EVALUATION OF DIFFERENT TREATMENTS TO IMPROVE THE DURABILITY OF CONCRETE HAVING DELETERIOUS CHERT PARTICLES AS ITS COARSE AGGREGATE

by

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I. INTRODUCTION

Since the time portland cement concrete became popular as a construction material, it has been used in every conceivable climatic and natural condition of exposure. In the beginning, quality of concrete was judged mainly by its strength characteristics. The recognition of the durability of concrete against natural disruptive forces as another more important quality came gradually, but at present it is the object of intensive research for the engineering profession. A variety of factors have been found to be responsible for producing these disruptive forces. The research has now provided a better understanding of the mechanism of deterioration of concrete durability.

As the demand for concrete is increasing, the supply of available good coarse aggregate is being exhausted. New sources have to be tapped, ways must be found to utilize the sources neglected so far because of their bad field record, and performance of borderline materials should be improved to make them more economical. A study of the aggregate is required to evaluate the durability of concrete before it can be recommended for use in the field. This poses a formidable problem in view of the complex nature and behavior of concrete.

The advent of air-entrained concrete has simplified the problem somewhat. Entrained air protects the mortar phase of concrete and thus makes it possible to gage more accurately the effect and extent of damage by the deleterious aggregate particles provided other variable factors are controlled within limits. Durability of concrete depends mostly on range of temperature, moisture contents and on the pore characteristics of the aggregate particles.

Various studies have been carried out to identify the deleterious particles and some qualitative evaluations were made suggesting ways for improving or eliminating their harmful characteristics. Recently some efforts have been made towards quantitative analysis of these factors, but they are still inconclusive. These studies and other theories of frost damage are described in Chapter III. This discussion is meant to provide a basic understanding of the behavior and characteristics of poor quality chert gravel in concrete. Investigations with regard to the factors such as the effect of particle size, moisture conditions, specific gravity, heavy media separation, quantitative estimate of percentage of deleterious particles required to damage the concrete are mentioned, and other suggestions in this context are noted.

In the study being presented here an attempt has been made to try some of the ideas to attain an improved performance of the aggregate and consequently of the durability of the concrete. Achievements of different treatments have been compared. The objective and scope has been confined to the chert gravel, a major source of aggregate supplies known to contain poor quality particles. It is hoped the thoughts and results will be of some practical use to enhance the field service of concrete.

II. PURPOSE AND SCOPE

This project is an effort to study some of the treatments used for the benefication of poor quality chert gravels. Three treatments were investigated and compared:

1. Separation of heavier and lighter chert aggregate by heavy liquid flotation into two groups: those having a specific gravity greater than 2.5, and those in the range of 2.4 to 2.5.
2. Substitution for 50 percent chert, untreated by heavy liquid, with a good durable aggregate in concrete.
3. Blending of deleterious chert particles with aggregates of proven good quality to determine the minimum percentage of chert causing the deterioration of concrete and making it non-durable.

The chert gravels are a major source of aggregate supply, but the bad field performance of many of them has rendered their free use dangerous and uneconomical. However, as the sources of good quality aggregates are being depleted, the emphasis is being placed on finding ways and means for the best and most economical utilization of the available aggregate sources. This necessitates the study of treatments to improve the performance of known deleterious aggregate particles.

High quality aggregates from two sources were used (Aggregates A and B) in this study. A third type used (Aggregate F) was a poor quality chert gravel.

In all, 109 test specimens were made from 29 concrete mixes using 10 different mix designs. Out of the 29 mixes, 24 were batch mixed in a Lancaster tub type mixer, and the rest were hand mixed. Freezing and thawing test results of 67 specimens are reported in this thesis. The remaining specimens were part of a related project not reported here.

III. LITERATURE DISCUSSION

Durability of Concrete

Earlier users of concrete concerned themselves primarily with its strength. It was realized very soon, especially in severe climates, that concrete designed to withstand external loads in a structure failed to give the expected service. Obviously some factors depending on the inherent properties of the constituents of the concrete were producing stresses and strains internally as well. There are many factors which influence the durability. A detailed outline has been prepared by Subcommittee II-d on Durability of Concrete of ASTM Committee C-9 on Concrete and Concrete Aggregates (1). The factors are subdivided into five major groups:

1. The physical properties of the hardened concrete.
2. The constituent materials of which the concrete is composed.
3. The construction methods used in fabricating or building the structure.
4. The nature of deteriorating influences to which the structure will be exposed, and
5. The type of loads which the structure is designed to carry and to which it will be subjected during its useful life.

All of these factors are not of equal importance in their effect upon the durability of the concrete structures, and some are obviously more important than others.

Investigations have shown that the durability of concrete is determined by its resistance to weathering, which in turn can be best determined by the tests of the resistance of concrete to freezing and thawing.

It has been now well established that air entrainment provides a high degree of protection for the cement paste (mortar phase) of the concrete but may not overcome the effects of larger aggregate particles which undergo volume changes on freezing. However, it can be expected that when durable fine aggregate and entrained air are used to protect the mortar, all test methods become essentially coarse aggregate tests.

Durability of Chert Aggregates

Among the known poor performing aggregates, cherts and chert gravels have been widely used and extensively studied. The word "chert" is used to put a name to an exceedingly wide variety of fine-grained hard rock composed of silica with certain impurities.

In reviewing all the investigations conducted so far with regard to chert, one single striking element of agreement was a generalized reference to a connection between porosity, absorption, permeability, specific gravity and the durability of chert.

Before entering into the discussion of the effects of different treatments on the durability and volume change characteristics of the poor quality chert gravel, it is necessary to study the mechanism of freeze and thaw damage of the concrete containing them in the light of different hypotheses and theories developed to date. This study should indicate also how it is possible to protect the cement and mortar phase of concrete by air-entrainment. The thought should be injected at this point that concrete durability must be examined as a whole and not by parts, namely hardened paste and aggregate particles. The confining nature of the mortar in concrete is important in determining the rate and amount of moisture movement into and out of the aggregates.

Mechanism of Frost Damage

Hardened Paste

Powers and Helmuth (2) have described the hardened paste to be composed of the hydration products of cement and water, such as calcium hydroxide and a material called cement-gel. Cement-gel is nothing but the residual of the original cement. It is a cohesive mass of tiny spherical particles bonded together chemically. Data have shown that when the cement-gel completely fills the space available to it, the porosity of the specimen is about 25 percent, a figure which is consistent with the spherical shape of the particles. These interstitial spaces among the spheres are called gel-pores. In most pastes the volume of the gel does not equal the apparent volume of the paste. There are always some water-filled spaces in the fresh paste. As the hydration proceeds with time these spaces become occupied partially by cement gel. There may be air voids included intentionally or non-intentionally and some other minor components. The pores in the gel are very small compared with the remaining capillary pores, and the air voids are larger than the capillary pores. The gel-pores are so small that freezing cannot occur at any temperature above -78°C.

Hydraulic Pressure and Diffusion Theories

Powers has proposed (2) two complementary theories to explain the damage of hardened paste due to freezing of the water. The first theory is based on the assumption that the hydraulic pressure is generated by water trying to escape from a frozen zone to a non-frozen zone. The water movement is caused in the paste to accomodate about nine percent increase in volume of freezing water. Generally speaking, in any structure, the outer exposed surfaces are cooled first so that the water has to move towards the interior portion and as such its escape from the structure itself is prevented.

Powers and Helmuth conducted experiments on specimens with and without air voids. They found that specimens with air voids contracted after freezing began. This contraction and certain other responses to change in rate of cooling could not be accounted for by the hydraulic pressure theory. This was, however, easily explained by another theory. It was surmised that after the water is frozen, first in larger capillary voids, the ice lenses so formed will grow by capillary attraction of available water from the gel. This process is also known as surface diffusion. The gel itself should contract but the overall effect on the volume of paste depends on the presence of sufficient air-voids. If there are no air-voids, the dilation of cavities containing ice may be more than the contraction of the gel, resulting in the expansion of the paste as a whole.

Hydraulic pressure and diffusion both can occur simultaneously in different parts of the paste. Diffusion, however, is a slow process. When freezing is rapid, as in laboratory tests, the expansion is due mainly to hydraulic pressure. Concrete in the field cools slowly, and low temperatures may be maintained for many hours or days. If paste is not protected with entrained air, it is likely to be damaged by both mechanisms: first, by hydraulic pressure, and then by growth of the ice bodies. The function of the air-voids is to limit hydraulic pressure and to limit time during which capillary ice can grow by diffusion of gel water.

Entrained Air

Although the beneficial effect of entrained air in concrete has been proven, care must be exercised for its maximum use. Air entrainment may reduce the strength as well as increase durability and workability, and a choice must be made as to the optimum percentage of air. Again entrained air must be differentiated from entrapped air in the form of large bubbles which do not increase the durability.

Influence of Pore Characteristics

Investigations have established the protection of the mortar phase of concrete by entraining air. However, the same is not true for frost susceptible aggregate particles in the concrete confined by the mortar. Emphasis in research to detect the unsound particles, particularly chert, in aggregate has shifted from one aspect to the other. However, as mentioned earlier, almost all the investigations have shown some relationship between porosity, absorption, permeability and specific gravity of the aggregates and the durability of concrete containing those aggregates. As a matter of fact, it can be stated that the characteristics of internal pore space in concrete aggregate are the most important of all aggregate physical properties. Upon these characteristics depend the absorption, permeability, specific gravity, etc. of the aggregates. Also the characteristics such as the abundance, size, shape and continuity of the pores determine the amount of water the aggregate can absorb, its absorption rate, its ease of draining (or water retention property), its internal surface area, and the portion of its bulk volume that is occupied by solid matter. Besides, the pore size influences the degree of temperature necessary to bring about freezing (3).

Frost Damage of Aggregates

Water, contained in the pore system, upon freezing is the cause of damage for aggregate particles according to the same theory as applied to the mortar phase of concrete. The hydraulic pressure theory of concrete can be applied to the air-entrained concrete containing chert aggregates. Powers (4) states, "the destruction of concrete by freezing is caused by hydraulic pressure generated by the expansion accompanying freezing of water rather than by direct crystal pressure developed through growth of bodies of ice crystals. Dilation of concrete with a protected paste is caused by water freezing in the aggregate particles. The water in the particle is trapped by ice or relatively impermeable paste surrounding the particle. The hydraulic pressure associated with freezing disrupts the particles and expands the specimens." He states further, "If the aggregate particles in a specimen of concrete are less permeable than the paste, then they should increase the intensity of hydraulic pressure in the region where the paste is saturated, since, for a part of the freezable water, they block the most direct paths to the unsaturated region."

"If the concrete contains unsaturated aggregate particles that are more permeable than the hardened paste, those particles should moderate the hydraulic pressure somewhat as cavities do, until the particles become saturated. When the particles are saturated, water must escape into the surrounding paste during freezing or pressures will develop that are high enough to disrupt the aggregate particles and the surrounding material. The intensity of the pressure in saturated particles then depends on the permeability of the paste that lies between the particles and the unsaturated region."

Schuster and McLaughlin (5) state that, "Probably for saturated aggregates of high porosity (e.g. lightweight cherts) the amount of excess water produced by freezing is too large to be taken on by the air bubbles entrained in the paste immediately adjacent to the aggregates."

Detection and Treatment of Unsound Chert

Critical Specific Gravity

In the light of these statements let us consider the treatments suggested to prevent frost damage or to improve the performance of chert aggregates. As discussed before, these treatments are basically related to the pore characteristics of the aggregates and vary in details only. The studies by Schuster and McLaughlin confirmed the fact that most porous cherts (those with lowest bulk specific gravities) cause the most severe freeze-thaw deterioration.

They showed that this concept holds for concretes with or without entrained air. Their investigations supported previous suggestions by Sweet and Woods (6) that bulk specific gravity level of 2.45 is the critical level of separation between unsound and durable cherts. Their quantitative analysis indicated that significant deep-seated and surface deterioration took place only in specimens containing 6 to 10 percent of materials from the minus 2.45 bulk specific gravity group.

Particle Size

Bloem (7) and others (5, 8) have shown that smaller sizes of chert gravel and other known deleterious aggregate particles are more durable. The durability of concrete increases when the maximum size used is reduced or when larger sizes are replaced by known durable aggregates. In this connection it was suggested that if the available larger size chert gravel contains predominantly low specific gravity and highly absorptive particles some technique, e.g. heavy media separation may be used to remove them. If such particles are few and no treatment is feasible then they may be used in combination with more durable aggregate. It appears that even if the pore characteristics are about the same, smaller sizes are more durable. The total force developed in a smaller size particle, upon the freezing and expansion of water, is not enough to cause disruption. As such it is also suggested by Walker (8) that if economical, all the larger particles may be crushed into smaller ones.

Moisture Condition

Resistance of the concrete to freezing and thawing is greatly enhanced if it has had an opportunity to dry partially before being frozen. This finding by Bloem (7) is consistent with, and confirms accepted concepts (4, 9, 10) on the effects of concrete moisture condition. Bloem (7) has summarized that, "If opportunity is provided for the concrete to lose excess moisture before being frozen, supplemented by reasonable efforts to prevent excessive resaturation, disruption from freezing can almost certainly be avoided.

Several other investigators have also reported the fact that certain aggregates in concrete reabsorb water reluctantly after they have been dried. In the resoaked concrete a greater proportion of the total absorbed water is in the mortar. The other reason,may be the capillary movement of water as described by Rhoades and Mielenz (11). "Water moving by capillarity will not enter aggregate containing only large voids, even if these voids are interconnected and penetrable. On the other hand, small voids will be penetrated; and if these openings are smaller than those of cement paste, the water will be preferentially drawn into them from the paste." This means the unsound cherts used had larger pores compared to mortar so that water cannot be reabsorbed easily. Schuster and McLaughlin (5) have stated that, "As the total porosity of chert increases in going from material of high to low bulk specific gravity, the voids larger than five microns in diameter constitute an increasingly larger percentage of total pore space." This certainly proves that more porous (i.e. low bulk specific gravity) cherts, which are more vulnerable to freeze-thaw, do have a greater percentage of pores larger in diameter than those generally present in mortar. This prevents the reabsorption of water by chert aggregates in concrete.

Comparing two types of cherts, Bloem (7) reported that, "the chert which has a higher capacity for absorbing water might be expected, therefore, to be more vulnerable to freezing under highly saturated conditions. The evidence also suggests, however, that water might be expected to move readily into and out of the pores of the former. Under certain circumstances, this might benefit the resistance to freezing for either or both of two reasons:

1. By permitting water to escape from the aggregate by allowing the concrete to dry.
2. By facilitating movement of water through aggregate pores during freezing."

Pore Size

The idea of a critical pore size was introduced by the earlier investigators. Sweet (12) stated that aggregate voids smaller than 4 to 5 microns (4 to 5 x 10^{-6} meters) in diameter enhance moisture absorption and promote generation of hydraulic pressure upon freezing water in them. Lewis and Dolch (13) stated that pores less than four microns in diameter will drain effectively only at pressures high enough to cause failure of aggregate particles and concretes in tension. More recent investigation by Schuster and McLaughlin (5) places less significance on the critical pore size of 4 to 5 microns. However, they still agree on the other qualitative characteristics of aggregate pore space that cause poor durability of concrete. Their microscopic petrography of thin sections of chert samples showed that only the minus 2.45 bulk specific gravity group contained voids large enough to be recognized. This indicated a direct correlation between the presence of these voids and the lack of durability as found in this lightweight group of cherts. Their subsequent discussion seemed to contradict the theory that freeze-thaw deterioration occurs primarily in voids less than five microns in diameter. However, there is a strong possibility that the larger voids are prime factors in the freeze-thaw breakdown of lightweight cherts due to higher degree of saturation afforded the chert by the larger voids. In this connection they had observed that "degree of saturation of the cherts increases with increasing total porosity and decreasing bulk specific gravity." This increase is probably caused by the greater percentage of voids larger than five microns in the more porous material.

Verbeck and Landgren (9) believe that an aggregate with a fine pore structure will reach a high degree of saturation much more rapidly than an aggregate with a coarse pore structure, even if the aggregates have the same porosity.

