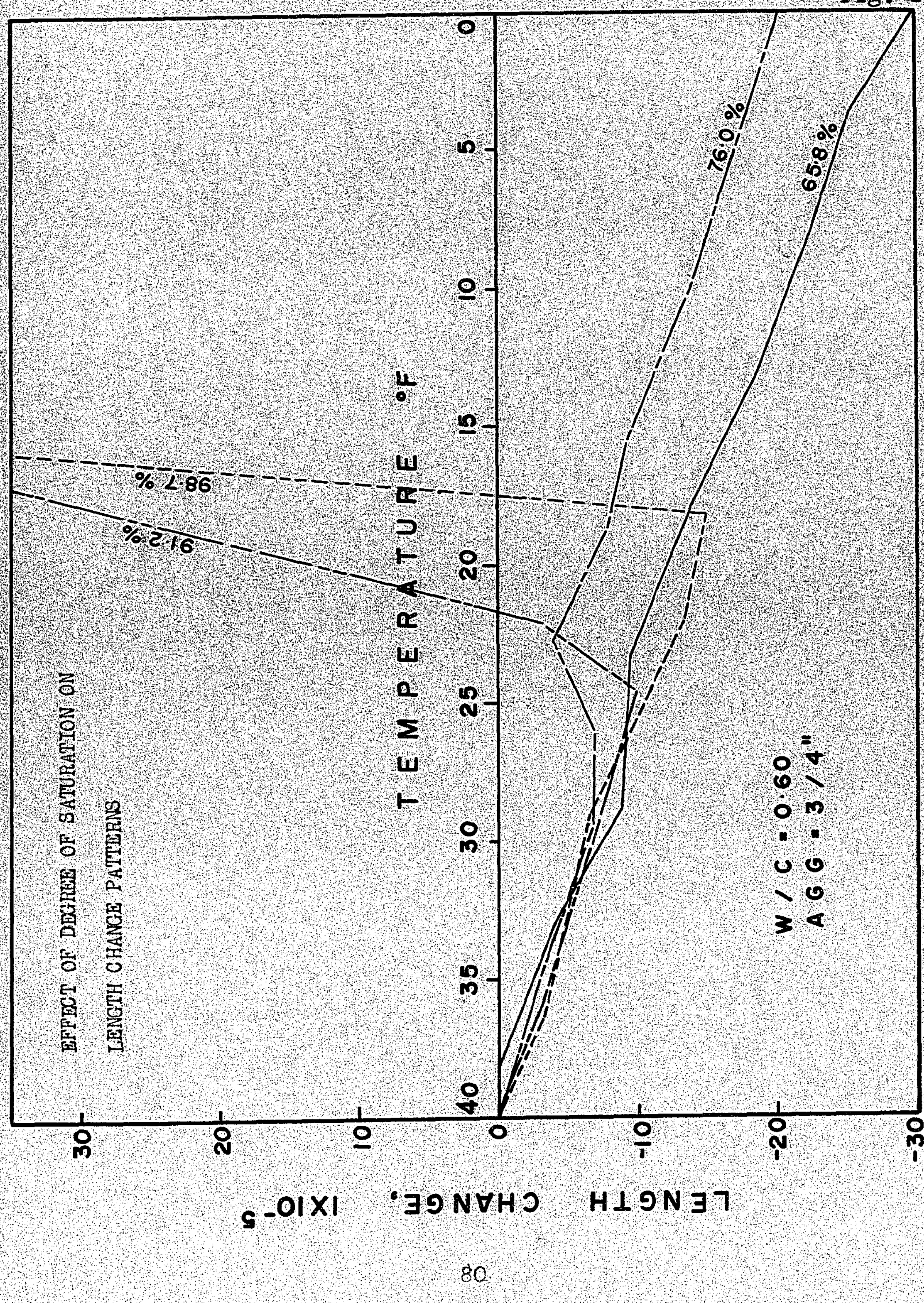

EFFECT OF DEGREE OF SATURATION ON
LENGTH CHANGE PATTERNS
TEMPERATURE °F
LENGTH CHANGE, l X 10^5
W / C = 0·55
AGG = 3 / 4"
100 %
91·0 %
67·7 %
75·6 %
0
5
10
15
20
25
30
35
40
30
20
10
0
-10
-20
-30

Fig. 23


EFFECT OF DEGREE OF SATURATION ON
LENGTH CHANGE PATTERNS
TEMPERATURE °F
0
5
10
15
20
25
30
35
40
LENGTH CHANGE, 1X10-5
30
20
10
0
-10
-20
-30
76.0 %
65.8 %
98.7 %
91.2 %
W / C = 0.60
AGG = 3 / 4"

12. CONCLUSIONS

1. The following air-entrained concretes have been proved to be highly frost-resistant:

   (a) Concretes with a water-cement ratio of 0.55 or less and having 1/4-in. maximum size aggregate.

   (b) Concretes with a water-cement ratio of 0.45 or less and having 3/8-in. maximum size aggregate.

2. The larger the maximum size of aggregate used the greater is the susceptibility of the concrete to frost action. That is to say, the magnitude of hydraulic pressures developed is significantly influenced by the size of the aggregate particles.

3. It is hard to assess a single value of critical degree of saturation for all concrete specimens. It is seen that critical degree of saturation is inversely proportional to water-cement ratio.

4. Expansion is an indication of moisture condition at which concretes are susceptible to freezing damage. The period of immersion after 24 hours in a vacuum tank required to produce measurable expansion is a significant measure of the resistance of concrete to freezing and thawing.

5. It has been demonstrated that this method of testing could be conveniently used for the routine evaluation of concrete durability and for research purposes.

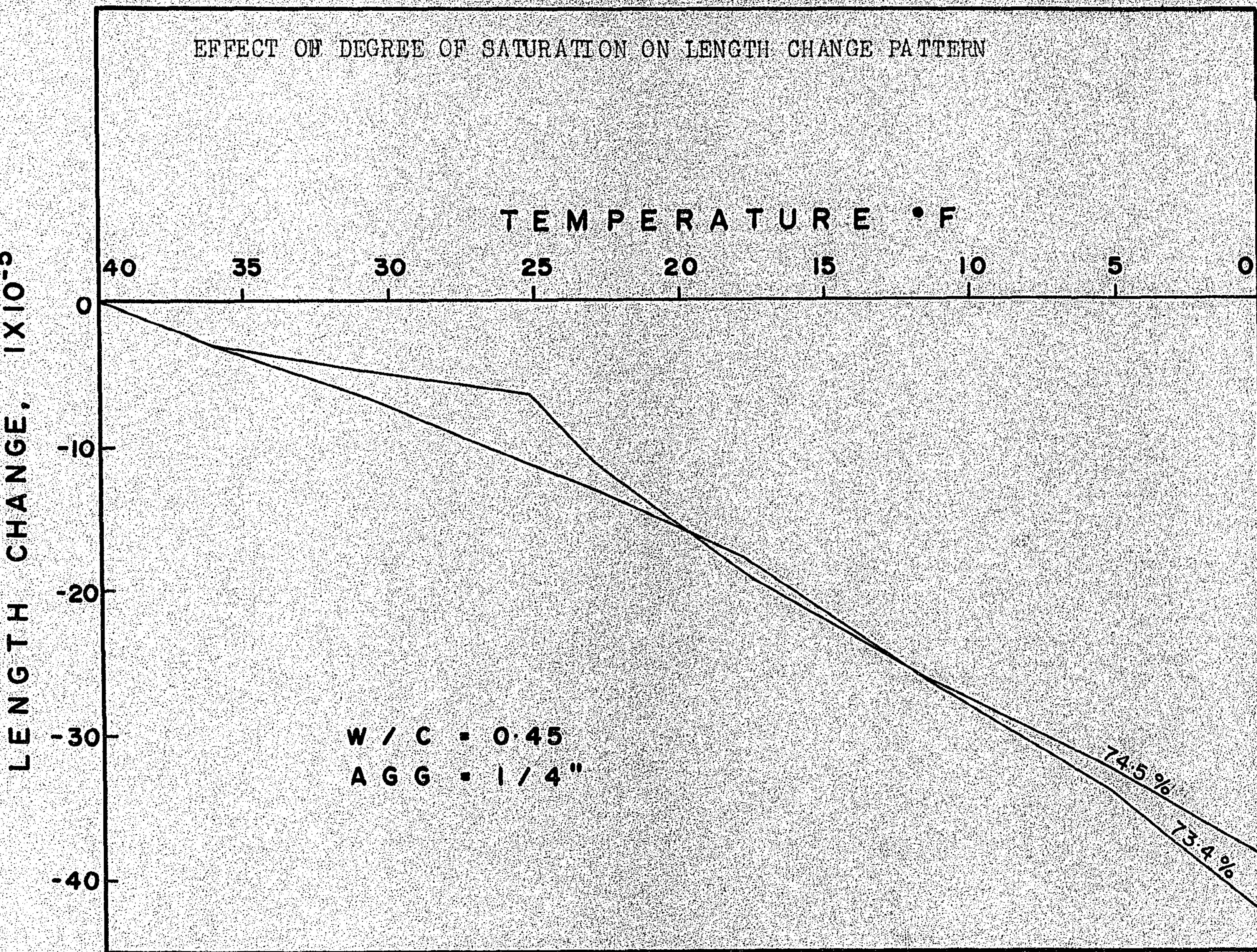
13. RECOMMENDATIONS FOR FURTHER WORK

1. Dry aggregates were used throughout this project. However, Powers noted the significance of using wet aggregates in order to simulate the moisture condition of aggregates sometimes used in field practice. He suggested that aggregates should be water-soaked for a period of 24 hours prior to mixing. It is recommended therefore, that further studies should be carried out using saturated aggregates.

2. The present program of studies was carried out using one source of coarse aggregate. Other coarse aggregates, having different porosities and absorptions, may well produce expansions at different degrees of saturation and different water-cement ratios, and different maximum sizes. It would be interesting therefore to check a variety of aggregates in concrete mixes using this testing technique.

3. The present program of studies was conducted using one air-void system, i.e., a nominal air content of 7% using a specific AEA. Further studies should be carried out to assess the extent to which other air-void systems (i.e., different AEA and different total air contents) might affect the picture of frost resistance for a given coarse aggregate.

APPENDIX



EFFECT OF DEGREE OF SATURATION ON LENGTH CHANGE PATTERN

W/C = 0.45 Curing Time = 14 days Date: June 4, 1967

Agg. = 1/4 in. Air Dried = 28 days

Air = 7%

SPEC.	Init.Rdg.	Surface / Centre	TEMPERATURES °F 40.0 / 40.1	35.5 / 37.0	29.70 / 32.0	25.0 / 25.0	22.8 / 23.0	17.5 / 19.3	11.5 / 12.0	5.0 / 5.6	1.5 / 2.0	
	---	$(\Delta L)10^3$										
		$(\Delta L/L)10^5$										
	---	$(\Delta L)10^3$										
		$(\Delta L/L)10^5$										
			272.50	272.70	272.80	272.90	273.20	273.70	274.10	274.60	274.90	
2	272.50	$(\Delta L)10^3$	0	-4.58	-6.86	-9.15	-16.01	-27.45	-36.60	-48.10	-57.20	
		$(\Delta L/L)10^5$	0	-3.22	-4.83	-6.44	-11.28	-19.31	-25.80	-33.80	-40.20	
			260.60	260.80	261.00	261.30	261.40	261.70	262.20	262.60	262.80	
3	262.60	$(\Delta L)10^3$	0	-4.62	-9.23	-16.18	-18.50	-25.40	-37.00	-46.20	-51.50	
		$(\Delta L/L)10^5$	0	-3.25	-6.50	-11.39	-13.02	-17.88	-26.00	-32.50	-36.20	

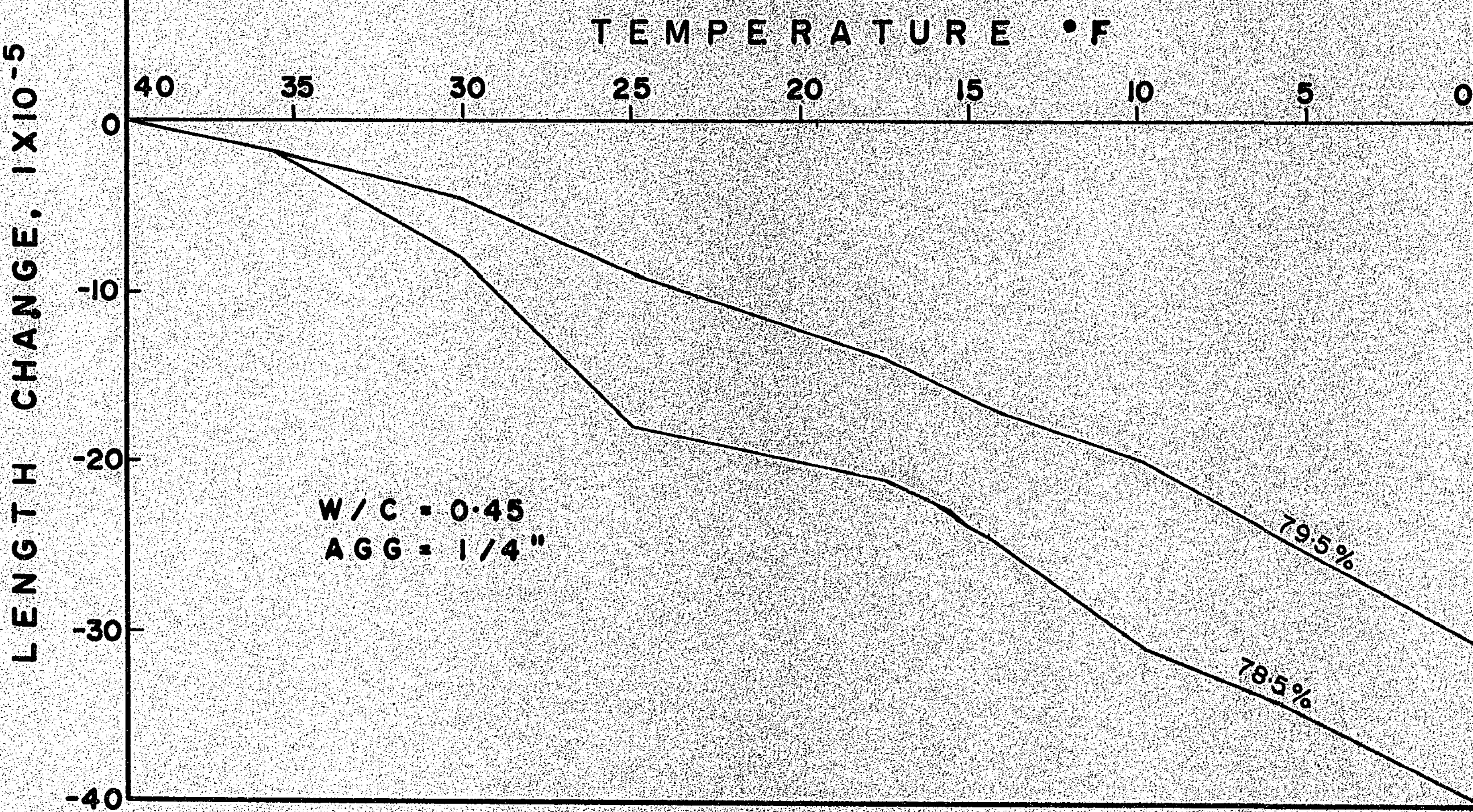
SPEC.	Partially Sat. Wt. (1)	Vacuum Sat. Wt. (2)	Oven-Dried Wt. (3)	(2) - (3)	(1) - (3)	% Sat. $\frac{(1)-(3)}{(2)-(3)}$
2	3.545 lb.	3.625 lb.	3.325 lb.	0.300 lb.	0.220 lb.	73.4
3	3.626 lb.	3.626 lb.	3.341 lb.	0.285 lb.	0.213 lb.	74.5

NOTE: Transmitter Calibration Constants:

(0) $2.38 \times 10^{-2} \frac{mm}{unit}$ (2) $2.31 \times 10^{-2} \frac{mm}{unit}$

(1) $2.29 \times 10^{-2} \frac{mm}{unit}$ (3) $2.19 \times 10^{-2} \frac{mm}{unit}$

EFFECT OF DEGREE OF SATURATION ON LENGTH CHANGE PATTERN



W/C = 0.45 Curing Time = 14 days Date: June 2, 1967

Agg. = 1/4 7% Air Dried = 20 days

Air =

SPEC.	Init.Rdg.	Surface Centre	40.0 40.1	35.0 36.5	29.5 30.2	24.0 25.7	17.0 18.5	13.5 14.8	9.0 10.4	5.2 6.4	0.5 1.4	

		$(\Delta L)10^3$										
		$(\Delta L/L)10^5$										
1	204.80		204.80	204.90	205.10	205.40	205.70	205.90	206.10	206.40	206.70	
		$(\Delta L)10^3$	0	-3.19	-6.56	-13.15	-19.70	-24.10	-28.50	-35.00	-41.60	
		$(\Delta L/L)10^5$	0	-1.54	-4.62	-9.27	-13.88	-17.00	-20.10	-24.60	-29.30	
2	244.90		244.90	245.00	245.40	246.00	246.20	246.40	246.80	247.00	247.30	
		$(\Delta L)10^3$	0	-2.31	-11.55	-25.40	-30.00	-34.65	-43.80	-48.50	-55.50	
		$(\Delta L/L)10^5$	0	-1.63	-8.13	-17.89	-21.10	-24.40	-30.80	-34.10	-39.10	

		$(\Delta L)10^3$										
		$(\Delta L/L)10^5$										

SPEC.	Partially Sat. Wt. (1)	Vacuum Sat. Wt. (2)	Oven-Dried Wt. (3)	(2) - (3)	(1) - (3)	% Sat. $\frac{(1)-(3)}{(2)-(3)}$
1	3.536 lb.	3.601 lb.	3.300 lb.	0.301 lb.	0.236 lb.	78.5
2	3.571 lb.	3.630 lb.	3.344 lb.	0.286 lb.	0.227 lb.	79.5

NOTE: Transmitter Calibration Constants:

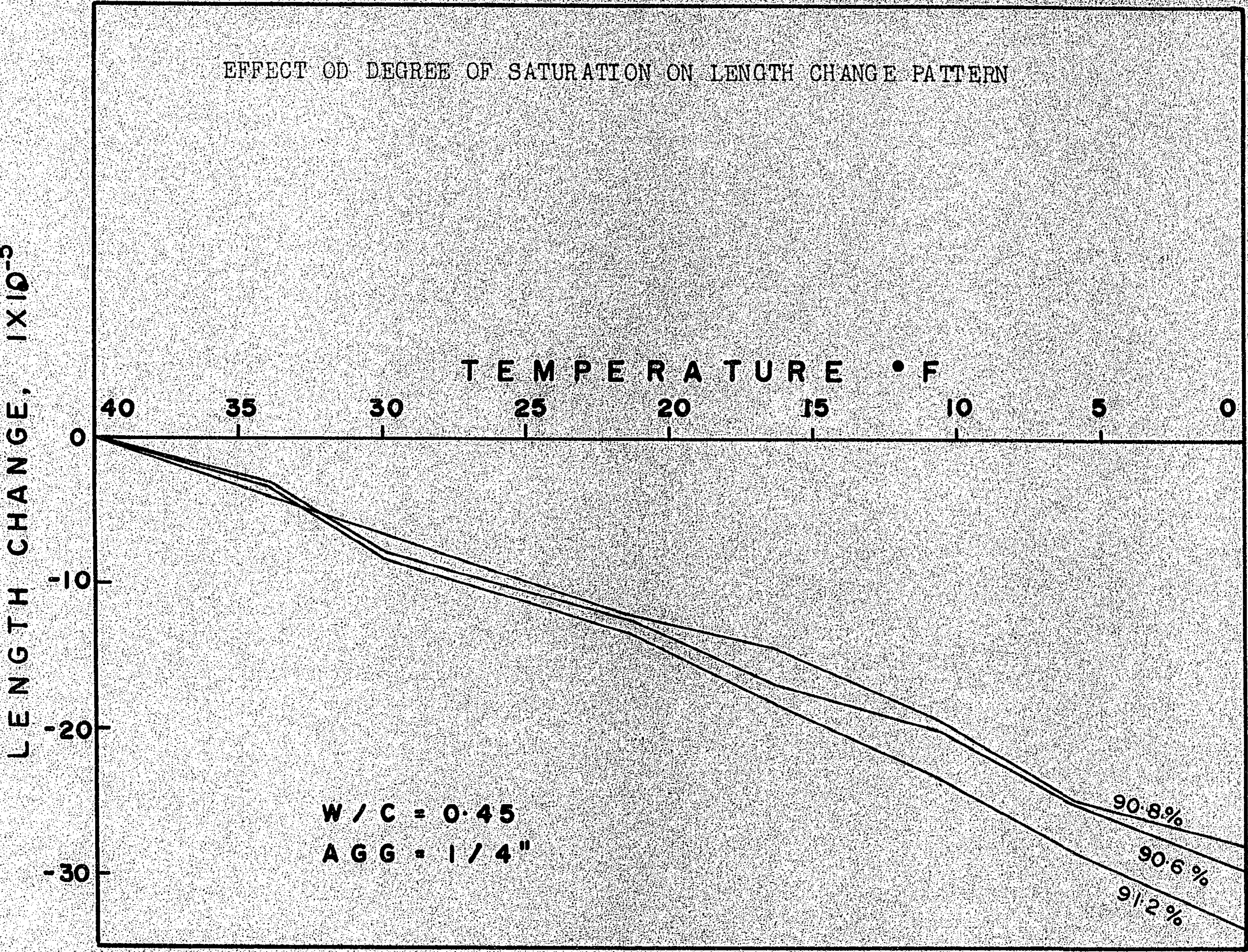
(0) 2.38×10^{-2} mm/unit

(1) 2.29×10^{-2} mm/unit

(2) 2.31×10^{-2} mm/unit

(3) 2.19×10^{-2} mm/unit

EFFECT OD DEGREE OF SATURATION ON LENGTH CHANGE PATTERN



W/C = 0.45
Agg. = 1/4 in.
Air = 7%

Curing Time = 14 days
Air Dried = 30 days

Date: July 9, 1967

SPEC.	Init.Rdg.	Surface / Centre	40.0 / 40.0	33.3 / 33.8	29.0 / 31.0	19.7 / 23.0	15.0 / 17.6	9.8 / 11.3	5.0 / 6.8	0.0 / 0.5		
			TEMPERATURES °F									

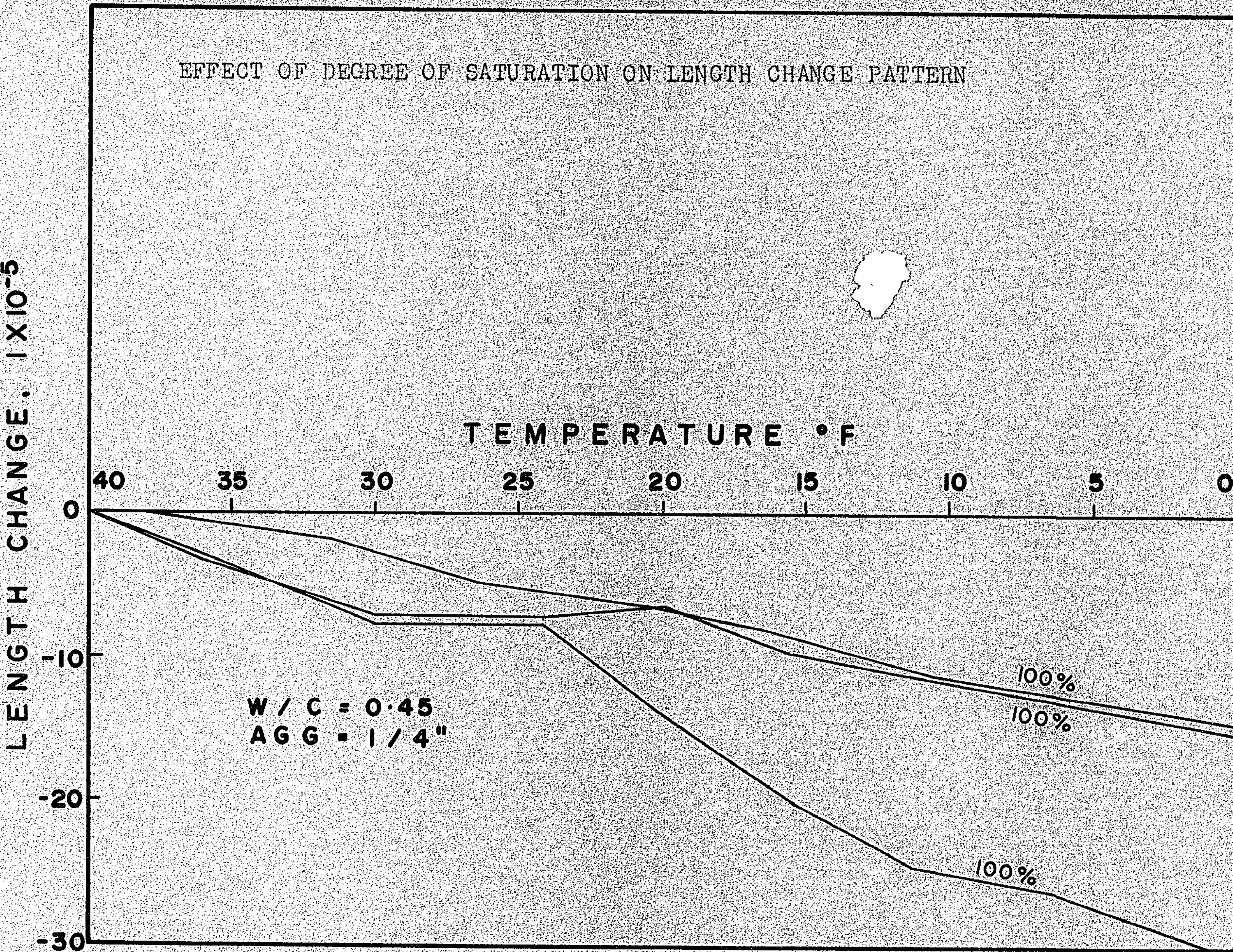
		$(\Delta L)10^3$										
		$(\Delta L/L)10^5$										
1	235.50		235.50	235.75	235.90	236.25	236.40	236.70	237.00	237.20		
		$(\Delta L)10^3$	0	-5.77	-9.24	-17.33	-20.80	-27.75	-34.65	-39.25		
		$(\Delta L/L)10^5$	0	-4.06	-6.51	-12.21	-14.65	-19.53	-24.40	-27.65		
2	246.70		246.70	246.90	247.20	247.50	247.80	248.10	248.40	248.70		
		$(\Delta L)10^3$	0	-4.76	-11.90	-19.03	-26.20	-33.30	-40.40	-47.60		
		$(\Delta L/L)10^5$	0	-3.35	-8.38	-13.40	-18.44	-23.44	-28.45	-33.50		
3	202.80		202.80	203.00	203.30	203.60	203.90	204.10	204.40	204.70		
		$(\Delta L)10^3$	0	-4.38	-10.95	-17.52	-24.10	-28.50	-35.20	-41.60		
		$(\Delta L/L)10^5$	0	-3.08	-7.72	-12.32	-16.97	-20.05	-24.80	-29.25		

SPEC.	Partially Sat. Wt.(1)	Vacuum Sat. Wt.(2)	Oven-Dried Wt.(3)	(2) - (3)	(1) - (3)	% Sat. $\frac{(1)-(3)}{(2)-(3)}$
1	3.569 lb.	3.595 lb.	3.311 lb.	0.284 lb.	0.258 lb.	90.8
2	3.598 lb.	3.623 lb.	3.342 lb.	0.281 lb.	0.256 lb.	91.2
3	3.594 lb.	3.623 lb.	3.326 lb.	0.299 lb.	0.271 lb.	90.6

NOTE: Transmitter Calibration Constants:

(0) 2.38×10^{-2} $\frac{mm}{unit}$ (2) 2.31×10^{-2} $\frac{mm}{unit}$

(1) 2.29×10^{-2} $\frac{mm}{unit}$ (3) 2.19×10^{-2} $\frac{mm}{unit}$


EFFECT OF DEGREE OF SATURATION ON LENGTH CHANGE PATTERN
TEMPERATURE °F
40
35
30
25
20
15
10
5
0
LENGTH CHANGE, 1X10-5
0
-10
-20
-30
W/C = 0·45
AGG = 1/4"
100%
100%
100%

W / C = [illegible]   Curing Time = [illegible]   Date: [illegible]

Agg. = 1/4   Air Dried = 22 days

Air = 7%

SPEC.	Init.Rdg.	Surface / Centre	TEMPERATURES °F									
			37 / 38.3	31.0 / 32.0	28.3 / 30.2	25.0 / 28.0	19.5 / 21.2	15.80 / 17.40	10.0 / 11.6	4.50 / 6.0	-1.0 / 0.5	
0	319.20		319.20	319.30	319.40	319.50	319.60	319.70	319.90	320.00	320.10	
		$(\Delta L)10^3$	0	-2.29	-4.58	-6.87	-9.16	-11.45	-16.0	-18.32	-20.6	
		$(\Delta L/L)10^5$	0	-1.61	-3.2	-4.83	-6.44	-8.07	-11.28	-12.9	-14.5	
	———											
		$(\Delta L)10^3$										
		$(\Delta L/L)10^5$										
	———											
		$(\Delta L)10^3$										
		$(\Delta L/L)10^5$										
	———											
		$(\Delta L)10^3$										
		$(\Delta L/L)10^5$										

SPEC.	Partially Sat. Wt. (1)	Vacuum Sat. Wt. (2)	Oven-Dried Wt. (3)	(2) - (3)	(1) - (3)	% Sat. $\frac{(1)-(3)}{(2)-(3)}$
0	3.575 lb.	3.575 lb.	3.201 lb.	0.274 lb.	0.000 lb.	100.0

NOTE: Transmitter Calibration Constants:

(0) $2.38 \times 10^{-2} \frac{mm}{unit}$ (2) $2.31 \times 10^{-2} \frac{mm}{unit}$

(1) $2.29 \times 10^{-2} \frac{mm}{unit}$ (3) $2.19 \times 10^{-2} \frac{mm}{unit}$

W/C = 0.49 Curing Time = 14 days Date: May 10,1967

Agg. = 1/4 Air Dried = 22 days

Air = 7%

SPEC.	Init.Rdg.	Surface / Centre	TEMPERATURES °F									
			39.8 40.0	36.0 36.0	29.9 30.2	23.5 24.5	20.0 20.5	15.0 15.8	11.0 12.0	5.70 6.80	2.0 2.3	
	---	$(\Delta L)10^3$										
		$(\Delta L/L)10^5$										
1	294.40		294.40	294.60	294.85	294.85	294.80	295.00	295.10	295.20	295.20	
		$(\Delta L)10^3$	0	-4.58	-10.3	-10.3	-9.16	-13.7	-16.0	-18.3	-20.6	
		$(\Delta L/L)10^5$	0	-3.23	-7.25	-7.25	-6.45	-9.65	-11.3	-12.9	-14.5	
2	302.50		302.50	302.70	303.00	303.00	303.40	303.80	304.10	304.20	304.40	
		$(\Delta L)10^3$	0	-4.38	-10.9	-10.9	-19.7	-28.4	-35.0	-37.2	-41.6	
		$(\Delta L/L)10^5$	0	-3.08	-7.68	-7.68	-13.9	-20.0	-24.6	-26.2	-29.3	
	---	$(\Delta L)10^3$										
		$(\Delta L/L)10^5$										

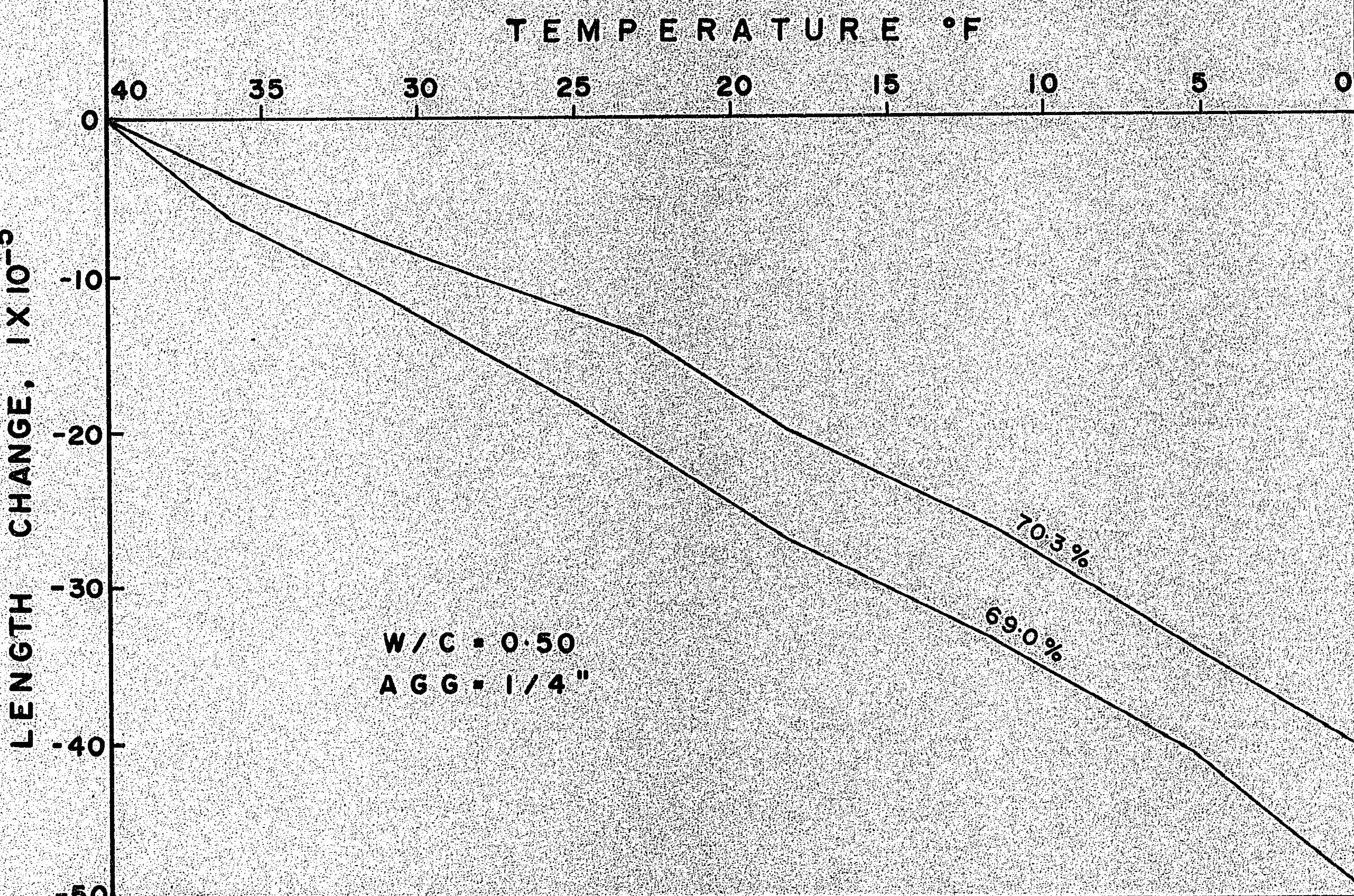
SPEC.	Partially Sat. Wt. (1)	Vacuum Sat. Wt. (2)	Oven-Dried Wt. (3)	(2) - (3)	(1) - (3)	% Sat. $\frac{(1)-(3)}{(2)-(3)}$
1	3.606 lb.	3.606 lb.	3.339 lb.	0.269 lb.	0.000	100.0
2	3.600 lb.	3.600 lb.	3.327 lb.	0.273 lb.	0.000	100.0

NOTE: Transmitter Calibration Constants:

(0) 2.38×10^{-2} $\frac{mm}{unit}$ (2) 2.31×10^{-2} $\frac{mm}{unit}$

(1) 2.29×10^{-2} $\frac{mm}{unit}$ (3) 2.19×10^{-2} $\frac{mm}{unit}$

EFFECT OF DEGREE OF SATURATION ON LENGTH CHANGE PATTERN



W/C = 0.50

Agg. = 1/4 in.