Expansive Properties

It has been recognized that there are certain other properties and conditions of the concrete constituents which are capable of producing disruptive volume changes just as the freezing of water in pore spaces. They include alkali-aggregate reaction, temperature change, wetting and drying. Although it is not possible to point out one single cause for the durability failure of concrete, the dominating factor is termed generally as the cause of damage. Actually the failure is the result of the combined effect of the different factors. Other investigations show evidence which differs sharply in their conclusions about the effects of certain properties. This only brings forth the complex nature of the problem. It is, therefore, important that other factors are taken into account when needed to make the results more conclusive.

Freezing and Thawing Durability Tests

The discussion of the durability of chert aggregates or for that matter any aggregate used in concrete would be incomplete if the freezing and thawing test methods employed to evaluate the durability are not brought into focus. In order to detect the frost susceptible aggregate through these tests we are required to know natural field conditions for which their durability is being determined. These tests, ideally, should simulate the field conditions as closely as possible so that the best possible correlation of test results with the field performance is obtained. There is no doubt that it may not be easy to find the relative severity of exposure to natural weathering conditions of different portions of a structure or of two adjacent structures. Scholer (1) states that he had "observed railway drainage structures in which one abutment was under considerable head of water on the back, while the opposite abutment was dry because drainage was from the structure on that side. Similarly due to changes in soil characteristics subgrade under a pavement may change in only a few feet. Also the effect of loads and traffic on deteriorating concrete is difficult to estimate."

These are practical difficulties with which one must contend. However, the current test procedures have come under criticism as they do not conform to the freezing and thawing conditions of nature. Powers (14) felt that in the light of the hydraulic pressure theory, 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 highest rates causing unrealistically high stress conditions. Powers states that, "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 temperatures are commonplace." The significance of moisture conditioning of aggregates and concretes in test methods was noted and related to several categories of field conditions. Many structures are in environments where some seasonal drying is possible and for this reason laboratory tests on only saturated concretes appeared too severe.

Powers (14) has proposed a simplified test procedure which is more realistic in simulating the field conditions in that it takes into account the effects of seasonal drying and a natural slow cooling rate of about 5°F per hour. He recommends the standard two weeks curing initially and then a period of air drying prior to freezing either in air or water. After freezing, he specifies a soaking period in water. The process is repeated until damage is observed as dilation occurs during the freezing cycle after freezing point. Normal behavior for a good specimen is to continue shrinking even after the freezing point. A primary measure of durability by this test is the period of immunity to freezing damage. It needs comparatively simple equipment and minimum manpower.

The first application of Powers' method was by the California Division of Highways in 1961. Aggregate evaluated by this method still appears to be performing well in one of their major highways. In an article (16) based on the thesis written by Wills (17), the application of Powers' method has confirmed hoped for results. Wills used two types of known poor performing aggregates, one of them being chert. The work of Wills indicates good correlation between the results of the slow-cycle as suggested by Powers, and those of the rapid cycle (ASTM method C291). It is suggested to compare similarly the three other ASTM standard procedures.

A recent study by Walker (18) has indicated a further development in the direction of simplifying the freeze-thaw test. The range of minimum slope in the length change vs. temperature curve during the first freeze of each specimen gave good correlation with the durability factor of the concrete specimen.

However, the work done until now indicates that the available standard procedures give results which can be correlated fairly well with field conditions. It does require sound engineering judgement to interpret them. New test methods, such as mentioned above, are needed to minimize the judgement factor.

IV. MATERIALS, LABORATORY PROCEDURES AND TEST OUTLINE

Materials Used

Coarse aggregates used were of three types as shown below.

Aggregate A: A high quality quartzite gravel from the eastern Piedmont region. This is a hard durable aggregate with an excellent field performance record and has been used both for comparative purposes and for blending with other aggregates.

Aggregate B: A high quality trap rock crushed stone from the eastern United States.

Aggregate F: A mid-western river gravel that is composed mostly of cherts. It has a poor field performance.

Physical characteristics of the coarse aggregates are given in Table 1. They were well-graded from ¼" to 1" size.

The same sand was used as fine aggregate in each case. The physical characteristics of the sand are given in Table 2.

A blend of equal amounts of three different brands of cement was used. All three brands were low alkali type I cements.

Procedures

Specific Gravities and Absorption

Bulk dry specific gravity (BD), bulk saturated surface dry (BSSD) specific gravity and absorption of the coarse

Table 1. Physical Characteristics of Coarse Aggregates

Aggregate	Sieve	B.S.S.D.* Sp.Gravity	Bulk Dry Sp.Gravity	Absorption %	Estimated Field Performance	Brief Description
A	1" -3/4"	2.639	2.624	0.380	Excellent	Quartzite gravel from eastern Piedmont
	3/4-1/2"	2.648	2.637	0.400		
	1/2-1/4"	2.644	2.633	0.421		
	Average	2.644	2.633	0.400		
B	1" -3/4"	2.944	2.929	0.521	Excellent	Crushed trap rock from eastern U.S.
	3/4-1/2"	2.943	2.926	0.602		
	1/2-1/4"	2.939	2.922	0.600		
	Average	2.941	2.925	0.581		
F-2	1" -3/4"	2.500	2.417	3.448	Poor	Midwestern chert river gravel
	3/4-1/2"	2.518	2.440	3.177		
	1/2-1/4"	2.510	2.422	3.601		
	Average	2.509	2.426	3.409		
F-2 Sp. Gr. +2.5	1" -3/4"	2.565	2.525	1.587	See F-2	See F-2
	3/4-1/2"	2.570	2.540	1.372		
	Average	2.567	2.533	1.480		
F-2 Sp. Gr. 2.4 to 2.5	1" -3/4"	2.480	2.400	3.320	See F-2	See F-2
	3/4-1/2"	2.510	2.430	3.320		
	Average	2.500	2.415	3.320		
F-3	1" -3/4"	2.540	2.470	2.980	See F-2	See F-2
	3/4-1/2"	2.510	2.420	3.540		
	1/2-1/4"	2.510	2.420	3.710		
	Average	2.520	2.440	3.410		

*B.S.S.D.S.G. = Bulk Saturated Surface Dry Specific Gravity.

Table 2. Physical Characteristics of Fine Aggregate

Sieve	Cumulative % Retained	
#4	4.5	
#8	18.5	
#16	27.8	F.M.=2.66
#30	43.0	
#50	75.2	
#100	95.2	
Pan	100.0	

Bulk Saturated Surface Dry Specific Gravity = 2.60

Bulk Dry Specific Gravity = 2.59

Absorption = 0.341%

aggregates were determined by a procedure similar to ASTM C127-59. For the fine aggregate the procedure adopted was similar to ASTM C128-59. These values are required to design the cement concrete mix.

Heavy Liquid Separation

A combination of tetrabromoethane and Varsol, in varying proportions, was used as heavy liquid media to separate cherts of different specific gravity levels. The two specific gravity levels chosen were +2.5 and 2.5 to 2.4. The sizes so separated were 1" to 3/4" and 3/4" to 1/2".

Concrete Mix

The coarse aggregates were saturated under vacuum and soaked 24 hours prior to incorporation in concrete mix. The fine aggregate was moistened and thoroughly mixed one day before mixing the batches, so that it would not absorb a portion of the mixing water. Concrete was proportioned on the basis of the ratio b/b_o (see reference 19 for design procedure). It contained 5.5 sacks of cement per cubic yard, and had an air content of 5 to 6 percent and a slump of about three inches. A neutralized vinsol resin solution added with the mixing water was used as the air entraining agent. Air contents were measured by the volumetric method using the Chase Air-Meter. A Lancaster counter current tub type batch mixer of 1.5 cubic foot capacity was used for mixing the concrete.

Molding of Specimens

The specimens were cast in molds of 3" x 3" x 16" prism shape. Brass plugs, on 10-inch centers, were installed in the top 3" x 16" face of each specimen for routine length measurements with a Whittemore strain gage. Thermocouples were placed in the center of each prism extending into the middle of 16 inches length from the 3" x 3" end face. Specimens were cast in accordance with the ASTM C192-62T procedure for Flexure Test Specimens. The thermocouples were placed in the center after the rodding of the first layer and before placing the second top layer. Care was taken not to damage the thermocouple while rodding the top layer.

Freezing and Thawing Equipment

The automatic freezing and thawing equipment used for the test is the same as that developed by the Engineering Experiment Station, Utah State University, for small laboratory purposes (20). It is a simple and efficient piece of equipment. The freezing and thawing cycle is controlled by means of a thermostat placed in the center of a control prism and relays which start the compressor and turn off the heaters at 40°F and reverse the procedure at 0°F. A gas charged thermometer bulb and a recording thermometer keep a continuous record of the temperature at the center of the control specimen. It is possible to adjust the cycle at any time to take care of variable conditions.

This equipment was used to perform the rapid freezing and thawing tests in water as described in ASTM C291-61T. The freezing period was of about 2-3/4 hours and thawing about 1-1/4 hours.

Dynamic Modulus of Elasticity

The non-destructive test method as described in ASTM C215-60 was used to determine the relative dynamic modulus of elasticity (E) of the specimen by use of sonic apparatus. These measurements were calculated in terms of relative (E) rather than exact value of (E). Modulus of elasticity depends on weight, length and cross-sectional area. These three quantities are variable during the test as the specimens disintegrate. In calculating the relative (E), however, it is implied that these values are constant which introduces only an insignificant error. This procedure is consistent with the conventional reporting of the freeze-thaw test results.

Outline of Tests

The chert gravel (F-2) was successively used to replace 8 to 20 percent of good performing coarse aggregate (A) between 1 and 1/4 inch, and then finally the entire quantity of good coarse aggregate. This treatment was incorporated in mix designs designated A, K-1, K-2, K-3 and F-2 (Table 3). In another treatment chert gravels (F-2) of 1"-1/2" size,

Table 3. Concrete Mixes and Their Nomenclature

S. No.	Mix Design	Aggregates Used	Percent of Coarse Aggregate in Mix 1"-3/4"	3/4"-1/2"	1/2"-1/4"	Total	Remarks
1	A	A*	25	25	50	100	-
2	B	B	25	25	50	100	-
3	F-2,3	F-2,3**	25	25	50	100	-
4	K-1	F-2 A	5 20	5 20	10 40	20 80	-
5	K-2	F-2 A	3 22	3 22	6 44	12 88	-
6	K-3	F-2 A	2 23	2 23	4 46	8 92	-
7	K-4	F-2 A	25 -	25 -	- 50	50 50	S.G.of F-2 +2.5
8	K-5	F-2 A	25 -	25 -	- 50	50 50	S.G.of F-2 2.4 to 2.5
9	L-1	F-3 B	25 -	25 -	- 50	50 50	14 days curing
10	L-2	F-3 B	25 -	25 -	- 50	50 50	7 days curing

* Several shipments of Aggregate A were received but were so uniform they were not treated separately.

** Refers to different shipments of aggregate from the same source.

separated by heavy liquid, were combined with aggregate (A) of 1/2"-3/4" size with a 50:50 percentage ratio in mix designs K-4, K-5. The next treatment was covered by the mixes L-1 and L-2 which utilized chert gravel (F-3), not separated by heavy liquid media, and high quality aggregate (B).

Concrete mixes were all air-entrained and the mix design was held constant, as far as possible, for each series. Mix designs K-4 and K-5, being one beam batches, were hand mixed. All the other mixes were batch mixed. A maximum of 0.6 cubic foot, representing concrete for six specimens, was mixed twice a week.

The curing procedures adopted were:

1. One day in open room while still in the molds, followed by 13 days in saturated lime water in the moist room.

2. One day in the mold as stated above, followed by six days in saturated lime water in the moist room (Mix L-2 only).

All the curing operations were at temperatures controlled within the range of 70° to 74°F.

At the end of curing period, the specimens were measured for length, weight and fundamental transverse frequency. They were placed immediately afterwards in the automatic freezing and thawing equipment. The placing of the new specimens and testing of the old ones was carried out at the end of the thawing phase of the cycle.

Measurements of weight, length and relative dynamic modulus of elasticity were noted as frequently as possible but never less than two or three times a week. Tests were terminated when the relative modulus of elasticity was reduced fifty percent or at the end of 300 cycles.

Half the specimens cast from each batch of concrete were used for the principal freezing and thawing tests. The remaining half of the specimens were used in tests not reported here.

V. RESULTS AND DISCUSSION

Terminology

Definitions of various terms used in this thesis are described here.

E and E_n: E is the dynamic modulus of elasticity, while E_n is the relative dynamic modulus of elasticity at nth cycle of freezing and thawing. The calculation procedures are given in ASTM designations C215-60 and C290-61T respectively.

DF_{100}, DF_{200} and DF_{300}: These are the durability factors at 100, 200 and 300 cycles respectively according to ASTM designation C290-61T. These factors range from zero to one hundred. The following arbitrary classification is indicated to facilitate discussion of the results.

a. Group I, DF_{100} = 0 - 5, indicative of potentially very bad field performance.

b. Group II, DF_{100} = 6 - 30, indicative of potentially bad field performance.

c. Group III, DF_{100} = 31 - 80, indicative of potentially fair field performance.

d. Group IV, DF_{100} = 81 - 100, indicative of potentially good field performance.

These groupings, arbitrary as they are, do agree quite well with the known field performance of the aggregates used in this thesis.

ΔL_n, ΔL_F: Cumulative length change is the difference of specimen lengths between zero and nth cycle at approximately 40°F. The units are 10^{-4} inches. ΔL_F is the final length change.

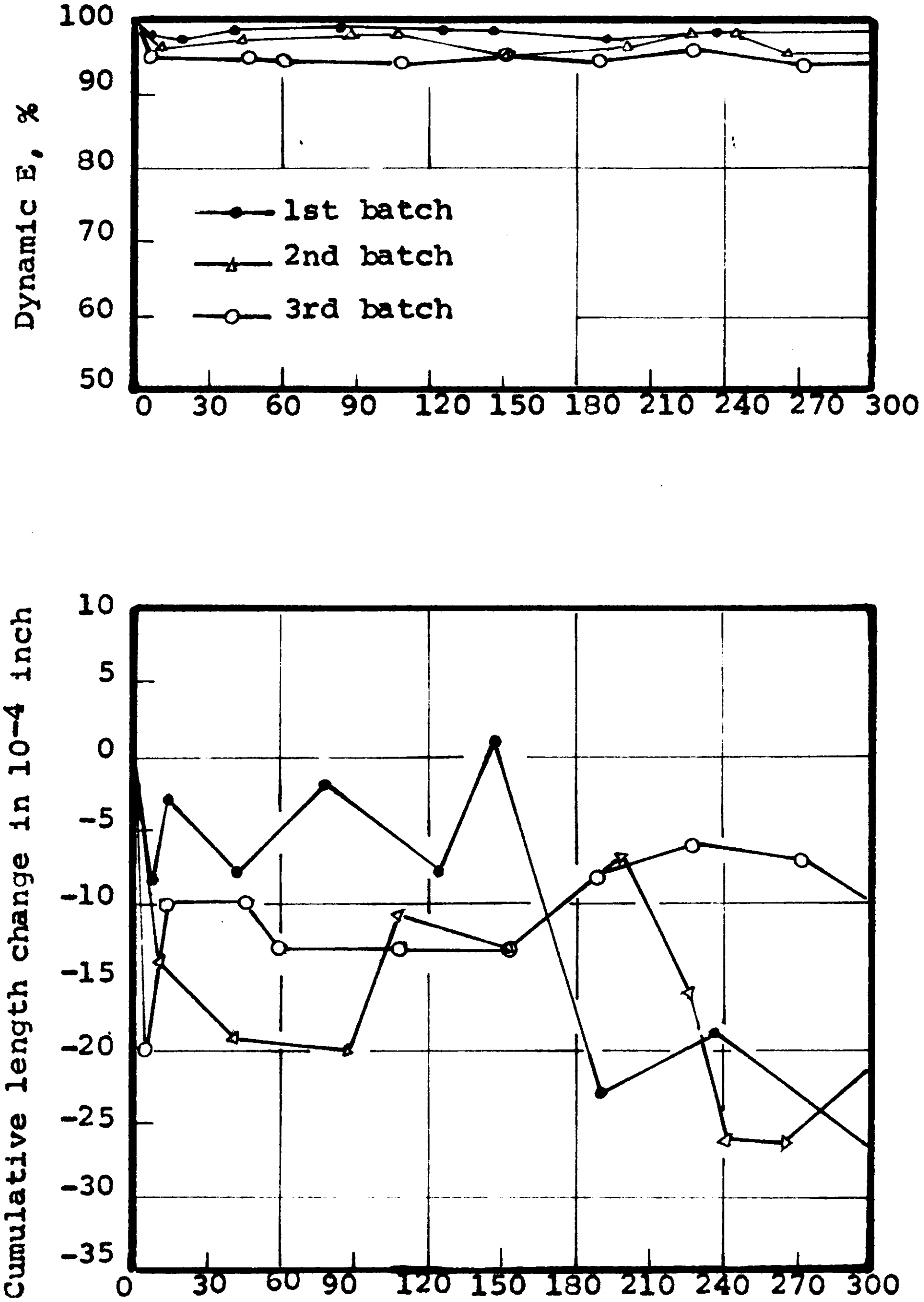
ΔW_n, ΔW_F: Cumulative weight change, measured similarly as ΔL_n. The units are grams. ΔW_F is the final length change.

Results

The data is presented in the form of line graphs, Figures 1 through 11, and in Tables 1 through 7. Line graphs are of three types, namely:

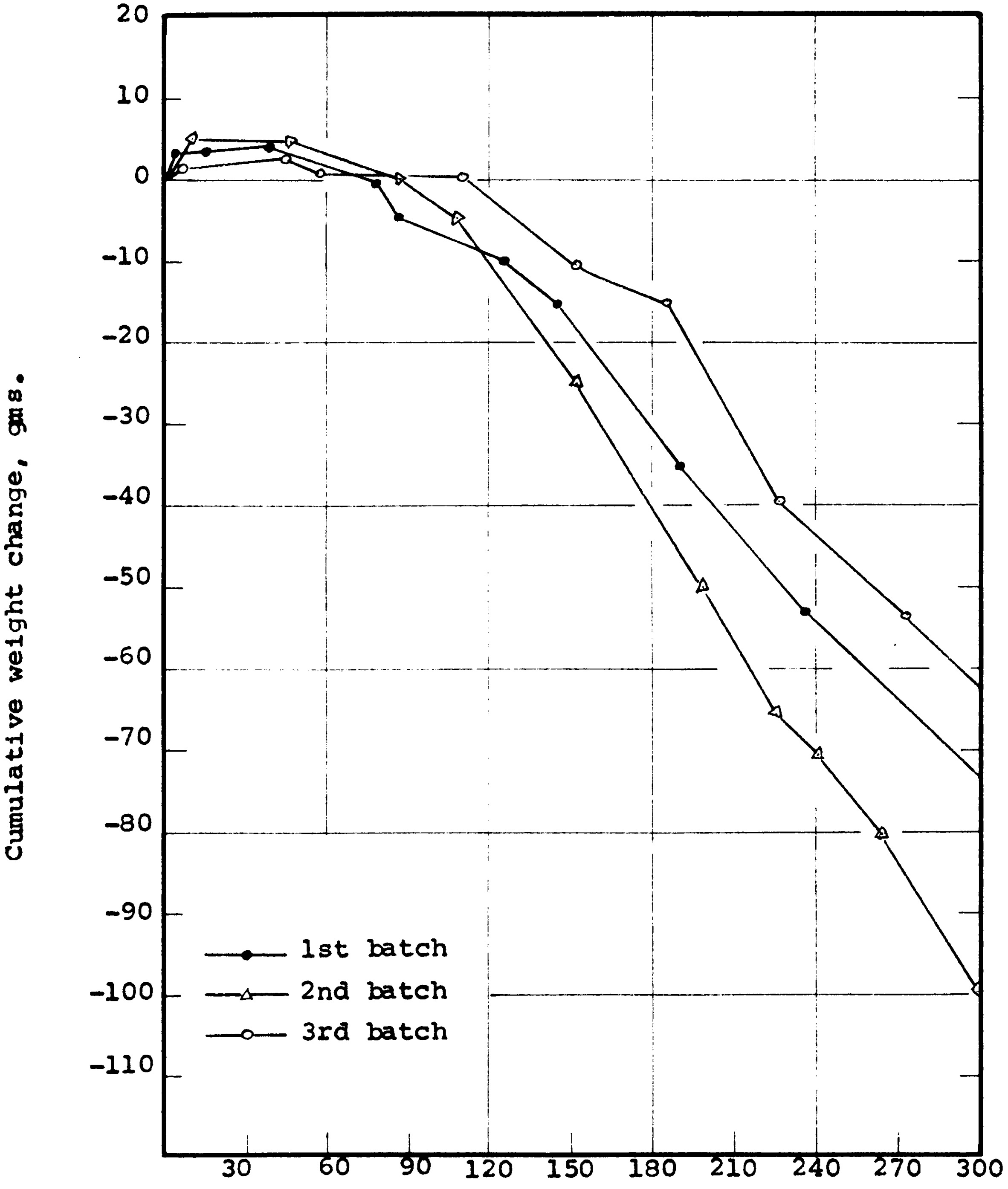
1. Relative modulus of elasticity vs. freezing and thawing cycles.
2. Cumulative length change vs. freezing and thawing cycles.
3. Cumulative weight change vs. freezing and thawing cycles.

The graphs were drawn separately for each series of mix design. Different lines in each graph represent batches of a particular mix design. The corresponding test results of all the specimens fabricated from a single mix were averaged for plotting the points joined by lines. The curve was discontinued at a point where any of the specimens failed, i.e. when average E_n was reduced to approximately 50 percent. If the nearest point is below 50 percent it was not shown and the line cut off at the abscissa for 50 percent. Similarly



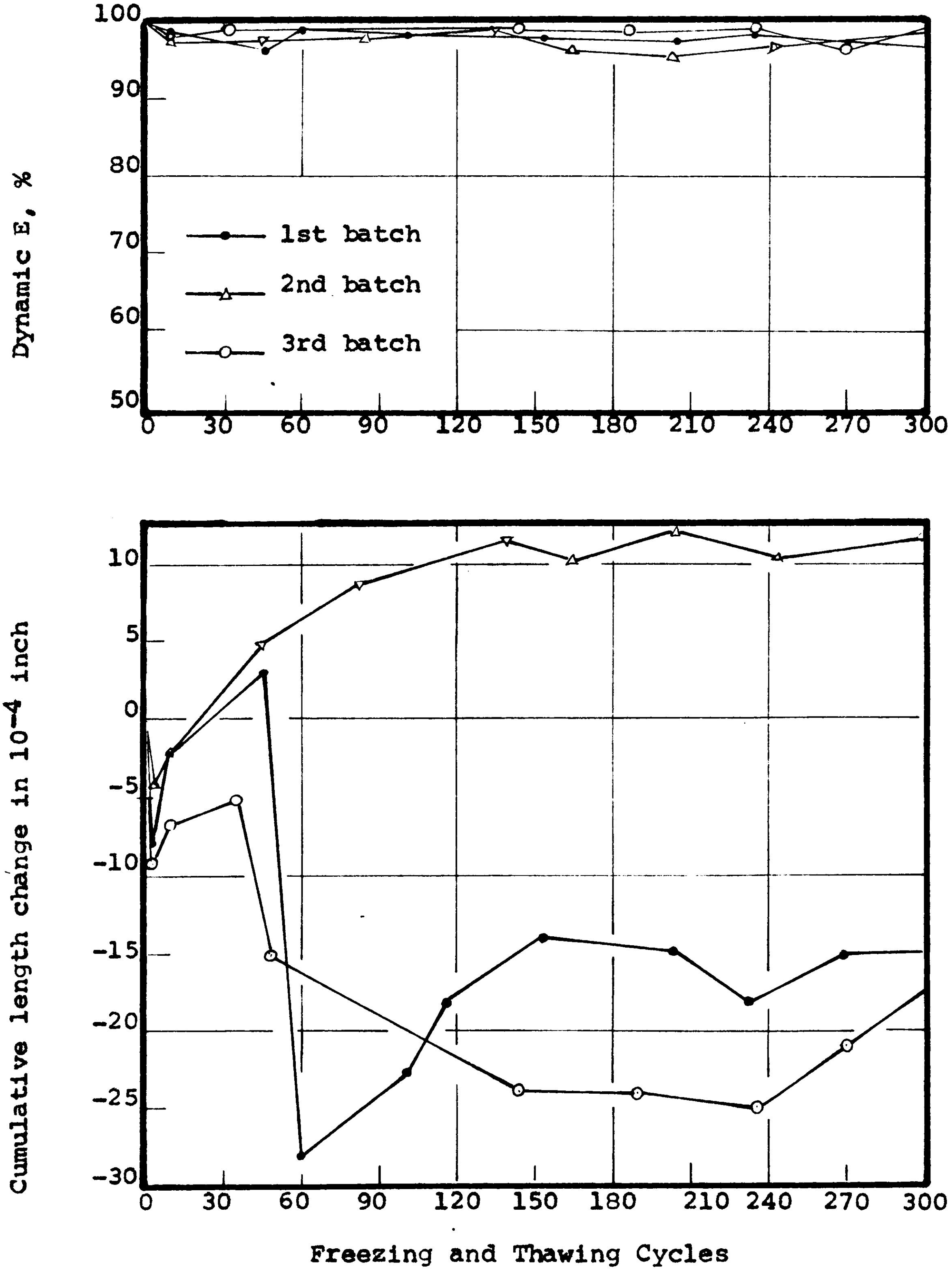
Mix A

Figure 1. Relationship Between Dynamic Modulus, Length Change, Weight Change and Cycles of Freezing and Thawing.



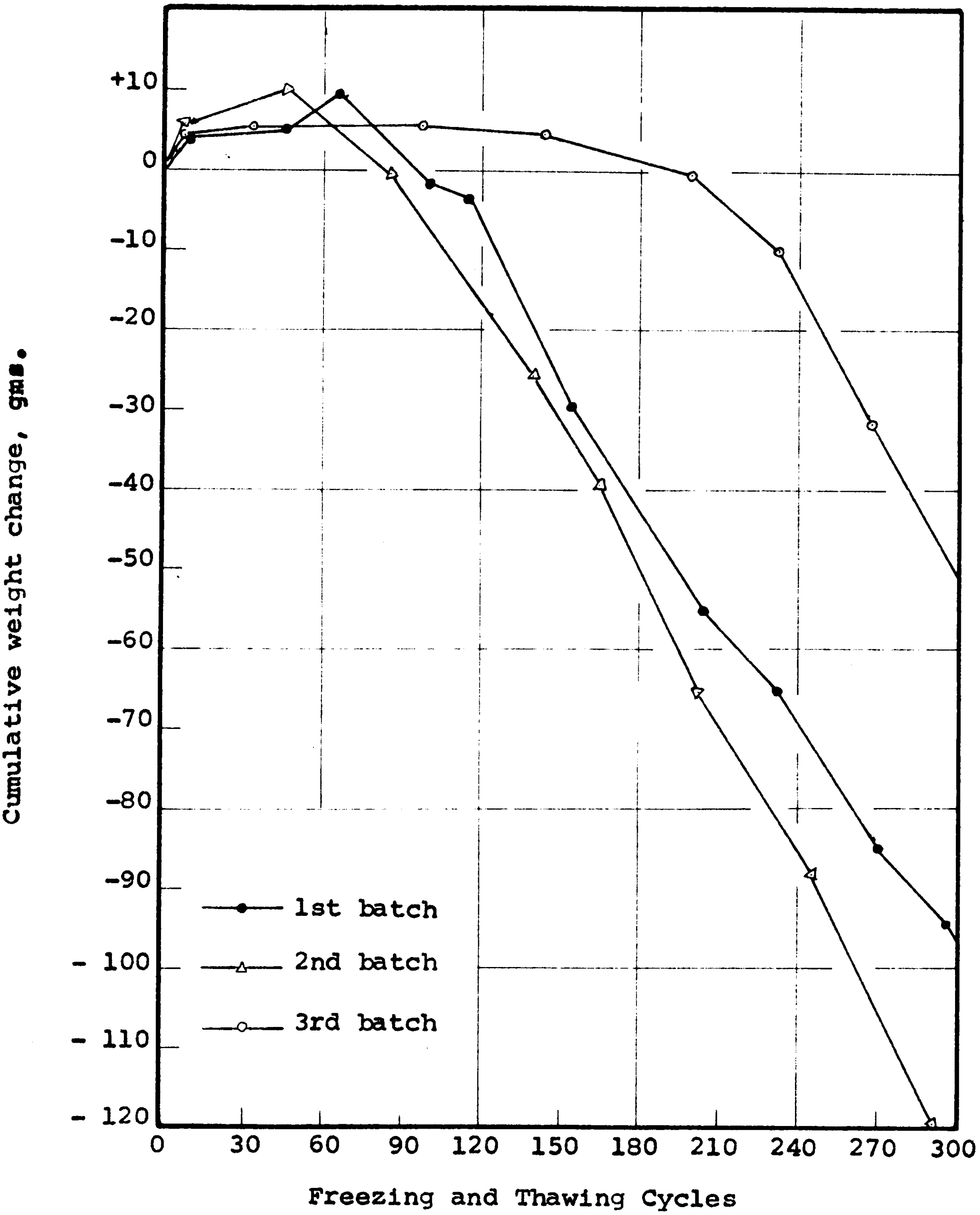
Mix A

Figure 1. (continued)



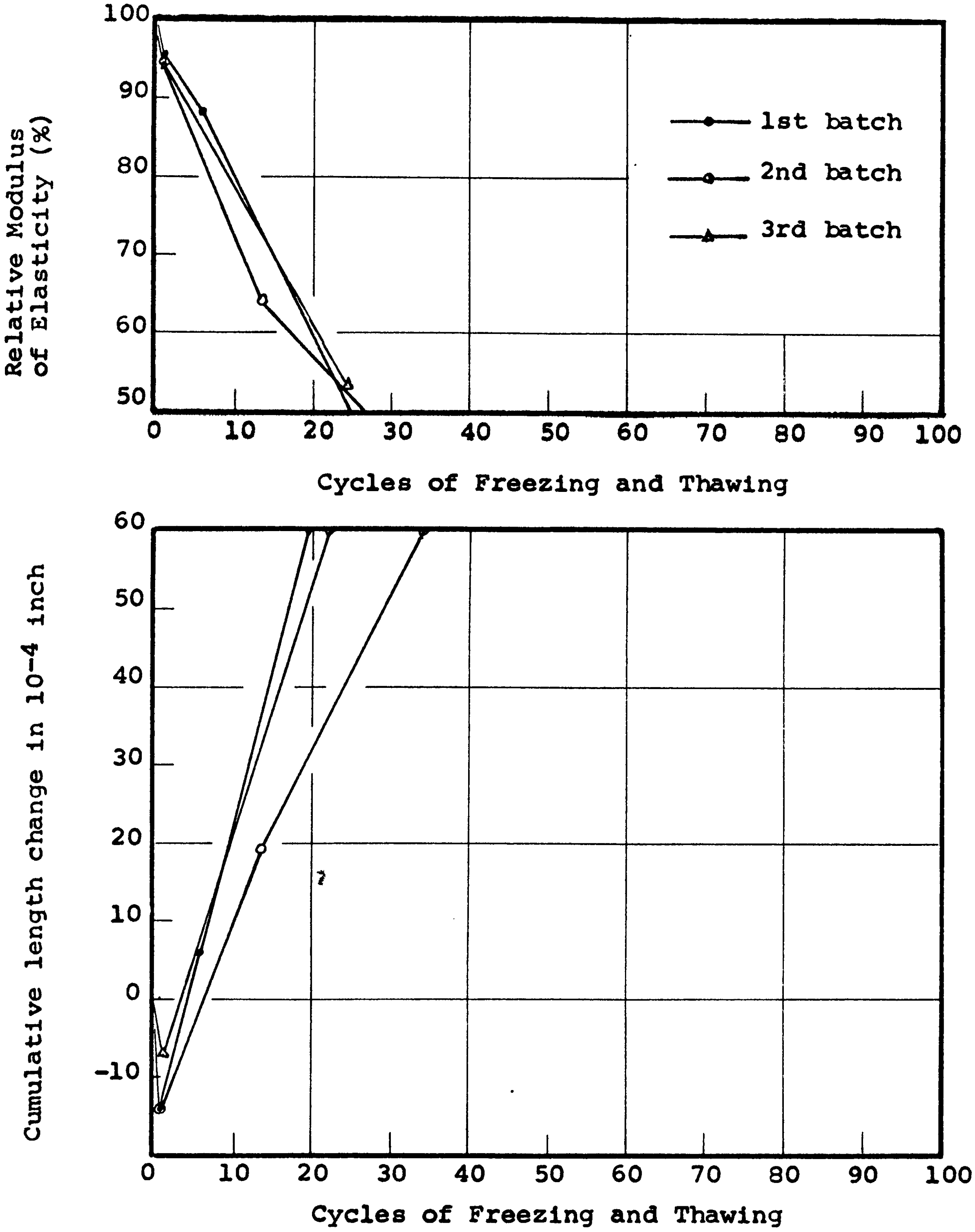
Mix B

Figure 2. Relationship Between Dynamic Modulus, Length Change, Weight Change and Cycles of Freezing and Thawing.