Air = 7%

Curing Time = 14 days

Air Dried = 30 days

Date: June 4, 1967

SPEC.	Init.Rdg.	Surface / Centre	40.0 / 40.1	35.5 / 37.0	29.70 / 32.0	25.0 / 25.0	22.8 / 23.0	17.5 / 19.3	11.5 / 12.0	5.0 / 5.6	1.5 / 2.0	

		$(\Delta L)10^3$										
		$(\Delta L/L)10^5$										
1	296.90		296.90	297.30	297.60	298.00	298.15	298.50	298.90	299.40	299.70	
		$(\Delta L)10^3$	0	-9.55	-16.71	-26.30	-29.9	-38.20	-47.70	-59.75	-66.90	
		$(\Delta L/L)10^5$	0	-6.73	-11.77	-18.52	-21.01	-26.90	-33.60	-40.50	-47.10	
3	215.80		215.80	216.10	216.30	216.60	216.70	217.10	217.50	218.00	218.30	
		$(\Delta L)10^3$	0	-6.57	-10.95	-17.50	-19.70	-28.45	-37.20	-48.20	-54.70	
		$(\Delta L/L)10^5$	0	-3.93	-7.72	-12.32	-13.87	-20.00	-26.20	-33.90	-38.50	

		$(\Delta L)10^3$										
		$(\Delta L/L)10^5$										

(Column headers: TEMPERATURES °F)

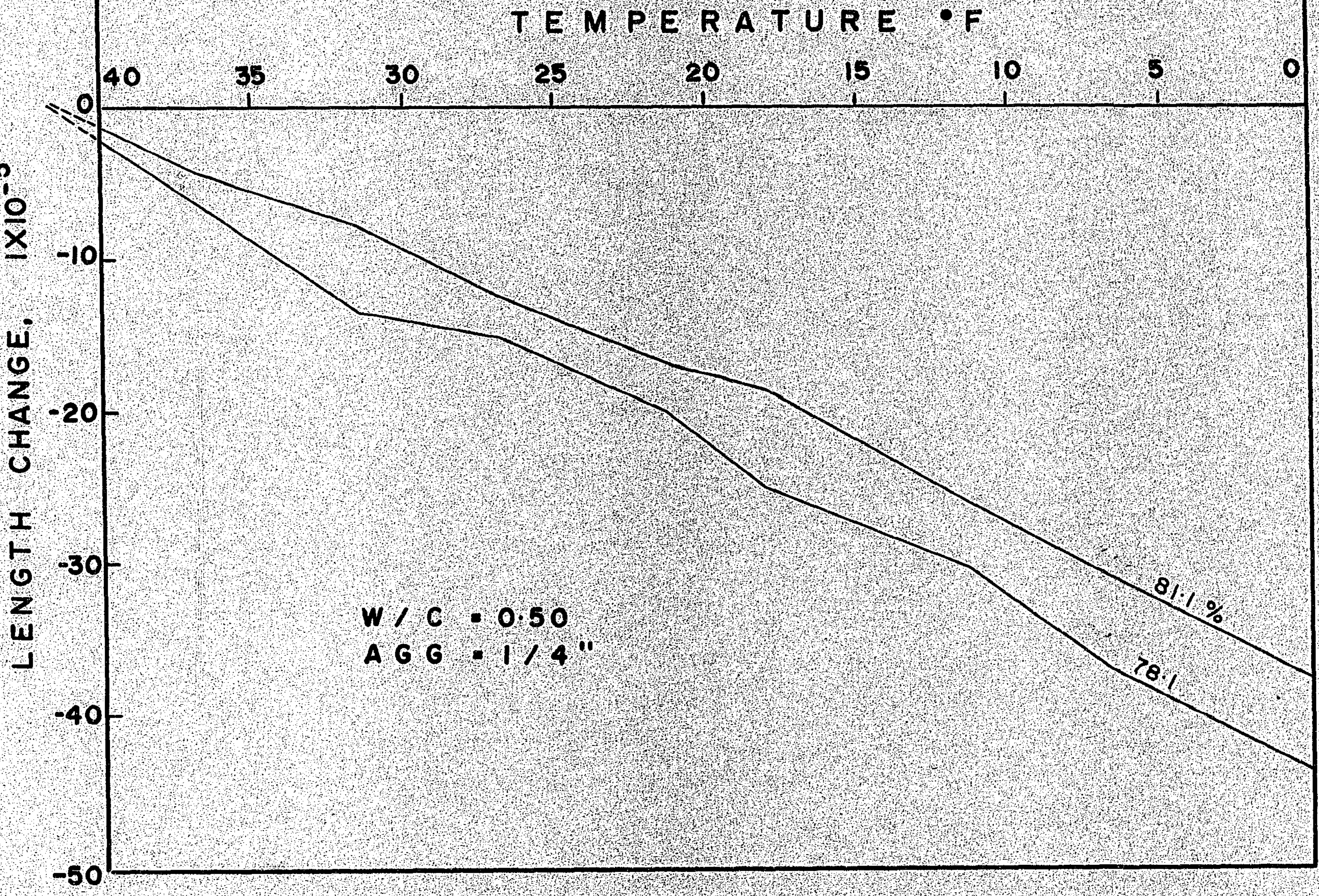
SPEC.	Partially Sat. Wt. (1)	Vacuum Sat. Wt. (2)	Oven-Dried Wt. (3)	(2) - (3)	(1) - (3)	% Sat. $\frac{(1)-(3)}{(2)-(3)}$
1	3.456 lb.	3.548 lb.	3.238 lb.	0.310 lb.	0.218 lb.	70.3
3	3.540 lb.	3.642 lb.	3.314 lb.	0.328 lb.	0.226 lb.	69.0

NOTE: Transmitter Calibration Constants:

(0) $2.38 \times 10^{-2} \frac{mm}{unit}$ (2) $2.31 \times 10^{-2} \frac{mm}{unit}$

(1) $2.29 \times 10^{-2} \frac{mm}{unit}$ (3) $2.19 \times 10^{-2} \frac{mm}{unit}$

EFFECT OF DEGREE OF SATURATION ON LENGTH CHANGE PATTERN



W / C = .50

Agg. = 1/4 in.

Air = 7%

Curing Time = 14 days

Air Dried = 32 days

Date: June 3, 1967

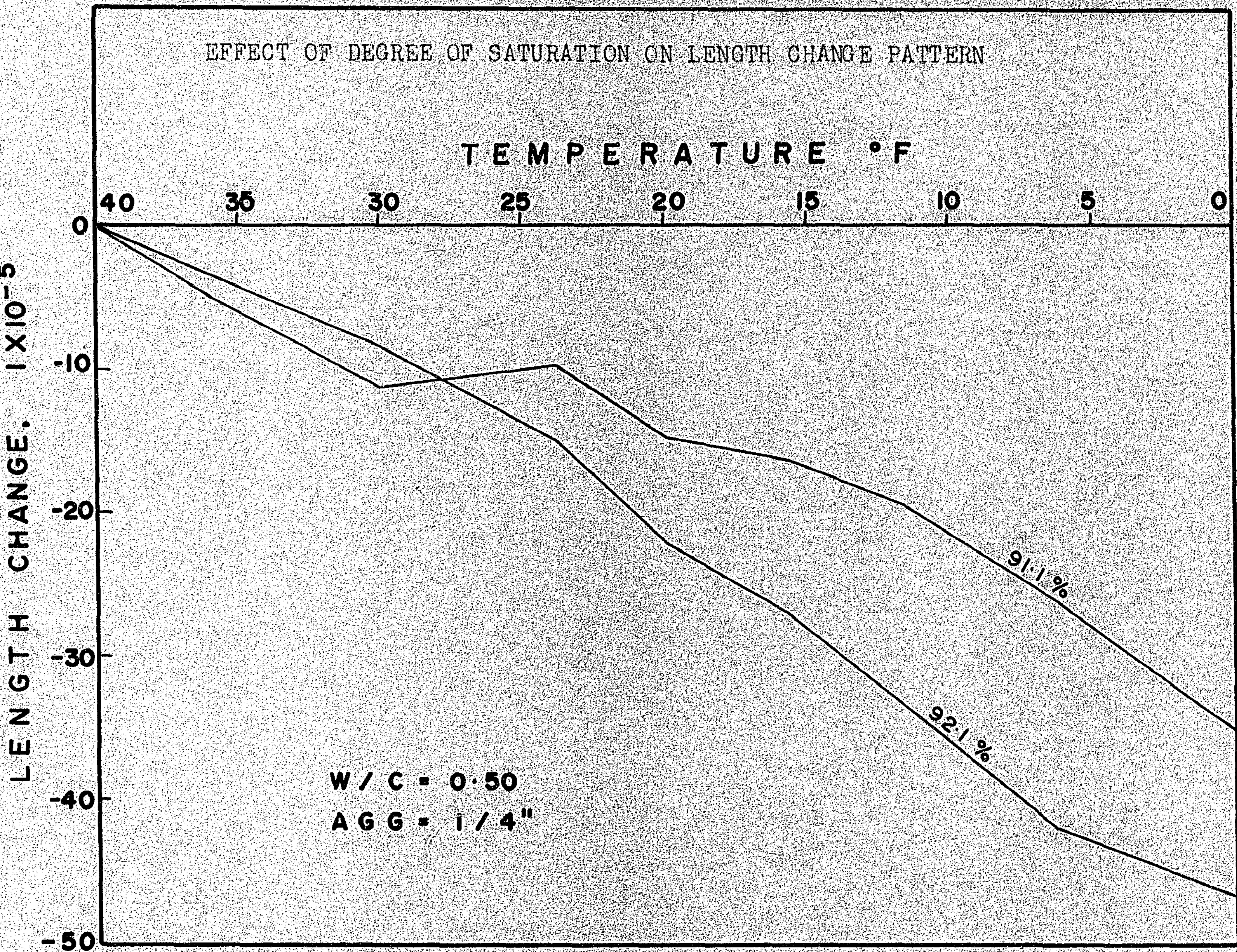
SPEC.	Init. Rdg.	Surface / Centre	TEMPERATURES °F 39.5 / 43.0	36.0 / 37.4	31.0 / 32.0	26.0 / 27.5	20.5 / 22.0	17.0 / 19.0	10.2 / 11.2	6.0 / 6.8	0.0 / 1.0	
	---	$(\Delta L)10^3$										
		$(\Delta L/L)10^5$										
	---	$(\Delta L)10^3$										
		$(\Delta L/L)10^5$										
			245.00	245.30	245.50	245.80	246.10	246.20	246.70	247.00	247.40	
2	245.00	$(\Delta L)10^3$	0	-6.56	-10.94	-17.50	-24.10	-26.30	-37.20	-43.80	-52.50	
		$(\Delta L/L)10^5$	0	-4.61	-7.70	-12.31	-16.97	-18.50	-26.20	-30.80	-37.00	
			301.40	301.80	302.20	302.30	302.60	302.70	303.60	304.00	304.40	
3	301.40	$(\Delta L)10^3$	0	-9.55	-19.12	-21.50	-28.70	-35.80	-43.00	-52.50	-62.00	
		$(\Delta L/L)10^5$	0	-6.72	-13.48	-15.12	-20.20	-25.20	-30.30	-37.00	-43.60	

SPEC.	Partially Sat. Wt. (1)	Vacuum Sat. Wt. (2)	Oven-Dried Wt. (3)	(2) - (3)	(1) - (3)	% Sat. $\frac{(1)-(3)}{(2)-(3)}$
2	3.613 lb.	3.672 lb.	3.367 lb.	0.309 lb.	0.250 lb.	81.1
3	3.565 lb.	3.631 lb.	3.331 lb.	0.300 lb.	0.234 lb.	78.1

NOTE: Transmitter Calibration Constants:

(0) $2.38 \times 10^{-2} \frac{mm}{unit}$ (2) $2.31 \times 10^{-2} \frac{mm}{unit}$

(1) $2.29 \times 10^{-2} \frac{mm}{unit}$ (3) $2.19 \times 10^{-2} \frac{mm}{unit}$


EFFECT OF DEGREE OF SATURATION ON LENGTH CHANGE PATTERN
TEMPERATURE °F
40
35
30
25
20
15
10
5
0
LENGTH CHANGE, 1X10⁻⁵
0
-10
-20
-30
-40
-50
91·1 %
92·1 %
W / C = 0·50
AGG = 1 / 4"

W/C = 0.50　　Curing Time = 14 days　　Date: May 13, 1967

Agg. = 1/4　　Air Dried = 23 days

Air = 7%

SPEC.	Init. Rdg.	Surface / Centre	TEMPERATURES °F									
			39.8 / 40.0	36.0 / 36.0	29.9 / 30.2	23.5 / 24.5	20.0 / 20.5	15.0 / 15.8	11.0 / 12.0	5.70 / 6.80	2.0 / 2.3	

		$(\Delta L)10^3$										
		$(\Delta L/L)10^5$										

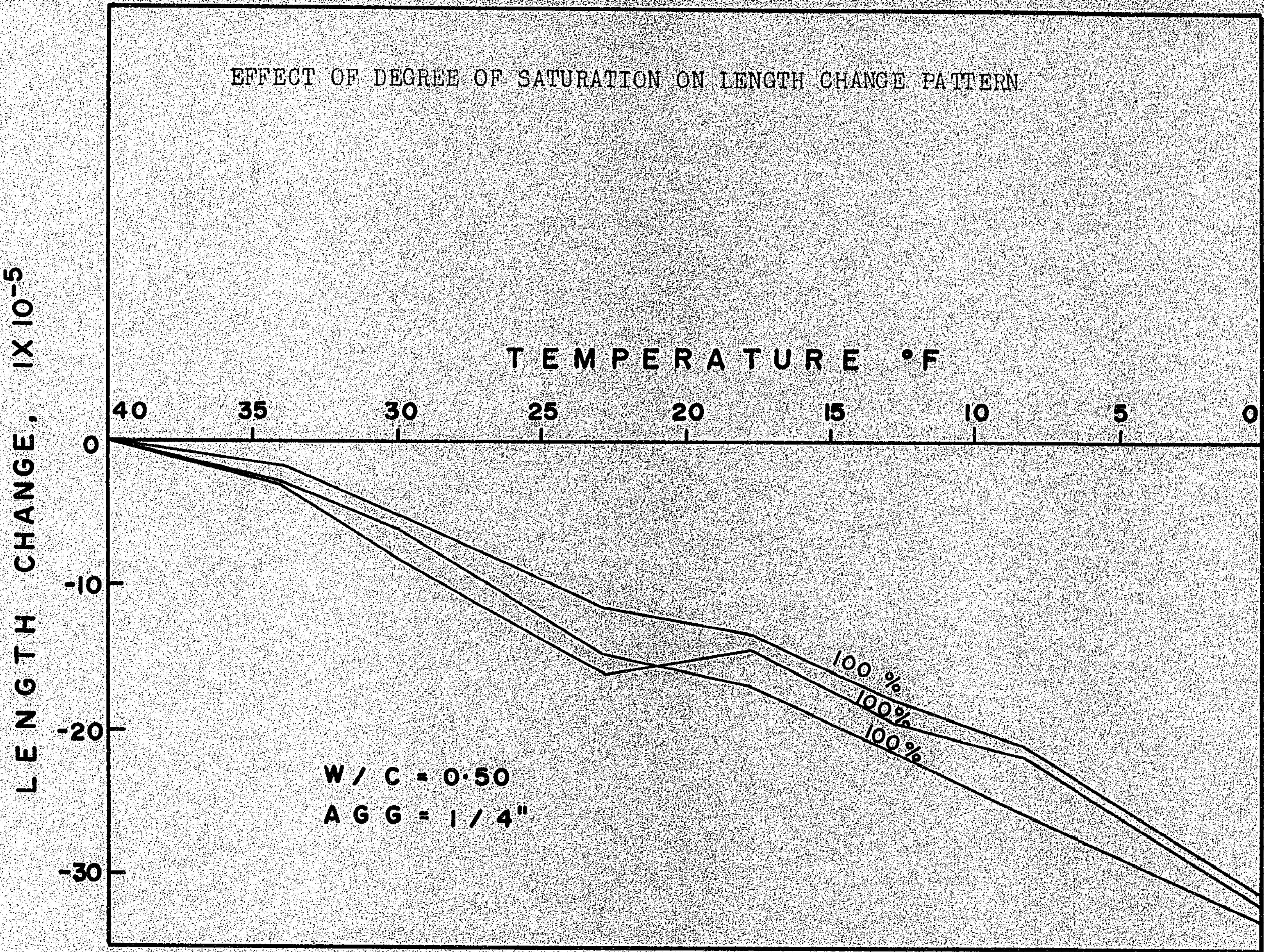
		$(\Delta L)10^3$										
		$(\Delta L/L)10^5$										
2	349.60		349.60	349.80	350.10	350.50	350.90	351.20	351.60	352.10	352.30	
		$(\Delta L)10^3$	0	-4.76	-11.9	-21.4	-31.0	-38.1	-47.6	-59.5	-64.3	
		$(\Delta L/L)10^5$	0	-3.35	-8.38	-15.0	-21.0	-26.8	-33.5	-41.9	-45.2	
3	279.10		279.10	279.40	279.80	279.70	280.00	280.10	280.30	280.70	281.10	
		$(\Delta L)10^3$	0	-6.94	-16.2	-13.9	-20.8	-23.1	-27.7	-37.0	-46.2	
		$(\Delta L/L)10^5$	0	-4.9	-11.4	-9.8	-14.7	-16.3	-19.5	-26.0	-32.9	

SPEC.	Partially Sat. Wt. (1)	Vacuum Sat. Wt. (2)	Oven-Dried Wt. (3)	(2) - (3)	(1) - (3)	% Sat. $\frac{(1)-(3)}{(2)-(3)}$
2	3.620 lb.	3.643 lb.	3.349 lb.	0.294 lb.	0.271 lb.	92.1
3	3.606 lb.	3.633 lb.	3.333 lb.	0.300 lb.	0.273 lb.	91.1

NOTE: Transmitter Calibration Constants:

(0) 2.38×10^{-2} $\frac{mm}{unit}$　　(2) 2.31×10^{-2} $\frac{mm}{unit}$

(1) 2.29×10^{-2} $\frac{mm}{unit}$　　(3) 2.19×10^{-2} $\frac{mm}{unit}$


EFFECT OF DEGREE OF SATURATION ON LENGTH CHANGE PATTERN
TEMPERATURE °F
40
35
30
25
20
15
10
5
0
LENGTH CHANGE, 1X 10-5
0
-10
-20
-30
100 %
100%
100%
W / C = 0·50
A G G = 1 / 4"

W/C = 0.50

Agg. = 1/4

Air = 7%

Curing Time = 14 days

Air Dried = 15 days

Date: July 5, 1967

SPEC.	Init.Rdg.	Surface / Centre	TEMPERATURES °F									
			39.5 / 39.5	33.5 / 34.7	29.6 / 30.2	22.5 / 23.0	17.3 / 18.5	12.5 / 13.0	8.2 / 8.6	0.5 / 1.4		

		$(\Delta L)10^3$										
		$(\Delta L/L)10^5$										
1	278.90		278.90	279.10	279.40	279.90	279.80	280.10	280.25	280.80		
		$(\Delta L)10^3$	0	-4.62	-11.54	-23.10	-20.80	-27.75	-31.20	-43.80		
		$(\Delta L/L)10^5$	0	-3.26	-8.14	-16.27	-14.63	-19.54	-21.95	-30.86		
2	200.00		200.00	200.10	200.30	200.70	200.80	201.10	201.25	201.80		
		$(\Delta L)10^3$	0	-2.38	-7.14	-16.67	-19.04	-25.20	-29.80	-42.80		
		$(\Delta L/L)10^5$	0	-1.68	-5.03	-11.71	-13.40	-17.72	-21.00	-30.10		
3	221.10		221.10	221.30	221.50	222.00	222.20	222.50	222.80	223.20		
		$(\Delta L)10^3$	0	-4.38	-8.75	-19.70	-24.10	-30.65	-37.20	-46.00		
		$(\Delta L/L)10^5$	0	-3.08	-6.16	-14.86	-16.97	-21.60	-26.20	-32.40		

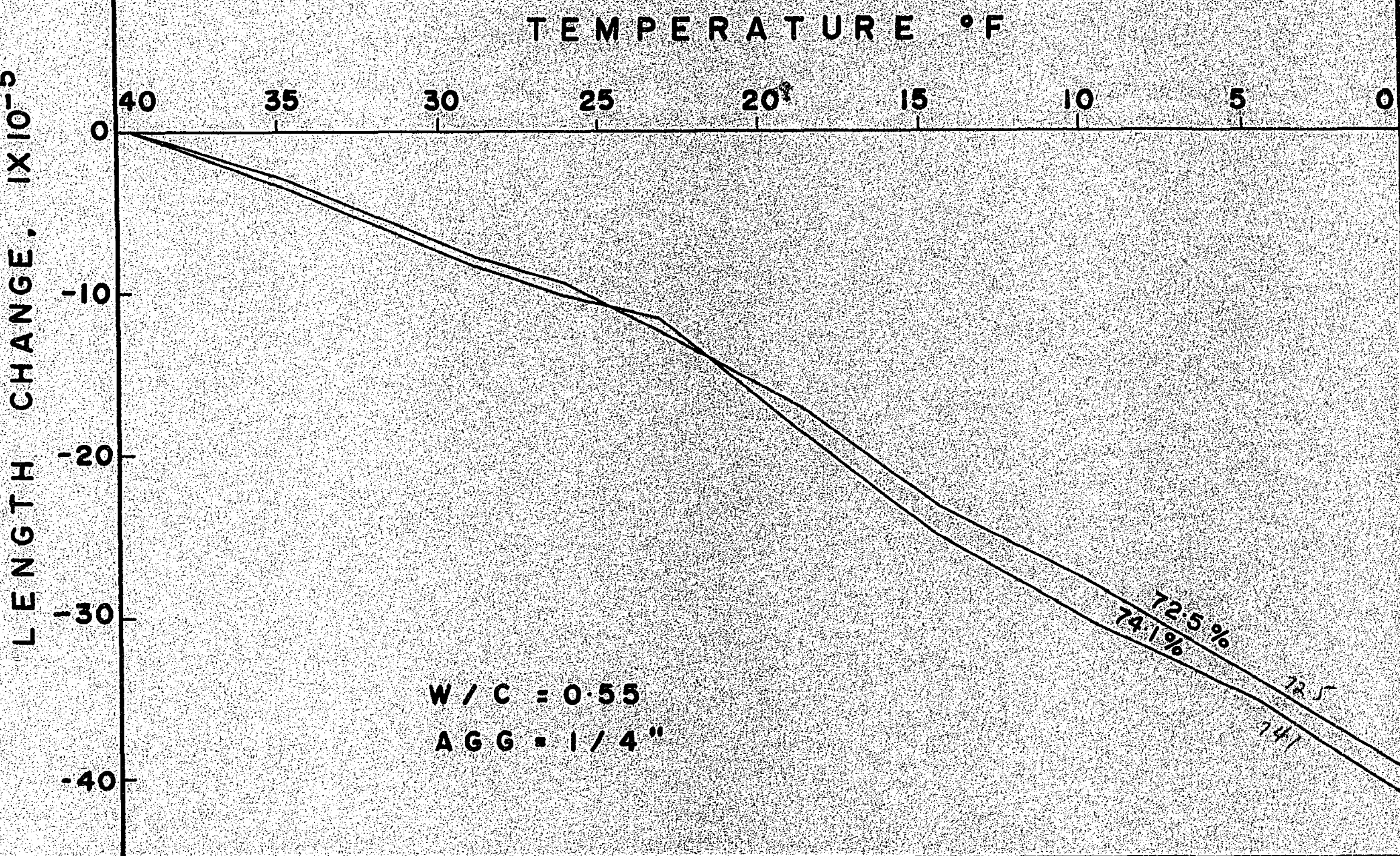
SPEC.	Partially Sat. Wt. (1)	Vacuum Sat. Wt. (2)	Oven-Dried Wt. (3)	(2) - (3)	(1) - (3)	% Sat. $\frac{(1)-(3)}{(2)-(3)}$
1	3.518 lb.	3.518 lb.	3.222 lb.	0.296 lb.	0.000	100.0
2	3.651 lb.	3.651 lb.	3.355 lb.	0.296 lb.	0.000	100.0
3	3.623 lb.	3.623 lb.	3.316 lb.	0.307 lb.	0.000	100.0

NOTE: Transmitter Calibration Constants:

(0) $2.38 \times 10^{-2} \frac{mm}{unit}$ (2) $2.31 \times 10^{-2} \frac{mm}{unit}$

(1) $2.29 \times 10^{-2} \frac{mm}{unit}$ (3) $2.19 \times 10^{-2} \frac{mm}{unit}$

EFFECT OF DEGREE OF SATURATION ON LENGTH CHANGE PATTERN



W / C = 0.55   Curing Time = 14 days   Date: June 6, 1967

Agg. = 1/4 in.   Air Dried = 47 days

Air = 7%

SPEC.	Init. Rdg.	Surface / Centre	39.2 / 39.4	34.0 / 35.2	28.0 / 29.3	25.0 / 26.6	22.3 / 24.0	18.0 / 19.4	13.6 / 14.9	9.3 / 10	4.0 / 5.0	0.0 / 1.0
			TEMPERATURES °F									

		$(\Delta L)10^3$										
		$(\Delta L/L)10^5$										
1	237.00		237.00	237.20	237.50	237.60	237.70	238.10	238.50	238.80	239.10	239.30
		$(\Delta L)10^3$	0	-4.76	-11.90	-14.29	-16.67	-26.20	-35.70	-42.80	-50.00	-57.20
		$(\Delta L/L)10^5$	0	-3.35	- 8.38	-10.08	-11.74	-18.43	-25.15	-30.20	-35.20	-40.30

		$(\Delta L)10^3$										
		$(\Delta L/L)10^5$										
3	211.50		211.50	211.70	212.00	212.10	212.30	212.60	213.00	213.30	213.70	214.00
		$(\Delta L)10^3$	0	-4.38	-10.95	-13.13	-17.52	-24.10	-32.80	-39.40	-48.20	-54.80
		$(\Delta L/L)10^5$	0	-3.08	-7.71	-9.25	-12.35	-16.97	-23.10	-27.75	-33.95	-38.60

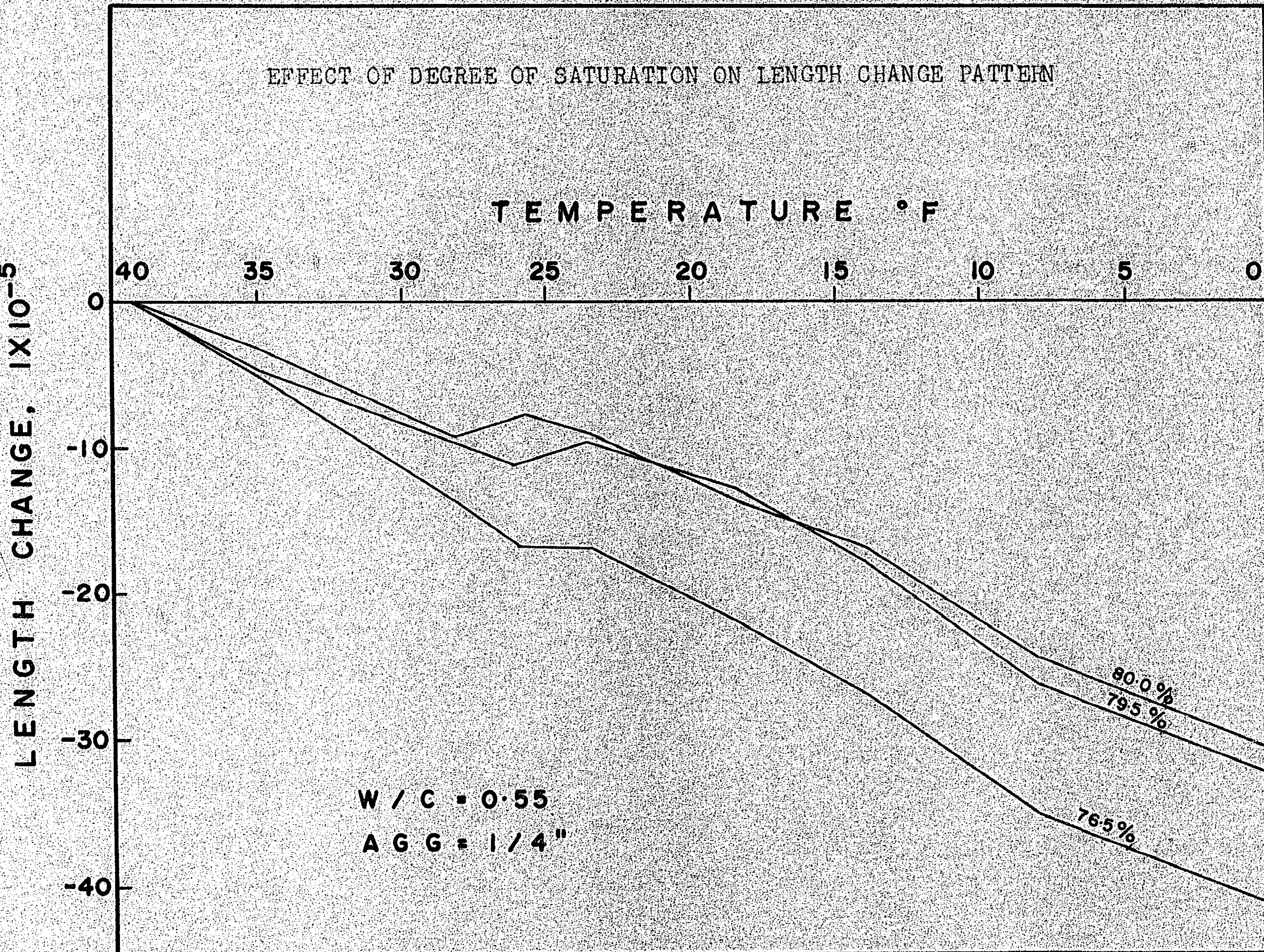
SPEC.	Partially Sat. Wt. (1)	Vacuum Sat. Wt. (2)	Oven-Dried Wt. (3)	(2) - (3)	(1) - (3)	% Sat. $\frac{(1)-(3)}{(2)-(3)}$
1	3.478 lb.	3.555 lb.	3.258 lb.	0.297 lb.	0.220 lb.	74.1
3	3.430 lb.	3.531 lb.	3.195 lb.	0.336 lb.	0.235 lb.	72.5

NOTE: Transmitter Calibration Constants:

(0) 2.38×10^{-2} $\frac{mm}{unit}$ (2) 2.31×10^{-2} $\frac{mm}{unit}$

(1) 2.29×10^{-2} $\frac{mm}{unit}$ (3) 2.19×10^{-2} $\frac{mm}{unit}$

EFFECT OF DEGREE OF SATURATION ON LENGTH CHANGE PATTERN



W/C = ____

Curing Time = ____

Date: ____

Agg. = 1/4 in.