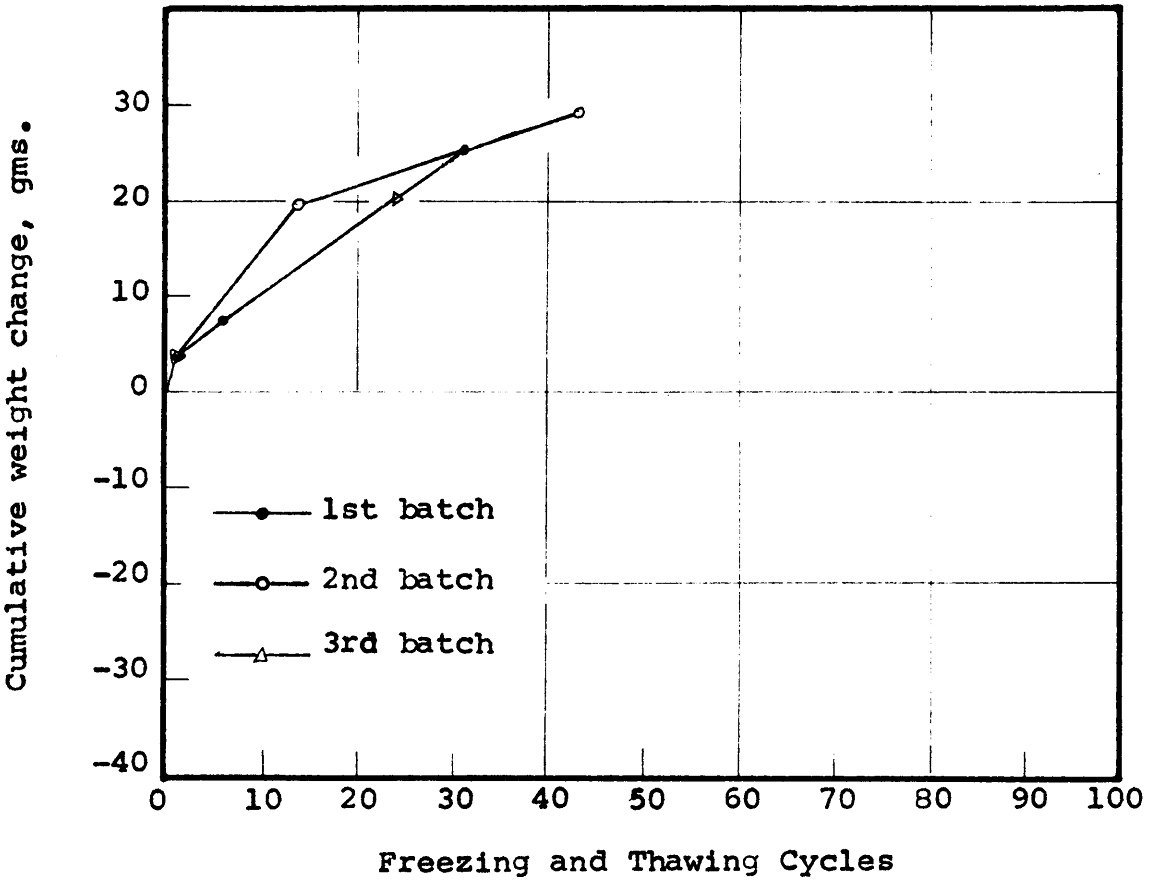
Mix B

Figure 2. (continued)



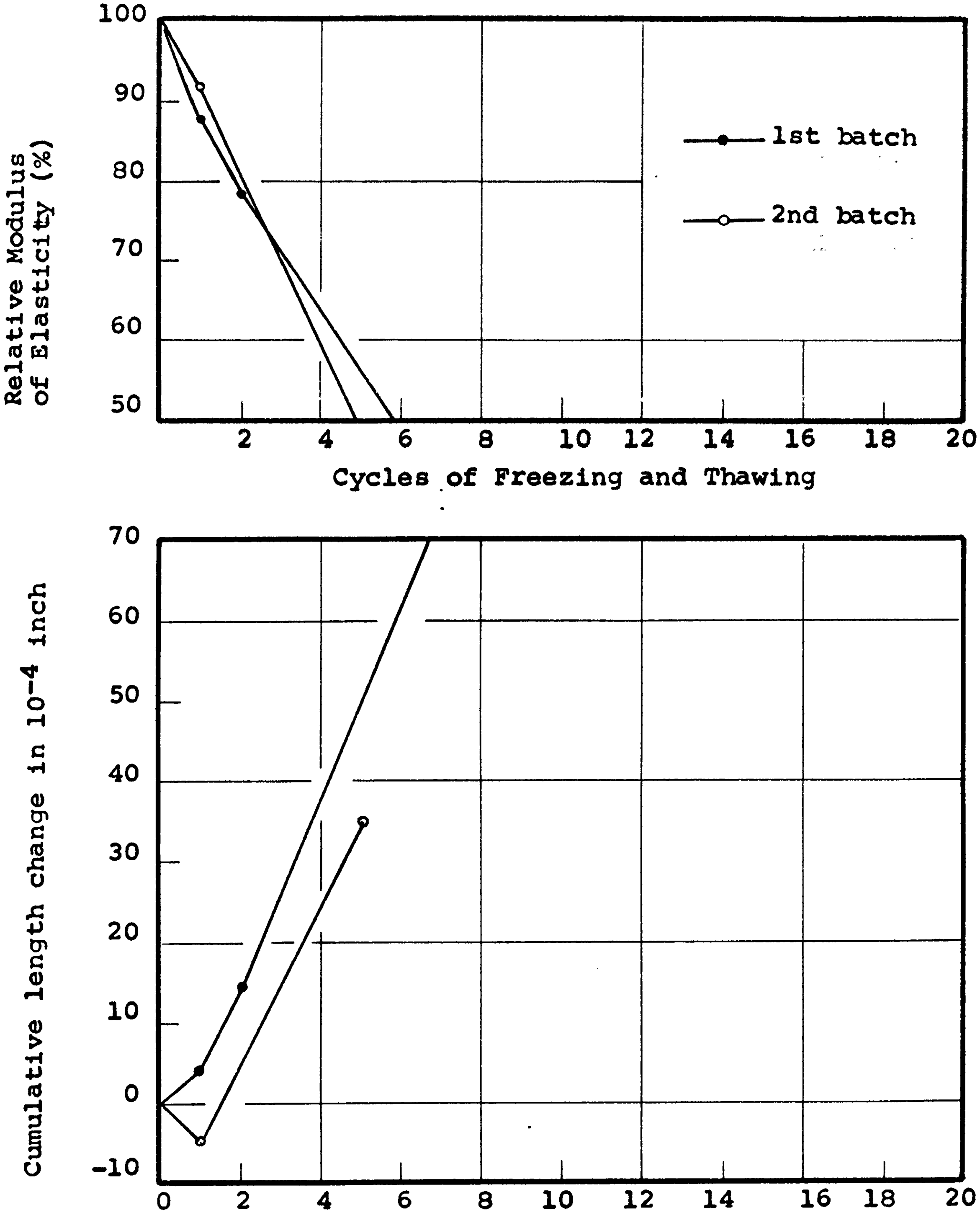
Mix F-2

Figure5. Relationship Between Dynamic Modulus, Length Change, Weight Change and Cycles of Freezing and Thawing



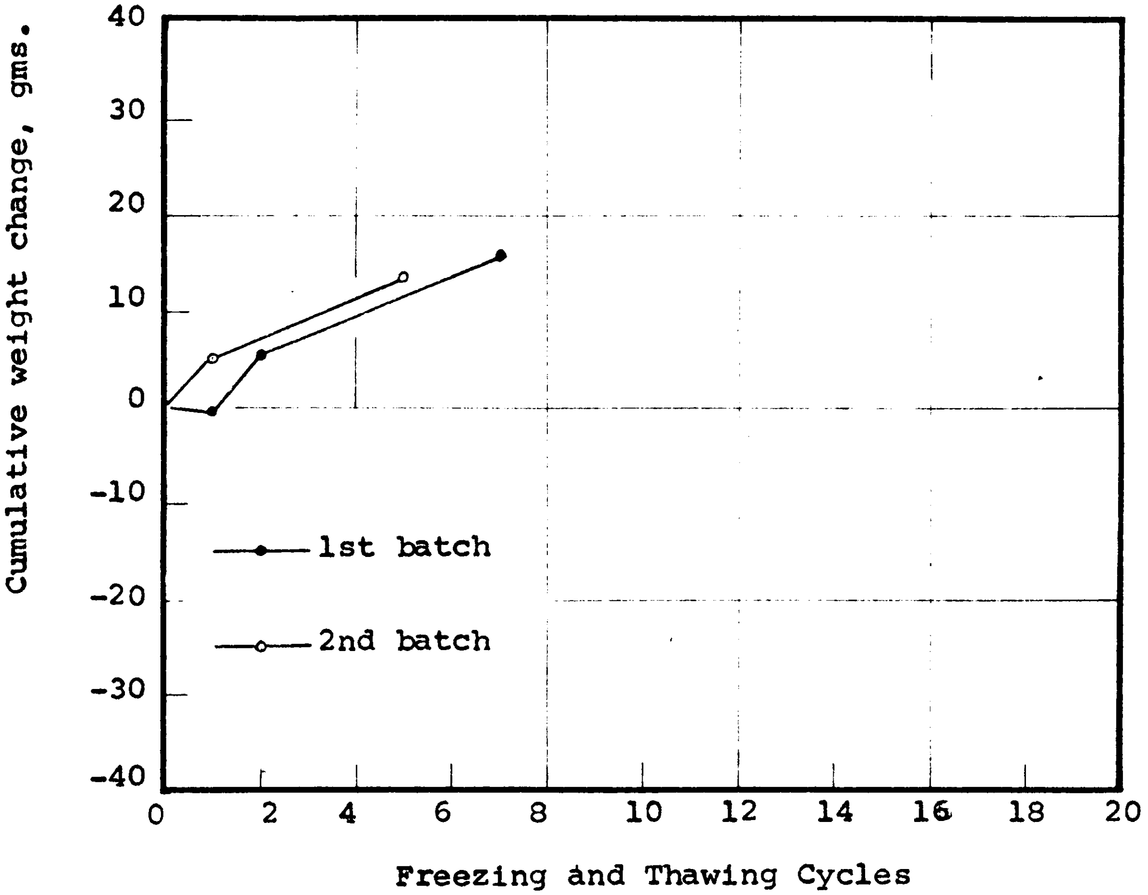
Mix F-2

Figure 3. (continued)



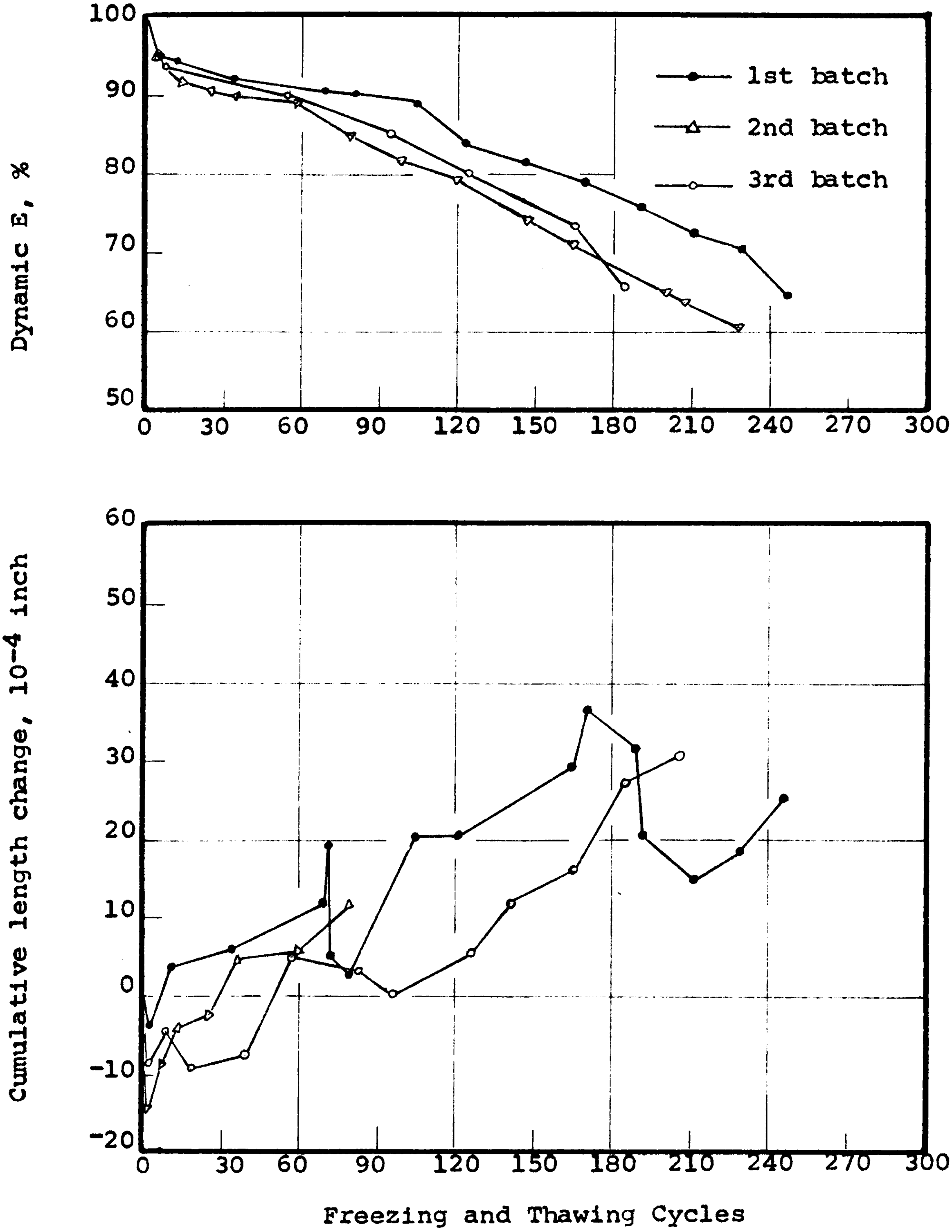
Mix F-3

Figure 4. Relationship Between Dynamic Modulus, Length Change, Weight Change and Cycles of Freezing and Thawing



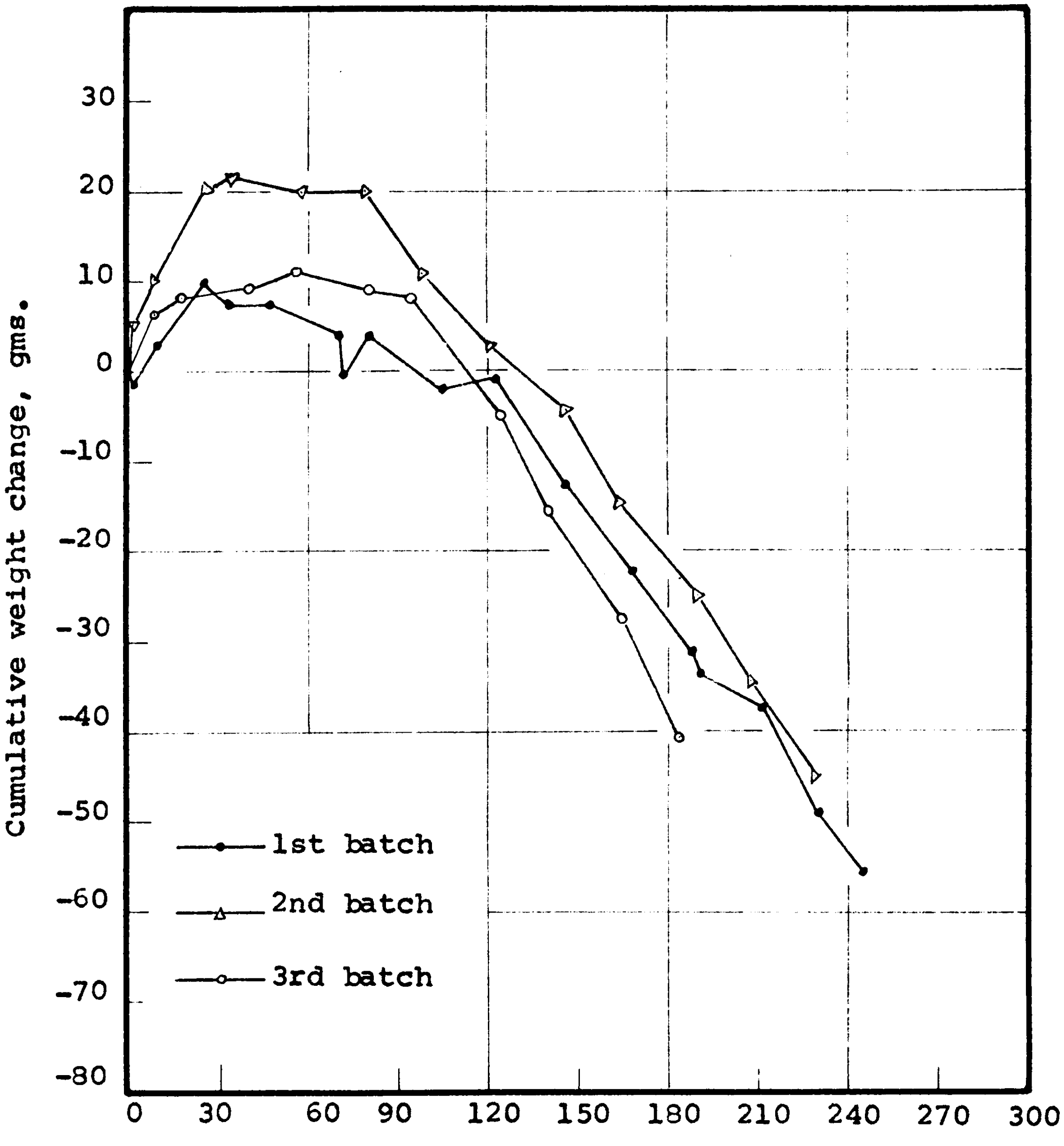
Mix F-3

Figure 4. (continued)



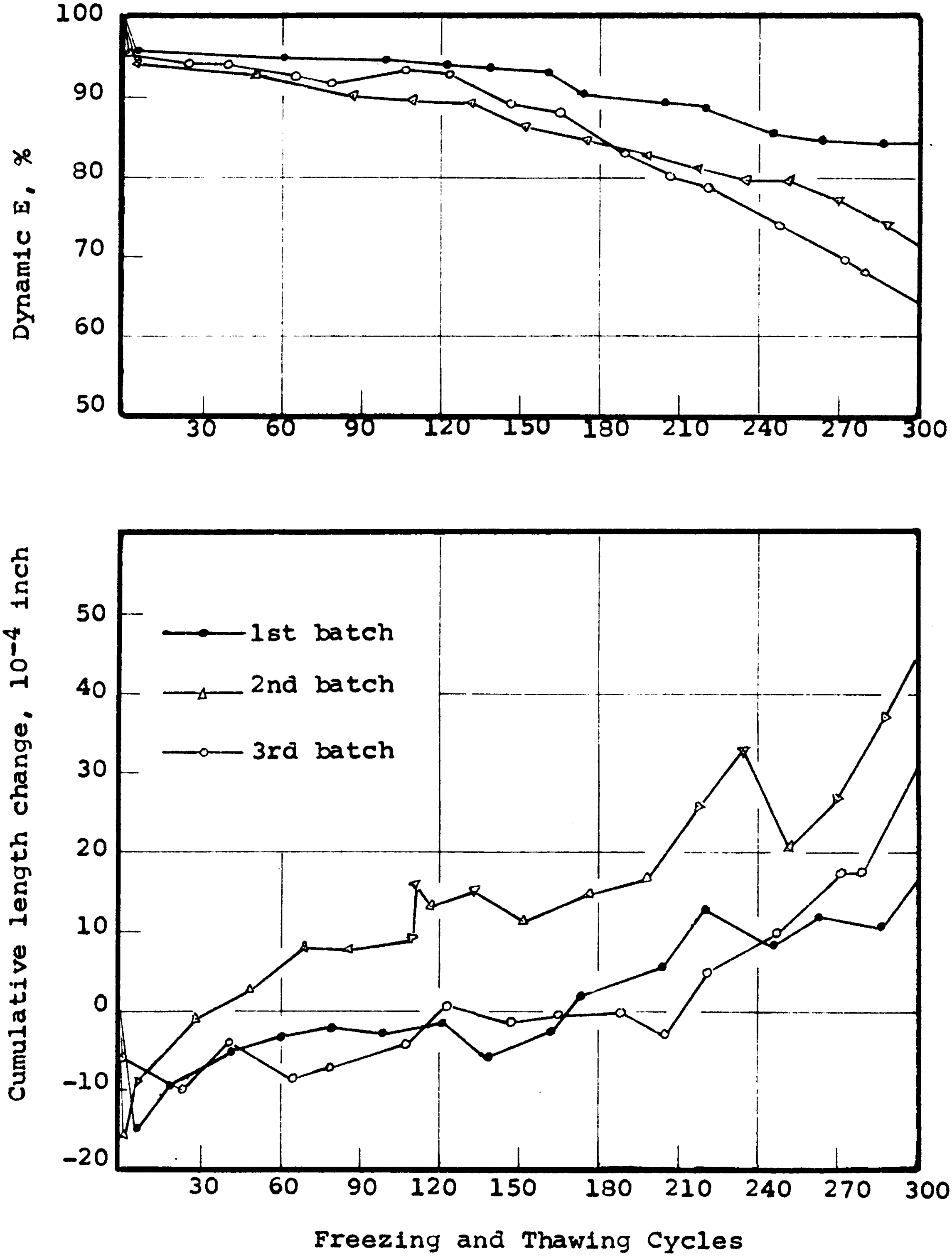
Mix K-1

Figure 5. Relationship Between Dynamic Modulus, Length Change, Weight Change and Cycles of Freezing and Thawing.



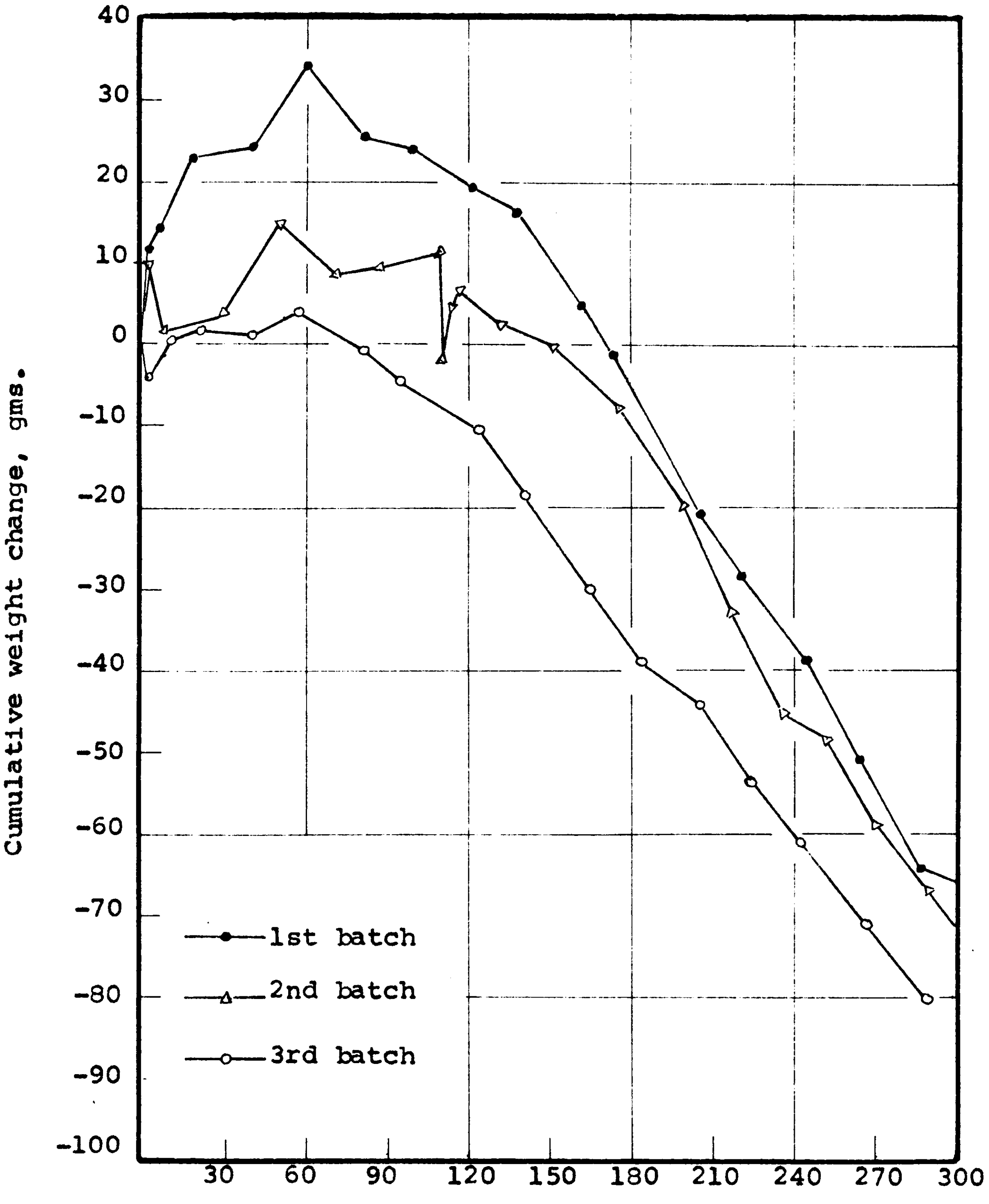
Mix K-1

Figure 5. (continued)



Mix K-2

Figure 6. Relationship Between Dynamic Modulus, Length Change, Weight Change and Cycles of Freezing and Thawing.



Freezing and Thawing Cycles

Mix K-2

Figure 6. (continued)

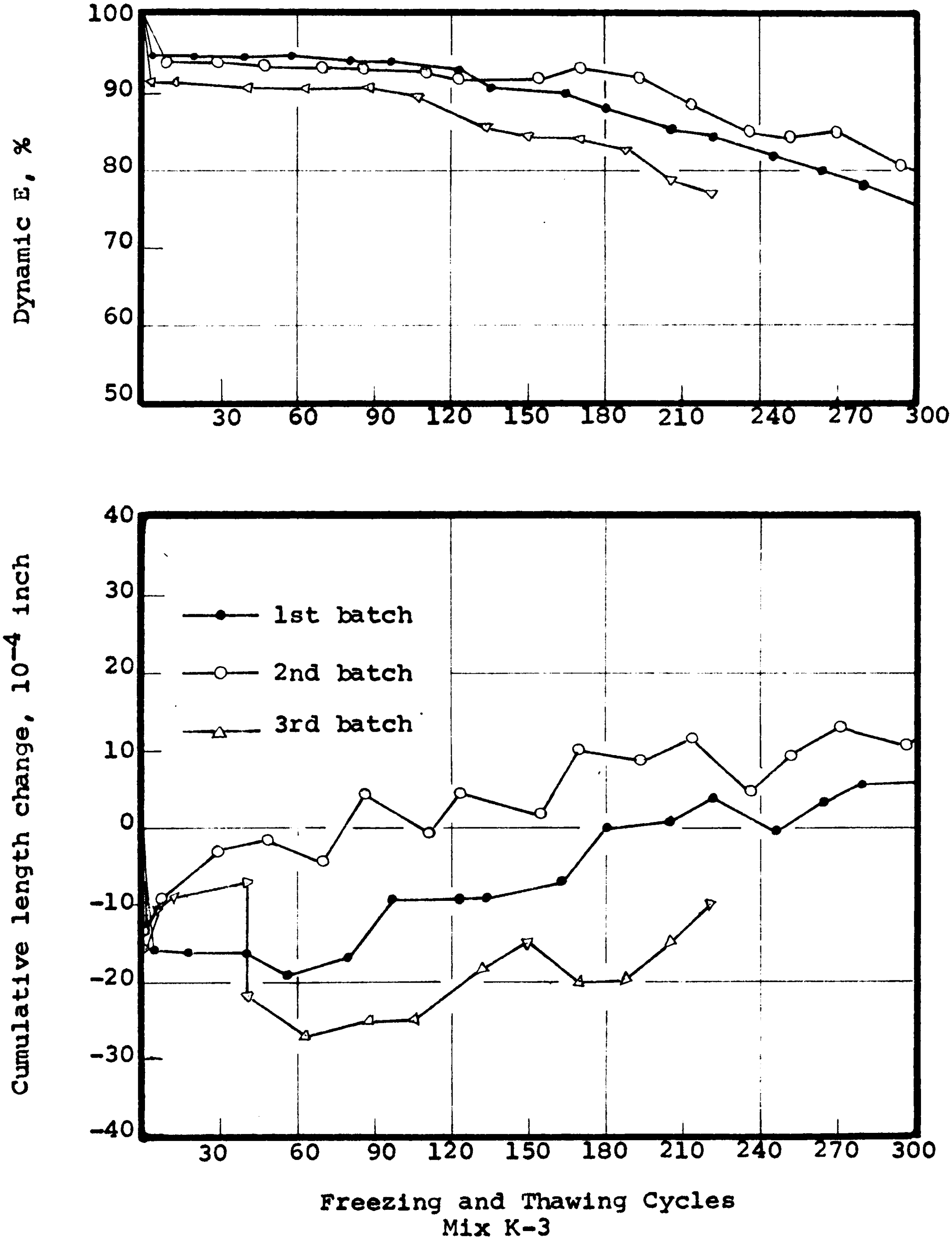
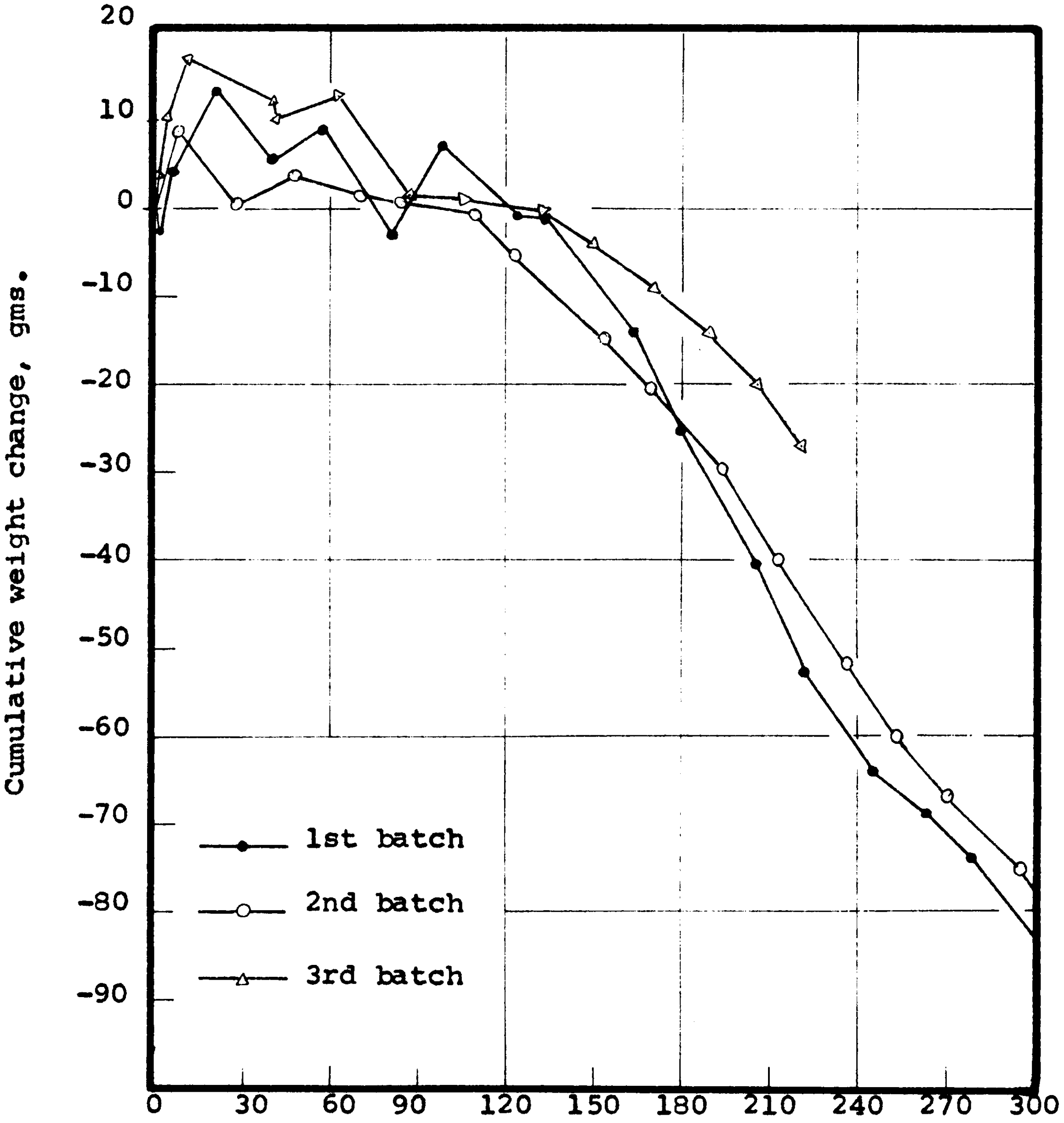


Figure 7. Relationship Between Dynamic Modulus, Length Change, Weight Change and Cycles of Freezing and Thawing.