Air Dried = 56 days

Air = 7%

SPEC.	Init.Rdg.	Surface / Centre	TEMPERATURES °F									
			39.0 / 39.3	35.0 / 35.0	28.0 / 28.6	25.9 / 26.2	23.2 / 24.0	17.5 / 19.4	14.0 / 14.0	8.0 / 8.2	1.5 / 2.0	

		$(\Delta L)10^3$										
		$(\Delta L/L)10^5$										
1	229.90		229.90	230.10	230.50	230.40	230.50	230.80	231.00	231.50	231.80	
		$(\Delta L)10^3$	0	-4.38	-13.13	-10.95	-13.13	-19.70	-24.10	-35.00	-41.60	
		$(\Delta L/L)10^5$	0	-3.08	-9.25	-7.72	-9.25	-13.88	-16.98	-24.60	-29.30	
4	281.20		281.20	281.50	282.00	282.20	282.20	282.50	282.80	283.20	283.60	
		$(\Delta L)10^3$	0	-7.14	-19.05	-23.80	-23.80	-30.95	-38.10	-50.00	-57.10	
		$(\Delta L/L)10^5$	0	-5.02	-13.40	-16.85	-16.75	-21.80	-26.80	-35.20	-40.10	
4A	264.50		264.50	264.80	265.10	265.202	265.10	265.30	265.60	266.10	266.40	
		$(\Delta L)10^3$	0	-6.92	-13.85	-16.15	-13.85	-18.45	-25.40	-36.95	-43.90	
		$(\Delta L/L)10^5$	0	-4.88	-9.77	-11.39	-9.77	-13.00	-17.90	-26.00	-30.90	

SPEC.	Partially Sat. Wt. (1)	Vacuum Sat. Wt. (2)	Oven-Dried Wt. (3)	(2) - (3)	(1) - (3)	% Sat. $\frac{(1)-(3)}{(2)-(3)}$
1	3.551 lb.	3.615 lb.	3.295 lb.	0.320 lb.	0.256 lb.	80.0
4	3.520 lb.	3.694 lb.	3.380 lb.	0.314 lb.	0.240 lb.	76.5
4A	3.570 lb.	3.635 lb.	3.319 lb.	0.316 lb.	0.251 lb.	79.5

NOTE: Transmitter Calibration Constants:

(0) $2.38 \times 10^{-2} \frac{mm}{unit}$ (2) $2.31 \times 10^{-2} \frac{mm}{unit}$

(1) $2.29 \times 10^{-2} \frac{mm}{unit}$ (3) $2.19 \times 10^{-2} \frac{mm}{unit}$

W/C = 0.55
Agg. = 1/4 in.
Air = 7%

Curing Time = 14 days
Air Dried = 57 days

Date: June 20, 1967

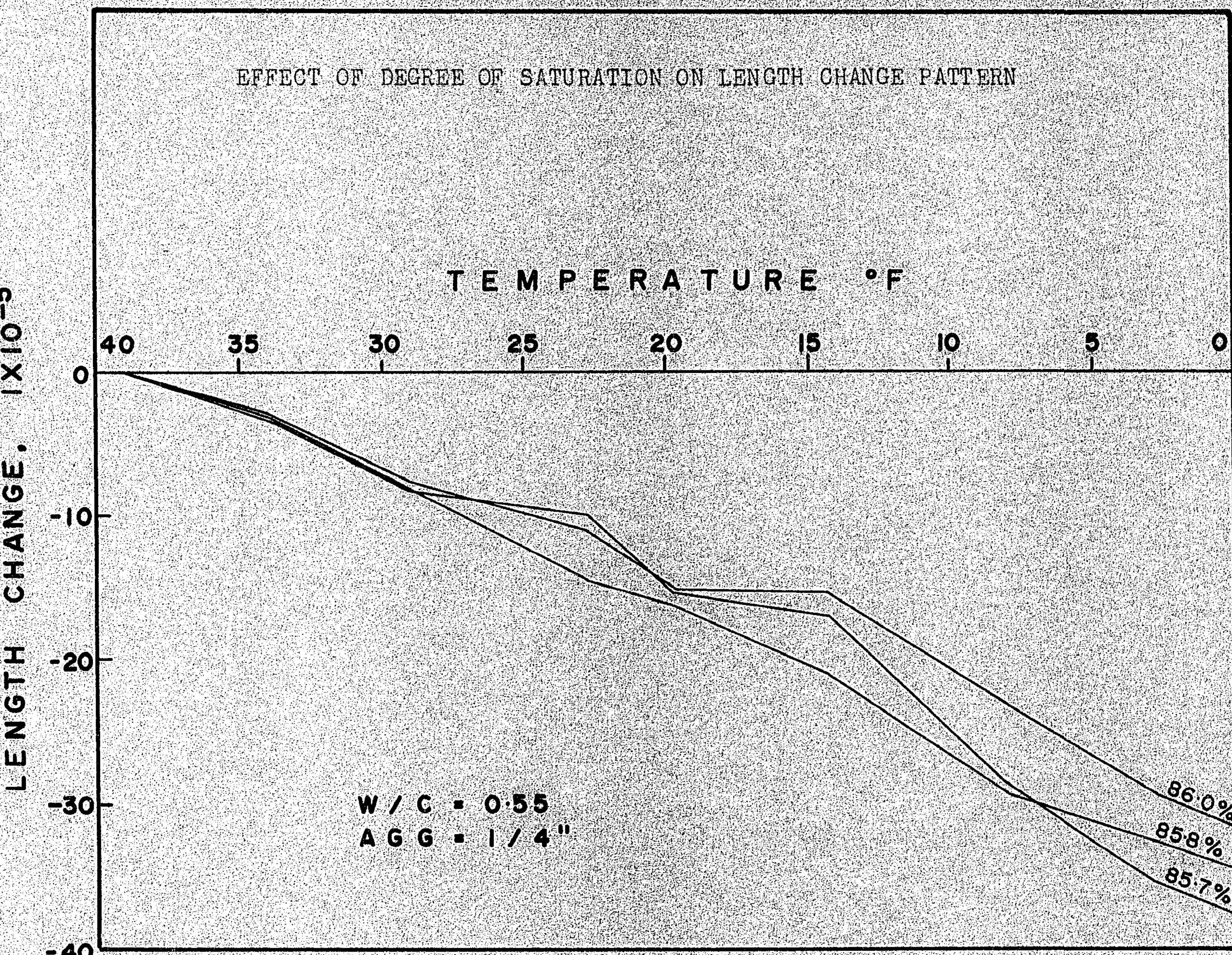
			TEMPERATURES °F									
SPEC.	Init.Rdg.	Surface Centre	38.5 39.2	33.4 34.4	28.2 29.8	21.9 23.5	19.0 20.8	13.8 14.9	7.3 8.8	2.0 3.5	0.0 1.0	
4	267.00		267.00	267.20	267.50	267.70	268.00	268.00	268.50	268.90	269.00	
		$(\Delta L)10^3$	0	-4.38	-10.95	-15.31	-21.90	-21.90	-32.85	-41.60	-43.80	
		$(\Delta L/L)10^5$	0	-3.08	-7.71	-10.79	-15.35	-15.35	-23.10	-29.30	-30.80	
4A	261.60		261.60	261.80	262.10	262.20	262.50	262.90	263.30	263.70	263.80	
		$(\Delta L)10^3$	0	-4.76	-11.90	-14.28	-21.60	-30.95	-40.50	-50.00	-52.40	
		$(\Delta L/L)10^5$	0	-3.35	-8.38	-10.01	-15.20	-21.80	-28.50	-35.20	-36.90	
4B	246.00		246.00	246.20	246.50	246.90	247.00	247.30	247.80	248.00	248.10	
		$(\Delta L)10^3$	0	-4.62	-11.54	-20.80	-23.10	-30.00	-41.60	-46.20	-48.50	
		$(\Delta L/L)10^5$	0	-3.25	-8.13	-14.65	-16.28	-21.10	-29.30	-32.50	-34.10	
	———											
		$(\Delta L)10^3$										
		$(\Delta L/L)10^5$										

SPEC.	Partially Sat. Wt. (1)	Vacuum Sat. Wt. (2)	Oven-Dried Wt. (3)	(2) - (3)	(1) - (3)	% Sat. $\frac{(1)-(3)}{(2)-(3)}$
4	3.616 lb.	3.661 lb.	3.341 lb.	0.320 lb.	0.275 lb.	86.0
4A	3.641 lb.	3.687 lb.	3.365 lb.	0.322 lb.	0.276 lb.	85.7
4B	3.612 lb.	3.659 lb.	3.338 lb.	0.321 lb.	0.274 lb.	85.8

NOTE: Transmitter Calibration Constants:

(0) $2.38 \times 10^{-2} \frac{mm}{unit}$ (2) $2.31 \times 10^{-2} \frac{mm}{unit}$

(1) $2.29 \times 10^{-2} \frac{mm}{unit}$ (3) $2.19 \times 10^{-2} \frac{mm}{unit}$


EFFECT OF DEGREE OF SATURATION ON LENGTH CHANGE PATTERN
TEMPERATURE °F
40
35
30
25
20
15
10
5
0
LENGTH CHANGE, 1X10⁻⁵
0
-10
-20
-30
-40
86.0%
85.8%
85.7%
W/C = 0.55
AGG = 1/4"

W/C = 0.55 | Curing Time = 14 days | Date: July 4, 1967

Agg. = 1/4 | Air Dried = 17 days

Air = 7%

SPEC.	Init.Rdg.	Surface / Centre	TEMPERATURES °F									
			39.2 / 39.2	35.0 / 36.5	29.5 / 31.0	22.1 / 23.4	18.2 / 19.7	13.9 / 14.0	7.5 / 7.6	1.0 / 1.0		
0	---											
		$(\Delta L)10^3$										
		$(\Delta L/L)10^5$										
1	267.90		267.90	268.00	268.20	268.60	268.90	269.20	269.50	269.80		
		$(\Delta L)10^3$	0	-2.31	-6.93	-16.16	-23.10	-28.75	-34.65	-41.60		
		$(\Delta L/L)10^5$	0	-1.63	-4.98	-11.38	-16.27	-20.15	-24.40	-29.30		
3A	253.80		253.80	254.00	254.40	254.70	255.00	255.30	255.60	255.90		
		$(\Delta L)10^3$	0	-4.76	-14.29	-21.60	-28.60	-35.70	-42.90	-50.00		
		$(\Delta L/L)10^5$	0	-3.35	-10.05	-15.20	-20.10	-25.10	-30.20	-35.20		
3	259.80		259.80	260.00	260.20	260.30	260.50	261.00	261.20	261.50		
		$(\Delta L)10^3$	0	-4.38	-8.75	-10.95	-15.32	-26.30	-30.60	-37.20		
		$(\Delta L/L)10^5$	0	-3.09	-6.18	-7.72	-10.80	-18.50	-21.55	-26.20		

SPEC.	Partially Sat. Wt.(1)	Vacuum Sat. Wt.(2)	Oven-Dried Wt.(3)	(2) - (3)	(1) - (3)	% Sat. $\frac{(1)-(3)}{(2)-(3)}$
0						
1	3.533 lb.	3.553 lb.	3.252 lb.	0.301 lb.	0.000	100.0
3A	3.524 lb.	3.524 lb.	3.208 lb.	0.316 lb.	0.000	100.0
3	3.531 lb.	3.531 lb.	3.220 lb.	0.311 lb.	0.000	100.0

NOTE: Transmitter Calibration Constants:

(0) 2.38×10^{-2} $\frac{mm}{unit}$ (2) 2.31×10^{-2} $\frac{mm}{unit}$

(1) 2.29×10^{-2} $\frac{mm}{unit}$ (3) 2.19×10^{-2} $\frac{mm}{unit}$

W/C = 0.60
Agg. = 1/4
Air = 7%

Curing Time = 14 days
Air Dried = 38 days

Date: May 25, 1967

SPEC.	Init.Rdg.	Surface / Centre	39.0 / 39.2	34.0 / 35.6	29.0 / 30.2	24.6 / 24.8	18.0 / 19.0	14.4 / 15.2	10.0 / 10.6	6.0 / 6.8	0.0 / 1.0	
	---	$(\Delta L)10^3$										
		$(\Delta L/L)10^5$										
3A	283.90		283.90	284.00	284.80	283.90	284.00	284.30	284.50	284.60	284.80	
		$(\Delta L)10^3$	0	-2.29	-2.29	0	-2.29	-9.15	-13.7	-16.0	-2.06	
		$(\Delta L/L)10^5$	0	-1.61	-1.61	0	-1.61	-6.44	-9.65	-11.3	-14.5	
2	260.70		260.70	261.00	261.20	261.40	261.20	261.40	261.80	262.30	262.60	
		$(\Delta L)10^3$	0	-6.93	-11.5	-16.2	-11.5	-16.2	-25.4	-37.0	-44.0	
		$(\Delta L/L)10^5$	0	-4.88	-8.1	-11.4	-8.1	-11.4	-17.9	-26.0	-31.0	
3	248.90		248.90	249.10	249.30	249.40	249.70	250.00	250.30	250.60	250.80	
		$(\Delta L)10^3$	0	-4.38	-8.76	-11.0	-17.5	-24.0	-30.6	-37.2	-41.6	
		$(\Delta L/L)10^5$	0	-3.08	-6.16	-7.75	-12.3	-16.9	-21.6	-26.2	-29.3	

(Temperature columns under the heading: TEMPERATURES °F)

SPEC.	Partially Sat. Wt.(1)	Vacuum Sat. Wt.(2)	Oven-Dried Wt.(3)	(2) - (3)	(1) - (3)	% Sat. $\frac{(1)-(3)}{(2)-(3)}$
3A	3.510 lb.	3.610 lb.	3.207 lb.	0.403 lb.	0.303 lb.	75.2
2	3.448 lb.	3.531 lb.	3.160 lb.	0.371 lb.	0.288 lb.	77.6
3	3.424 lb.	3.527 lb.	3.137 lb.	0.390 lb.	0.287 lb.	73.7

NOTE: Transmitter Calibration Constants:

(0) $2.38 \times 10^{-2} \frac{mm}{unit}$ (2) $2.31 \times 10^{-2} \frac{mm}{unit}$

(1) $2.29 \times 10^{-2} \frac{mm}{unit}$ (3) $2.19 \times 10^{-2} \frac{mm}{unit}$

W / C = 0.60

Agg. = 1/4

Air = 7%

Curing Time = 14 days

Air Dried = 38 days

Date: June 1, 1967

SPEC.	Init.Rdg.		TEMPERATURES °F									
		Surface Centre	40.0 40.1	35.0 36.4	29.0 30.2	23.0 24.5	20.3 21.7	15.5 16.5	11.2 12.0	6.2 6.8	2.5 2.5	1.0 1.0

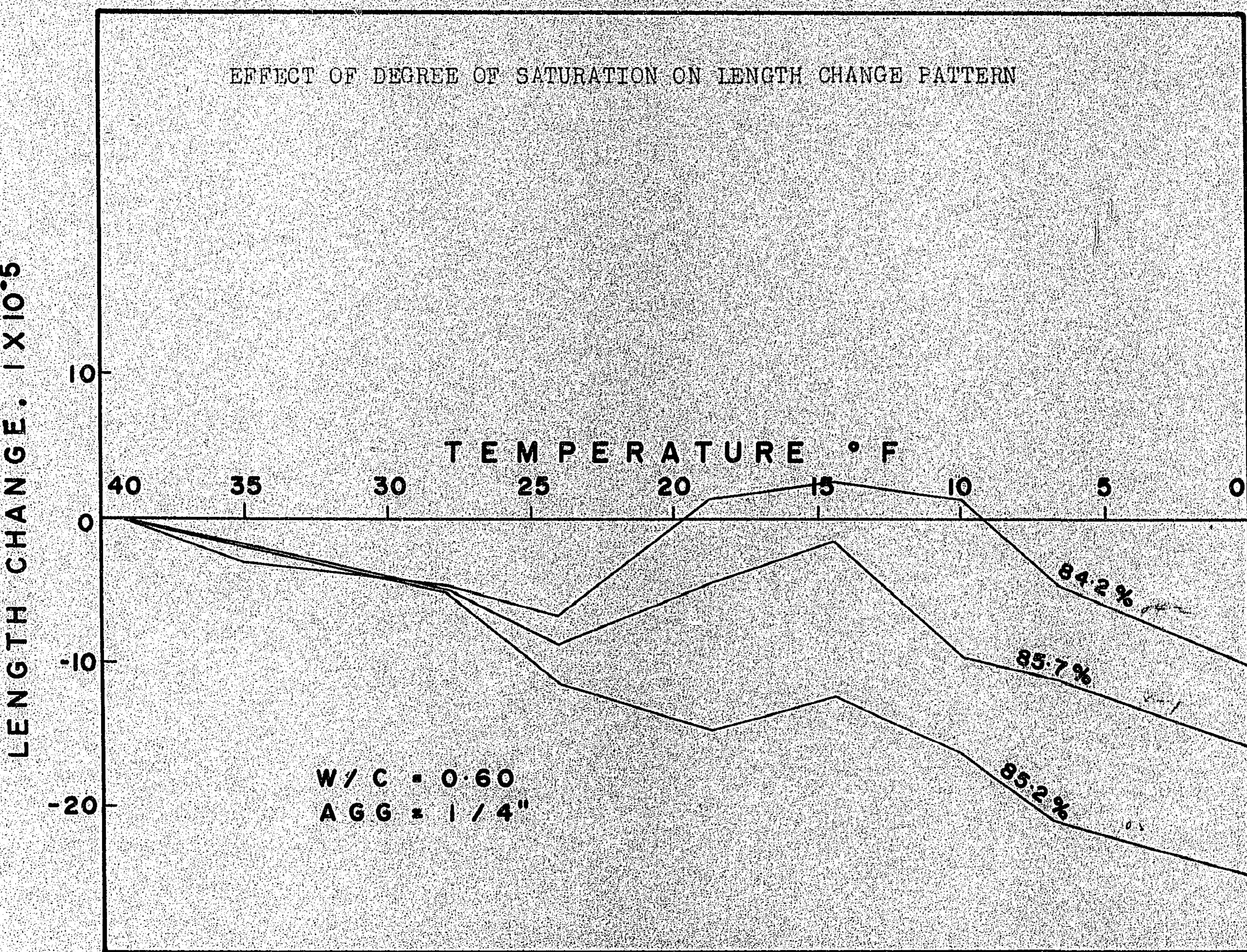
		(ΔL)10³										
		(ΔL/L)10⁵										
2	247.90		247.90	248.00	248.30	248.70	248.40	248.30	247.80	247.50	247.80	248.00
		(ΔL)10³	0	-2.31	-9.25	-18.48	-11.54	-9.25	2.31	9.25	2.31	-2.31
		(ΔL/L)10⁵	0	-1.63	-6.52	-13.01	-8.14	-6.52	1.63	6.52	1.63	-1.63
2A	227.90		227.90	228.10	228.30	228.00	228.30	227.00	226.90	226.30	226.10	226.50
		(ΔL)10³	0	-4.38	-8.75	-2.19	-8.75	19.70	21.90	35.05	39.40	30.65
		(ΔL/L)10⁵	0	-3.09	-6.17	-1.54	-6.17	13.88	15.41	24.70	27.75	21.60
3	239.90		239.90	240.00	240.20	239.80	239.70	239.80	239.90	239.90	240.00	240.00
		(ΔL)10³	0	-2.29	-6.87	2.29	4.58	2.29	0	0	-2.29	-2.29
		(ΔL/L)10⁵	0	-1.61	-4.84	1.61	3.22	1.61	0	0	-1.61	-1.61

SPEC.	Partially Sat. Wt.(1)	Vacuum Sat. Wt.(2)	Oven-Dried Wt.(3)	(2) - (3)	(1) - (3)	% Sat. $\frac{(1)-(3)}{(2)-(3)}$
2	3.495 lb.	3.521 lb.	3.133 lb.	0.388 lb.	0.362 lb.	93.3
2A	3.540 lb.	3.566 lb.	3.193 lb.	0.373 lb.	0.347 lb.	93.0
3	3.470 lb.	3.503 lb.	3.116 lb.	0.387 lb.	0.354 lb.	91.5

NOTE: Transmitter Calibration Constants:

(0) $2.38 \times 10^{-2} \frac{mm}{unit}$ (2) $2.31 \times 10^{-2} \frac{mm}{unit}$

(1) $2.29 \times 10^{-2} \frac{mm}{unit}$ (3) $2.19 \times 10^{-2} \frac{mm}{unit}$


EFFECT OF DEGREE OF SATURATION ON LENGTH CHANGE PATTERN
TEMPERATURE °F
40
35
30
25
20
15
10
5
0
LENGTH CHANGE. 1 X 10⁻⁵
10
0
-10
-20
84.2 %
85.7 %
85.2 %
W/C = 0.60
AGG = 1/4"

W / C = 0.60
Agg. = 1/4
Air = 7%

Curing Time = 14 days
Air Dried = 40 days

Date: May 29, 1967

SPEC.	Init.Rdg.	Surface Centre	38.4 39.2	34.6 35.6	27.8 28.2	23.3 24.8	18.0 19.4	14.0 15.3	9.80 10.0	6.40 7.30	0.0 1.0	
			TEMPERATURES °F									

		$(\Delta L)10^3$										
		$(\Delta L/L)10^5$										
2A	287.00		287.00	287.10	287.30	287.70	287.90	287.50	288.00	288.30	288.50	
		$(\Delta L)10^3$	0	-2.31	-6.94	-16.20	-20.8	-11.55	-23.1	-30.0	-34.6	
		$(\Delta L/L)10^5$	0	-1.63	-4.88	-11.40	-14.65	-12.30	-16.25	-21.1	-24.4	
2	187.00		187.00	187.10	187.30	187.50	187.30	187.10	187.60	187.70	188.00	
		$(\Delta L)10^3$	0	-2.19	-6.57	-11.95	-6.57	-2.19	-13.15	-15.33	-21.9	
		$(\Delta L/L)10^5$	0	-1.54	-4.62	-8.42	-4.62	-1.54	-9.26	-10.80	-15.41	
3	259.20		259.20	259.40	259.50	259.60	259.10	259.15	259.10	259.50	259.80	
		$(\Delta L)10^3$	0	-4.58	-6.86	-9.15	2.29	3.43	2.29	-6.86	-13.72	
		$(\Delta L/L)10^5$	0	-3.23	-4.83	-6.45	1.61	2.42	1.61	-4.85	-9.66	

SPEC.	Partially Sat. Wt. (1)	Vacuum Sat. Wt. (2)	Oven-Dried Wt. (3)	(2) - (3)	(1) - (3)	% Sat. $\frac{(1)-(3)}{(2)-(3)}$
2A	3.479 lb.	3.533 lb.	3.170 lb.	0.363 lb.	0.309 lb.	85.2
2	3.488 lb.	3.541 lb.	3.170 lb.	0.371 lb.	0.318 lb.	85.7
3	3.430 lb.	3.492 lb.	3.100 lb.	0.390 lb.	0.330 lb.	84.2

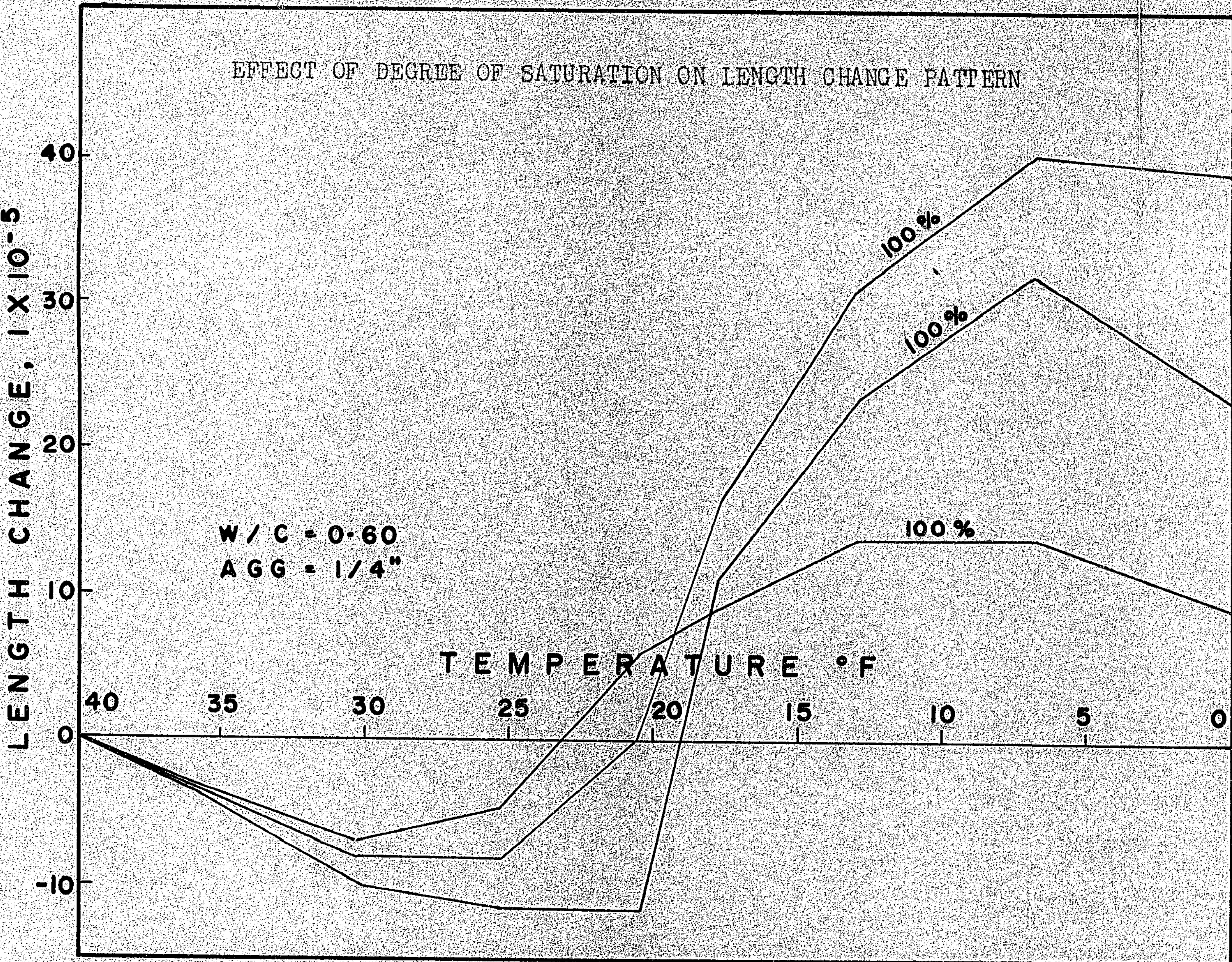
NOTE: Transmitter Calibration Constants:

(0) $2.38 \times 10^{-2}\ \frac{mm}{unit}$

(1) $2.29 \times 10^{-2}\ \frac{mm}{unit}$

(2) $2.31 \times 10^{-2}\ \frac{mm}{unit}$

(3) $2.19 \times 10^{-2}\ \frac{mm}{unit}$



EFFECT OF DEGREE OF SATURATION ON LENGTH CHANGE PATTERN
100%
100%
100%
W/C = 0·60
AGG = 1/4"
TEMPERATURE °F
40
35
30
25
20
15
10
5
0
LENGTH CHANGE, 1 X 10-5
-10

W / C = 0.60 | Curing Time = 14 days | Date: July 3, 1967
Agg. = 1/4 | Air Dried = 15 days
Air = 7%

SPEC.	Init. Rdg.	Surface / Centre	TEMPERATURES °F									
			40.0 / 40.0	35.0 / 37.4	29.1 / 31.4	24.0 / 26.4	20.0 / 21.2	17.0 / 18.5	13.0 / 13.2	6.0 / 7.6	0.0 / 0.0	

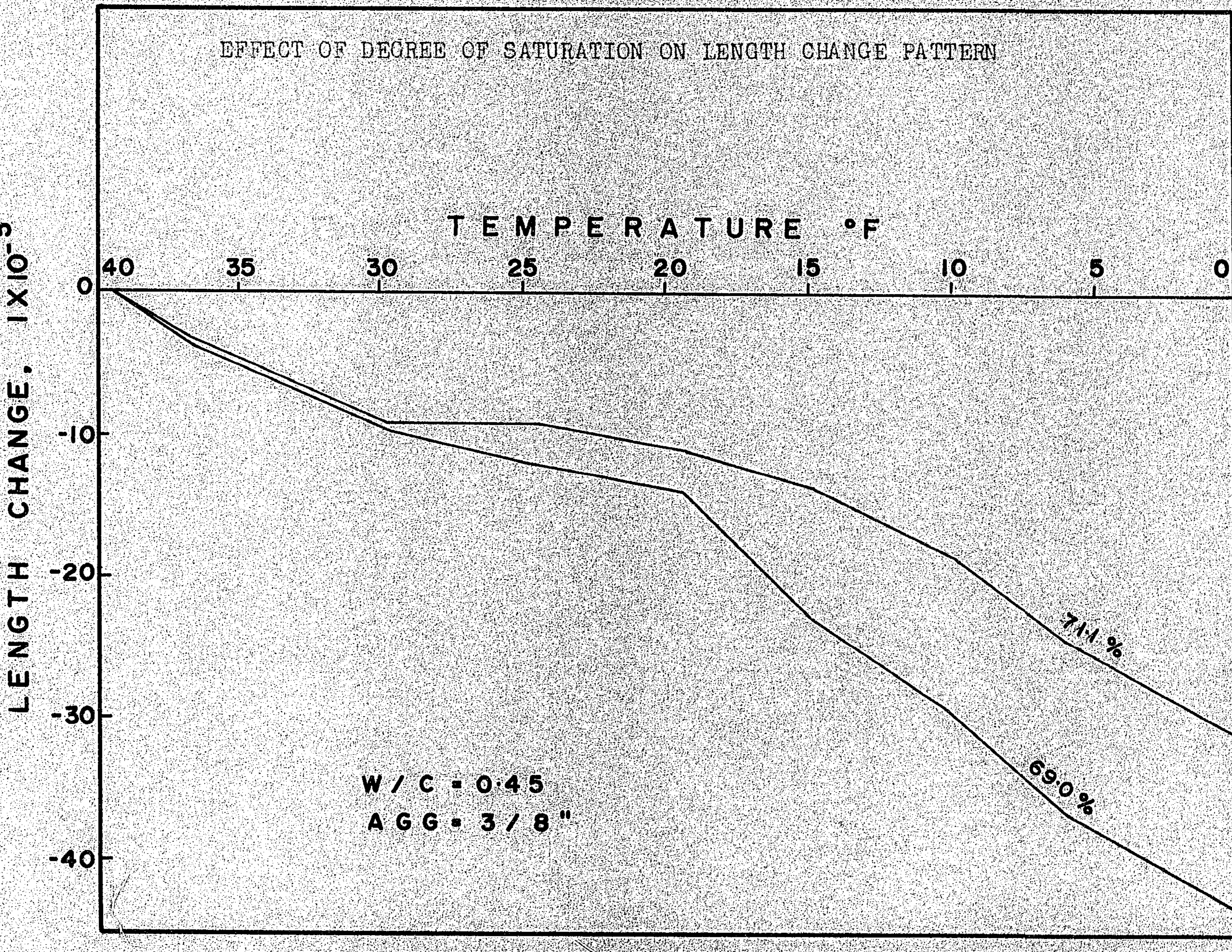
		$(\Delta L)10^3$										
		$(\Delta L/L)10^5$										
1	259.30		259.30	259.50	259.80	259.80	259.30	258.30	257.40	256.80	256.90	
		$(\Delta L)10^3$	0	-4.62	-11.55	-11.55	0	23.10	43.80	57.70	55.40	
		$(\Delta L/L)10^5$	0	-3.25	-8.13	-8.13	0	16.28	30.90	40.60	39.00	
2	242.30		242.30	242.50	242.90	243.00	243.00	241.60	240.90	240.40	240.90	
		$(\Delta L)10^3$	0	-4.76	-14.28	-16.66	-16.66	16.66	33.30	45.30	33.30	
		$(\Delta L/L)10^5$	0	-3.35	-10.06	-11.72	-11.72	11.72	23.45	31.90	23.45	
1A	197.40		197.40	197.60	197.85	197.70	197.00	196.80	196.50	196.40	196.80	
		$(\Delta L)10^3$	0	-4.38	-9.85	-6.56	8.76	13.13	19.70	19.70	13.13	
		$(\Delta L/L)10^5$	0	-3.08	-6.94	-4.62	6.16	9.25	13.87	13.87	9.25	

SPEC.	Partially Sat. Wt. (1)	Vacuum Sat. Wt. (2)	Oven-Dried Wt. (3)	(2) - (3)	(1) - (3)	% Sat. $\frac{(1)-(3)}{(2)-(3)}$
1	3.511 lb.	3.511 lb.	3.150 lb.	0.361 lb.	0.000	100.0
2	3.490 lb.	3.490 lb.	3.165 lb.	0.325 lb.	0.000	100.0
1A	3.529 lb.	3.529 lb.	3.162 lb.	0.367 lb.	0.000	100.0

NOTE: Transmitter Calibration Constants:

(0) 2.38×10^{-2} $\frac{mm}{unit}$ (2) 2.31×10^{-2} $\frac{mm}{unit}$

(1) 2.29×10^{-2} $\frac{mm}{unit}$ (3) 2.19×10^{-2} $\frac{mm}{unit}$



EFFECT OF DEGREE OF SATURATION ON LENGTH CHANGE PATTERN

W/C = 0.45

Agg. = 3/8 in.

Air = 7%

Curing Time = 14 days

Air Dried = 55 days

Date: June 5, 1967

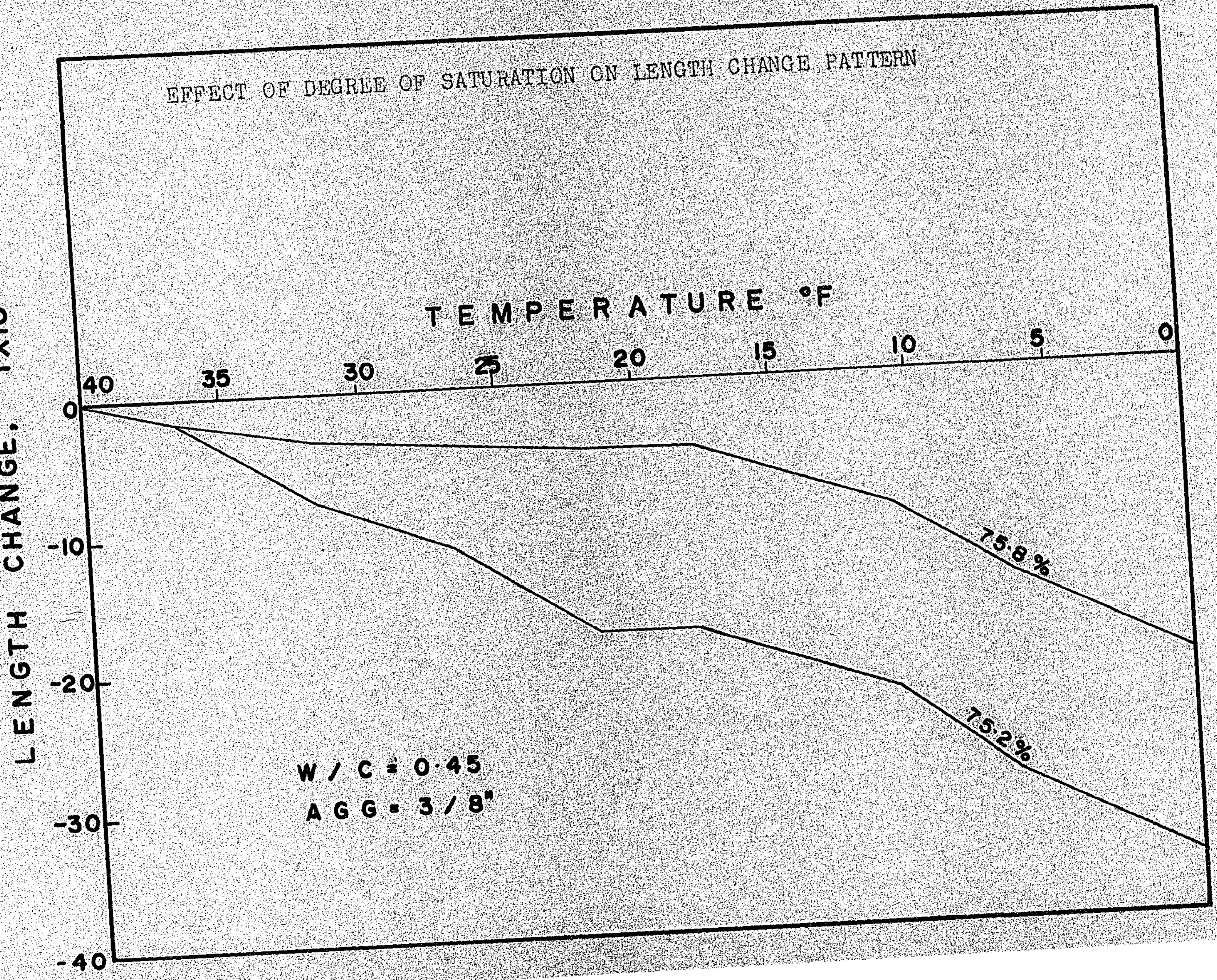
SPEC.	Init.Rdg.	Surface / Centre	TEMPERATURES °F									
			39.0 / 39.2	35.0 / 36.0	29.0 / 30.2	23.5 / 25.1	19.0 / 20.8	14.1 / 15.6	9.4 / 10.4	5.1 / 6.8	-1.0 / 0.5	
	---	$(\Delta L)10^3$										
		$(\Delta L/L)10^5$										
1	239.40		239.40	239.60	240.00	240.00	240.10	240.30	240.60	241.00	241.40	
		$(\Delta L)10^3$	0	-4.38	-13.15	-13.15	-15.32	-19.70	-26.30	-35.10	-43.8	
		$(\Delta L/L)10^5$	0	-3.08	-9.25	-9.25	-10.80	-13.88	-18.51	-24.75	-30.85	
	---	$(\Delta L)10^3$										
		$(\Delta L/L)10^5$										
3	295.40		295.40	295.60	296.00	296.10	296.20	296.70	297.10	297.50	297.90	
		$(\Delta L)10^3$	0	-4.76	-14.88	-17.35	-19.83	-32.20	-42.10	-52.05	-62.00	
		$(\Delta L/L)10^5$	0	-3.36	-9.54	-12.20	-14.00	-22.60	-29.60	-36.70	-43.60	

SPEC.	Partially Sat.Wt.(1)	Vacuum Sat.Wt.(2)	Oven-Dried Wt.(3)	(2) - (3)	(1) - (3)	%Sat. $\frac{(1)-(3)}{(2)-(3)}$
1	3.673 lb.	3.759 lb.	3.462 lb.	0.297 lb.	0.211	71.1
3	3.695 lb.	3.695 lb.	3.392 lb.	0.305 lb.	0.210 lb.	69.0

NOTE: Transmitter Calibration Constants:

(0) 2.38×10^{-2} $\frac{mm}{unit}$ (2) 2.31×10^{-2} $\frac{mm}{unit}$

(1) 2.29×10^{-2} $\frac{mm}{unit}$ (3) 2.19×10^{-2} $\frac{mm}{unit}$


EFFECT OF DEGREE OF SATURATION ON LENGTH CHANGE PATTERN
TEMPERATURE °F
40
35
30
25
20
15
10
5
0
LENGTH CHANGE, 1X10-5
0
-10
-20
-30
-40
75·8 %
75·2 %
W / C = 0·45
AGG = 3 / 8"