Freezing and Thawing Cycle
Mix K-3

Figure 7. (Continued)

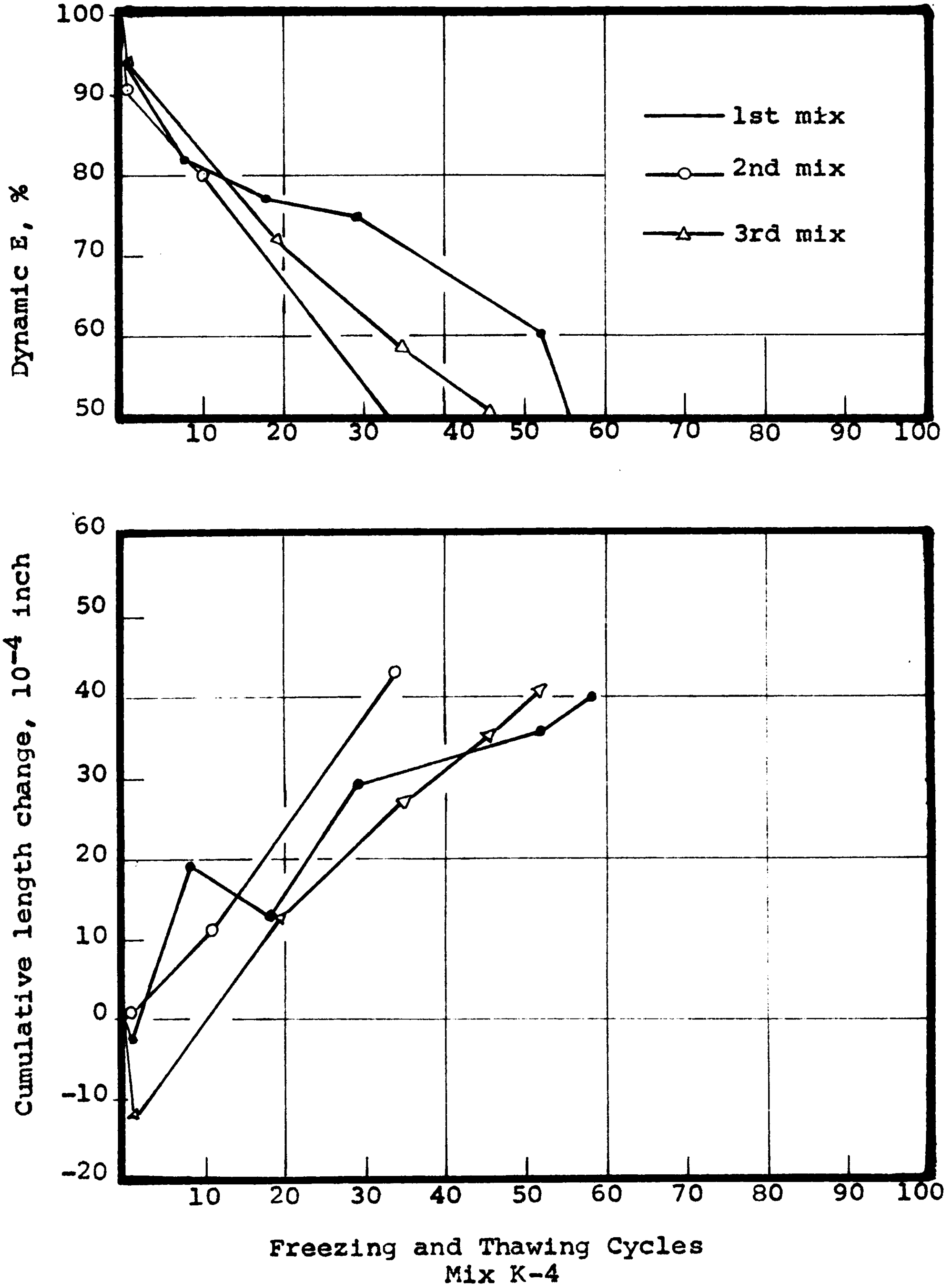


Figure 8. Relationship Between Dynamic Modulus, Length Change, Weight Change and Cycles of Freezing and Thawing.

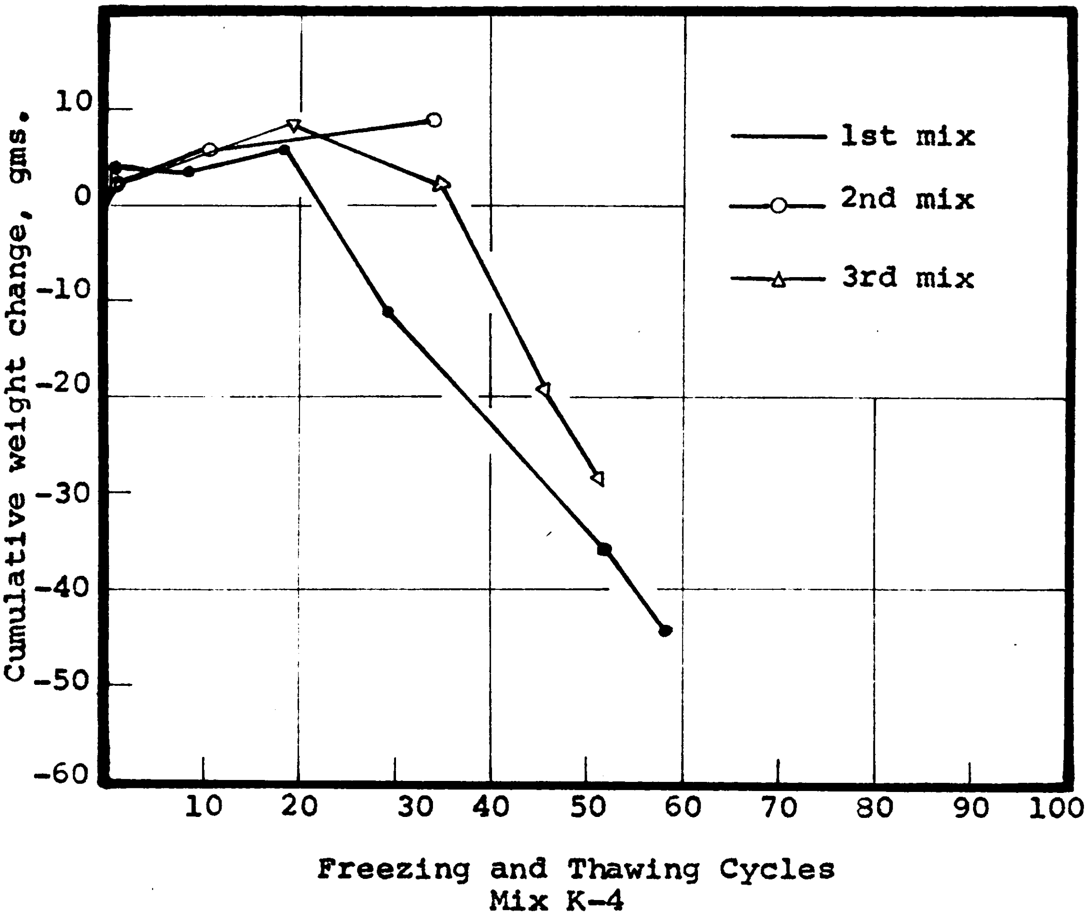


Figure 8. (Continued)

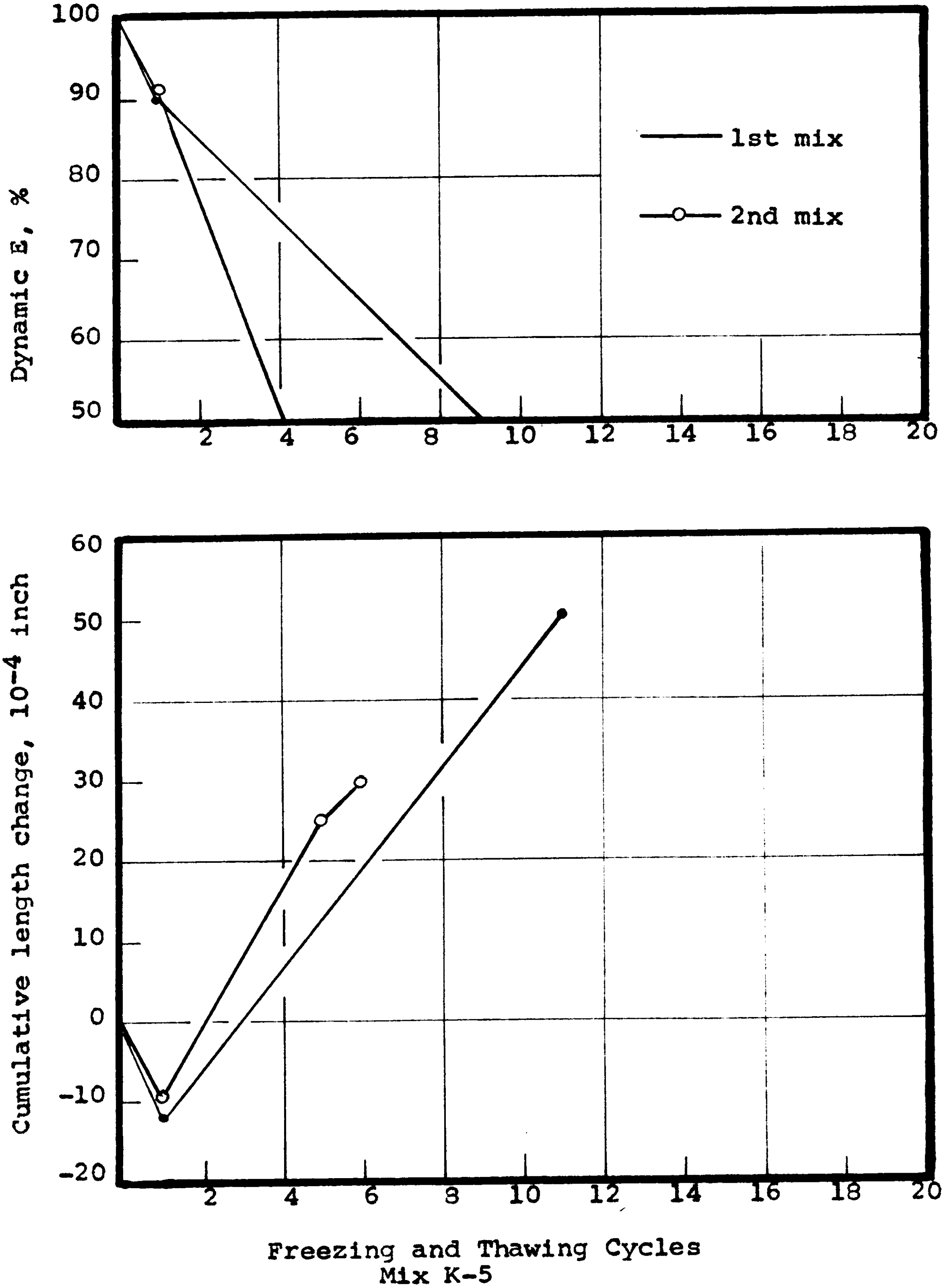
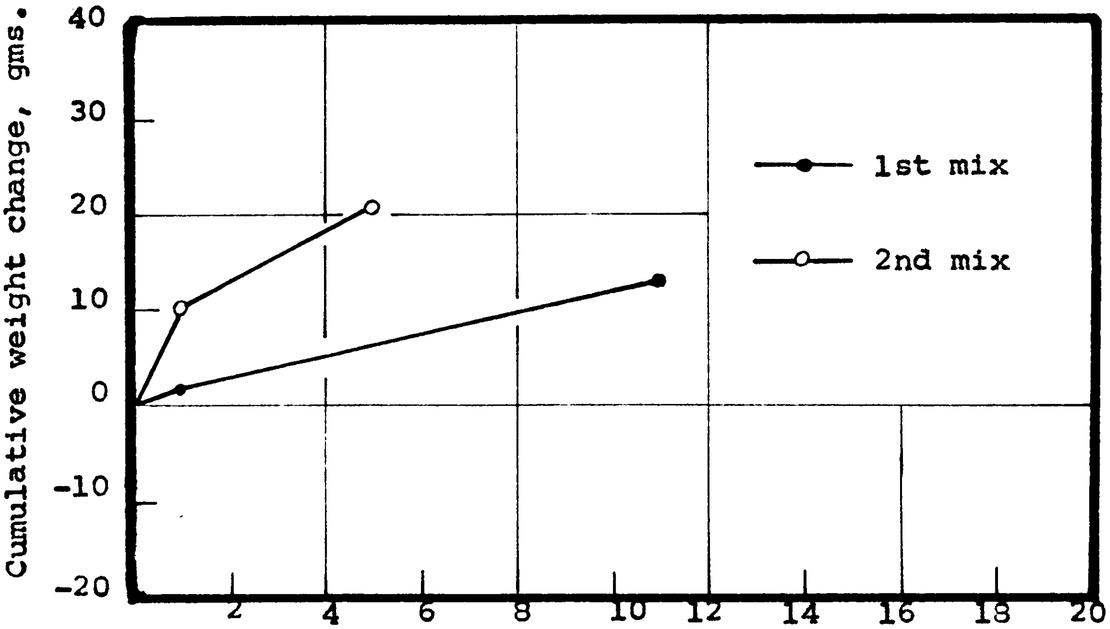
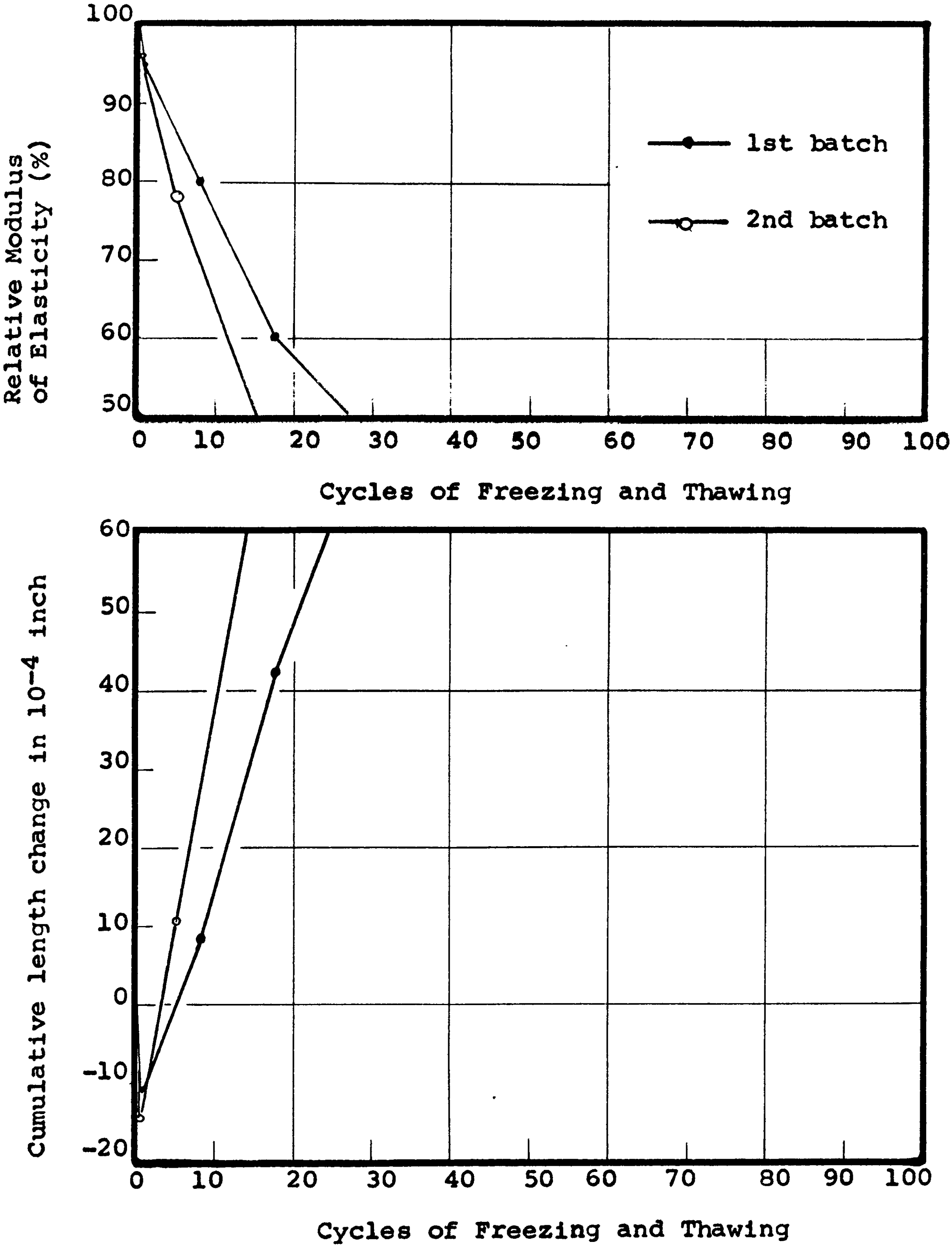