W / C = .45
Agg. = 3/8 in.
Air = 7%

Curing Time = 14 days
Air Dried = 52 days

Date: June 3, 1967

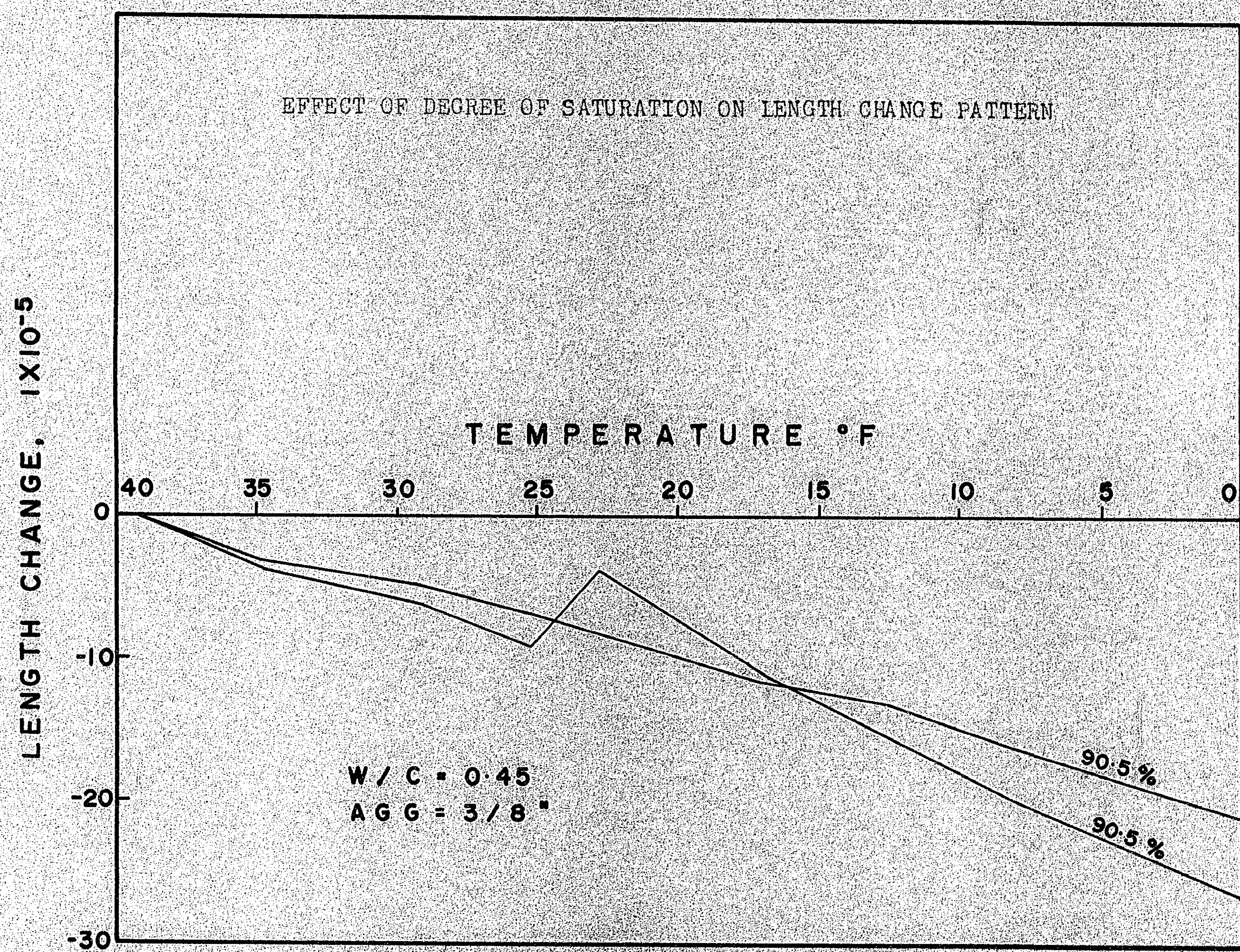
SPEC.	Init.Rdg.	Surface Centre	TEMPERATURES °F									
			39.5 43.0	36.0 37.4	31.0 32.0	26.0 27.5	20.5 22.0	17.0 19.0	10.2 11.2	6.0 6.8	0.0 1.0	
1A	217.10		217.10	217.20	217.60	217.80	218.20	218.20	218.50	218.90	219.30	
		$(\Delta L)10^3$	0	-2.31	-11.55	-16.17	-25.40	-25.40	-32.30	-41.60	-50.90	
		$(\Delta L/L)10^5$	0	-1.61	-8.15	-11.38	-17.90	-17.90	-22.75	-29.30	-35.80	
1	257.70		258.00	258.10	258.20	258.25	258.30	258.30	258.60	258.90	259.30	
		$(\Delta L)10^3$	0	-2.29	-4.58	-5.73	-6.86	-6.86	-13.74	-20.80	-29.80	
		$(\Delta L/L)10^5$	0	-1.61	-3.22	-4.03	-4.83	-4.83	-9.66	-14.62	-21.00	
	———	$(\Delta L)10^3$										
		$(\Delta L/L)10^5$										
	———	$(\Delta L)10^3$										
		$(\Delta L/L)10^5$										

SPEC.	Partially Sat. Wt. (1)	Vacuum Sat. Wt. (2)	Oven-Dried Wt. (3)	(2) - (3)	(1) - (3)	% Sat. $\frac{(1)-(3)}{(2)-(3)}$
1A	3.678 lb.	3.750 lb.	3.460 lb.	0.290 lb.	0.218 lb.	75.2
1	3.705 lb.	3.775 lb.	3.488 lb.	0.287 lb.	0.217 lb.	75.8

NOTE: Transmitter Calibration Constants:

(0) $2.38 \times 10^{-2} \frac{mm}{unit}$ (2) $2.31 \times 10^{-2} \frac{mm}{unit}$

(1) $2.29 \times 10^{-2} \frac{mm}{unit}$ (3) $2.19 \times 10^{-2} \frac{mm}{unit}$


EFFECT OF DEGREE OF SATURATION ON LENGTH CHANGE PATTERN
TEMPERATURE °F
40
35
30
25
20
15
10
5
0
LENGTH CHANGE, 1X10-5
0
-10
-20
-30
90·5 %
90·5 %
W / C = 0·45
AGG = 3/8"

W/C = 0.45 Curing Time = 14 days Date: May 17, 1967

Agg. = 3/8 Air Dried = 31 days

Air = 6%

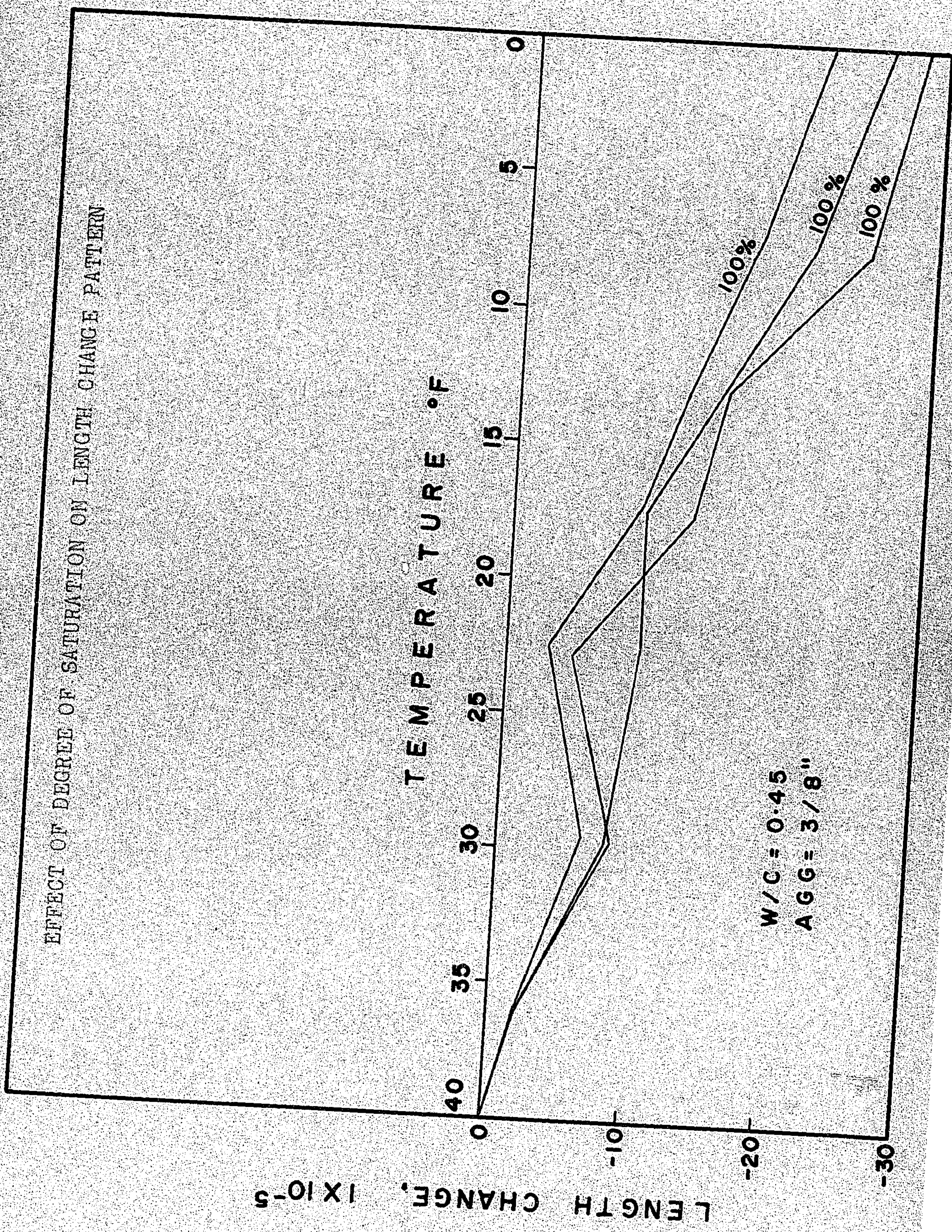
SPEC.	Init.Rdg.	Surface / Centre	TEMPERATURES °F									
			39.0 39.2	34.3 35.3	28.80 29.30	25.0 25.70	22.2 23.0	17.0 17.6	12.3 13.0	7.8 8.6	2.0 3.2	
0	----											
		$(\Delta L)10^3$										
		$(\Delta L/L)10^5$										
1	----											
		$(\Delta L)10^3$										
		$(\Delta L/L)10^5$										
2	288.00		288.00	288.20	288.30	288.40	288.50	288.70	288.80	289.00	289.20	
		$(\Delta L)10^3$	0	-4.58	-6.87	-9.15	-11.5	-16.0	-18.3	-22.9	-27.5	
		$(\Delta L/L)10^5$	0	-3.22	-4.84	-6.44	-8.10	-11.3	-12.9	-16.1	-19.4	
2A	214.90		214.90	215.15	215.30	215.50	215.10	215.60	215.90	216.20	216.50	
		$(\Delta L)10^3$	0	-5.48	-8.76	-13.1	-4.37	-15.3	-21.9	-28.5	-35.0	
		$(\Delta L/L)10^5$	0	-3.86	-6.17	-9.24	-3.08	-10.8	-15.4	-20.0	-24.6	

SPEC.	Partially Sat. Wt.(1)	Vacuum Sat. Wt.(2)	Oven-Dried Wt.(3)	(2) - (3)	(1) - (3)	%Sat. $\frac{(1)-(3)}{(2)-(3)}$
0						
1						
2	3.702 lb.	3.729 lb.	3.448 lb.	0.281 lb.	0.254 lb.	90.5
2A	3.712 lb.	3.739 lb.	3.455 lb.	0.284 lb.	0.257 lb.	90.5

NOTE: Transmitter Calibration Constants:

(0) $2.38 \times 10^{-2} \frac{mm}{unit}$ (2) $2.31 \times 10^{-2} \frac{mm}{unit}$

(1) $2.29 \times 10^{-2} \frac{mm}{unit}$ (3) $2.19 \times 10^{-2} \frac{mm}{unit}$



EFFECT OF DEGREE OF SATURATION ON LENGTH CHANGE PATTERN

W/C = 0.45
Agg. = 3/4
Air = 7%

Curing Time = 14 days
Air Dried = 30 days

Date: July 1, 1967

SPEC.	Init.Rdg.	Surface / Centre	TEMPERATURES °F									
		Surface	39.8	35.7	29.0	22.0	17.0	12.4	7.0	0.0		
		Centre	41.0	37.4	30.2	23.3	17.6	13.4	8.2	0.0		

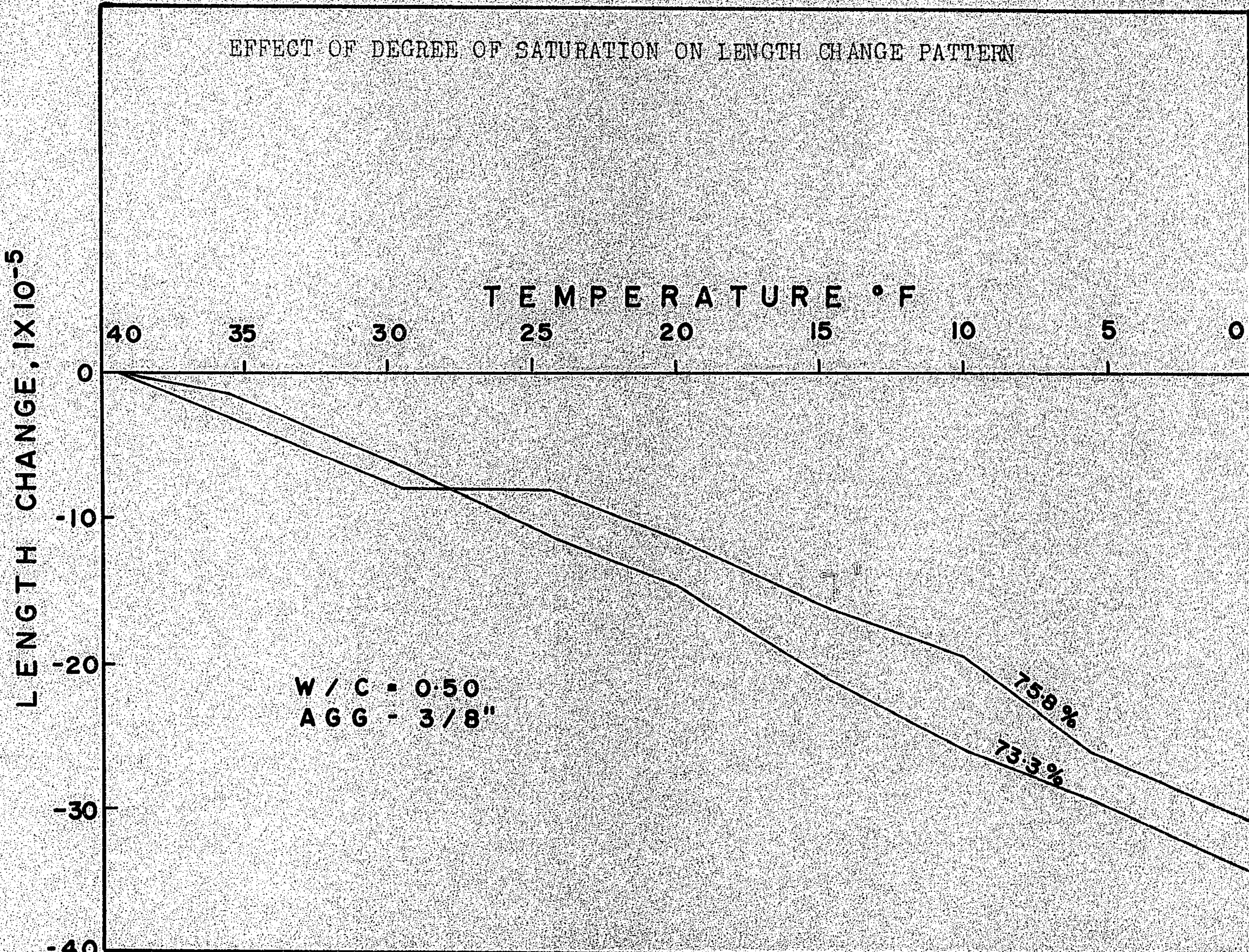
		$(\Delta L)10^3$										
		$(\Delta L/L)10^5$										
1	252.50		252.50	252.60	253.00	253.10	253.10	253.40	253.80	254.10		
		$(\Delta L)10^3$	0	-2.31	-11.53	-13.85	-13.85	-20.80	-30.00	-37.00		
		$(\Delta L/L)10^5$	0	-1.63	-8.14	-9.75	-9.75	-14.65	-21.10	-26.05		
2A	257.70		257.70	257.80	258.20	258.00	258.50	258.90	259.20	259.40		
		$(\Delta L)10^3$	0	-2.38	-11.90	-7.14	-19.05	-28.60	-35.70	-40.50		
		$(\Delta L/L)10^5$	0	-1.68	-8.38	-5.03	-13.40	-20.15	-25.10	-28.45		
3	242.90		242.90	243.00	243.30	243.10	243.50	243.70	244.00	244.30		
		$(\Delta L)10^3$	0	-2.19	-8.75	-4.38	-13.13	-17.51	-24.10	-30.70		
		$(\Delta L/L)10^5$	0	-1.54	-6.16	-3.08	-9.25	-12.33	-16.97	-21.60		

SPEC.	Partially Sat. Wt. (1)	Vacuum Sat. Wt. (2)	Oven-Dried Wt. (3)	(2) - (3)	(1) - (3)	% Sat. $\frac{(1)-(3)}{(2)-(3)}$
1	3.741 lb.	3.741 lb.	3.473 lb.	0.268 lb.	0.000	100.0
2A	3.731 lb.	3.731 lb.	3.459 lb.	0.272 lb.	0.000	100.0
3	3.662 lb.	3.662 lb.	3.389 lb.	0.273 lb.	0.000	100.0

NOTE: Transmitter Calibration Constants:

(0) $2.38 \times 10^{-2} \frac{mm}{unit}$ (2) $2.31 \times 10^{-2} \frac{mm}{unit}$

(1) $2.29 \times 10^{-2} \frac{mm}{unit}$ (3) $2.19 \times 10^{-2} \frac{mm}{unit}$


EFFECT OF DEGREE OF SATURATION ON LENGTH CHANGE PATTERN
TEMPERATURE °F
40
35
30
25
20
15
10
5
0
LENGTH CHANGE, 1X10-5
0
-10
-20
-30
-40
W / C = 0·50
AGG - 3/8"
75·8 %
73·3 %

W / C = 0.50

Agg. = 3/8 in.

Air = 7%

Curing Time = 14 days

Air Dried = 52 days

Date: June 5, 1967

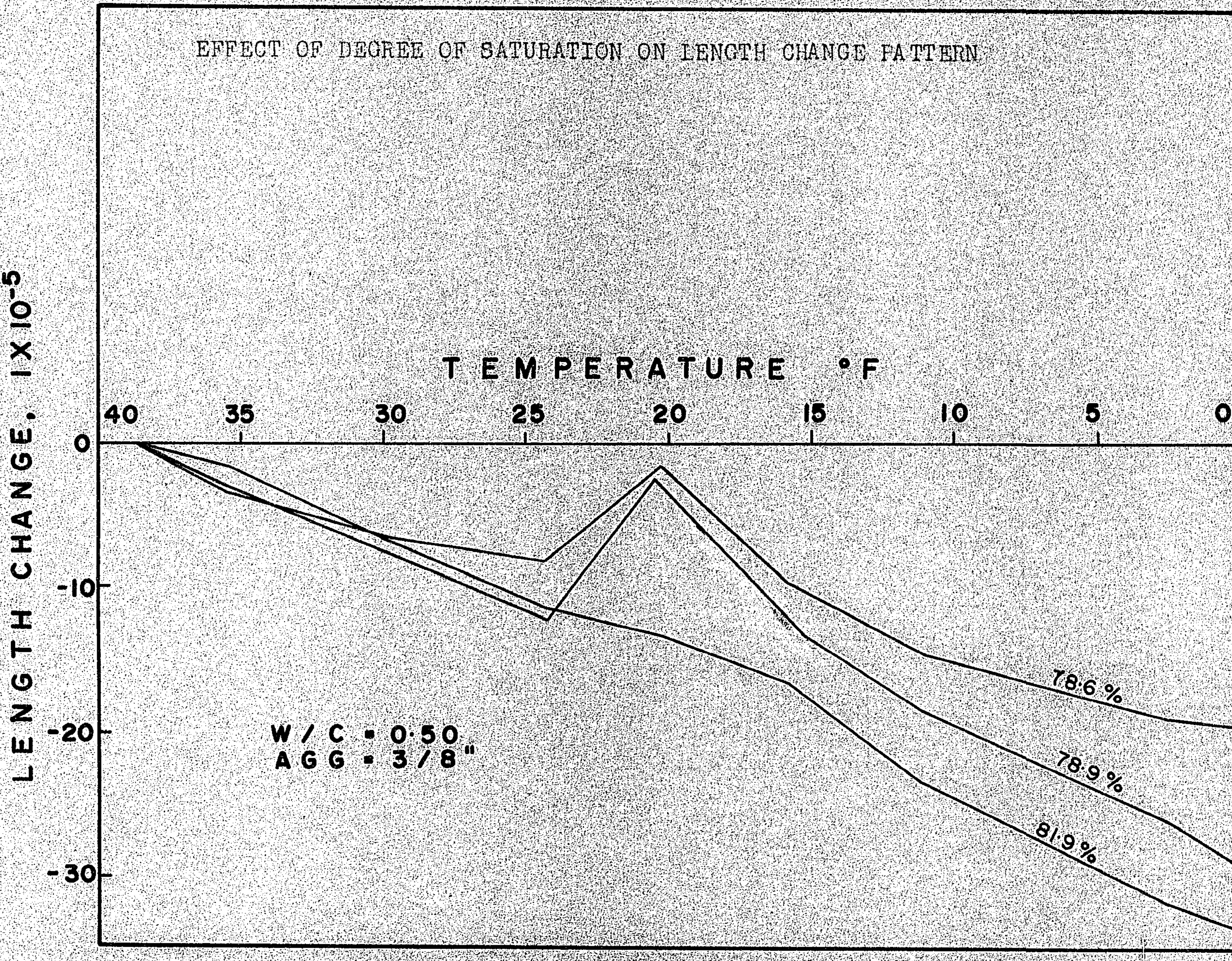
SPEC.	Init.Rdg.	Surface / Centre	TEMPERATURES °F									
			39.0 / 39.2	35.0 / 36.0	29.0 / 30.2	23.5 / 25.1	19.0 / 20.8	14.1 / 15.6	9.4 / 10.4	5.1 / 6.8	-1.0 / 0.5	
	---	$(\Delta L)10^3$										
		$(\Delta L/L)10^5$										
1	277.50		277.50	277.60	277.90	278.20	278.40	278.80	279.10	279.30	279.60	
		$(\Delta L)10^3$	0	-2.31	-9.23	-16.20	-20.80	-30.00	-37.00	-41.60	-48.50	
		$(\Delta L/L)10^5$	0	-1.63	-6.50	-11.40	-14.65	-21.10	-26.05	-29.30	-34.20	
	---	$(\Delta L)10^3$										
		$(\Delta L/L)10^5$										
3	221.30		221.30	221.50	221.80	221.80	222.80	222.30	222.50	222.90	223.20	
		$(\Delta L)10^3$	0	-4.58	-11.45	-11.45	-16.02	-22.90	-27.50	-36.60	-43.50	
		$(\Delta L/L)10^5$	0	-3.23	-8.06	-8.06	-11.29	-16.10	-19.40	-25.80	-30.60	

SPEC.	Partially Sat. Wt. (1)	Vacuum Sat. Wt. (2)	Oven-Dried Wt. (3)	(2) - (3)	(1) - (3)	% Sat. $\frac{(1)-(3)}{(2)-(3)}$
1	3.645 lb.	3.720 lb.	3.410 lb.	0.310 lb.	0.235 lb.	75.8
3	3.577 lb.	3.672 lb.	3.318 lb.	0.354 lb.	0.259 lb.	73.3

NOTE: Transmitter Calibration Constants:

(0) $2.38 \times 10^{-2} \frac{mm}{unit}$ (2) $2.31 \times 10^{-2} \frac{mm}{unit}$

(1) $2.29 \times 10^{-2} \frac{mm}{unit}$ (3) $2.19 \times 10^{-2} \frac{mm}{unit}$


EFFECT OF DEGREE OF SATURATION ON LENGTH CHANGE PATTERN
TEMPERATURE °F
40
35
30
25
20
15
10
5
0
LENGTH CHANGE. 1X10-5
0
-10
-20
-30
78.6 %
78.9 %
81.9 %
W / C = 0.50
AGG = 3/8"

W/C = 0.50 | Curing Time = 14 days | Date: June 14, 1967

Agg. = 3/8 | Air Dried = 32 days

Air = 7%

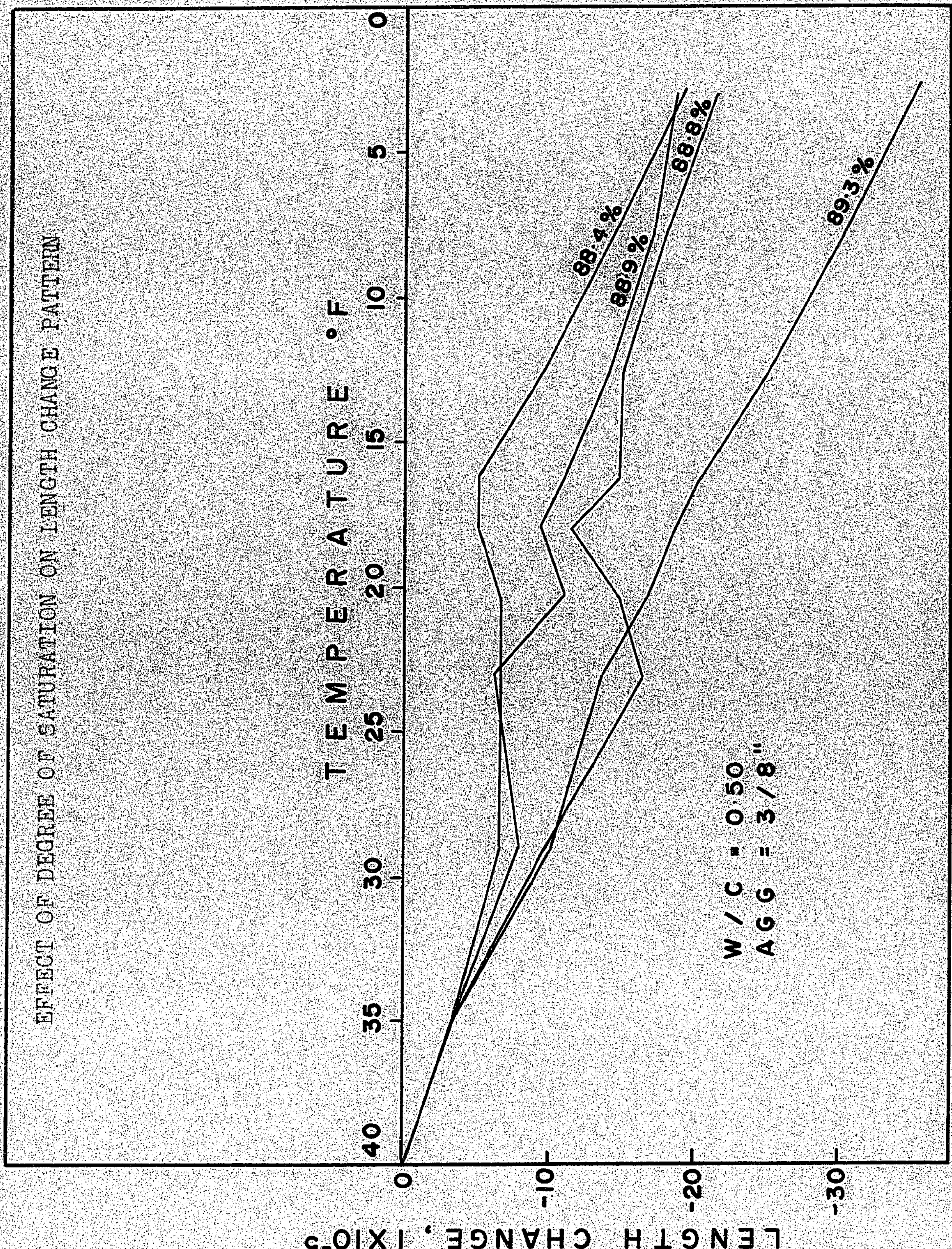
SPEC.	Init. Rdg.	Surface / Centre	TEMPERATURES °F									
			38.0 / 39.0	35.0 / 36.0	29.5 / 30.2	23.5 / 24.8	19.5 / 20.8	15.5 / 15.8	11.0 / 11.3	2.4 / 2.8	0.0 / 0.7	
1A	216.70		216.70	216.90	217.20	217.50	216.80	217.50	217.90	218.40	218.60	
		$(\Delta L)10^3$	0	-4.38	-10.98	-17.58	-2.19	-17.58	-26.30	-37.20	-41.60	
		$(\Delta L/L)10^5$	0	-3.08	-7.74	-12.38	-1.54	-12.38	-18.51	-26.20	-29.30	
1	294.80		294.80	294.90	299.20	295.50	295.60	295.80	296.20	296.70	296.80	
		$(\Delta L)10^3$	0	-2.38	-9.52	-16.66	-19.05	-23.80	-33.35	-45.20	-47.60	
		$(\Delta L/L)10^5$	0	-1.68	-6.70	-11.72	-13.41	-16.76	-23.45	-31.85	-33.55	
2	261.90		261.90	262.10	262.30	262.40	262.00	262.50	262.80	263.00	263.10	
		$(\Delta L)10^3$	0	-4.62	-9.24	-11.55	-2.31	-13.86	-20.80	-25.40	-27.70	
		$(\Delta L/L)10^5$	0	-3.26	-6.51	-8.15	-1.63	-9.75	-14.65	-17.90	-19.50	
	———	$(\Delta L)10^3$										
		$(\Delta L/L)10^5$										

SPEC.	Partially Sat. Wt. (1)	Vacuum Sat. Wt. (2)	Oven-Dried Wt. (3)	(2) - (3)	(1) - (3)	% Sat. $\frac{(1)-(3)}{(2)-(3)}$
1A	3.650 lb.	3.721 lb.	3.385 lb.	0.336 lb.	0.265 lb.	78.9
1	3.671 lb.	3.733 lb.	3.391 lb.	0.342 lb.	0.280 lb.	81.9
2	3.481 lb.	3.561 lb.	3.188 lb.	0.373 lb.	0.293 lb.	78.6

NOTE: Transmitter Calibration Constants:

(0) $2.38 \times 10^{-2} \frac{mm}{unit}$ (2) $2.31 \times 10^{-2} \frac{mm}{unit}$

(1) $2.29 \times 10^{-2} \frac{mm}{unit}$ (3) $2.19 \times 10^{-2} \frac{mm}{unit}$



EFFECT OF DEGREE OF SATURATION ON LENGTH CHANGE PATTERN

W/C = 0.50 Curing Time = 14 days Date: May 24, 1967

Agg. = 3/8 Air Dried = 42 days

Air = 2%

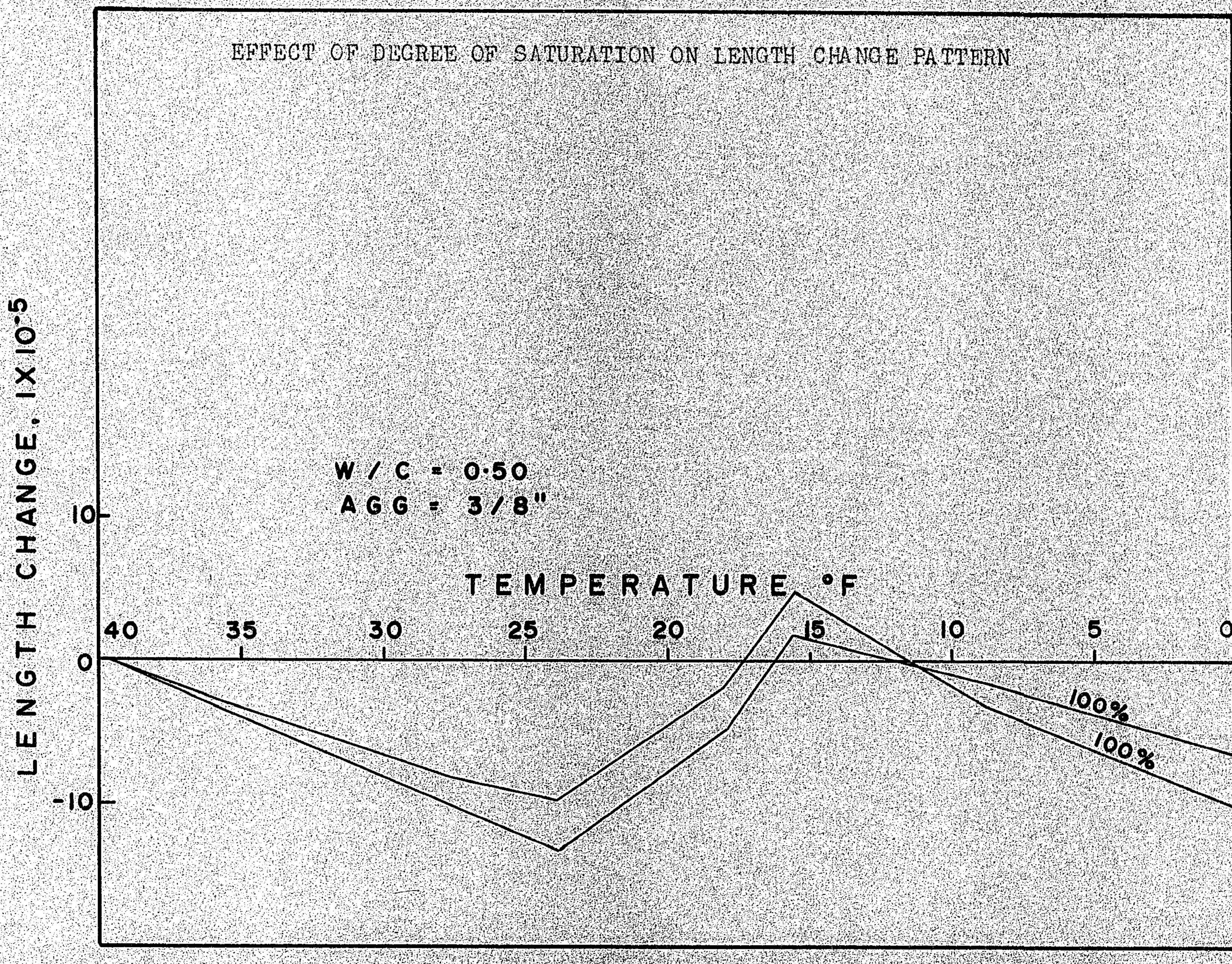
SPEC.	Init. Rdg.	Surface / Centre	40.0 / 40.0	34.0 / 36.0	27.5 / 30.6	22.0 / 23.8	19.2 / 21.4	17.0 / 19.4	15.0 / 17.6	11.2 / 13.6	6.50 / 9.00	2.0 / 4.0
			TEMPERATURES °F									
1	313.90		313.90	314.10	314.30	314.30	314.30	314.20	314.20	314.50	314.80	315.10
		$(\Delta L)10^3$	0	-4.58	-9.15	-9.15	-9.15	-6.86	-6.86	-13.7	-20.6	-27.5
		$(\Delta L/L)10^5$	0	-3.23	-6.45	-6.45	-6.45	-4.83	-4.83	-9.65	-14.5	-19.4
1A	289.00		289.00	289.20	289.60	289.80	290.00	290.10	290.20	290.50	290.85	291.10
		$(\Delta L)10^3$	0	-4.76	-14.3	-19.0	-23.8	-26.2	-28.6	-35.7	-44.0	-50.0
		$(\Delta L/L)10^5$	0	-3.35	-10.1	-13.4	-16.7	-18.4	-20.1	-25.1	-31.0	-35.2
2	304.90		304.90	305.10	305.50	305.90	305.80	305.60	305.80	305.80	306.00	306.20
		$(\Delta L)10^3$	0	-4.62	-13.85	-23.1	-20.8	-16.2	-20.8	-20.8	-25.4	-30.0
		$(\Delta L/L)10^5$	0	-3.26	-9.75	-16.3	-14.6	-11.4	-14.6	-14.6	-17.9	-21.1
3	272.80		272.80	273.00	273.30	273.20	273.50	273.40	273.50	273.70	273.90	274.00
		$(\Delta L)10^3$	0	-4.38	-10.95	-8.76	-15.3	-13.1	-15.3	-19.7	-24.1	-26.3
		$(\Delta L/L)10^5$	0	-3.08	-7.72	-6.17	-10.8	-9.22	-10.8	-13.9	-17.0	-18.5