Figure 9. Relationship Between Dynamic Modulus, Length Change, Weight Change and Cycles of Freezing and Thawing.



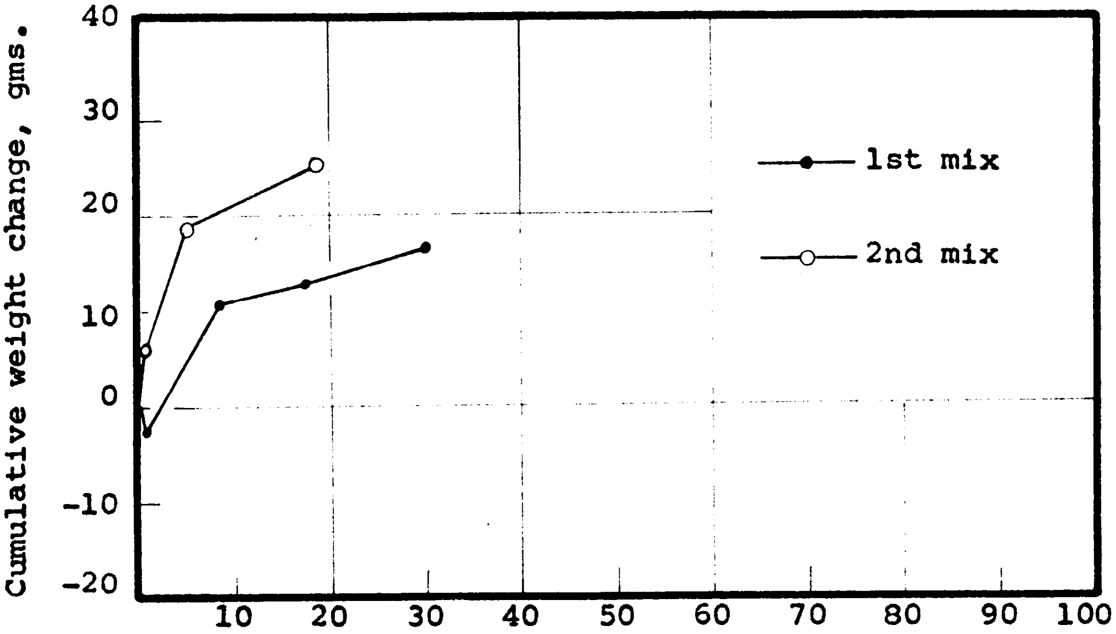
Freezing and Thawing Cycles
Mix K-5

Figure 9. (continued)



Mix L-1

Figure 10. Relationship Between Dynamic Modulus, Length Change, Weight Change and Cycles of Freezing and Thawing



Freezing and Thawing Cycles
Mix L-1

Figure 10. (continued)

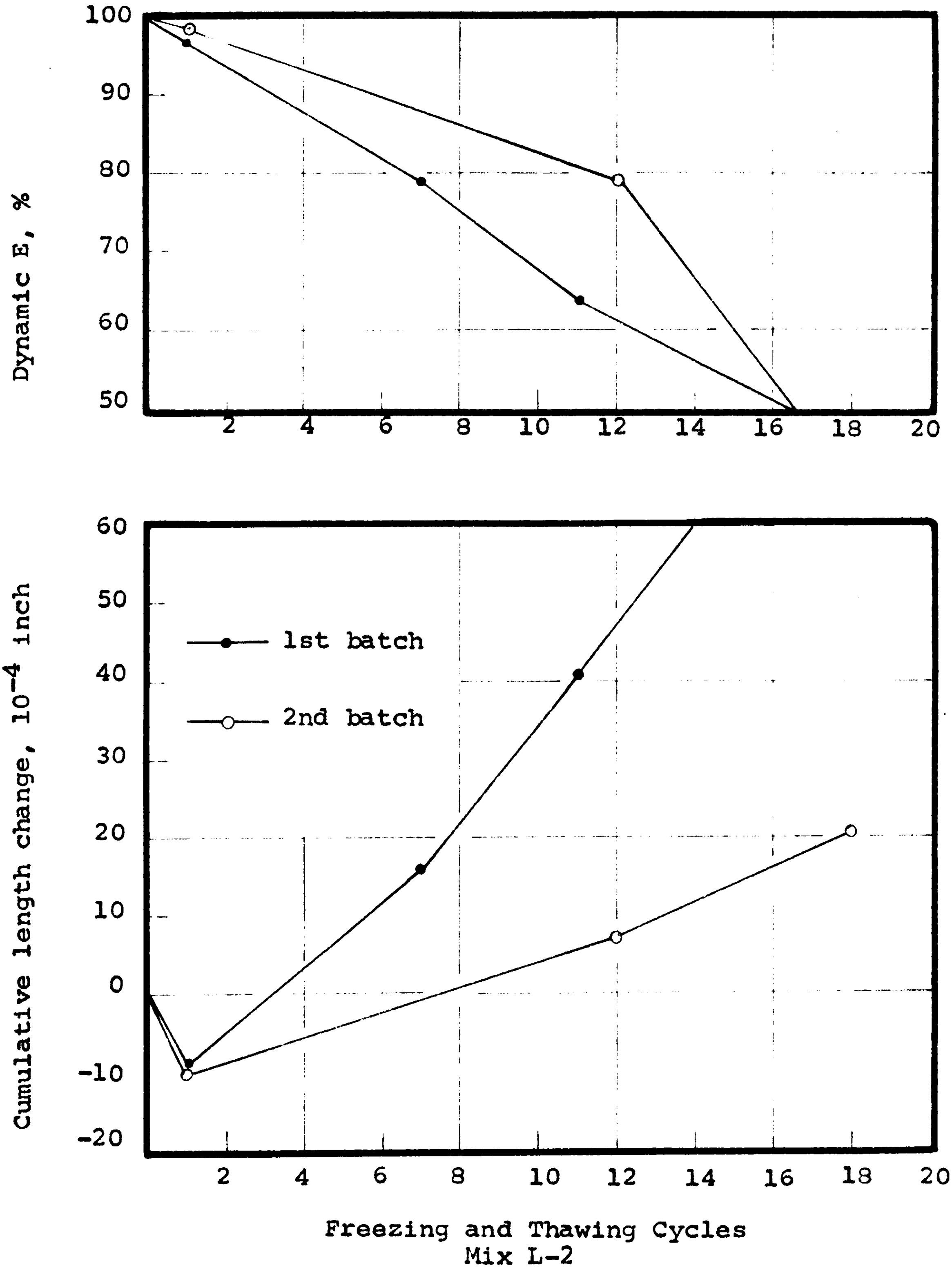


Figure 11. Relationship Between Dynamic Modulus, Length Change, Weight Change and Cycles of Freezing and Thawing.

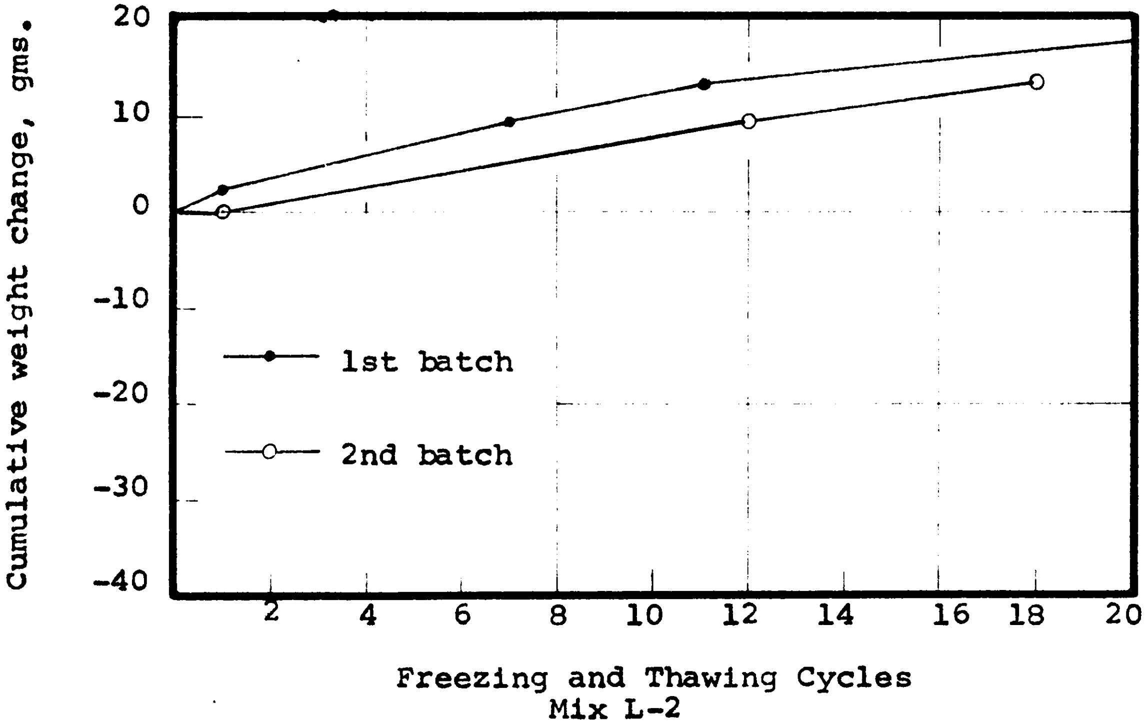


Figure 11. (continued)

for other graphs if the last point was outside the graph limits it was not shown and the line was cut off at the limits.

To establish a basis for comparison whether a particular specimen is durable or not and to correlate the inferences from the corresponding graphs to those of DF_{100}, the characteristics of the graphs for high and poor quality aggregates are studied and noted.

High Quality Aggregates A and B, Figure (1,2):

a. Relative Dynamic E_n vs. F. and T. Cycles

Curves are flat and lie between 100 and 95 percent E even beyond 300 cycles. Hence DF_{100}, DF_{200} and DF_{300} lie in group IV.

b. Length Change vs. F. and T. Cycles

Except for first batch in Figure 2, all the other curves show an overall contraction proving that high quality durable aggregates do not dilate destructively.

c. Weight Change vs. F. and T. Cycles

In each case there is an initial gain in weight and then there is a gradual drop. The maximum gain in weight is less than 10 gms. The initial gain is perhaps due to absorption of water by concrete which may not have been saturated completely during curing. Part of the water can find its way into minor contraction cracks. The loss of weight is due to the scaling of the surface mortar of a concrete specimen.

Poor Quality Aggregates F-2 and F-3, Figure (3,4).

a. Relative Dynamic E_n vs. F. and T. Cycles:

There is a rapid and continuous drop of E_n. E_n is reduced by 50 percent after 25 cycles in case of F-2 and after about 5 cycles for F-3. DF_{100} for F-2 is 22 in group II and is equal to 3 for F-3 in group I (Table 4).

b. Length Change vs. F. and T. Cycles:

After an initial contraction there is a constant and rapid expansion. This expansion is faster for F-3.

c. Weight Change vs. F. and T. Cycles:

There is a gain in weight throughout the test. This is due to the deterioration caused by freezing and thawing. Fissures and cracks developed because of rapid expansion get filled with water.

Table 4 for DF_{100} is the best source of information to classify concrete dealt with under different treatments of aggregate beneficiation. The values used in this table are averages of the total specimens of a mix design made for each treatment. The original data for each specimen and comparison of durability factor for 100, 200 and 300 cycles is given in Table 7 in the Appendix.

To get a better idea of the critical level of maximum chert percentage giving just enough improved durability, the data is further simplified in Table 5.

Table 4. Comparative Study of the Effects of Treatments on DF_{100}, ΔW_F and ΔL_F

	I Extremely Bad DF100 = 0-5				II Bad DF100 = 6-30				IV Good DF100 = 81-100			
Treatment*	Mix	DF_{100}	ΔW_F	ΔL_F	Mix	DF_{100}	ΔW_F	ΔL_F	Mix	DF_{100}	ΔW_F	ΔL_F
-	F-3	3.0	+15	+55	F-2	12	+25	+97	A	97	-78	-13
									B	98	-89	- 9
1	K-5	3.2	+12	+40	K-4	22	-16	+38				
2					L-1	10	+22	+90				
					L-2	9	+17	+72				
3									K-1	85	-66	+42
									K-2	93	-73	+22
									K-3	93	-77	+ 8

*1. 50 percent cherts treated by heavy liquid with K-4 having those heavier than 2.5 and K-5 lighter than 2.5, size 1"-1/2".

2. 50 percent untreated cherts, with L-1 specimens cured for 14 days and L-2 for 7 days, size 1"-1/2".

3. Untreated cherts percentages used were 20, 12 and 8, size 1"-1/4".

Table 5. Effect of Various Blends of Chert Aggregate F-2 with A

Percentages			
F-2	A	DF_{100}	Remarks
100	-	12	No separation
50	50	3	2.4 to 2.5 SG(F-2)
50	50	22	+2.5 SG (F-2)
20	80	85	-
12	88	93	-
8	92	93	-
0	100	97	-

Discussion

Heavy Liquid Separation (Treatment 1)

Table 4 shows that DF_{100} of K-4 concrete containing aggregate heavier than 2.5 specific gravity is much higher than that of K-5 where specific gravity level was between 2.4 to 2.5. DF_{100} for K-4 is still in Group II, but the removal of lighter cherts has effected a definite improvement.