SPEC.	Partially Sat. Wt. (1)	Vacuum Sat. Wt. (2)	Oven-Dried Wt. (3)	(2) - (3)	(1) - (3)	% Sat. $\frac{(1)-(3)}{(2)-(3)}$
1	3.662 lb.	3.700 lb.	3.374 lb.	0.326 lb.	0.288 lb.	88.4
1A	3.660 lb.	3.695 lb.	3.371 lb.	0.324 lb.	0.289 lb.	89.3
2	3.519 lb.	3.560 lb.	3.193 lb.	0.367 lb.	0.326 lb.	88.8
3	3.638 lb.	3.679 lb.	3.311 lb.	0.368 lb.	0.327 lb.	88.9

NOTE: Transmitter Calibration Constants:

(0) $2.38 \times 10^{-2} \frac{mm}{unit}$ (2) $2.31 \times 10^{-2} \frac{mm}{unit}$

(1) $2.29 \times 10^{-2} \frac{mm}{unit}$ (3) $2.19 \times 10^{-2} \frac{mm}{unit}$


EFFECT OF DEGREE OF SATURATION ON LENGTH CHANGE PATTERN
W / C = 0·50
AGG = 3/8"
TEMPERATURE °F
40
35
30
25
20
15
10
5
0
LENGTH CHANGE, 1X10-5
10
0
-10
100%
100%

W/C = 0.50
Agg. = 3/8
Air = 7%

Curing Time = 14 days
Air Dried = 15 days

Date: June 29, 1967

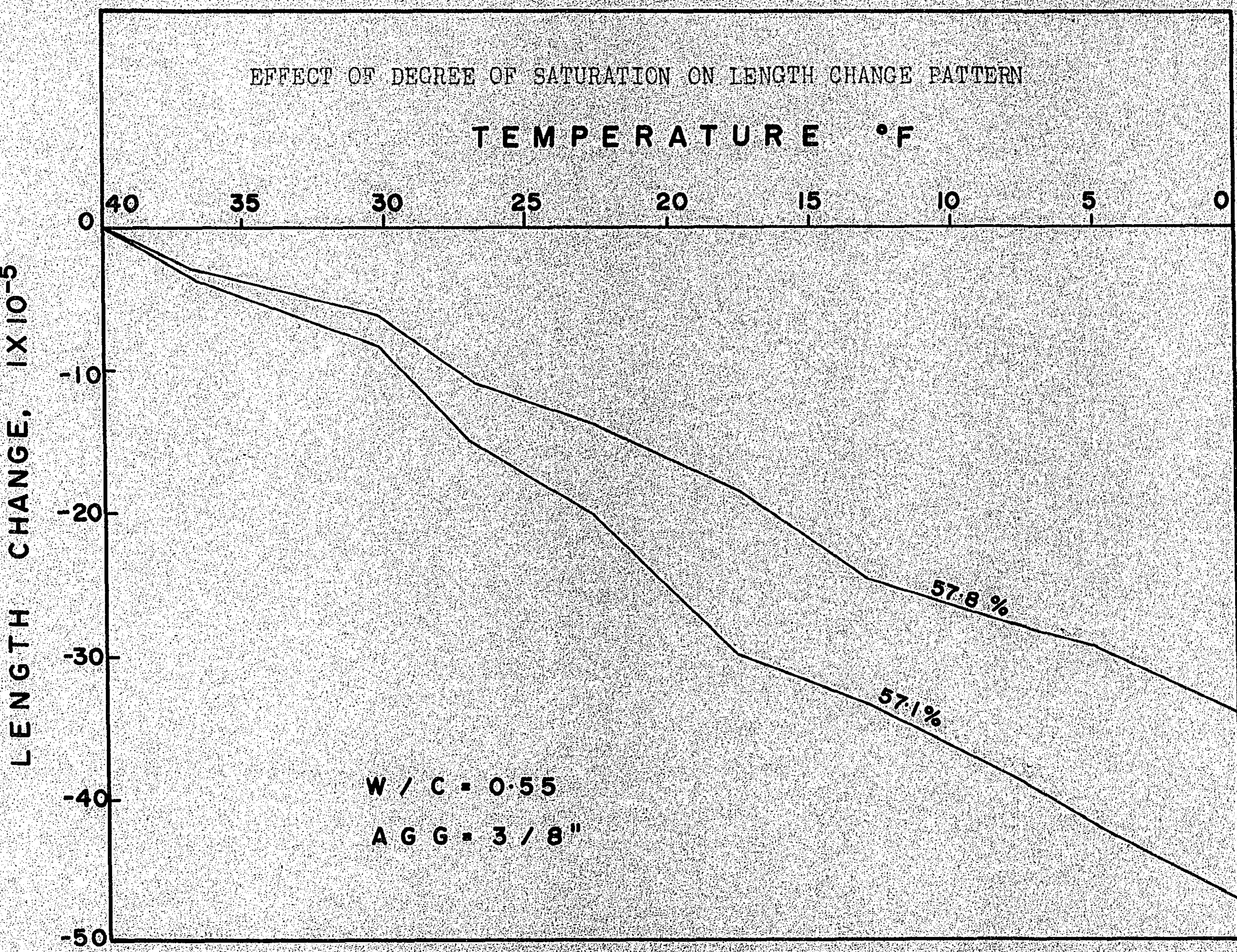
SPEC.	Init.Rdg.	Surface / Centre	39.0 / 39.2	35.0 / 36.0	27.1 / 28.4	23.2 / 24.5	17.6 / 18.5	15.2 / 16.0	7.8 / 9.5	2.0 / 3.2		
			TEMPERATURES °F									
	---	$(\Delta L)10^3$										
		$(\Delta L/L)10^5$										
2	295.60		295.60	295.80	296.20	296.40	295.90	295.50	295.70	295.90		
		$(\Delta L)10^3$	0	-4.76	-14.28	-19.04	-7.15	2.38	-2.38	-7.15		
		$(\Delta L/L)10^5$	0	-3.35	-10.06	-13.41	-5.03	1.68	-1.68	-5.03		
2A	269.90		269.90	270.10	270.40	270.50	270.00	269.60	270.10	270.40		
		$(\Delta L)10^3$	0	-4.62	-11.52	-13.85	-2.31	6.93	-4.62	-11.82		
		$(\Delta L/L)10^5$	0	-3.25	-8.12	-9.75	-1.63	4.81	-3.25	-8.12		
	---	$(\Delta L)10^3$										
		$(\Delta L/L)10^5$										

SPEC.	Partially Sat. Wt. (1)	Vacuum Sat. Wt. (2)	Oven-Dried Wt. (3)	(2) - (3)	(1) - (3)	% Sat. $\frac{(1)-(3)}{(2)-(3)}$
2	3.499 lb.	3.499 lb.	3.182 lb.	0.317 lb.	0.000	100.0
2A	3.516 lb.	3.516 lb.	3.202 lb.	0.314 lb.	0.000	100.0

NOTE: Transmitter Calibration Constants:

(0) $2.38 \times 10^{-2} \frac{mm}{unit}$ (2) $2.31 \times 10^{-2} \frac{mm}{unit}$

(1) $2.29 \times 10^{-2} \frac{mm}{unit}$ (3) $2.19 \times 10^{-2} \frac{mm}{unit}$


EFFECT OF DEGREE OF SATURATION ON LENGTH CHANGE PATTERN
TEMPERATURE °F
40
35
30
25
20
15
10
5
0
LENGTH CHANGE, 1X10^-5
0
-10
-20
-30
-40
-50
57.8 %
57.1%
W / C = 0.55
AGG = 3 / 8"

W / C = 0.55
Agg. = 3/8 in.
Air = 7 %

Curing Time = 14 days
Air Dried = 60 days

Date: June 7, 1967

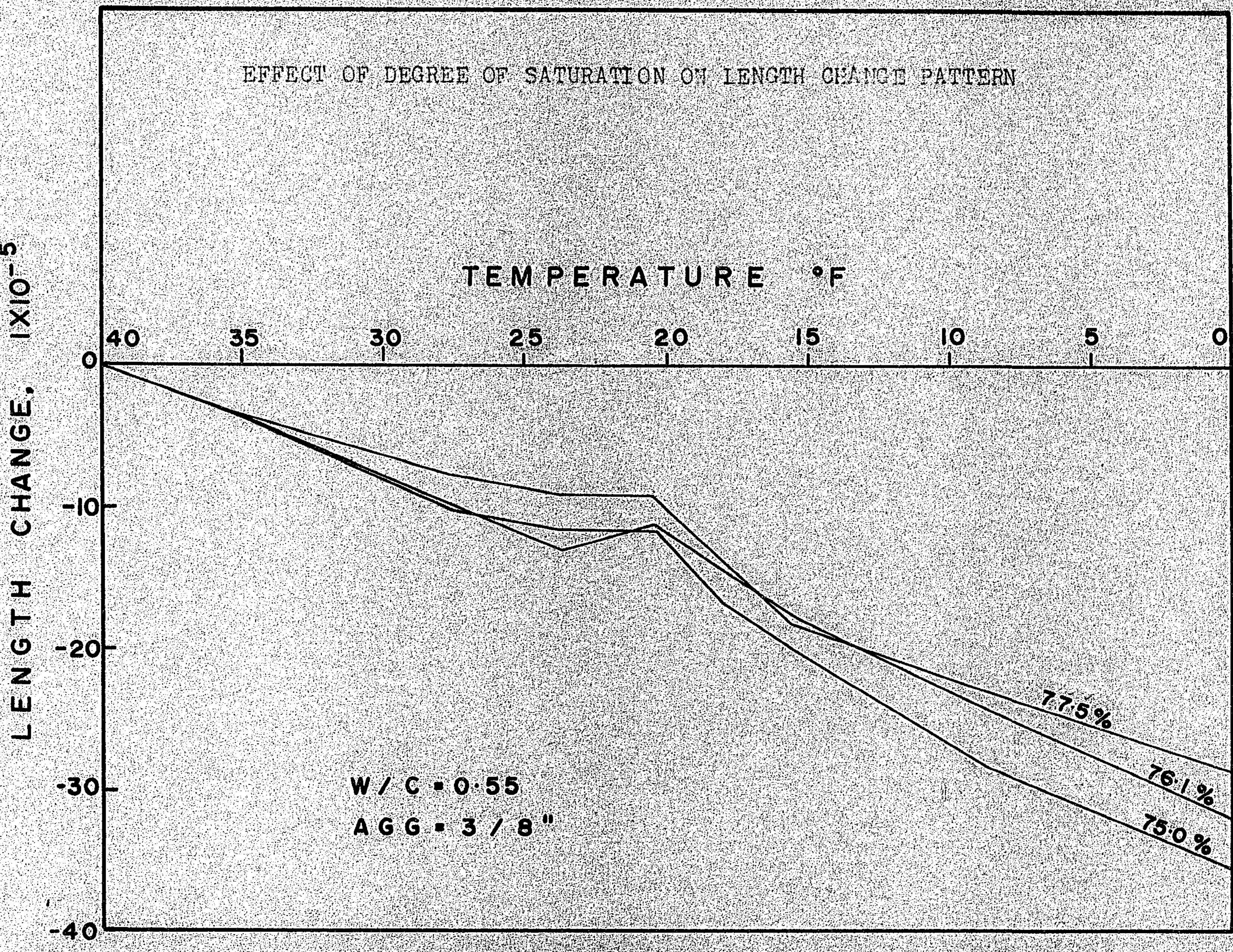
SPEC.	Init.Rdg.		TEMPERATURES °F									
		Surface Centre	40.5 40.0	36.2 37.0	30.0 30.5	26.8 27.2	22.3 23.0	17.1 17.6	12.8 13.1	7.8 7.9	5.0 5.0	0 0
	---	(ΔL)10³										
		(ΔL/L)10⁵										
			246.20	246.40	246.70	247.10	247.40	248.00	248.20	248.50	248.70	249.00
1	246.20	(ΔL)10³	0	-4.76	-11.90	-21.45	-28.55	-42.80	-47.60	-54.70	-59.50	-66.60
		(ΔL/L)10⁵	0	-3.35	-8.39	-15.10	-20.10	-30.20	-33.50	-38.50	-41.90	-46.90
			198.10	198.30	198.50	198.80	199.00	199.30	199.70	199.90	200.00	200.30
2	198.10	(ΔL)10³	0	-4.38	-8.75	-15.31	-19.70	-26.30	-35.00	-39.40	-41.60	-48.20
		(ΔL/L)10⁵	0	-3.08	-6.16	-10.80	-13.88	-18.51	-24.65	-27.75	-29.25	-33.90
	---	(ΔL)10³										
		(ΔL/L)10⁵										

SPEC.	Partially Sat. Wt. (1)	Vacuum Sat. Wt. (2)	Oven-Dried Wt. (3)	(2) - (3)	(1) - (3)	% Sat. $\frac{(1)-(3)}{(2)-(3)}$
1	3.445 lb.	3.620 lb.	3.212 lb.	0.408 lb.	0.233 lb.	57.1
2	3.461 lb.	3.632 lb.	3.325 lb.	0.407 lb.	0.236 lb.	57.8

NOTE: Transmitter Calibration Constants:

(0) $2.38 \times 10^{-2} \frac{mm}{unit}$ (2) $2.31 \times 10^{-2} \frac{mm}{unit}$

(1) $2.29 \times 10^{-2} \frac{mm}{unit}$ (3) $2.19 \times 10^{-2} \frac{mm}{unit}$


EFFECT OF DEGREE OF SATURATION ON LENGTH CHANGE PATTERN
TEMPERATURE °F
40
35
30
25
20
15
10
5
0
LENGTH CHANGE, 1X10⁻⁵
0
-10
-20
-30
-40
77.5%
76.1%
75.0%
W/C = 0.55
AGG = 3/8"

W / C = 0.55 Curing Time = 14 days Date: June 29, 1967

Agg. = 3/8 in. Air Dried = 30 days

Air = 7%

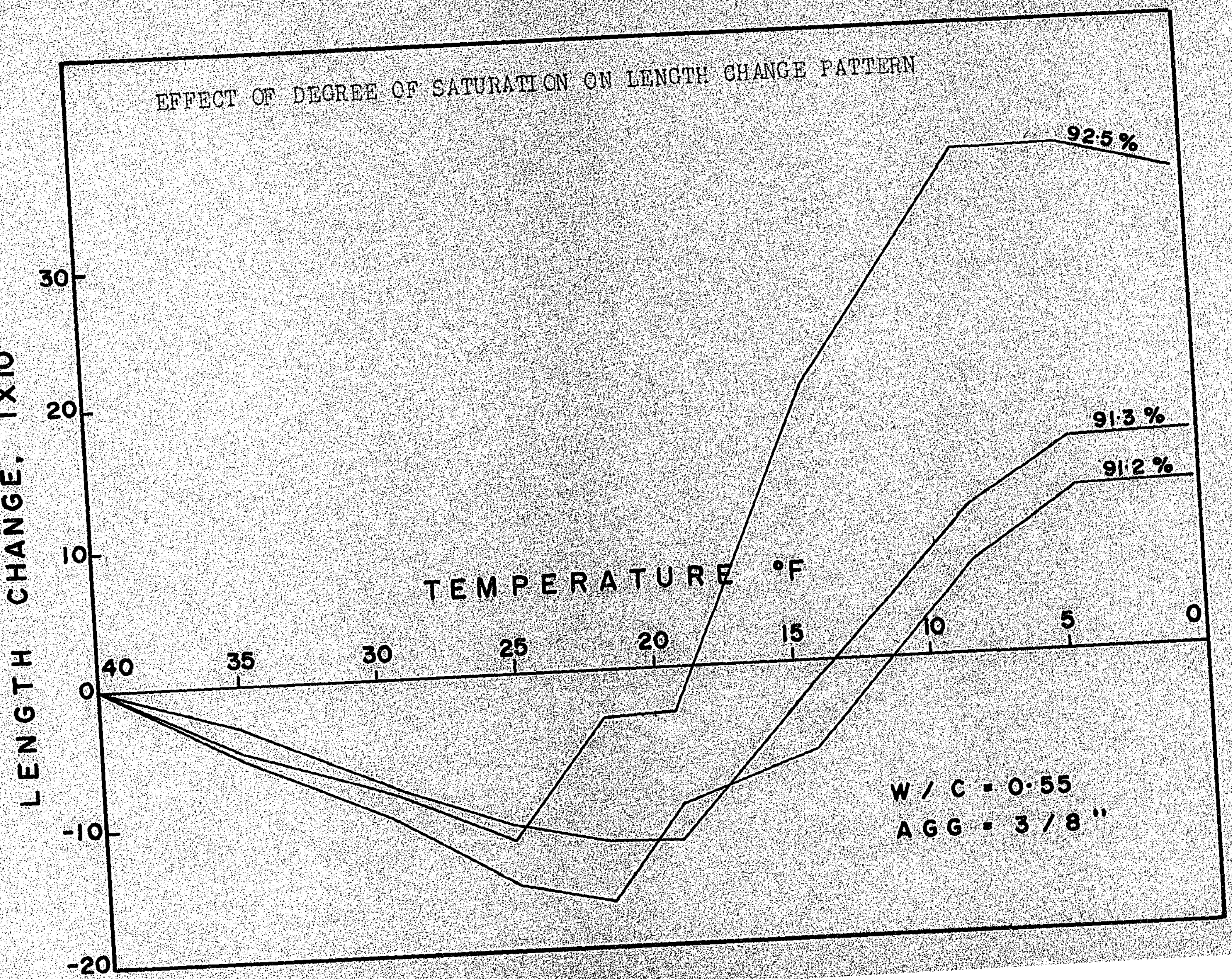
			TEMPERATURES °F									
SPEC.	Init.Rdg.	Surface Centre	40.0 40.0	35.0 36.0	27.1 28.4	23.2 24.5	20.1 20.8	17.6 18.5	15.2 16.0	7.8 9.5	1.0 1.5	

		$(\Delta L)10^3$										
		$(\Delta L/L)10^5$										
1	224.80		224.80	225.00	225.30	225.50	225.50	225.70	226.00	226.30	226.60	
		$(\Delta L)10^3$	0	-4.38	-10.95	-15.32	-15.32	-19.70	-26.30	-32.85	-39.40	
		$(\Delta L/L)10^5$	0	-3.08	-7.71	-9.28	-9.28	-13.88	-18.50	-23.10	-27.75	
2	251.80		251.80	252.00	252.40	252.60	252.50	252.70	252.90	253.30	253.70	
		$(\Delta L)10^3$	0	-4.62	-13.85	-18.48	-16.16	-20.80	-25.40	-34.60	-43.90	
		$(\Delta L/L)10^5$	0	-3.25	-9.75	-13.00	-11.38	-14.65	-17.90	-24.35	-30.90	
3	308.40		308.40	308.60	309.00	309.10	309.10	309.40	309.60	310.10	310.50	
		$(\Delta L)10^3$	0	-4.76	-14.28	-16.65	-16.65	-23.80	-28.60	-40.50	-50.00	
		$(\Delta L/L)10^5$	0	-3.35	-10.05	-11.72	-11.72	-16.75	-20.15	-28.55	-35.20	

SPEC.	Partially Sat. Wt.(1)	Vacuum Sat. Wt.(2)	Oven-Dried Wt.(3)	(2) - (3)	(1) - (3)	% Sat. $\frac{(1)-(3)}{(2)-(3)}$
1	3.542 lb.	3.632 lb.	3.232 lb.	0.400 lb.	0.310 lb.	77.5
2	3.562 lb.	3.659 lb.	3.254 lb.	0.405 lb.	0.308 lb.	76.1
3	3.500 lb.	3.599 lb.	3.201 lb.	0.398 lb.	0.299 lb.	75.0

NOTE: Transmitter Calibration Constants: (0) $2.38 \times 10^{-2} \frac{mm}{unit}$ (2) $2.31 \times 10^{-2} \frac{mm}{unit}$

(1) $2.29 \times 10^{-2} \frac{mm}{unit}$ (3) $2.19 \times 10^{-2} \frac{mm}{unit}$


EFFECT OF DEGREE OF SATURATION ON LENGTH CHANGE PATTERN
92.5 %
91.3 %
91.2 %
TEMPERATURE °F
40
35
30
25
20
15
10
5
0
LENGTH CHANGE, 1X10-5
30
20
10
0
-10
-20
W / C = 0·55
AGG = 3 / 8"

W/C = 0.55 Curing Time = 14 days Date: June 12, 1967

Agg. = 3/8 in. Air Dried = 64 days

Air = 7%

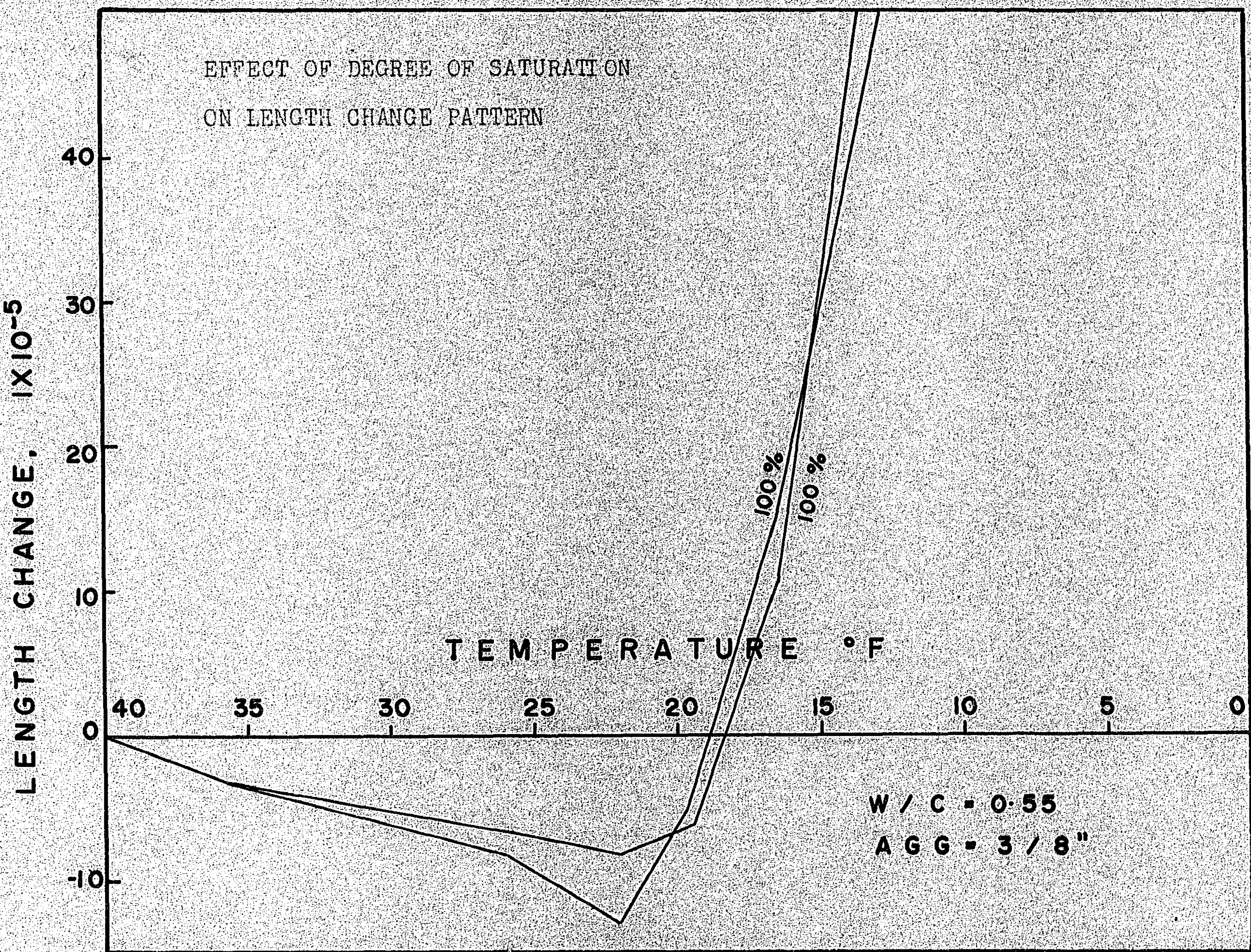
SPEC.	Init. Rdg.	Surface Centre	TEMPERATURES °F 38.5 41.0	34.0 35.8	29.0 30.0	24.5 26.2	21.1 22.6	18.9 19.8	14.0 14.5	8.8 9.8	4.0 5.0	0.0 1.0
	---	(ΔL)10³										
		(ΔL/L)10⁵										
1	234.00		234.00	234.30	234.50	234.70	234.20	234.20	232.80	231.80	231.80	231.70
		(ΔL)10³	0	-6.93	-11.55	-16.17	-4.62	-4.62	27.70	50.80	50.80	48.50
		(ΔL/L)10⁵	0	-4.88	-8.13	-11.38	-3.25	-3.25	19.50	35.80	35.80	34.15
2	253.90		253.90	254.10	254.40	254.60	254.70	254.70	254.00	253.20	252.90	252.90
		(ΔL)10³	0	-4.38	-10.94	-15.31	-17.50	-17.50	-2.19	15.31	21.90	21.90
		(ΔL/L)10⁵	0	-3.08	-7.71	-10.78	-12.32	-12.32	-1.54	10.78	15.40	15.40
2A	288.60		286.60	288.90	289.20	289.50	289.30	289.20	289.00	288.20	287.90	287.90
		(ΔL)10³	0	-7.14	-14.28	-21.40	-16.66	-14.28	-9.53	9.53	16.66	16.66
		(ΔL/L)10⁵	0	-5.03	-10.05	-15.06	-11.72	-10.05	-6.71	6.71	11.72	11.72

SPEC.	Partially Sat. Wt. (1)	Vacuum Sat. Wt. (2)	Oven-Dried Wt. (3)	(2) - (3)	(1) - (3)	% Sat. $\frac{(1)-(3)}{(2)-(3)}$
1	3.631 lb.	3.662 lb.	3.241 lb.	0.421 lb.	0.390 lb.	92.5
2	3.510 lb.	3.545 lb.	3.143 lb.	0.402 lb.	0.367 lb.	91.3
2A	3.492 lb.	3.527 lb.	3.131 lb.	0.396 lb.	0.361 lb.	91.2

NOTE: Transmitter Calibration Constants:

(0) $2.38 \times 10^{-2} \frac{mm}{unit}$ (2) $2.31 \times 10^{-2} \frac{mm}{unit}$

(1) $2.29 \times 10^{-2} \frac{mm}{unit}$ (3) $2.19 \times 10^{-2} \frac{mm}{unit}$


EFFECT OF DEGREE OF SATURATION
ON LENGTH CHANGE PATTERN
LENGTH CHANGE, 1X10-5
40
30
20
10
0
-10
TEMPERATURE °F
40
35
30
25
20
15
10
5
0
100 %
100 %
W / C = 0·55
AGG = 3 / 8"

W / C = 0.55
Agg. = 3/8
Air = 7%

Curing Time = 14 days
Air Dried = 16 days

Date: June 21, 1967

			TEMPERATURES °F									
SPEC.	Init.Rdg.	Surface Centre	40.0 41.0	35.6 36.0	25.8 26.4	21.6 22.6	17.0 17.5	16.2 16.7	11.2 11.2	6.0 6.0	0.0 1.0	
	---	$(\Delta L)10^3$										
		$(\Delta L/L)10^5$										
			273.00	273.20	273.50	273.80	273.80	272.10	269.10	268.00	267.50	
1	273.00	$(\Delta L)10^3$	0	-4.62	-11.55	-18.45	-18.45	20.80	90.00	115.50	127.00	
		$(\Delta L/L)10^5$	0	-3.25	-8.14	-13.00	-13.00	14.65	63.40	81.50	89.50	
			224.10	224.50	224.50	224.60	224.50	223.50	219.30	218.60	217.70	
1A	224.10	$(\Delta L)10^3$	0	-4.76	-9.52	-11.90	-9.52	14.28	114.10	131.00	152.10	
		$(\Delta L/L)10^5$	0	-3.28	-6.56	-8.39	-6.56	9.93	80.50	92.20	93.40	
	---	$(\Delta L)10^3$										
		$(\Delta L/L)10^5$										

SPEC.	Partially Sat. Wt. (1)	Vacuum Sat. Wt. (2)	Oven-Dried Wt. (3)	(2) - (3)	(1) - (3)	% Sat. $\frac{(1)-(3)}{(2)-(3)}$
0						
1	3.612 lb.	3.612 lb.	3.300 lb.	0.312 lb.	0.000	100.0
1A	3.547 lb.	3.547 lb.	3.231 lb.	0.316 lb.	0.000	100.0

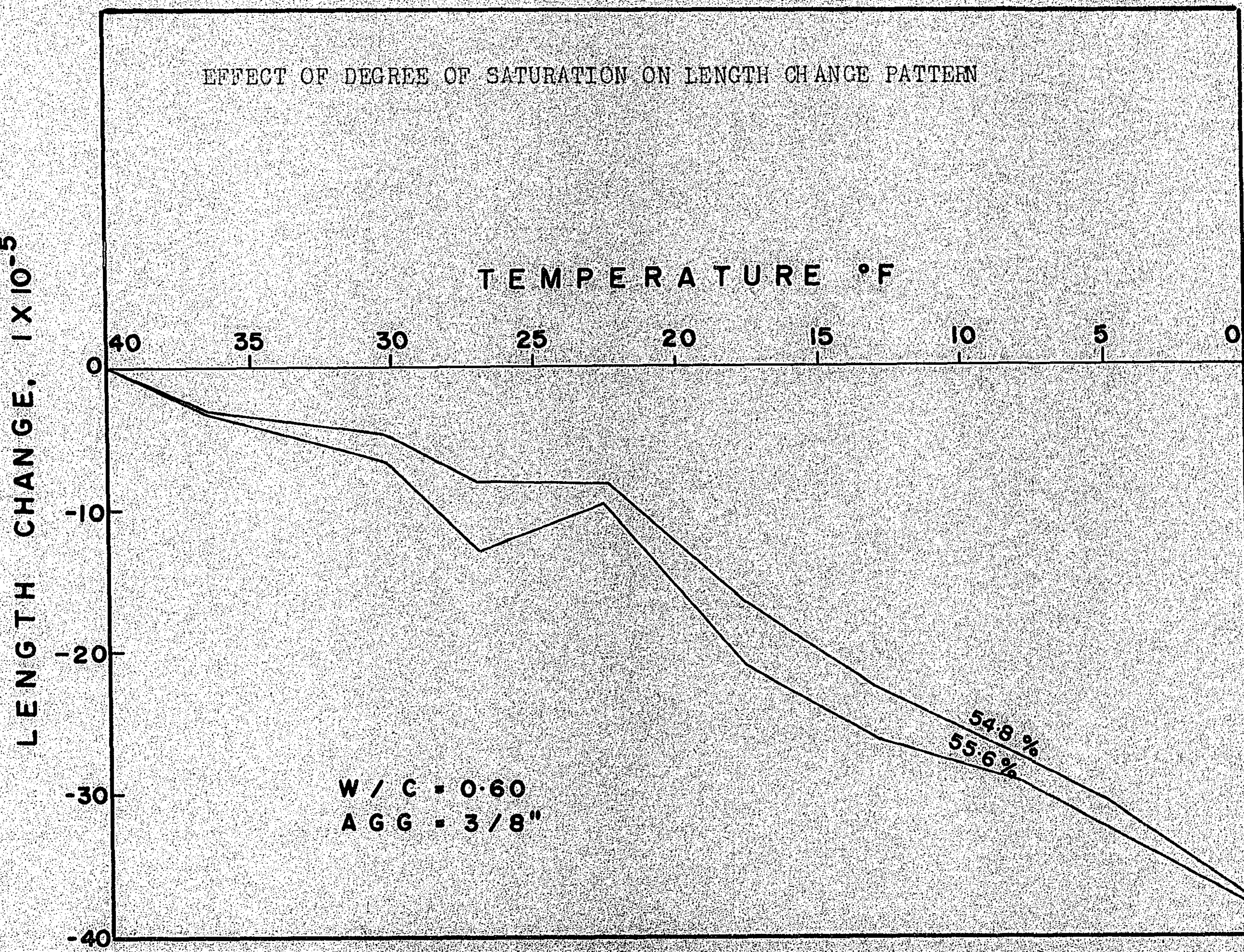
NOTE: Transmitter Calibration Constants:

(0) 2.38×10^{-2} $\frac{mm}{unit}$

(1) 2.29×10^{-2} $\frac{mm}{unit}$

(2) 2.31×10^{-2} $\frac{mm}{unit}$

(3) 2.19×10^{-2} $\frac{mm}{unit}$


EFFECT OF DEGREE OF SATURATION ON LENGTH CHANGE PATTERN
TEMPERATURE °F
40
35
30
25
20
15
10
5
0
LENGTH CHANGE, 1 X 10^-5
0
-10
-20
-30
-40
54·8 %
55·6 %
W / C = 0·60
AGG = 3/8"

W / C = 0.60

Agg. = 3/8 in.

Air = 7%

Curing Time = 14 days

Air Dried = 40 days

Date: June 7, 1967

SPEC.	Init.Rdg.	Surface / Centre	TEMPERATURES °F									
			40.3 / 40.0	36.2 / 37.0	30.0 / 30.5	26.8 / 27.2	22.3 / 23.0	17.1 / 17.6	12.8 / 13.1	7.8 / 7.8	5.0 / 5.0	0 / 0

		$(\Delta L)10^3$										
		$(\Delta L/L)10^5$										
4	153.00		153.00	153.20	153.30	153.50	153.50	154.00	154.40	154.70	154.90	155.20
		$(\Delta L)10^3$	0	-4.58	-6.86	-11.45	-11.45	-23.80	-32.05	-38.90	-43.50	-52.70
		$(\Delta L/L)10^5$	0	-3.23	-4.84	-8.07	-8.07	-16.75	-22.60	-27.40	-30.60	-37.15
5	240.80		240.80	241.00	241.20	241.60	241.40	242.10	242.40	242.60	242.80	243.20
		$(\Delta L)10^3$	0	-4.62	-9.24	-18.50	-13.85	-30.00	-36.95	-41.60	-46.20	-53.20
		$(\Delta L/L)10^5$	0	-3.26	-6.51	-13.01	-9.75	-21.10	-26.05	-29.30	-32.60	-37.45

		$(\Delta L)10^3$										
		$(\Delta L/L)10^5$										

SPEC.	Partially Sat. Wt. (1)	Vacuum Sat. Wt. (2)	Oven-Dried Wt. (3)	(2) - (3)	(1) - (3)	% Sat. $\frac{(1)-(3)}{(2)-(3)}$
4	3.438 lb.	3.612 lb.	3.227 lb.	0.385 lb.	0.211 lb.	54.8
5	3.432 lb.	3.595 lb.	3.228 lb.	0.367 lb.	0.204 lb.	55.6

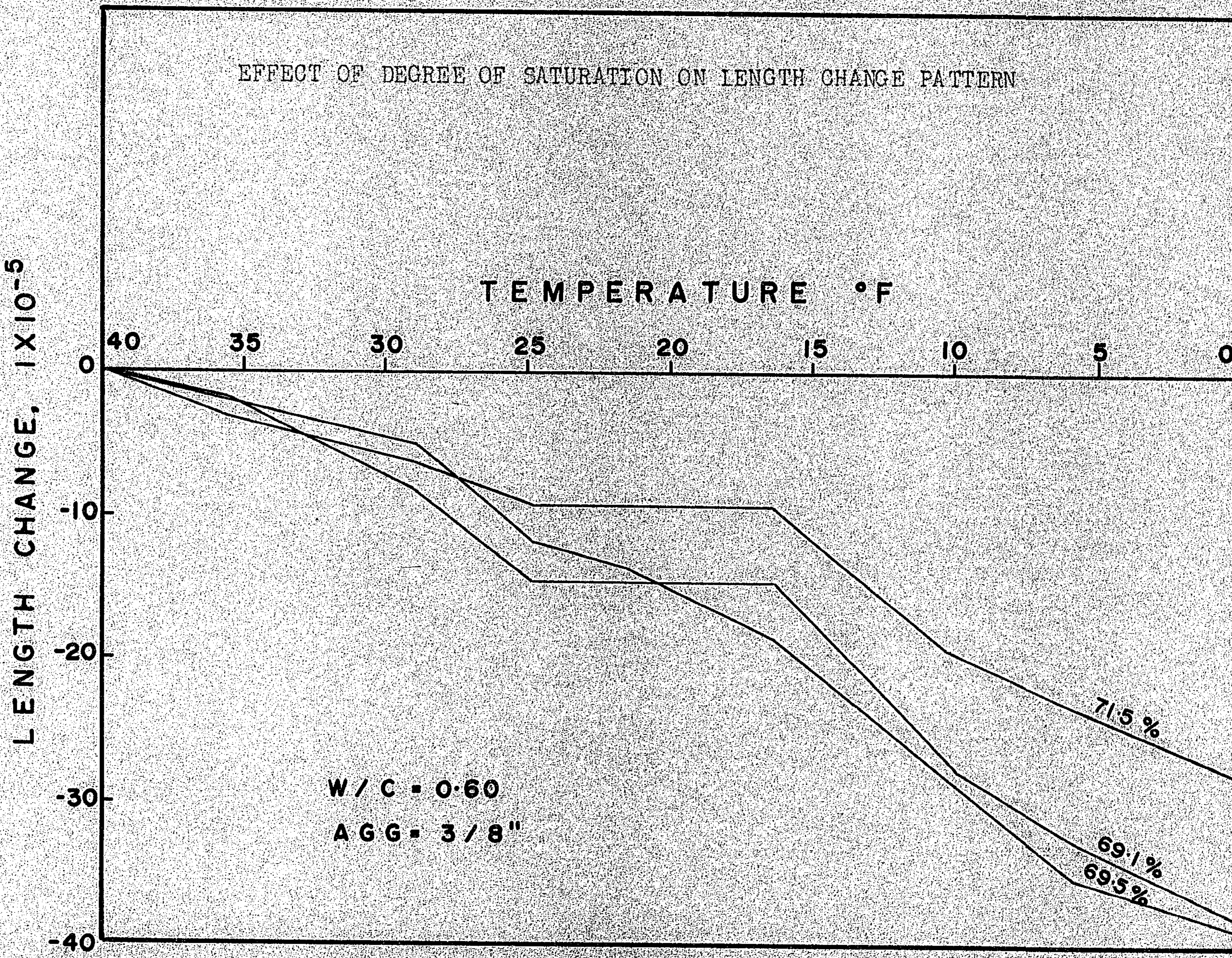
NOTE: Transmitter Calibration Constants:

(0) $2.38 \times 10^{-2} \frac{mm}{unit}$

(1) $2.29 \times 10^{-2} \frac{mm}{unit}$

(2) $2.31 \times 10^{-2} \frac{mm}{unit}$

(3) $2.19 \times 10^{-2} \frac{mm}{unit}$


EFFECT OF DEGREE OF SATURATION ON LENGTH CHANGE PATTERN
TEMPERATURE °F
40
35
30
25
20
15
10
5
0
LENGTH CHANGE, 1X10⁻⁵
0
-10
-20
-30
-40
71.5 %
69.1 %
69.5 %
W/C = 0.60
AGG = 3/8"

W / C = 0.60　　　　Curing Time = 14 days　　　　Date: June 19, 1967

Agg. = 3/8 in.　　　　Air Dried = 45 days

Air = 7%

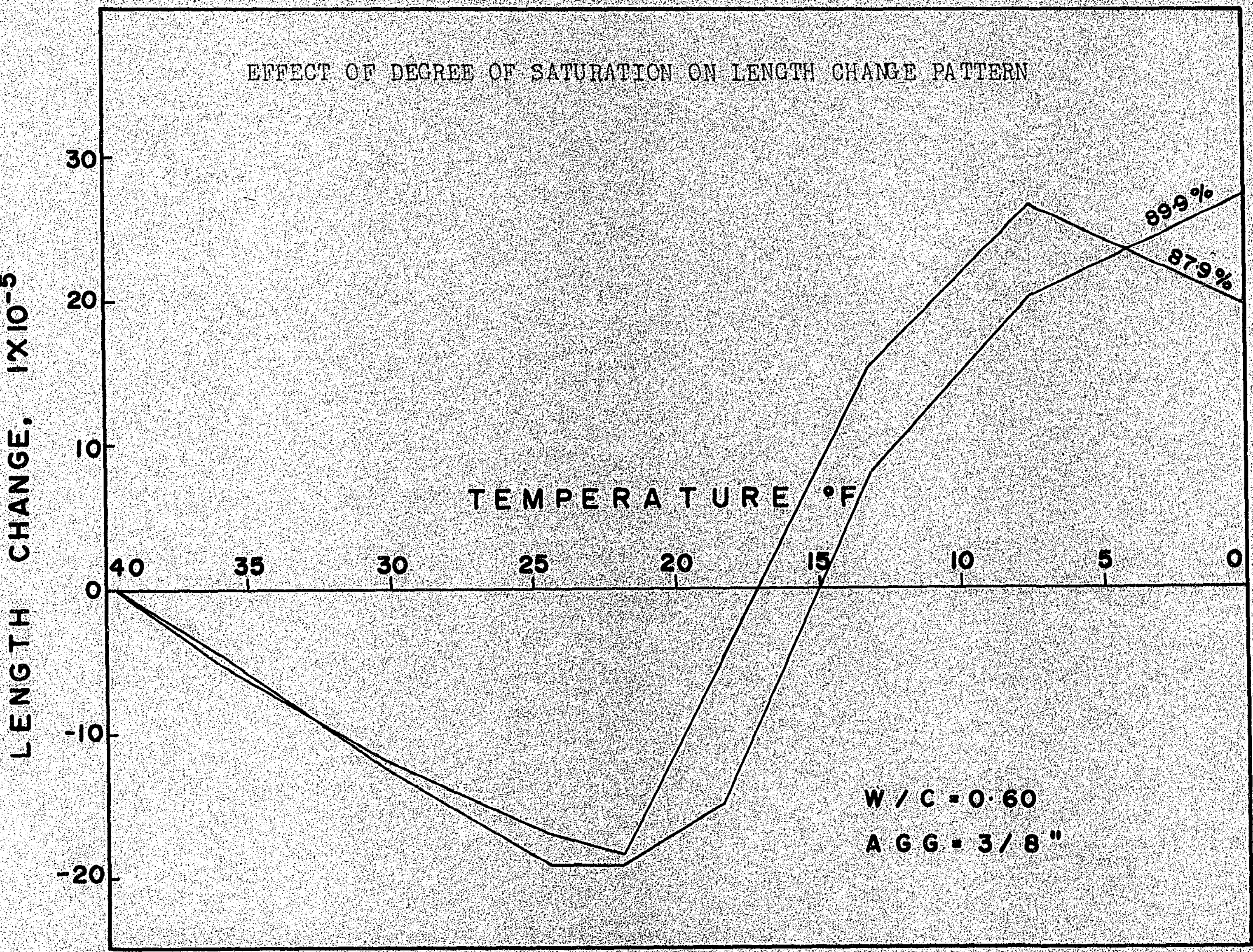
SPEC.	Init. Rdg.	Surface / Centre	TEMPERATURES °F									
			39.6 / 39.6	35.0 / 36.0	28.8 / 29.0	24.0 / 24.8	21.5 / 21.7	16.2 / 16.7	9.9 / 10.0	5.7 / 5.7	0.0 / 0.5	
4	280.10		280.10	280.20	280.60	281.00	281.00	281.00	281.80	282.10	282.50	
		$(\Delta L)10^3$	0	-2.31	-11.52	-20.80	-20.80	-20.80	-39.30	-46.20	-53.20	
		$(\Delta L/L)10^5$	0	-1.63	-8.13	-14.64	-14.64	-14.64	-27.65	-32.50	-37.40	
4A	210.80		210.80	211.00	211.20	211.40	211.40	211.40	212.10	212.30	212.60	
		$(\Delta L)10^3$	0	-4.38	-8.75	-13.14	-13.14	-13.14	-27.45	-32.80	-39.40	
		$(\Delta L/L)10^5$	0	-3.09	-6.17	-9.26	-9.26	-9.26	-19.33	-23.10	-27.85	
5	221.90		221.90	222.00	222.20	222.60	222.70	223.00	223.60	224.00	224.20	
		$(\Delta L)10^3$	0	-2.38	-7.14	-16.68	-19.05	-26.20	-40.50	-50.00	-54.80	
		$(\Delta L/L)10^5$	0	-1.68	-5.03	-11.75	-13.40	-18.45	-28.50	-35.20	-38.60	
	———	$(\Delta L)10^3$										
		$(\Delta L/L)10^5$										

SPEC.	Partially Sat. Wt. (1)	Vacuum Sat. Wt. (2)	Oven-Dried Wt. (3)	(2) - (3)	(1) - (3)	% Sat. $\frac{(1)-(3)}{(2)-(3)}$
4	3.418 lb.	3.536 lb.	3.154 lb.	0.382 lb.	0.264 lb.	69.1
4A	3.420 lb.	3.535 lb.	3.159 lb.	0.376 lb.	0.261 lb.	71.5
5	3.491 lb.	3.611 lb.	3.220 lb.	0.391 lb.	0.271 lb.	69.5

NOTE: Transmitter Calibration Constants:

(0) $2.38 \times 10^{-2} \frac{mm}{unit}$　　(2) $2.31 \times 10^{-2} \frac{mm}{unit}$

(1) $2.29 \times 10^{-2} \frac{mm}{unit}$　　(3) $2.19 \times 10^{-2} \frac{mm}{unit}$


EFFECT OF DEGREE OF SATURATION ON LENGTH CHANGE PATTERN
LENGTH CHANGE, 1"X10^-5
TEMPERATURE °F
89.9%
87.9%
W/C = 0·60
AGG = 3/8"
30
20
10
0
-10
-20
40
35
30
25
20
15
10
5
0

W / C = 0.60

Agg. = 3/8 in.

Air = 7%

Curing Time = 14 days

Air Dried = 45 days

Date: June 18, 1967

SPEC.	Init.Rdg.	Surface / Centre	TEMPERATURES °F									
			39.5 / 39.5	35.5 / 36.5	30.1 / 30.7	24.1 / 24.8	21.7 / 22.2	18.5 / 18.5	13.0 / 13.4	7.60 / 7.80	0.5 / 1.0	

		$(\Delta L)10^3$										
		$(\Delta L/L)10^5$										
4	232.00		232.00	232.30	232.80	233.20	233.20	233.00	231.50	230.70	230.30	
		$(\Delta L)10^3$	0	-6.56	-17.51	-26.30	-26.30	-21.9	10.95	28.60	37.20	
		$(\Delta L/L)10^5$	0	-4.61	-12.31	-19.20	-19.20	-15.42	7.70	20.10	26.20	
5	230.70		230.70	231.00	231.40	231.70	231.80	231.00	229.80	229.10	229.50	
		$(\Delta L)10^3$	0	-7.14	-16.67	-23.80	-26.20	-7.14	21.40	38.10	28.60	
		$(\Delta L/L)10^5$	0	-5.03	-11.72	-16.75	-18.45	-5.03	15.08	26.80	20.15	

		$(\Delta L)10^3$										
		$(\Delta L/L)10^5$										

SPEC.	Partially Sat. Wt. (1)	Vacuum Sat. Wt. (2)	Oven-Dried Wt. (3)	(2) - (3)	(1) - (3)	% Sat. $\frac{(1)-(3)}{(2)-(3)}$
4	3.518 lb.	3.557 lb.	3.518 lb.	0.382 lb.	0.343 lb.	89.9
5	3.598 lb.	3.645 lb.	3.598 lb.	0.388 lb.	0.341 lb.	87.9

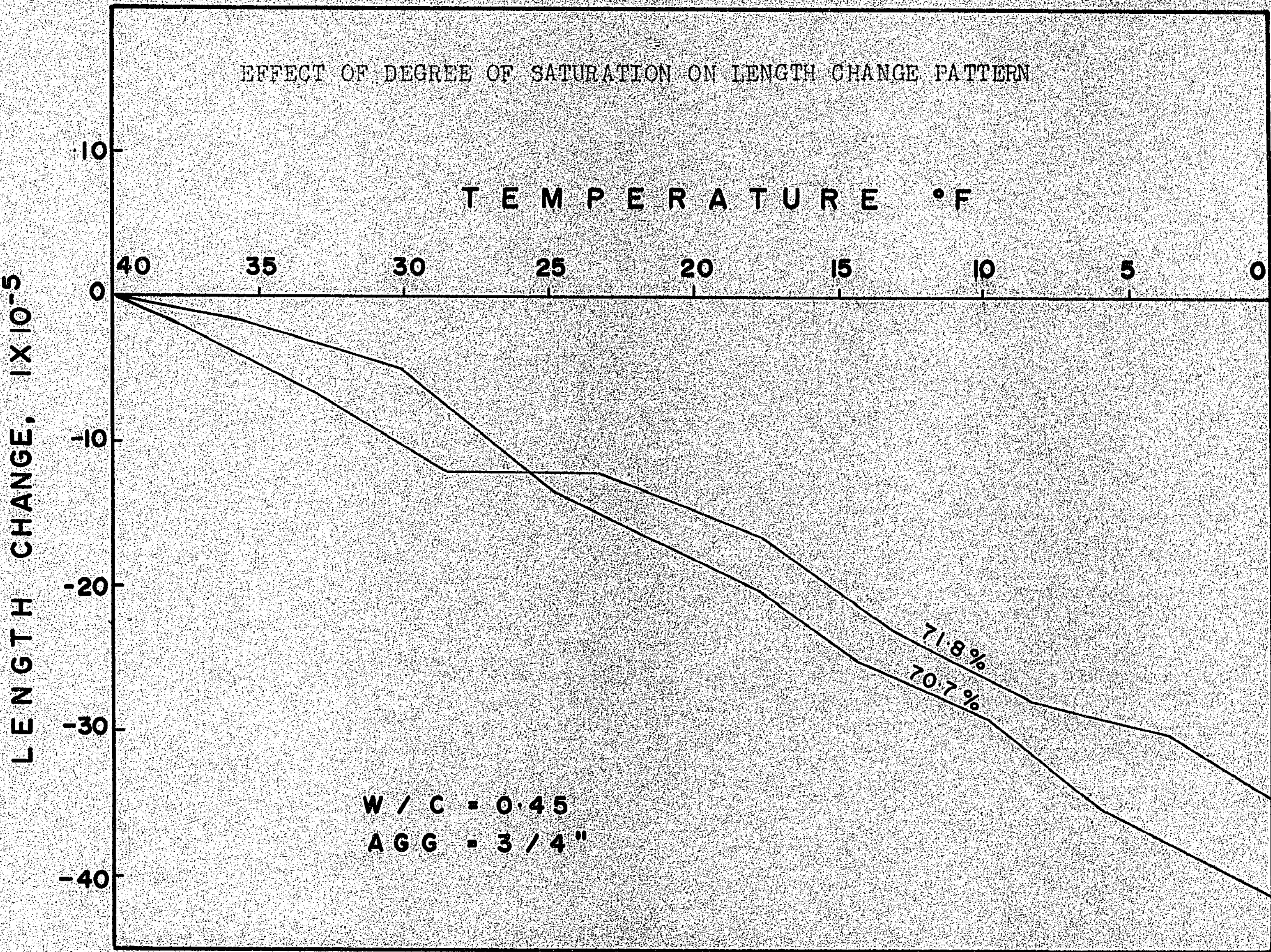
NOTE: Transmitter Calibration Constants:

(0) $2.38 \times 10^{-2} \frac{mm}{unit}$

(1) $2.29 \times 10^{-2} \frac{mm}{unit}$

(2) $2.31 \times 10^{-2} \frac{mm}{unit}$

(3) $2.19 \times 10^{-2} \frac{mm}{unit}$


EFFECT OF DEGREE OF SATURATION ON LENGTH CHANGE PATTERN
TEMPERATURE °F
40
35
30
25
20
15
10
5
0
LENGTH CHANGE, 1X10-5
10
0
-10
-20
-30
-40
71.8%
70.7%
W / C = 0.45
AGG = 3/4"

W/C = 0.45
Agg. = 3/4 in.
Air = 7%

Curing Time = 14 days
Air Dried = 62 days

Date: June 2, 1967

SPEC.	Init.Rdg.	Surface / Centre	40.0 / 40.1	35.0 / 36.5	29.5 / 30.2	24.0 / 25.7	17.0 / 18.5	13.5 / 14.8	9.0 / 10.4	5.2 / 6.4	0.5 / 1.4	
	---	$(\Delta L)10^3$										
		$(\Delta L/L)10^5$										
	---	$(\Delta L)10^3$										
		$(\Delta L/L)10^5$										
			276.90	277.00	277.20	277.70	278.10	278.40	278.60	279.00	279.30	
3B	276.90	$(\Delta L)10^3$	0	-2.38	-7.14	-19.03	-28.60	-35.70	-40.40	-50.00	-57.10	
		$(\Delta L/L)10^5$	0	-1.68	-5.03	-13.40	-20.15	-25.15	-28.48	-35.20	-40.20	
	---	$(\Delta L)10^3$										
		$(\Delta L/L)10^5$										

(Column group heading: TEMPERATURES °F)

SPEC.	Partially Sat. Wt. (1)	Vacuum Sat. Wt. (2)	Oven-Dried Wt. (3)	(2) - (3)	(1) - (3)	% Sat. $\frac{(1)-(3)}{(2)-(3)}$
3B	3.811 lb.	3.895 lb.	3.613 lb.	0.280 lb.	0.198 lb.	70.7

NOTE: Transmitter Calibration Constants:

(0) $2.38 \times 10^{-2} \frac{mm}{unit}$ (2) $2.31 \times 10^{-2} \frac{mm}{unit}$

(1) $2.29 \times 10^{-2} \frac{mm}{unit}$ (3) $2.19 \times 10^{-2} \frac{mm}{unit}$

W/C = 0.45
Agg. = 3/4 in.
Air = 7%

Curing Time = 14 days
Air Dried = 62 days

Date: June 8, 1967

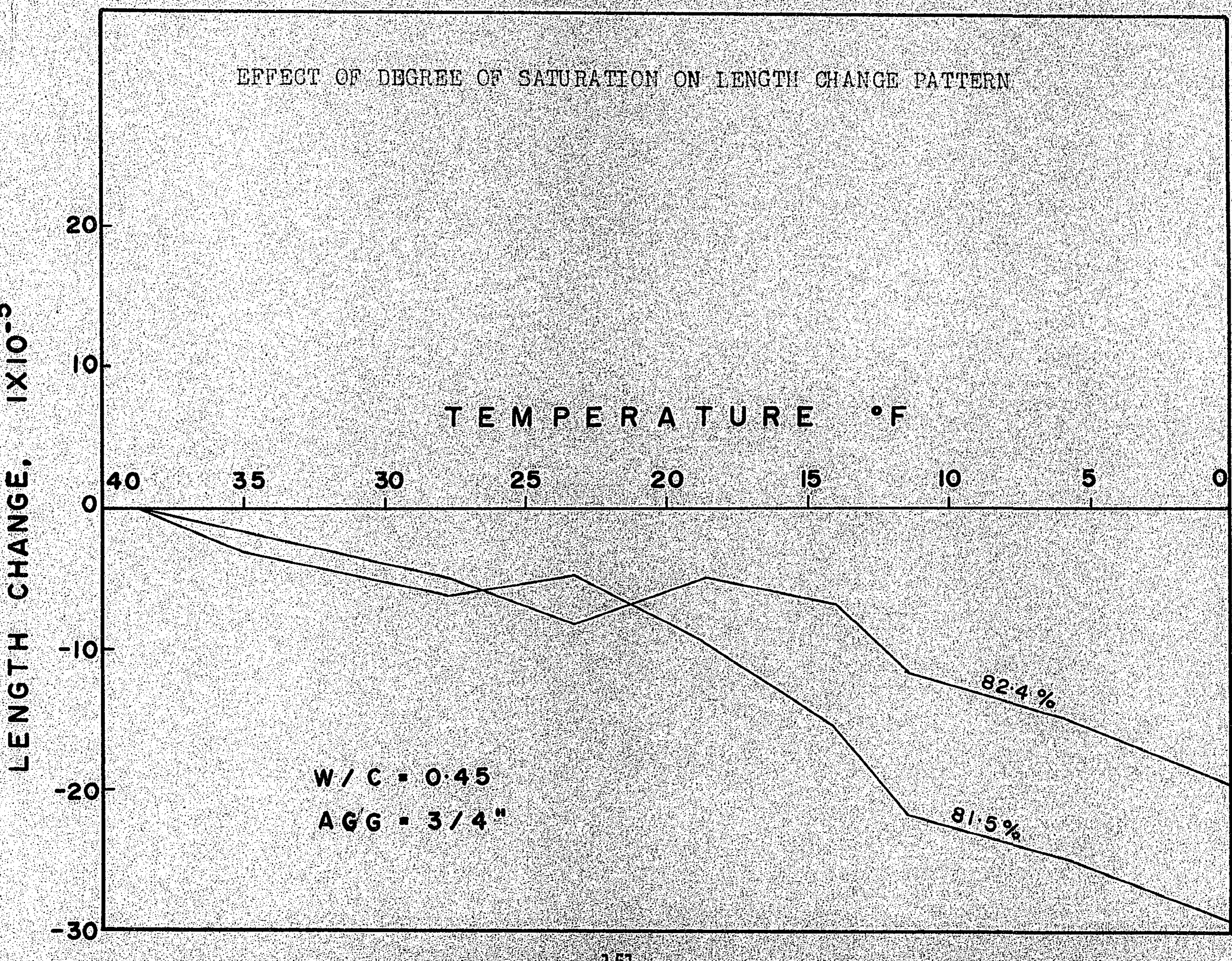
SPEC.	Init.Rdg.	Surface Centre	TEMPERATURES °F 38.0 38.0	32.5 33.8	28.0 29.3	22.1 24.4	16.8 18.5	12.5 13.5	7.5 8.5	3.0 4.4	-0.5 0.5	
	---	$(\Delta L)10^3$										
		$(\Delta L/L)10^5$										
	---	$(\Delta L)10^3$										
		$(\Delta L/L)10^5$										
	---	$(\Delta L)10^3$										
		$(\Delta L/L)10^5$										
			249.40	249.70	250.00	250.00	250.30	250.70	251.00	251.10	251.40	
3	249.30 ---	$(\Delta L)10^3$	-2.31	-9.24	-16.16	-16.16	-23.10	-32.30	-39.20	-41.60	-48.50	
		$(\Delta L/L)10^5$	-1.63	-6.51	-11.38	-11.38	-16.30	-22.75	-27.60	-29.30	-34.20	

SPEC.	Partially Sat. Wt. (1)	Vacuum Sat. Wt. (2)	Oven-Dried Wt. (3)	(2) - (3)	(1) - (3)	% Sat. $\frac{(1)-(3)}{(2)-(3)}$
3	3.783 lb.	3.849 lb.	3.615 lb.	0.234 lb.	0.168 lb.	71.8

NOTE: Transmitter Calibration Constants:

(0) $2.38 \times 10^{-2} \frac{mm}{unit}$ (2) $2.31 \times 10^{-2} \frac{mm}{unit}$

(1) $2.29 \times 10^{-2} \frac{mm}{unit}$ (3) $2.19 \times 10^{-2} \frac{mm}{unit}$


EFFECT OF DEGREE OF SATURATION ON LENGTH CHANGE PATTERN
TEMPERATURE °F
LENGTH CHANGE, 1X10⁻⁵
40
35
30
25
20
15
10
5
0
20
10
0
-10
-20
-30
82·4 %
81·5 %
W/C = 0·45
AGG = 3/4"

W / C = 0.45　　Curing Time = 14 days　　Date: May 30, 1967

Agg. = 3/4　　Air Dried = 60 days

Air = 7%

SPEC.	Init. Rdg.	Surface / Centre	TEMPERATURES °F									
			38.5 / 38.5	34.8 / 35.0	27.5 / 28.0	23.0 / 23.4	18.6 / 19.0	14.0 / 14.0	11.5 / 11.5	5.9 / 5.9	0.0 / 0.0	
0	---											
		$(\Delta L)10^3$										
		$(\Delta L/L)10^5$										
1	296.00		296.00	296.10	296.30	296.50	296.30	296.40	296.70	296.90	297.20	
		$(\Delta L)10^3$	0	-2.31	-6.93	-11.52	-6.93	-9.24	-16.17	-20.8	-27.70	
		$(\Delta L/L)10^5$	0	-1.63	-4.88	-8.12	-4.88	-6.50	-11.40	-14.66	-19.50	
2	238.60		238.60	238.80	239.00	238.90	239.20	239.60	240.00	240.20	240.50	
		$(\Delta L)10^3$	0	-4.38	-8.75	-6.56	-13.12	-21.9	-30.7	-35.00	-41.60	
		$(\Delta L/L)10^5$	0	-3.08	-6.16	-4.61	-9.25	-15.41	-21.6	-24.6	-29.3	

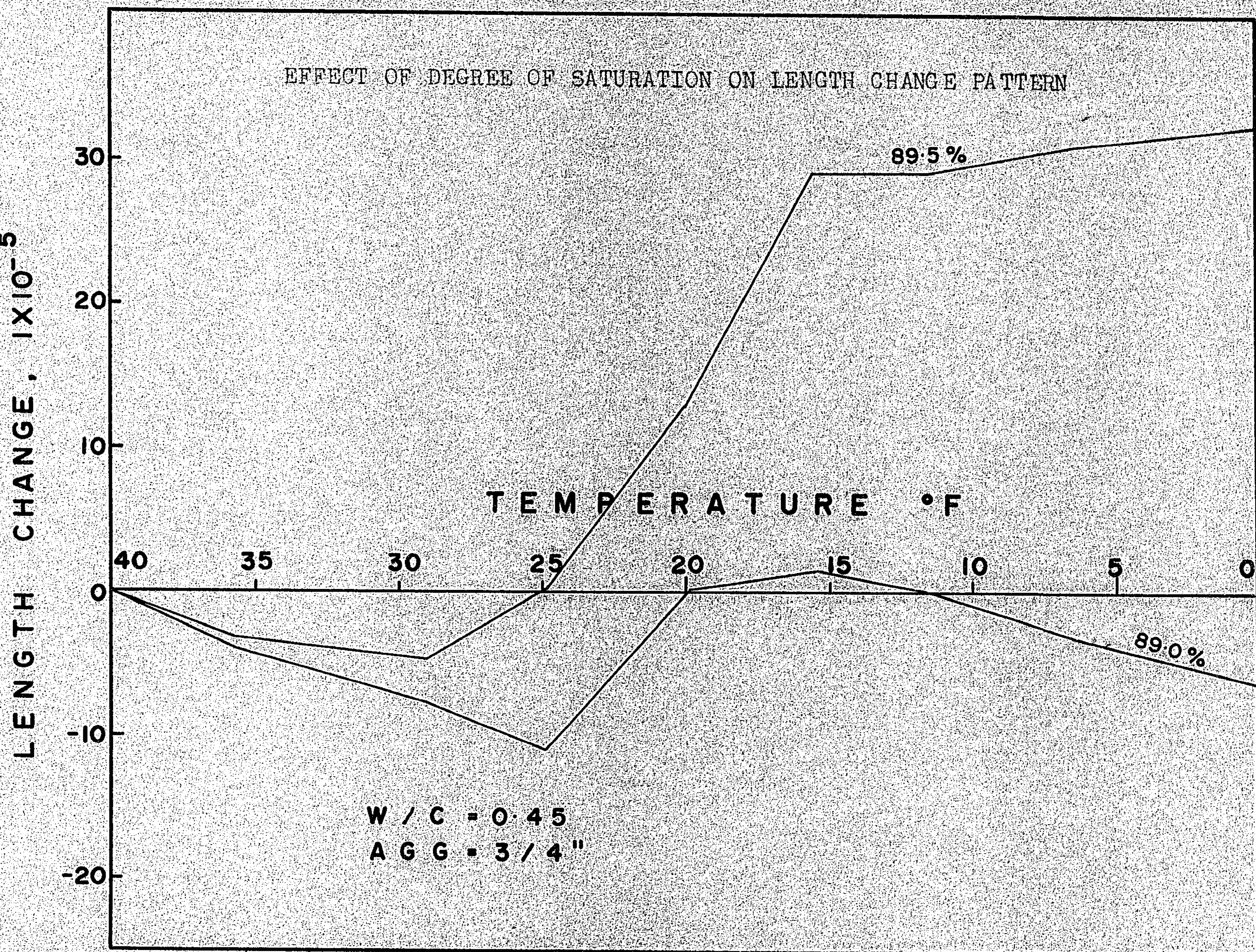
		$(\Delta L)10^3$										
		$(\Delta L/L)10^5$										

SPEC.	Partially Sat. Wt. (1)	Vacuum Sat. Wt. (2)	Oven-Dried Wt. (3)	(2) - (3)	(1) - (3)	% Sat. $\frac{(1)-(3)}{(2)-(3)}$
0						
1	3.789 lb.	3.841 lb.	3.537 lb.	0.306 lb.	0.252 lb.	82.4
2	3.767 lb.	3.824 lb.	3.516 lb.	0.308 lb.	0.251 lb.	81.5

NOTE: Transmitter Calibration Constants:

(0) 2.38×10^{-2} $\frac{mm}{unit}$　　(2) 2.31×10^{-2} $\frac{mm}{unit}$

(1) 2.29×10^{-2} $\frac{mm}{unit}$　　(3) 2.19×10^{-2} $\frac{mm}{unit}$


EFFECT OF DEGREE OF SATURATION ON LENGTH CHANGE PATTERN
89·5 %
89·0 %
TEMPERATURE °F
LENGTH CHANGE, 1X10⁻⁵
W / C = 0·45
AGG = 3/4"
30
20
10
0
-10
-20
40
35
30
25
20
15
10
5
0

W/C = 0.45 Curing Time = 14 days Date: May 31, 1967

Agg. = 3/4 Air Dried = 60 days

Air = 7%

SPEC.	Init.Rdg.	Surface / Centre	TEMPERATURES °F									
			40.50 / 40.6	35.0 / 36.5	28.0 / 30.0	24.0 / 25.7	19.4 / 20.3	15.0 / 15.8	11.0 / 12.2	6.0 / 7.0	-1.0 / 0.0	

		$(\Delta L)10^3$										
		$(\Delta L/L)10^5$										
1	265.00		265.00	265.25	265.50	265.70	265.00	265.10	265.00	264.80	265.20	
		$(\Delta L)10^3$	0	-5.47	-10.94	-15.32	0	2.19	0	-4.38	-8.76	
		$(\Delta L/L)10^5$	0	-3.85	-7.71	-10.79	0	1.54	0	-3.08	-6.16	
2	263.80		265.80	264.00	264.10	263.80	263.00	262.00	262.00	261.90	261.80	
		$(\Delta L)10^3$	0	-4.58	-6.86	0	18.32	41.3	41.30	43.50	45.80	
		$(\Delta L/L)10^5$	0	-3.23	-4.84	0	12.90	29.10	29.10	30.80	32.30	

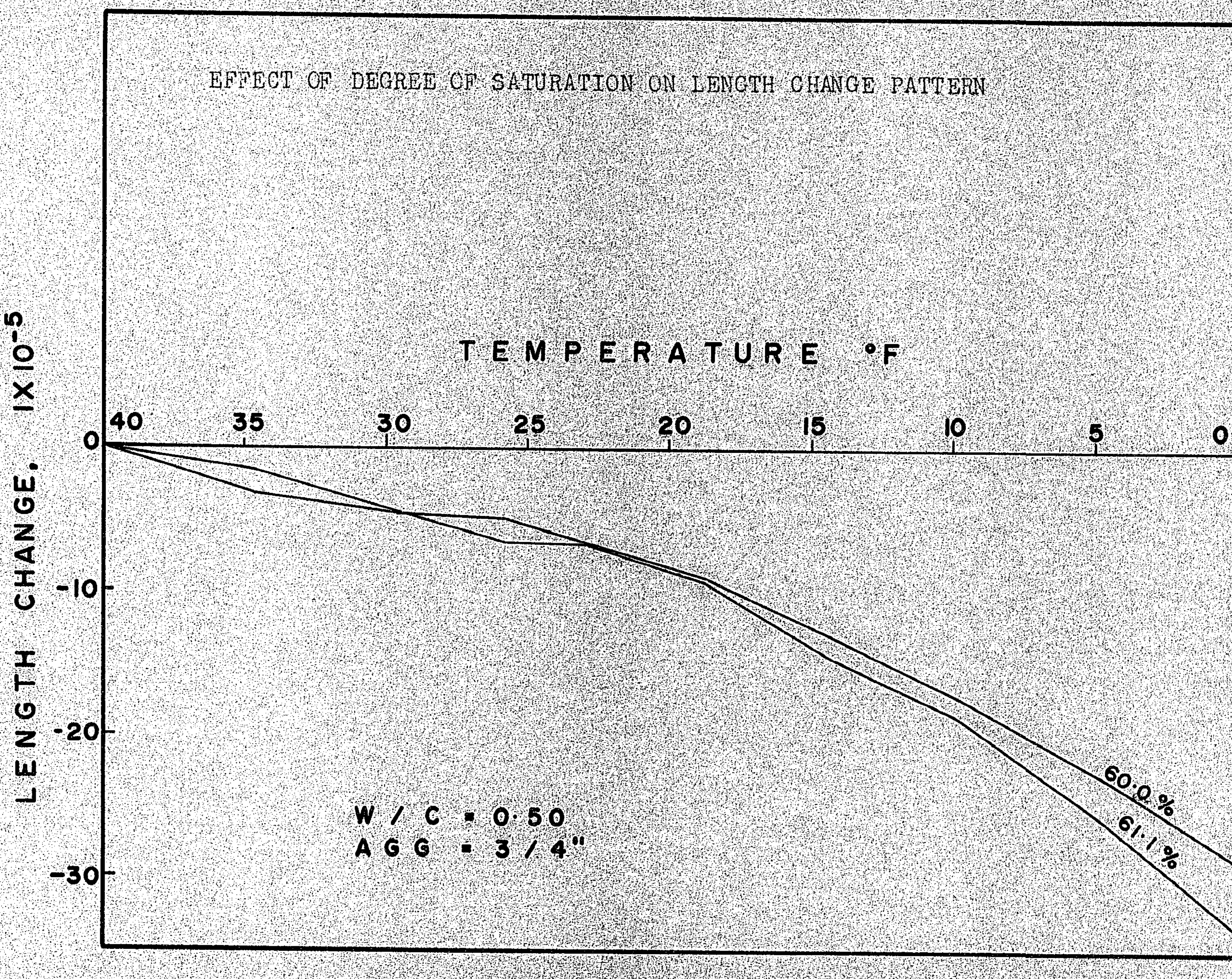
		$(\Delta L)10^3$										
		$(\Delta L/L)10^5$										

SPEC.	Partially Sat. Wt. (1)	Vacuum Sat. Wt. (2)	Oven-Dried Wt. (3)	(2) - (3)	(1) - (3)	% Sat. $\frac{(1)-(3)}{(2)-(3)}$
1	3.829 lb.	3.861 lb.	3.568 lb.	0.293 lb.	0.262 lb.	89.5
2	3.830 lb.	3.862 lb.	3.562 lb.	0.300 lb.	0.267 lb.	89.0

NOTE: Transmitter Calibration Constants:

(0) $2.38 \times 10^{-2} \frac{mm}{unit}$ (2) $2.31 \times 10^{-2} \frac{mm}{unit}$

(1) $2.29 \times 10^{-2} \frac{mm}{unit}$ (3) $2.19 \times 10^{-2} \frac{mm}{unit}$


EFFECT OF DEGREE OF SATURATION ON LENGTH CHANGE PATTERN
TEMPERATURE °F
40
35
30
25
20
15
10
5
0
LENGTH CHANGE, 1X10-5
0
-10
-20
-30
60·0 %
61·1 %
W / C = 0·50
AGG = 3 / 4"

W/C = 0.50
Agg. = 3/4 in.
Air = 7%

Curing Time = 14 days
Air Dried = 68 days

Date: June 6, 1967

SPEC.	Init.Rdg.	Surface / Centre	39.2 / 39.4	34.0 / 35.2	28.0 / 29.3	25.0 / 26.6	22.3 / 24.0	18.0 / 19.4	13.6 / 14.9	9.3 / 10	4.0 / 5.0	0.0 / 1.0
	---	$(\Delta L)10^3$										
		$(\Delta L/L)10^5$										
	---	$(\Delta L)10^3$										
		$(\Delta L/L)10^5$										
2	215.90		215.90	216.00	216.20	216.30	216.30	216.40	216.80	217.20	217.50	217.90
	---	$(\Delta L)10^3$	0	-2.29	-6.86	-9.15	-9.15	-11.45	-20.60	-29.80	-36.65	-45.80
		$(\Delta L/L)10^5$	00	-1.61	-4.84	-6.45	-6.45	-8.07	-14.51	-21.00	-25.80	-32.25
3	259.50		259.50	259.70	259.80	259.80	259.90	260.00	260.30	260.60	260.90	261.20
		$(\Delta L)10^3$	0	-4.62	-6.83	-6.93	-9.25	-11.55	-18.48	-25.40	-32.30	-39.30
		$(\Delta L/L)10^5$	0	-3.22	-4.88	-4.88	-6.52	-8.14	-13.00	-17.90	-22.75	-27.70

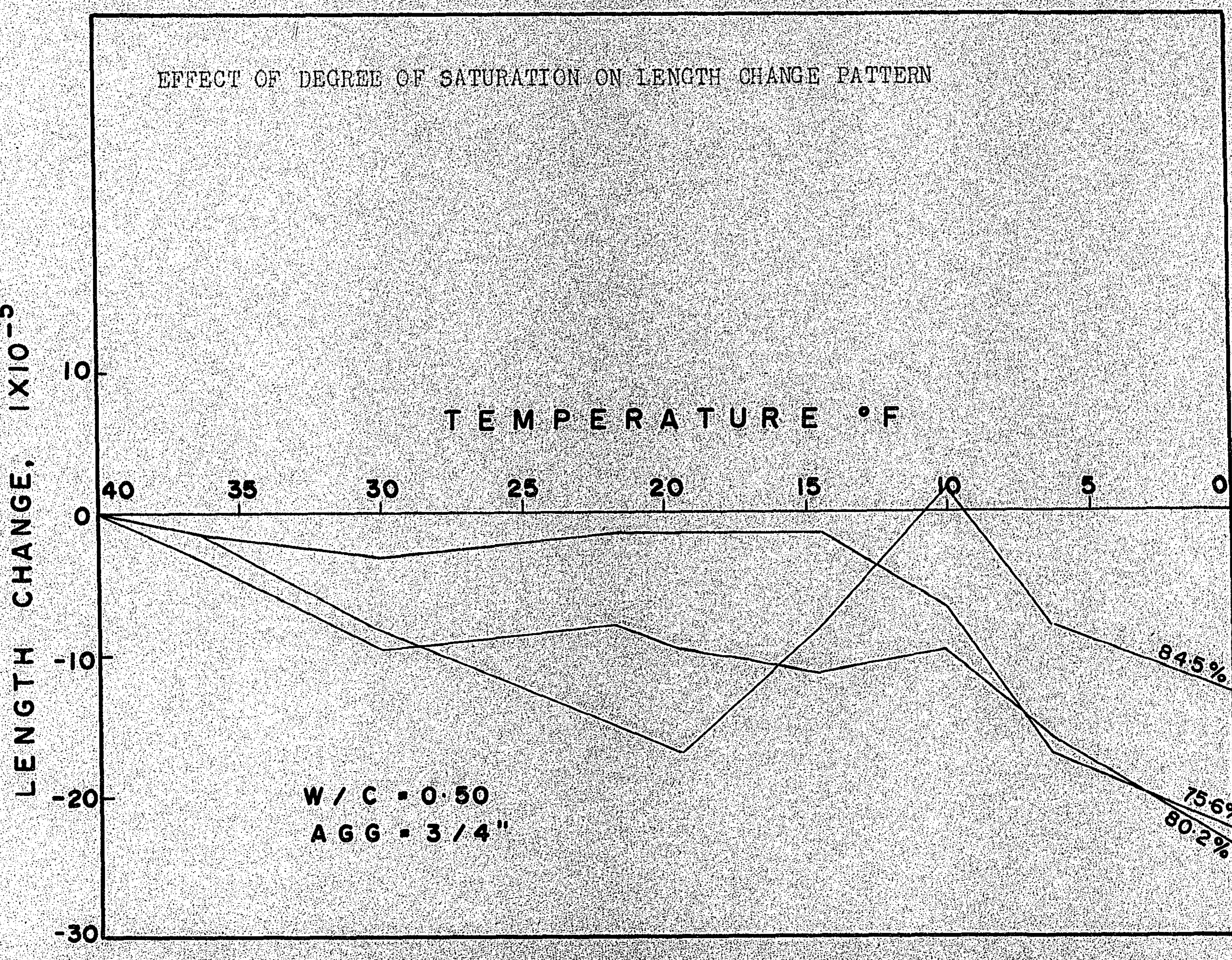
(Column group heading: TEMPERATURES °F)

SPEC.	Partially Sat. Wt. (1)	Vacuum Sat. Wt. (2)	Oven-Dried Wt. (3)	(2) - (3)	(1) - (3)	% Sat. $\frac{(1)-(3)}{(2)-(3)}$
2	3.628 lb.	3.753 lb.	3.431 lb.	0.322 lb.	0.197 lb.	61.1
3	3.461 lb.	3.596 lb.	3.259 lb.	0.337 lb.	0.202 lb.	60.0

NOTE: Transmitter Calibration Constants:

(0) $2.38 \times 10^{-2}\ \frac{mm}{unit}$ (2) $2.31 \times 10^{-2}\ \frac{mm}{unit}$

(1) $2.29 \times 10^{-2}\ \frac{mm}{unit}$ (3) $2.19 \times 10^{-2}\ \frac{mm}{unit}$


EFFECT OF DEGREE OF SATURATION ON LENGTH CHANGE PATTERN
TEMPERATURE °F
40
35
30
25
20
15
10
5
0
LENGTH CHANGE, 1X10⁻⁵
10
0
-10
-20
-30
84.5%
75.6%
80.2%
W / C = 0.50
AGG = 3/4"

W / C = 0.50

Agg. = 3/4 in.

Air = 7%

Curing Time = 14 days

Air Dried = 76 days

Date: June 15, 1967

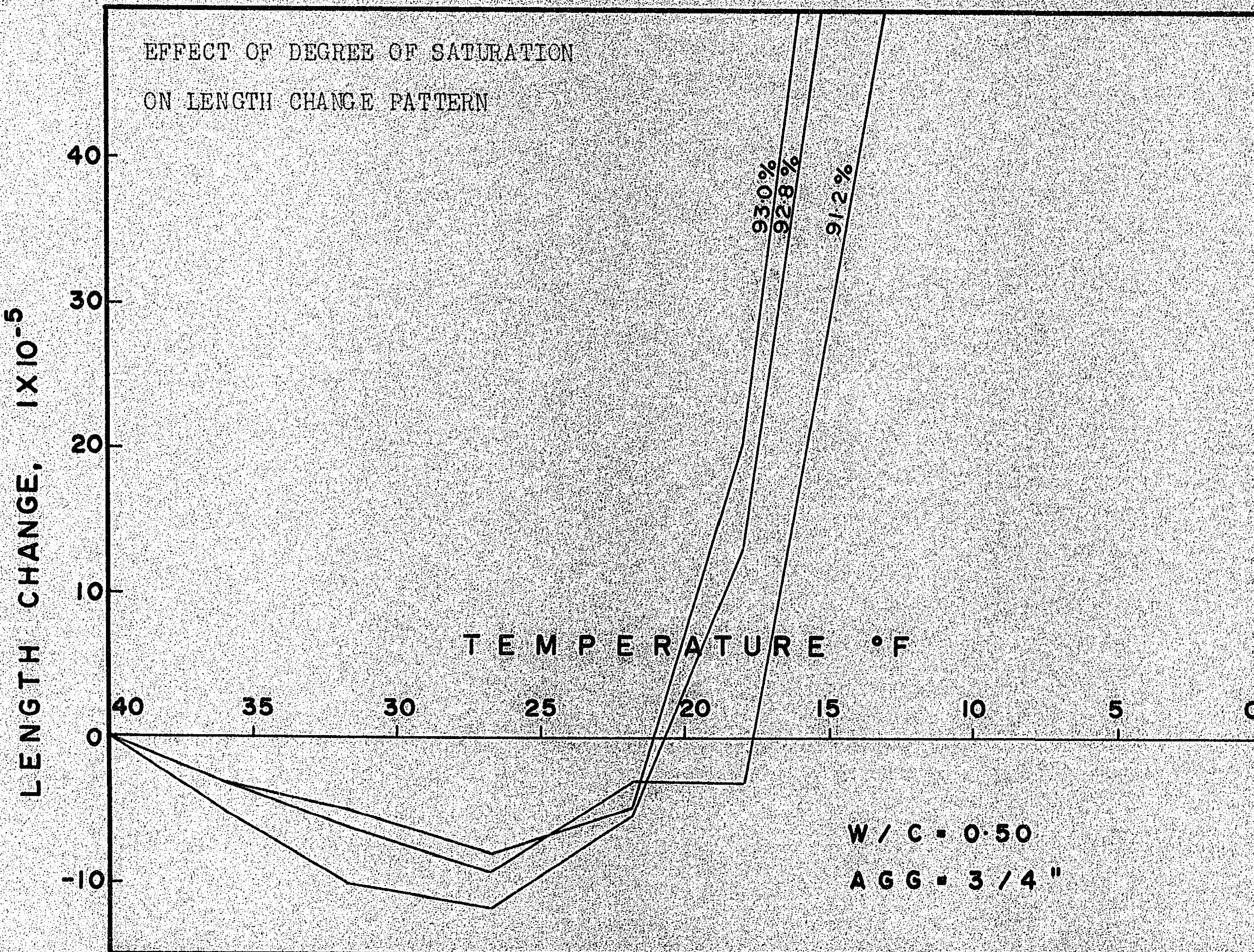
SPEC.	Init.Rdg.		TEMPERATURES °F									
		Surface Centre	40.0 40.0	36.0 36.4	29.5 30.2	21.5 21.5	18.9 20.3	14.0 14.9	10.0 10.7	6.0 6.8	1.0 1.5	
	---	$(\Delta L)10^3$										
		$(\Delta L/L)10^5$										
1	213.40		213.40	213.50	213.80	213.50	213.80	213.80	214.00	214.50	214.80	
		$(\Delta L)10^3$	0	-2.19	-8.75	-2.19	-8.75	-8.75	-13.12	-24.10	-30.70	
		$(\Delta L/L)10^5$	0	-1.54	-6.16	-1.54	-1.54	-1.54	-9.25	-16.97	-21.60	
2	322.30		322.30	322.40	322.80	323.20	323.30	322.80	322.20	322.80	323.00	
		$(\Delta L)10^3$	0	-2.38	-11.90	-21.60	-23.80	-11.90	2.38	-11.90	-16.67	
		$(\Delta L/L)10^5$	0	-1.68	-8.38	-15.20	-16.75	-8.38	1.68	-8.38	-11.72	
2A	244.30		244.30	244.50	244.90	244.80	244.90	245.00	244.90	245.30	245.70	
		$(\Delta L)10^3$	0	-4.62	-13.86	-11.43	-13.86	-16.17	-13.16	-23.10	-31.20	
		$(\Delta L/L)10^5$	0	-3.27	-9.76	-8.06	-9.76	-11.38	-9.76	-16.27	-21.95	

SPEC.	Partially Sat. Wt. (1)	Vacuum Sat. Wt. (2)	Oven-Dried Wt. (3)	(2) - (3)	(1) - (3)	% Sat. $\frac{(1)-(3)}{(2)-(3)}$
1	3.631 lb.	3.712 lb.	3.368 lb.	0.343 lb.	0.262 lb.	76.5
2	3.730 lb.	3.780 lb.	3.458 lb.	0.322 lb.	0.272 lb.	84.5
2A	3.728 lb.	3.789 lb.	3.482 lb.	0.307 lb.	0.246 lb.	80.2

NOTE: Transmitter Calibration Constants:

(0) $2.38 \times 10^{-2} \frac{mm}{unit}$ (2) $2.31 \times 10^{-2} \frac{mm}{unit}$

(1) $2.29 \times 10^{-2} \frac{mm}{unit}$ (3) $2.19 \times 10^{-2} \frac{mm}{unit}$


EFFECT OF DEGREE OF SATURATION
ON LENGTH CHANGE PATTERN
LENGTH CHANGE, 1X10^-5
40
30
20
10
0
-10
TEMPERATURE °F
40
35
30
25
20
15
10
5
0
93.0%
92.8%
91.2%
W/C = 0.50
AGG = 3/4"

W / C = 0.50

Agg. = 3/4 in.

Air = 7%

Curing Time = 14 days

Air Dried = 74 days

Date: June 13, 1967

SPEC.	Init. Rdg.	Surface / Centre	TEMPERATURES °F									
			40.0 / 40.0	36.0 / 36.0	31.5 / 32.0	26.1 / 27.5	21.0 / 22.5	17.5 / 18.5	11.0 / 12.2	6.2 / 7.3	0.0 / 1.0	
	---	$(\Delta L)10^3$										
		$(\Delta L/L)10^5$										
1	175.80		175.80	176.00	176.20	176.40	176.00	176.00	171.50	170.00	169.70	
		$(\Delta L)10^3$	0	-4.38	-8.76	-13.14	-4.38	-4.38	94.30	126.90	133.40	
		$(\Delta L/L)10^5$	0	-3.08	-6.16	-9.25	-3.08	-3.08	66.25	89.40	94.10	
2	228.60		228.60	228.80	228.90	229.10	228.90	227.80	222.50	221.50	220.80	
		$(\Delta L)10^3$	0	-4.62	-6.93	-11.53	-6.93	18.47	140.80	164.00	180.00	
		$(\Delta L/L)10^5$	0	-3.25	-4.88	-8.12	-4.88	13.00	99.10	115.40	126.80	
3	290.80		290.80	291.10	291.40	291.50	291.10	289.60	283.50	283.00	283.20	
		$(\Delta L)10^3$	0	-7.14	-14.28	-16.67	-7.14	28.60	173.70	185.60	183.20	
		$(\Delta L/L)10^5$	0	-5.03	-9.95	-11.72	-5.03	20.15	122.40	130.80	129.00	

SPEC.	Partially Sat. Wt. (1)	Vacuum Sat. Wt. (2)	Oven-Dried Wt. (3)	(2) - (3)	(1) - (3)	% Sat. $\frac{(1)-(3)}{(2)-(3)}$
1	3.712 lb.	3.744 lb.	3.364 lb.	0.380 lb.	0.348 lb.	91.6
2	3.788 lb.	3.813 lb.	3.460 lb.	0.353 lb.	0.328 lb.	93.0
3	3.607 lb.	3.633 lb.	3.271 lb.	0.362 lb.	0.336 lb.	92.8

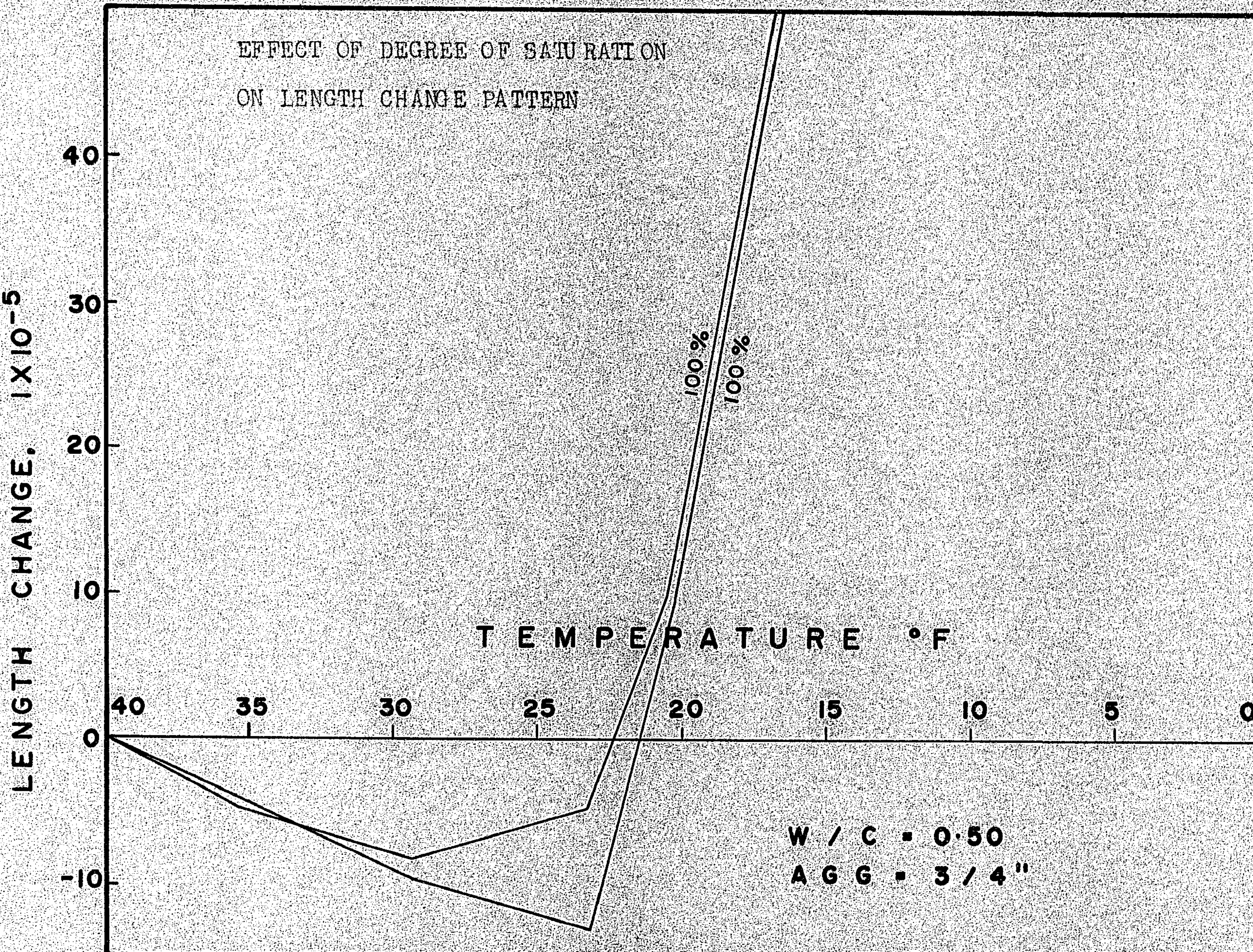
NOTE: Transmitter Calibration Constants:

(0) $2.38 \times 10^{-2} \frac{mm}{unit}$

(1) $2.29 \times 10^{-2} \frac{mm}{unit}$

(2) $2.31 \times 10^{-2} \frac{mm}{unit}$

(3) $2.19 \times 10^{-2} \frac{mm}{unit}$


EFFECT OF DEGREE OF SATURATION
ON LENGTH CHANGE PATTERN
LENGTH CHANGE, 1X10⁻⁵
40
30
20
10
0
-10
TEMPERATURE °F
40
35
30
25
20
15
10
5
0
100%
100%
W / C = 0·50
AGG = 3 / 4"

W / C = 0.50

Agg. = 3/4

Air = 7%

Curing Time = 14 days

Air Dried = 23 days

Date: June 27, 1967

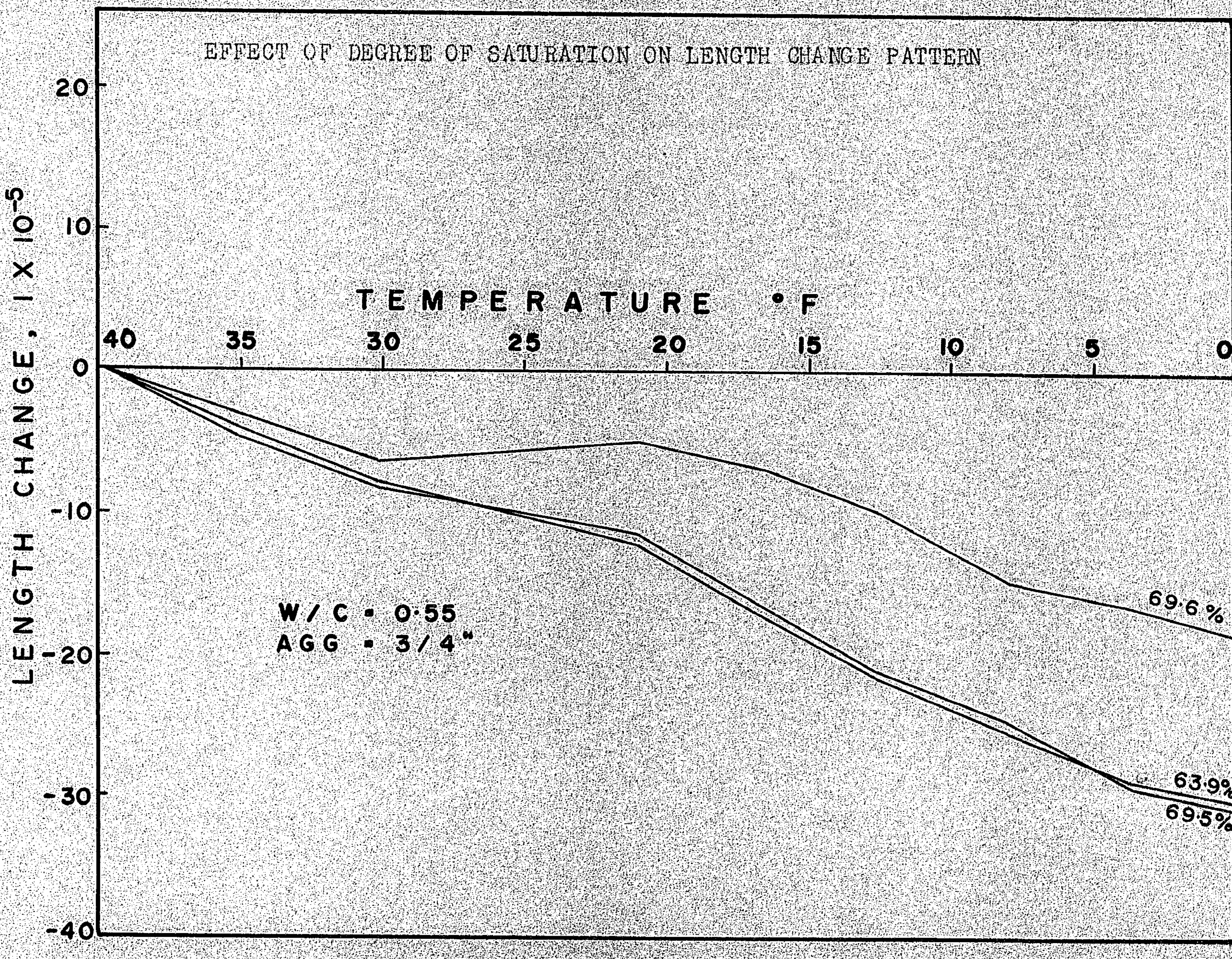
SPEC.	Init.Rdg.	Surface / Centre	TEMPERATURES °F									
			40.50 / 41.00	35.0 / 36.1	29.0 / 29.8	23.2 / 23.4	20.0 / 20.8	15.0 / 15.4	10.1 / 10.8	5.0 / 5.4	0.0 / 1.0	
0	---											
		$(\Delta L)10^3$										
		$(\Delta L/L)10^5$										
1	312.00		312.00	312.25	312.60	312.80	311.50	308.20	306.90	305.80	305.00	
		$(\Delta L)10^3$	0	-5.78	-13.86	-18.48	11.55	90.00	117.60	143.10	161.60	
		$(\Delta L/L)10^5$	0	-4.07	-9.75	-13.01	8.13	63.40	82.80	100.90	113.60	
2	---											
		$(\Delta L)10^3$										
		$(\Delta L/L)10^5$										
3A	284.60		284.60	284.90	285.10	284.90	284.00	280.40	278.90	277.70	277.00	
		$(\Delta L)10^3$	0	-6.87	-11.45	-6.87	13.72	96.00	131.50	158.00	174.00	
		$(\Delta L/L)10^5$	0	-4.83	-8.06	-4.83	9.66	67.60	92.50	111.10	122.30	

SPEC.	Partially Sat. Wt. (1)	Vacuum Sat. Wt. (2)	Oven-Dried Wt. (3)	(2) - (3)	(1) - (3)	% Sat. $\frac{(1)-(3)}{(2)-(3)}$
0						
1	3.660 lb.	3.660 lb.	3.346 lb.	0.314 lb.	0.000	100.0
2						
3A	3.597 lb.	3.597 lb.	3.285 lb.	0.312 lb.	0.000	100.0

NOTE: Transmitter Calibration Constants:

(0) $2.38 \times 10^{-2} \frac{mm}{unit}$ (2) $2.31 \times 10^{-2} \frac{mm}{unit}$

(1) $2.29 \times 10^{-2} \frac{mm}{unit}$ (3) $2.19 \times 10^{-2} \frac{mm}{unit}$


EFFECT OF DEGREE OF SATURATION ON LENGTH CHANGE PATTERN
TEMPERATURE °F
40
35
30
25
20
15
10
5
0
LENGTH CHANGE, l X 10-5
20
10
0
-10
-20
-30
-40
W/C = 0·55
AGG = 3/4"
69·6 %
63·9%
69·5%

W / C = 0.55

Agg. = 3/4

Air = 7%

Curing Time = 14 days

Air Dried = 60 days

Date: May 27, 1967

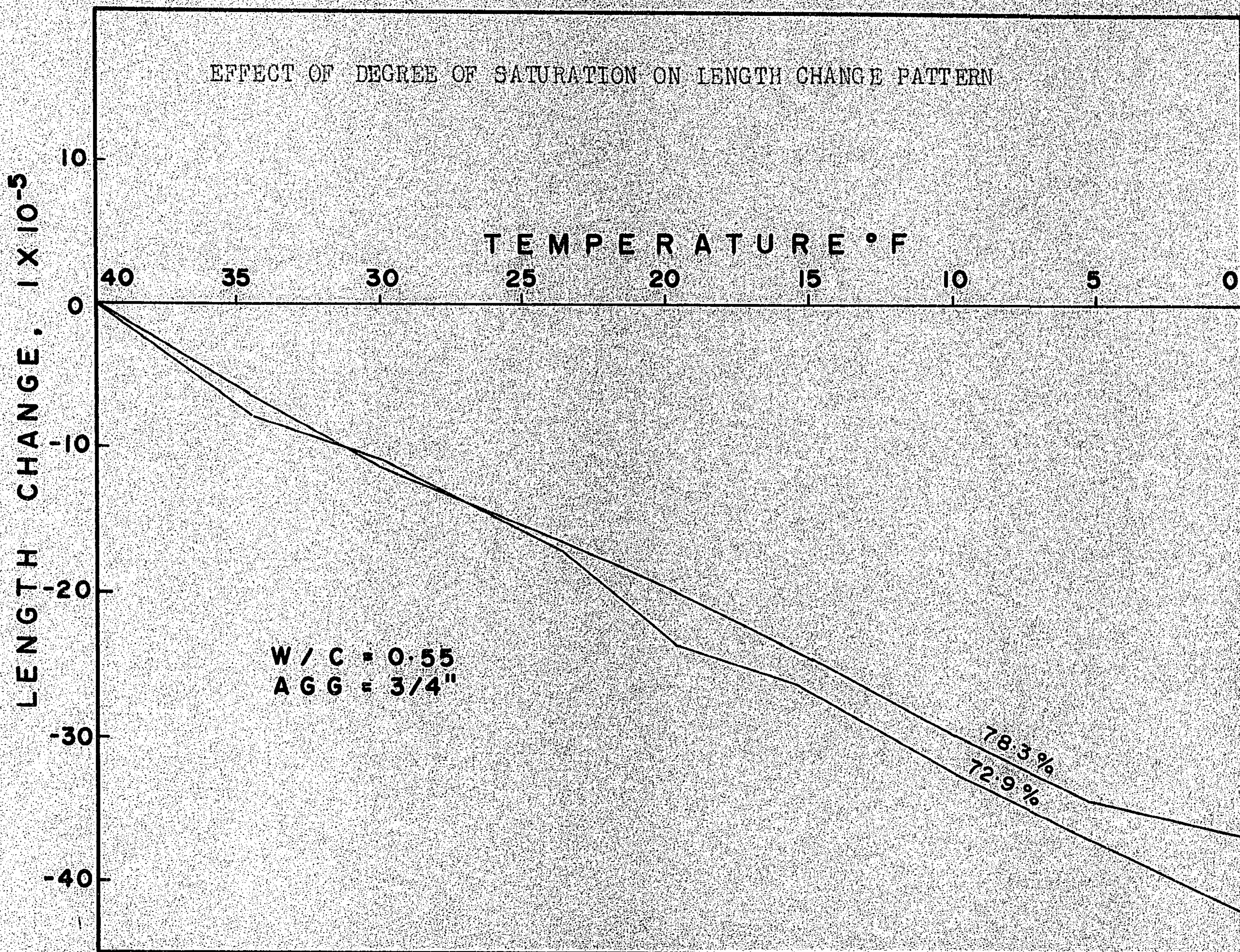
			TEMPERATURES °F									
SPEC.	Init.Rdg.	Surface Centre	39.4 39.4	35.0 35.0	29.2 31.0	20.0 22.0	16.2 17.6	11.9 13.0	7.5 8.6	3.0 4.0	1.0 2.0	
4	241.00		241.00	241.30	241.50	241.70	242.00	242.30	242.50	242.80	242.85	
		$(\Delta L)10^3$	0	-6.93	-11.6	-16.2	-23.1	-30.0	-34.6	-41.6	-42.7	
		$(\Delta L/L)10^5$	0	-4.88	-8.17	-11.4	-16.3	-21.1	-24.4	-29.3	-30.0	
1	240.00		240.00	240.30	240.50	240.90	241.10	241.40	241.70	241.80	241.90	
		$(\Delta L)10^3$	0	-6.56	-11.0	-19.7	-24.1	-30.6	-37.2	-39.4	-41.6	
		$(\Delta L/L)10^5$	0	-4.61	-7.75	-13.9	-17.0	-21.6	-25.2	-27.8	-29.3	
4A	280.70		280.70	280.90	281.10	281.00	281.10	281.30	281.60	281.70	218.75	
		$(\Delta L)10^3$	0	-4.58	-9.15	-6.88	-9.15	-13.7	-20.6	-22.9	-24.1	
		$(\Delta L/L)10^5$	0	-3.22	-6.44	-4.85	-6.44	-9.65	-14.5	-16.2	-17.0	
		$(\Delta L)10^3$										
		$(\Delta L/L)10^5$										

SPEC.	Partially Sat. Wt. (1)	Vacuum Sat. Wt. (2)	Oven-Dried Wt. (3)	(2) - (3)	(1) - (3)	% Sat. $\frac{(1)-(3)}{(2)-(3)}$
4	3.678 lb.	3.791 lb.	3.479 lb.	0.312 lb.	0.199 lb.	63.8
1	3.778 lb.	3.866 lb.	3.571 lb.	0.295 lb.	0.207 lb.	69.5
4A	3.708 lb.	3.819 lb.	3.454 lb.	0.365 lb.	0.254 lb.	69.6

NOTE: Transmitter Calibration Constants:

(0) $2.38 \times 10^{-2} \frac{mm}{unit}$ (2) $2.31 \times 10^{-2} \frac{mm}{unit}$

(1) $2.29 \times 10^{-2} \frac{mm}{unit}$ (3) $2.19 \times 10^{-2} \frac{mm}{unit}$



EFFECT OF DEGREE OF SATURATION ON LENGTH CHANGE PATTERN
TEMPERATURE °F
40
35
30
25
20
15
10
5
0
LENGTH CHANGE, 1 X 10-5
10
0
-10
-20
-30
-40
W / C = 0·55
AGG = 3/4"
78·3 %
72·9 %

W/C = 0.55
Agg. = 3/4
Air = 7%

Curing Time = 14 days
Air Dried = 66 days

Date: May 26, 1967

SPEC.	Init.Rdg.	Surface / Centre	TEMPERATURES °F								
			39.0 / 40.3	34.0 / 35.2	29.4 / 30.5	23.2 / 24.5	19.6 / 20.4	15.2 / 16.0	10.0 / 10.2	5.0 / 5.4	0.0 / 1.4
4	268.20		268.30	268.80	269.00	269.40	269.80	270.00	270.40	270.70	271.00
		$(\Delta L)10^3$	0	-11.0	-15.3	-24.1	-32.9	-37.3	-46.0	-52.6	-59.2
		$(\Delta L/L)10^5$	0	-7.75	-10.8	-17.0	-23.2	-26.2	-32.4	-37.0	-41.6
4A	293.60		293.60	294.00	294.30	294.60	294.80	295.10	295.40	295.70	295.80
		$(\Delta L)10^3$	0	-9.25	-16.2	-23.1	-27.7	-34.7	-41.6	-48.5	-50.8
		$(\Delta L/L)10^5$	0	-6.5	-11.4	-16.3	-19.5	-24.4	-29.2	-34.2	-35.8
	___										
		$(\Delta L)10^3$									
		$(\Delta L/L)10^5$									
	___										
		$(\Delta L)10^3$									
		$(\Delta L/L)10^5$									

SPEC.	Partially Sat.Wt.(1)	Vacuum Sat.Wt.(2)	Oven-Dried Wt.(3)	(2) - (3)	(1) - (3)	%Sat. $\frac{(1)-(3)}{(2)-(3)}$
4	3.730 lb.	3.802 lb.	3.471 lb.	0.331 lb.	0.259 lb.	78.3
4A	3.712 lb.	3.791 lb.	3.500 lb.	0.291 lb.	0.212 lb.	72.9

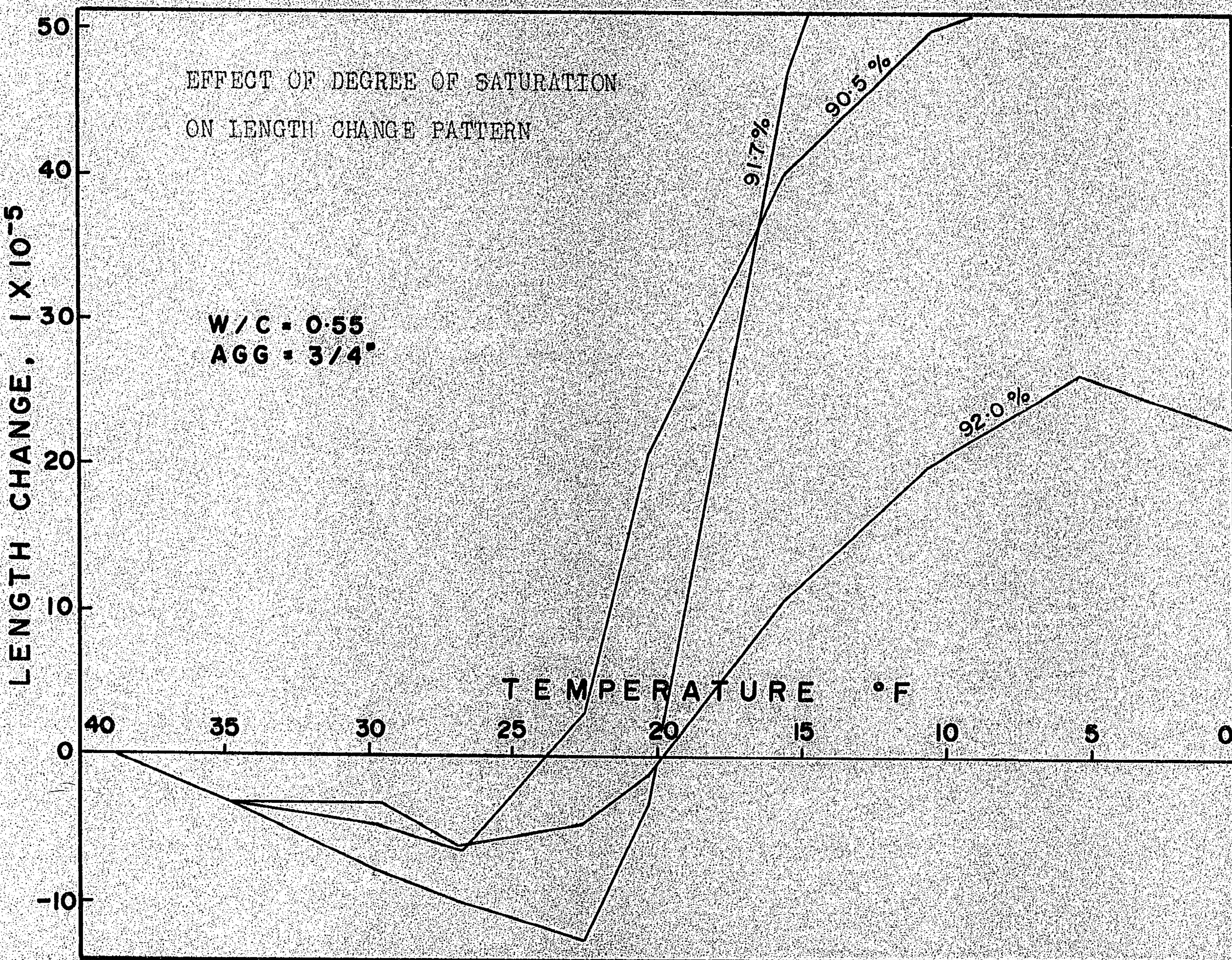
NOTE: Transmitter Calibration Constants:

(0) $2.38 \times 10^{-2} \frac{mm}{unit}$

(1) $2.29 \times 10^{-2} \frac{mm}{unit}$

(2) $2.31 \times 10^{-2} \frac{mm}{unit}$

(3) $2.19 \times 10^{-2} \frac{mm}{unit}$


EFFECT OF DEGREE OF SATURATION
ON LENGTH CHANGE PATTERN
W / C = 0·55
AGG = 3/4"
91·7%
90·5 %
92·0 %
TEMPERATURE °F
40
35
30
25
20
15
10
5
0
LENGTH CHANGE, I X 10⁻⁵
50
40
30
20
10
0
-10

W / C = 0.55
Agg. = 3/4
Air = 7%

Curing Time = 14 days
Air Dried = 60 days

Date: May 28, 1967

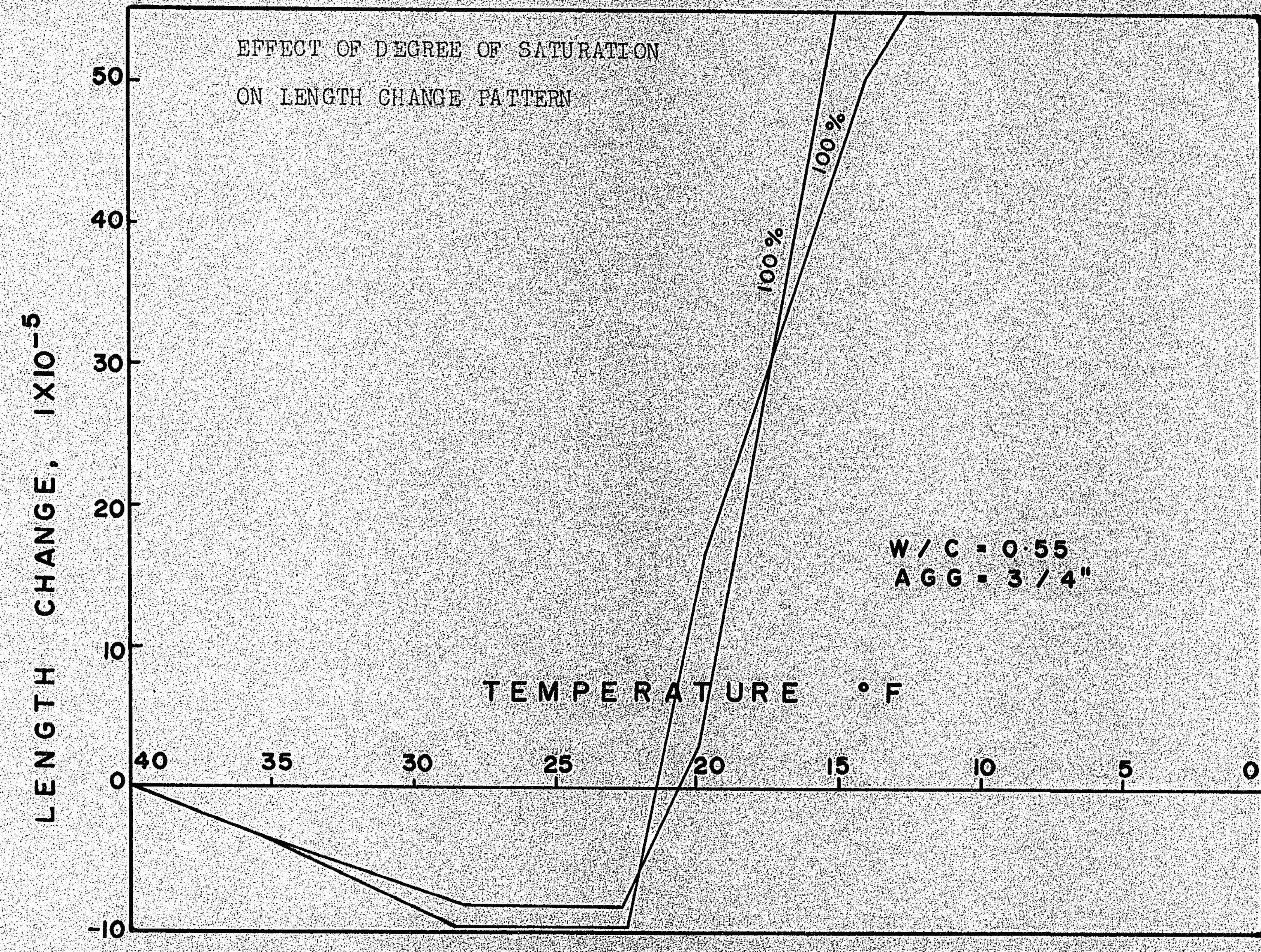
			TEMPERATURES °F									
SPEC.	Init.Rdg.	Surface Centre	38.0 38.3	34.0 35.6	29.1 30.2	26.3 27.5	22.0 23.0	20.0 20.8	15.0 16.3	10.0 11.0	5.3 5.9	0.0 1.0
4	294.50		294.50	294.70	295.00	295.10	295.25	294.30	291.60	289.40	289.20	289.00
		$(\Delta L)10^3$	0	-4.62	-11.5	-13.9	-17.3	4.62	67.0	117.80	122.10	127.0
		$(\Delta L/L)10^5$	0	-3.25	-8.1	-9.8	-12.2	3.25	47.1	82.50	86.10	89.5
1	210.90		210.70	211.10	211.10	211.30	211.20	211.00	210.20	209.60	209.20	209.40
		$(\Delta L)10^3$	0	-4.38	-4.38	-8.75	-6.56	-2.19	15.3	28.5	37.2	32.8
		$(\Delta L/L)10^5$	0	-3.08	-3.08	-6.16	-4.63	-1.54	10.8	20.1	26.2	23.1
3	278.30		278.30	278.50	278.60	278.70	278.10	277.00	275.80	275.20	275.00	274.80
		$(\Delta L)10^3$	0	-4.58	-6.86	-9.15	4.58	29.8	57.3	71.0	75.5	80.0
		$(\Delta L/L)10^5$	0	-3.23	-4.84	-6.42	3.23	21.1	40.4	50.0	53.1	56.4
	----	$(\Delta L)10^3$										
		$(\Delta L/L)10^5$										

SPEC.	Partially Sat. Wt. (1)	Vacuum Sat. Wt. (2)	Oven-Dried Wt. (3)	(2) - (3)	(1) - (3)	% Sat. $\frac{(1)-(3)}{(2)-(3)}$
4	3.778 lb.	3.805 lb.	3.481. lb.	0.324 lb.	0.297 lb.	91.7
1	3.879 lb.	3.902 lb.	3.612 lb.	0.290 lb.	0.267 lb.	92.0
3	3.804 lb.	3.834 lb.	3.520 lb.	0.314 lb.	0.284 lb.	90.5

NOTE: Transmitter Calibration Constants:

(0) $2.38 \times 10^{-2} \frac{mm}{unit}$ (2) $2.31 \times 10^{-2} \frac{mm}{unit}$

(1) $2.29 \times 10^{-2} \frac{mm}{unit}$ (3) $2.19 \times 10^{-2} \frac{mm}{unit}$


EFFECT OF DEGREE OF SATURATION
ON LENGTH CHANGE PATTERN
LENGTH CHANGE, 1X10⁻⁵
TEMPERATURE °F
W / C = 0·55
AGG = 3 / 4"
100 %
100 %
50
40
30
20
10
0
-10
40
35
30
25
20
15
10
5
0

W / C = 0.55 Curing Time = 14 days Date: June 28, 1967

Agg. = 3/4 Air Dried = 100 days

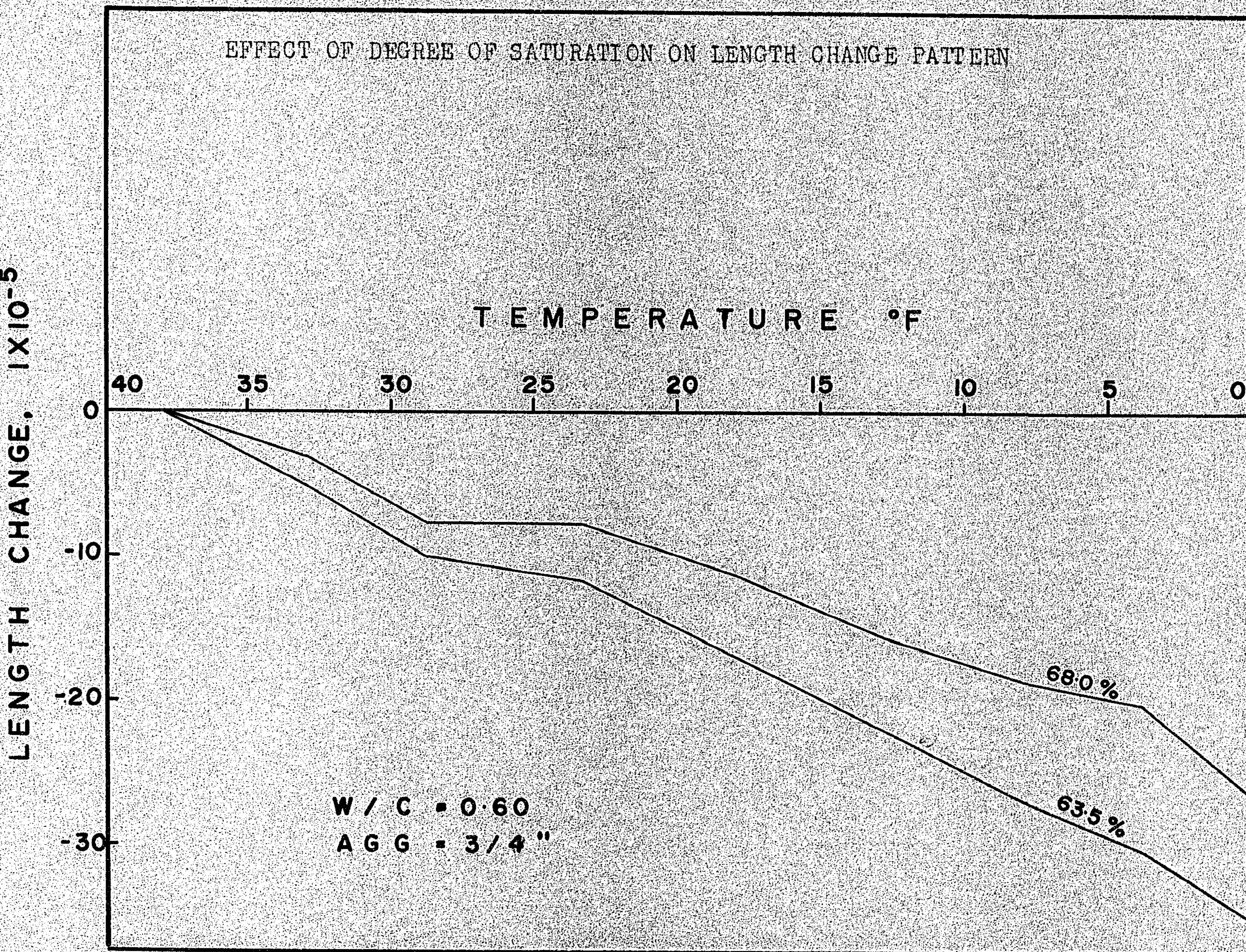
Air = 7%

SPEC.	Init.Rdg.	Surface / Centre	TEMPERATURES °F									
			41.0 / 41.0	35.2 / 36.0	28.4 / 28.6	22.0 / 23.0	19.8 / 19.8	13.9 / 14.0	9.0 / 8.0	3.8 / 4.4	1.0 / 1.4	
	–––											
		$(\Delta L)10^3$										
		$(\Delta L/L)10^5$										
1	230.50		230.50	230.70	231.00	231.00	230.00	226.50	224.30	223.10	222.50	
		$(\Delta L)10^3$	0	-4.76	-11.90	-11.90	4.76	95.20	147.50	170.00	181.20	
		$(\Delta L/L)10^5$	0	-3.35	-8.39	-8.39	3.35	67.10	103.90	119.70	127.70	
	–––											
		$(\Delta L)10^3$										
		$(\Delta L/L)10^5$										
3	234.00		234.00	234.20	234.60	234.60	233.00	230.90	229.90	229.10	228.70	
		$(\Delta L)10^3$	0	-4.62	-13.85	-13.85	23.10	71.60	94.80	113.30	122.50	
		$(\Delta L/L)10^5$	0	-3.25	-9.75	-9.75	16.29	50.40	66.80	80.00	86.30	

SPEC.	Partially Sat. Wt.(1)	Vacuum Sat. Wt.(2)	Oven-Dried Wt.(3)	(2) - (3)	(1) - (3)	% Sat. $\frac{(1)-(3)}{(2)-(3)}$
1	3.855 lb.	3.855 lb.	3.580 lb.	0.275 lb.	0.000	100.0
3	3.802 lb.	3.802 lb.	3.521 lb.	0.281 lb.	0.000	100.0

NOTE: Transmitter Calibration Constants: (0) 2.38×10^{-2} $\frac{mm}{unit}$ (2) 2.31×10^{-2} $\frac{mm}{unit}$

(1) 2.29×10^{-2} $\frac{mm}{unit}$ (3) 2.19×10^{-2} $\frac{mm}{unit}$


EFFECT OF DEGREE OF SATURATION ON LENGTH CHANGE PATTERN
TEMPERATURE °F
40
35
30
25
20
15
10
5
0
LENGTH CHANGE, 1X10-5
0
-10
-20
-30
68·0 %
63·5 %
W / C = 0·60
AGG = 3/4"

W / C = 0.60 | Curing Time = 14 days | Date: June 8, 1967

Agg. = 3/4 in. | Air Dried = 90 days

Air = 7%

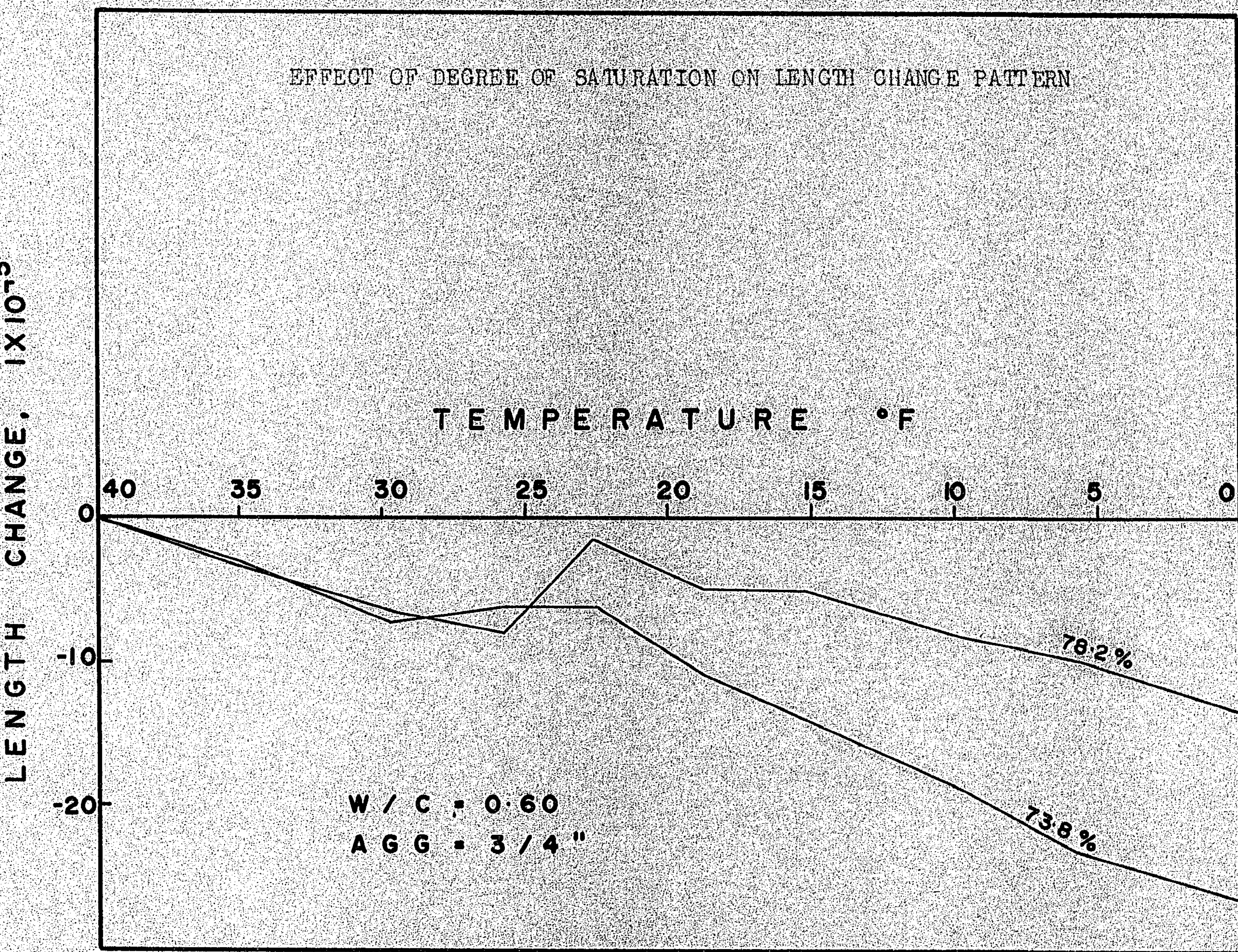
SPEC.	Init. Rdg.	Surface / Centre	TEMPERATURES °F									
			38.0 / 38.0	32.5 / 33.8	28.0 / 29.3	22.1 / 24.4	16.8 / 18.5	12.5 / 13.5	7.5 / 8.5	3.0 / 4.4	-0.5 / 0.5	
	---	$(\Delta L)10^3$										
		$(\Delta L/L)10^5$										
5	269.60		269.60	269.90	270.20	270.30	270.60	270.90	271.20	271.40	271.70	
		$(\Delta L)10^3$	0	-7.14	-14.28	-16.66	-23.80	-30.90	-38.05	-42.80	-50.00	
		$(\Delta L/L)10^5$	0	-5.03	-10.05	-11.73	-16.75	-21.80	-26.80	-30.15	-35.20	
5A	218.00		218.00	218.20	218.50	218.50	218.80	219.00	219.20	219.30	219.70	
		$(\Delta L)10^3$	0	-4.38	-10.95	-10.95	-17.52	-21.90	-26.30	-28.50	-37.25	
		$(\Delta L/L)10^5$	0	-3.08	-7.71	-7.71	-12.33	-15.41	-18.52	-20.05	-26.20	
	---	$(\Delta L)10^3$										
		$(\Delta L/L)10^5$										

SPEC.	Partially Sat. Wt. (1)	Vacuum Sat. Wt. (2)	Oven-Dried Wt. (3)	(2) - (3)	(1) - (3)	% Sat. $\frac{(1)-(3)}{(2)-(3)}$
5	3.502 lb.	3.631 lb.	3.279 lb.	0.352 lb.	0.223 lb.	63.5
5A	3.535 lb.	3.642 lb.	3.309 lb.	0.333 lb.	0.226 lb.	68.0

NOTE: Transmitter Calibration Constants:

(0) $2.38 \times 10^{-2} \frac{mm}{unit}$ (2) $2.31 \times 10^{-2} \frac{mm}{unit}$

(1) $2.29 \times 10^{-2} \frac{mm}{unit}$ (3) $2.19 \times 10^{-2} \frac{mm}{unit}$


EFFECT OF DEGREE OF SATURATION ON LENGTH CHANGE PATTERN
TEMPERATURE °F
40
35
30
25
20
15
10
5
0
LENGTH CHANGE, 1×10^{-5}
0
-10
-20
78.2 %
73.8 %
W / C = 0.60
AGG = 3/4"

W/C = 0.60

Agg. = 3/4 in.

Air = 7%

Curing Time = 14 days

Air Dried = 40 days

Date: June 17, 1967

SPEC.	Init.Rdg.	Surface / Centre	TEMPERATURES °F									
			40.0 / 40.0	34.3 / 36.0	29.0 / 30.2	25.5 / 26.2	22.0 / 23.3	18.6 / 18.8	15.0 / 15.7	10.0 / 10.4	5.5 / 5.9	0.0 / 1.0
	---	$(\Delta L)10^3$										
		$(\Delta L/L)10^5$										
5	247.80		247.80	248.00	248.30	248.20	248.20	248.50	248.70	249.00	249.30	249.50
		$(\Delta L)10^3$	0	-4.38	-10.95	-8.75	-8.75	-15.33	-19.22	-26.30	-32.80	-37.20
		$(\Delta L/L)10^5$	0	-3.08	-7.72	-6.16	-6.16	-10.80	-13.90	-18.54	-23.10	-26.20
6	234.50		234.50	234.70	234.90	235.00	234.60	234.80	234.80	235.00	235.10	235.30
		$(\Delta L)10^3$	0	-4.62	-9.24	-11.54	-2.31	-6.93	-6.93	-11.54	-13.87	-18.50
		$(\Delta L/L)10^5$	0	-3.26	-6.52	-8.14	-1.63	-4.88	-4.88	-8.13	-9.78	-13.02
	---	$(\Delta L)10^3$										
		$(\Delta L/L)10^5$										

SPEC.	Partially Sat. Wt.(1)	Vacuum Sat. Wt.(2)	Oven-Dried Wt.(3)	(2) - (3)	(1) - (3)	% Sat. $\frac{(1)-(3)}{(2)-(3)}$
5	3.590 lb.	3.675 lb.	3.351 lb.	0.324 lb.	0.239 lb.	73.8
6	3.581 lb.	3.665 lb.	3.282 lb.	0.383 lb.	0.299 lb.	78.2

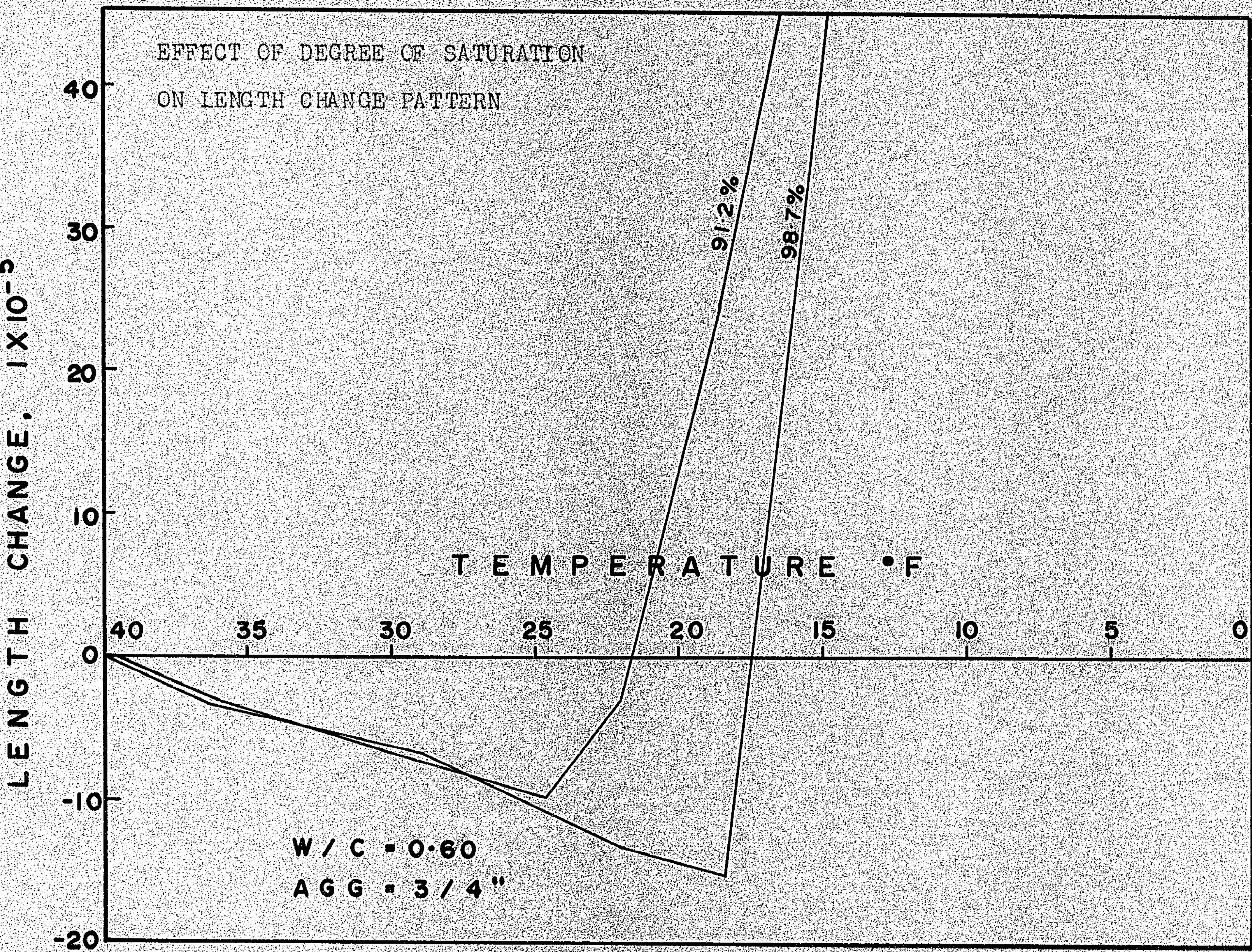
NOTE: Transmitter Calibration Constants:

(0) 2.38×10^{-2} mm/unit

(1) 2.29×10^{-2} mm/unit

(2) 2.31×10^{-2} mm/unit

(3) 2.19×10^{-2} mm/unit


EFFECT OF DEGREE OF SATURATION
ON LENGTH CHANGE PATTERN
LENGTH CHANGE, 1X10⁻⁵
40
30
20
10
0
-10
-20
TEMPERATURE °F
40
35
30
25
20
15
10
5
0
91·2%
98·7%
W / C = 0·60
AGG = 3 / 4"

W/C = 0.60 Curing Time = 14 days Date: JULY 9, 1967

Agg. = 3/4 in. Air Dried = 60 days

Air = 7%

			TEMPERATURES °F									
SPEC.	Init.Rdg.	Surface Centre	40.0 40.0	36.0 36.5	29.0 29.3	21.0 23.0	18.0 18.5	13.0 13.1	9.5 10.0	7.0 7.5	0.0 1.0	
5	250.00		253.00	253.20	253.40	253.80	253.90	248.60	242.00	239.80	238.80	
		$(\Delta L)10^3$	0	-4.76	-9.52	-19.04	-21.40	104.80	262.00	314.00	338.00	
		$(\Delta L/L)10^5$	0	-3.35	-6.70	-13.40	-15.07	73.80	184.50	221.00	238.00	
	---	$(\Delta L)10^3$										
		$(\Delta L/L)10^5$										
	---	$(\Delta L)10^3$										
		$(\Delta L/L)10^5$										
	---	$(\Delta L)10^3$										
		$(\Delta L/L)10^5$										

SPEC.	Partially Sat. Wt. (1)	Vacuum Sat. Wt. (2)	Oven-Dried Wt. (3)	(2) - (3)	(1) - (3)	% Sat. $\frac{(1)-(3)}{(2)-(3)}$
5	3.686 lb.	3.690 lb.	3.388 lb.	0.302 lb.	0.298 lb.	98.7%

NOTE: Transmitter Calibration Constants:

(0) $2.38 \times 10^{-2} \frac{mm}{unit}$ (2) $2.31 \times 10^{-2} \frac{mm}{unit}$

(1) $2.29 \times 10^{-2} \frac{mm}{unit}$ (3) $2.19 \times 10^{-2} \frac{mm}{unit}$

W/C = 0.60

Agg. = 3/4 in.

Air = 7%

Curing Time = 14 days

Air Dried = 40 days

Date: June 18, 1967

SPEC.	Init.Rdg.	Surface / Centre	TEMPERATURES °F									
			39.5 / 39.5	35.5 / 36.5	30.1 / 30.7	24.1 / 24.8	21.7 / 22.2	18.5 / 18.5	13.0 / 13.4	7.60 / 7.80	0.5 / 1.0	
	---	$(\Delta L)10^3$										
		$(\Delta L/L)10^5$										
	---	$(\Delta L)10^3$										
		$(\Delta L/L)10^5$										
5A	265.80		265.80	266.00	266.20	266.40	266.80	264.30	261.00	260.70	260.50	
	---	$(\Delta L)10^3$	0	-4.58	-9.16	-13.72	-4.58	34.40	110.00	116.90	122.50	
		$(\Delta L/L)10^5$	0	-3.23	-6.46	-9.66	-3.23	24.20	77.50	82.50	86.30	
	---	$(\Delta L)10^3$										
		$(\Delta L/L)10^5$										

SPEC.	Partially Sat. Wt. (1)	Vacuum Sat. Wt. (2)	Oven-Dried Wt. (3)	(2) - (3)	(1) - (3)	% Sat. $\frac{(1)-(3)}{(2)-(3)}$
5A	3.602 lb.	3.632 lb.	3.291 lb.	0.341 lb.	0.311 lb.	91.2

NOTE: Transmitter Calibration Constants:

(0) $2.38 \times 10^{-2}\ \frac{mm}{unit}$

(1) $2.29 \times 10^{-2}\ \frac{mm}{unit}$

(2) $2.31 \times 10^{-2}\ \frac{mm}{unit}$

(3) $2.19 \times 10^{-2}\ \frac{mm}{unit}$

W / C = 0.45 Curing Time = 14 days Date: June 30, 1967

Agg. = 3/4 Air Dried = 20 days

Air = 7%

SPEC.	Init. Rdg.	Surface / Centre	TEMPERATURES °F									
		Surface Centre	40.0 40.0	35.2 36.0	28.3 29.3	22.0 23.0	17.1 17.4	12.4 12.4	7.1 7.5	0 0.5		
0	---											
		(ΔL)10³										
		(ΔL/L)10⁵										
1	316.80		316.80	316.90	317.40	316.20	315.60	314.80	314.80	314.50		
		(ΔL)10³	0	-2.31	-13.86	9.25	27.70	46.20	46.20	34.60		
		(ΔL/L)10⁵	0	-1.63	-9.76	6.51	19.50	32.50	32.50	24.35		
2	261.20		261.20	261.40	262.00	261.40	260.90	260.40	260.90	260.50		
		(ΔL)10³	0	-4.76	-16.67	-4.76	7.14	19.05	7.14	16.67		
		(ΔL/L)10⁵	0	-3.38	-11.73	-3.38	5.04	13.42	5.04	11.73		
3A	217.30		217.30	217.40	217.90	216.30	216.30	216.00	216.50	216.00		
		(ΔL)10³	0	-2.19	-15.30	21.9	21.9	28.50	39.40	28.50		
		(ΔL/L)10⁵	0	-1.54	-10.78	15.42	15.42	20.05	27.80	20.05		

SPEC.	Partially Sat. Wt. (1)	Vacuum Sat. Wt. (2)	Oven-Dried Wt. (3)	(2) - (3)	(1) - (3)	% Sat. $\frac{(1)-(3)}{(2)-(3)}$
0						
1	3.742 lb.	3.742 lb.	3.451 lb.	0.291 lb.	0.000	100.0
2	3.844 lb.	3.844 lb.	3.560 lb.	0.284 lb.	0.000	100.0
3A	3.803 lb.	3.803 lb.	3.522 lb.	0.281 lb.	0.000	100.0

NOTE: Transmitter Calibration Constants:

(0) 2.38×10^{-2} $\frac{mm}{unit}$ (2) 2.31×10^{-2} $\frac{mm}{unit}$

(1) 2.29×10^{-2} $\frac{mm}{unit}$ (3) 2.19×10^{-2} $\frac{mm}{unit}$

W/C = 0.60 Curing Time = 14 days Date: July 3, 1967

Agg. = 3/8 in. Air Dried = 30 days

Air = 7%

SPEC.	Init.Rdg.	Surface / Centre	TEMPERATURES °F									
			40.0 40.0	34.5 34.7	30.0 30.4	28.0 28.2	26.5 28.2	25.8 26.2	21.0 22.3	14.2 15.0	8.0 9.0	1.0 1.4
4	310.50		310.50	310.75	210.90	311.00	311.10	311.25	310.90	308.50	308.20	308.20
		$(\Delta L)10^3$	0	-5.73	-9.15	-11.43	-13.73	-17.17	-9.15	45.80	52.60	52.60
		$(\Delta L/L)10^5$	0	-4.03	-6.44	-8.05	-9.67	-12.08	-6.44	32.24	37.10	37.10

		$(\Delta L)10^3$										
		$(\Delta L/L)10^5$										

		$(\Delta L)10^3$										
		$(\Delta L/L)10^5$										

		$(\Delta L)10^3$										
		$(\Delta L/L)10^5$										

SPEC.	Partially Sat. Wt.(1)	Vacuum Sat. Wt.(2)	Oven-Dried Wt.(3)	(2) - (3)	(1) - (3)	% Sat. $\frac{(1)-(3)}{(2)-(3)}$
4	3.805 lb.	3.818 lb.	3.519 lb.	0.299 lb.	0.286 lb.	96.0

NOTE: Transmitter Calibration Constants:

(0) 2.38×10^{-2} $\frac{mm}{unit}$ (2) 2.31×10^{-2} $\frac{mm}{unit}$

(1) 2.29×10^{-2} $\frac{mm}{unit}$ (3) 2.19×10^{-2} $\frac{mm}{unit}$

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VITA AUCTORIA

Eddie C. Lau was born in Hong Kong, 16 March 1942. He finished primary school in 1954. In 1955 he entered Wah Yan College and was matriculated in Loyola College (Montreal) in 1962. In September 1962, he entered first year Civil Engineering at the University of Windsor and he received his degree of Bachelor of Applied Science in May, 1966.

Eddie C. Lau was awarded a Board of Governor's Gold Medal from the University of Windsor in May 1966 and an Achievement Gold Medal from the Association of Professional Engineers of the Province of Ontario in February 1967.