It is interesting to note that the absorption of F-2 with minus 2.5 specific gravity is about the same as for untreated F-2 (Table 1) and is nearly twice that of F-2 with plus 2.5 specific gravity. This is according to the known fact that aggregates with higher specific gravity have lower absorption and vice versa. Consequent to this fact is the durability which should be higher with higher specific gravity aggregates and vice versa. However a contradiction occurs when durability of F-2 (untreated) and K-5 (minus 2.5) is compared. Although the average BSSD specific gravity and absorption of untreated F-2 is nearly the same as for the lighter F-2 in mix K-5, K-5 has only 50 percent cherts aggregate. Also cherts lighter than 2.5 represent more than 50 percent of F-2 aggregate (Table 9). As such it could be expected that DF_{100} for K-5 might be higher than the mix containing only untreated F-2 aggregate. The results, as they appear, are inconsistent. The explanation might well be the fact that only a few specimens were cast from K-4 and K-5 mixes. The difference between 12 and 3 DF_{100}'s is, from a practical standpoint, small.

Looking at the graphs, the weight change curve (Figures 8, 9) gives a better correlation with DF_{100} as compared to length change. Weight change graph for K-4 shows a gain and then a gradual loss in weight while for K-5 there is always a gain. This compares favorably with A (Figure 1) and F-2 (Figure 3) respectively. The relative E graph for K-5 is steeper than K-4, indicating a slower drop in E for K-4. The final changes in weight and length as given with DF_{100} Table 4 do not show any tangible correlation. It is possible that K-4 is closer to Group III than I which has produced a final loss in weight as compared to gain for F-2 as shown in the same group.

Unseparated 50 Percent Cherts and Curing Period
(Treatment 2)

DF_{100} for L-1 shows a marked improvement over F-3 which contains 100 percent coarse aggregate from chert gravel. The L-2 specimens which were cured for seven days showed a slightly lower durability factor than L-1. This is due to the fact that concrete mortar could not reach its full strength in seven days and was more quickly disrupted.

The water absorbed during the curing was approximately the same for the two different periods.

Table 6. Gain in Weight During Water Curing

Curing Period	Mix Design	Mix No.	Wt. after curing in gms.	Wt. before curing in gms.	Gain in wt.
14 days	L-1	1	5932	5885	47
		1	6098	6054	44
		2	5942	5962	46
				Average	45
7 days	L-2	1	6033	5993	40
		1	6095	6060	35
		2	6051	6006	45
		2	5891	5851	40
				Average	40

Dynamic E, length change and weight change graphs (Figures 10, 11) show good correlation with the durability factor. Final weight and length changes have also produced some visible correlation as both have increased positively like those of F-2 and F-3.

Blending of Cherts with Durable Aggregates (Treatment 3)

As the percentage of cherts is decreased from 20 percent to 12 percent DF_{100} is increased from 85 to 93. Further decrease to 8 percent has not caused any increase in DF_{100}. Decrease to zero percent allowed an increase in DF_{100} to 97 percent. This shows that reduction of cherts below 12 percent does not produce any significant improvement of DF_{100} (Table 5).

E_n graph shows a slow and gradual decrease in durability as is indicated by DF_{100}. Length change graph also compares well with the characteristic of the length change graphs for aggregates A and B as the increase is slight and slow. The rate of increase is damped as the amount of chert is decreased.

The weight change graph shows a gain and then a loss for all three blends as indicative of durable concrete.

The final length change values are deceptive. They vary from -70 to +57 in mix A (Table 6a), -22 to +130 for K-1, K-2, K-3 mixes (Table 6e, f, g). As only average values are given in Table 4, the signs are reversed although the durabilities are in the same group.

A better correlation is observed for ΔW_F. There is a loss of weight in all cases grouped in DF_{100} = 81-100 category. Most of the values are between 65-80 grams as compared to 75-90 grams for the high quality aggregates A and B. None of the mixes tested came under Group III. This leaves a gap as to how much encroachment these values had on Group III.

VI. CONCLUSIONS

On the basis of freezing and thawing tests of air-entrained concretes having poor quality cherts as coarse aggregates subjected to three different treatments for improving durability, the following conclusions have been derived:

1. Removal of cherts lighter than the BSSD specific gravity of 2.5 by heavy liquid definitely improved the durability of the concrete. To bring the durability further up into the fair field performance (Group III), separation would have to be done at a higher specific gravity, which for this aggregate would mean the removal of most of its particles and hence uneconomical.

2. Combining 50 percent durable aggregate (½"-¼" size) with 50 percent untreated cherts (1"-½" size) did not show any significant improvement in durability over that containing 100 percent chert.

3. As much as 12 percent chert could be blended with durable aggregate without an appreciable reduction in durability. Adding 20 percent chert, durability was still in the good field performance group but had shown a significant reduction. More tests are needed to find a maximum critical percentage of cherts above 20 percent to give a durability factor between fair and good performance.

4. Relative E_n, length change, and weight change plots against freeze and thaw cycles do not give reliable correlations with durability. They are good only for extremely good or bad aggregates as tested in the present project. Borderline performance becomes difficult to interpret. The same is true for the average final length and weight change values.

VII. LIST OF REFERENCES AND BIBLIOGRAPHY

List of References

1. Scholer, C. H., "Resistance to Weathering - General Aspects," Significance of Tests and Properties of Concrete Aggregates, ASTM Special Technical Publication No. 169, p. 175.
2. Powers, T. C. and Helmuth, R. H., "Theory of Volume Changes in Hardened Portland Cement Paste During Freezing," Proceedings HRB, Vol. 32, 1953, p. 285.
3. Lewis, D. W. and Dolch, W. L., "Porosity and Absorption," Significance of Tests and Properties of Concrete Aggregates, ASTM Special Technical Publication No. 169, p. 303.
4. Powers, T. C., "A Working Hypothesis for Further Studies of Frost Resistance of Concrete," Proceedings American Concrete Institute, Vol. 41, 1945, p. 245.
5. Schuster, R. L., and McLaughlin, J. F., "A Study of Chert and Shale Gravel in Concrete," Highway Research Board, Bulletin 305, January 1963.
6. Sweet, H. S. and Woods, K. B., "A Study of Chert as a Deleterious Constituent in Aggregates," Engineering Bulletin of Purdue University, Research Series 86, September 1942.

7. Bloem, D. L., "Factors Affecting Freezing and Thawing Resistance of Chert Gravel Concrete," Highway Research Board Record No. 18, January, 1963.

8. Walker, R. D. Lt. and McLaughlin, J. F., "Effect of Heavy Media Separation on Durability of Concrete Made with Indiana Gravels," Highway Research Board Bulletin 143, 1956.

9. Verbeck, G. and Landgren, R., "Influence of Physical Characteristics of Aggregates on Frost Resistance of Concrete," Proceedings ASTM, Vol. 60, 1960, p. 1063.

10. Powers, T. C., "The Air Requirements of Frost-Resistant Concrete," HRB Proceedings, Vol. 29, 1949, p. 184.

11. Rhoades, R. and Mielenz, R. C., "Petrography of Concrete Aggregates," Journal, American Concrete Institute, June 1946, p. 581.

12. Sweet, H. S., "Research on Concrete Durability as Affected by Coarse Aggregates," Proceedings ASTM, Vol. 48, 1948, p. 988.

13. Lewis, D. W., Dolch, W. L., and Woods, K. B., "Porosity Determinations and the Significance of Pore Characteristics of Aggregates," Proceedings ASTM, Vol. 53, 1953, p. 949.

14. Powers, T. C., "Basic Considerations Pertaining to Freezing and Thawing Tests," Proceedings ASTM, Vol. 55, 1955, p. 1132.

15. Larson, T., Cady, P., Franzen, M., and Reed, J., "A Critical Review of Literature Treating Methods of Identifying Aggregates Subject to Destructive Volume Change When Frozen in Concrete and a Proposed Program of Research," HRB, Special Report 80, 1964.

16. Wills, M. H. Jr., Lepper, H. A, Jr., Gaynor, R. D., and Walker, S., "Volume Change as a Measure of Freezing-and-Thawing Resistance of Concrete Made with Different Aggregates," Proceedings ASTM, Vol. 63, 1963, p. 946.

17. Wills, M. H. Jr., "An Investigation of the Behavior of Two Frost Susceptible Concretes When Exposed to a Slow Freeze-Thaw Test Method," Master's Thesis, University of Maryland, 1962.

18. Walker, R. D., "Identification of Coarse Aggregates That Undergo Destructive Volume Changes When Frozen in Concrete," Draft copy prepared for presentation at the 44th Annual Meeting of the Highway Research Board, Civil Engineering Department, Virginia Polytechnic Institute, 1964.

19. Goldbeck, A. T. and Gray, J. E., "A Method of Proportioning Concrete for Strength, Workability, and Durability," National Crushed Stone Association, Bulletin No. 11, Nov. 1953.

20. Cordon, W. A., "Automatic Freezing and Thawing Equipment for a Small Laboratory," Highway Research Board, Bulletin 259, January 1960.

Bibliography

1. Bartel, F. F., "Air Content," Significance of Tests and Properties of Concrete and Concrete Aggregates, ASTM Special Technical Bulletin No. 169, 1956, p. 61.
2. Goldbeck, A. T., "Needed Research," Significance of Tests and Properties of Concrete and Concrete Aggregates, ASTM Special Technical Bulletin No. 169, 1956, p. 26.
3. Hubbard, F., "Workability and Plasticity," Significance of Tests and Properties of Concrete and Concrete Aggregates, ASTM Special Technical Bulletin No. 169, 1956, p. 47.
4. Pickett, G., "Flow of Moisture in Hardened Portland Cement During Freezing," Proceedings HRB, Vol. 32, p. 276.
5. Verbeck, G. J., "Pore Structure," Significance of Tests and Properties of Concrete and Concrete Aggregates, ASTM Special Technical Bulletin No. 169, 1956, p. 136.
6. Walker, R. D., "Engineering Aggregates," Class Notes, Virginia Polytechnic Institute, C.E. 5013, 1963.

7. Whitehurst, E. A., and Parker, W. E., "Dynamic Tests," *Significance of Tests and Properties of Concrete and Concrete Aggregates*, ASTM Special Publication No. 169, 1956, p. 106.

8. Wuerpel, C. E., and Rexford, E. P., "The Soundness of Chert as Measured by Bulk Specific Gravity and Absorption," Proceedings ASTM, Vol. 40, 1940, p. 1021.

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XI. APPENDIX

Table 7. Freeze-Thaw Durability Test Results

a. Mix Design A

Mix No.	DF_{100}	DF_{200}	DF_{300}	Final Weight Change in gms.	Final Length Change in 10^{-4} in.
1	100	100	100	-76	--
	98	93	97	-84	+57
	100	97	99	-68	--
	99	100	97	-70	-70
Mix 1 Average	99	98	98	-74	- 7
2	99	93	92	-109	-12
	99	99	96	-101	-20
	97	95	94	-96	-29
Mix 2 Average	98	96	94	-101	-20
3	94	94	93	-57	- 4
	92	95	93	-74	- 7
	97	96	96	-47	-23
Mix 3 Average	94	95	94	-59	-11
Average all mixes	97	96	95	-78	-13

Table 7. (continued)

b. Mix Design B

Mix No.	DF_{100}	DF_{200}	DF_{300}	Final Weight Change in gms.	Final Length Change in 10^{-4} in.
1	98	98	95	-97	-16
	97	96	96	-90	-69
	100	100	100	-91	+17
	100	96	96	-98	- 2
Mix 1 Average	99	98	97	-94	-18
2	99	97	99	-112	+17
	97	95	97	-122	- 1
	99	96	97	-122	+11
Mix 2 Average	98	96	98	-119	+ 9
3	99	99	97	-60	+47
	98	98	99	-53	-101
	98	97	97	-46	+ 4
Mix 3 Average	98	98	98	-53	-17
Average all mixes	98	97	98	-89	- 9

Table 7. (continued)

c. Mix Design F-2

Mix No.	DF$_{100}$	DF$_{200}$	DF$_{300}$	Final Weight Change in gms.	Final Length Change in 10^{-4} in.
1	12	6	4	+17	+102
	11	6	4	+23	+106
Mix 1 Average	12	6	4	+20	+104
2	14	7	5	+24	+81
	14	7	5	+33	+77
Mix 2 Average	14	7	5	+29	+79
3	13	7	4	+31	+122
	8	4	3	+23	+95
Mix 3 Average	11	6	4	+27	+109
Average all mixes	12	6	4	+25	+97

d. Mix Design F-3

1	3	1	1	+16	+73
1	3	1	1	+15	+76
2	2	1	1	+12	+41
2	2	1	1	+15	+28
Average	3	1	1	+15	+55

Table 7. (continued)

e. Mix Design K-1

Mix No.	DF_{100}	DF_{200}	DF_{300}	Final Weight Change in gms.	Final Length Change in 10^{-4} in.
1	94	86	72	-75	+21
1	86	57	35	-50	+130
1	92	79	64	-86	+11
2	74	56	37	-51	--
2	83	59	40	-65	+20
2	85	77	--	--	--
3	90	76	53	-89	+42
3	76	48	32	-45	+30
Average	85	67	48	-66	+42

Table 7. (continued)

f. Mix Design K-2

Mix No.	DF_{100}	DF_{200}	DF_{300}	Final Weight Change in gms.	Final Length Change in 10^{-4} in.
1	97	94	92	-75	+19
1	95	87	83	-68	+11
1	93	87	76	-60	+23
2	83	70	46	-86	+140
2	95	92	85	-73	-17
2	92	88	81	-70	+ 7
3	93	71	50	-84	-38
3	94	89	77	-77	+29
Average	93	85	74	-73	+22

g. Mix Design K-3

1	94	83	69	-95	+40
1	94	82	74	-83	- 1
1	95	91	83	-77	-22
2	91	92	80	-50	+20
2	96	93	87	-76	- 9
2	92	92	76	-79	+20
3	93	81	--	--	--
3	86	78	--	--	--
Average	93	86	78	-77	+ 8

Table 7. (continued)

h. Mix Design K-4

Mix No.	DF_{100}	DF_{200}	DF_{300}	Final Weight Change in gms.	Final Length Change in 10^{-4} in.
1	28	14	9	-36	+36
2	16	8	5	+ 8	+43
3	23	11	8	-19	+35
Average	22	11	7	-16	+38

i. Mix Design K-5

1	4.5	2.2	1.5	+13	+51
2	2.0	1.0	0.7	+21	+29
Average	3.2	1.6	1.1	+12	+40

j. Mix Design L-1

1	17	9	6	+18	+74
1	9	4	3	+15	+94
2	9	5	3	+23	+85
2	6	3	2	+30	+105
Average	10	5	4	+22	+90

Table 8. (continued)

k. Mix Design L-2

Mix No.	DF_{100}	DF_{200}	DF_{300}	Final Weight Change in gms.	Final Length Change in 10^{-4} in.
1	8	4	3	+18	+148
1	7	4	2	+22	+ 97
2	9	5	3	+10	+ 21
2	10	5	3	+16	+ 22
Average	9	5	3	+17	+ 72

Table 8. Physical Characteristics of Fresh Concrete

Mix Design	Mix No.	Air Content	Cement Factor	Water Cement Ratio	Remarks
A	1	6.0	5.58	0.390	Batch Mix
	2	9.0	5.37	0.490	
	3	10.5	5.08	0.605	
B	1	8.5	5.38	0.525	"
	2	12.0	5.16	0.560	
	3	7.0	5.50	0.500	
F-2	1	6.66	5.37	0.530	"
	2	6.66	5.42	0.510	
	3	6.50	5.38	0.530	
F-3	1	5.50	5.46	0.530	"
	2	5.50	5.47	0.510	
K-1	1	8.33	5.27	0.550	"
	2	9.75	5.22	0.520	
	3	7.00	5.27	0.590	
K-2	1	9.08	5.27	0.520	"
	2	7.75	5.35	0.510	
	3	7.17	5.32	0.550	

Table 8. (Continued)

Mix Design	Mix No.	Air Content	Cement Factor	Water Cement Ratio	Remarks
K-3	1	7.17	5.37	0.520	Batch Mix
	2	6.00	5.38	0.550	
	3	6.75	5.45	0.480	
K-4	1	6.50	5.37	0.54	Hand mix
	2	6.10	5.37	0.55	
	3	5.83	5.36	0.57	
K-5	1	6.00	5.36	0.56	"
	2	5.00	--	--	
L-1 (14 days cure)	1	5.30	5.47	0.54	Batch mix
	2	5.83	5.38	0.58	
L-2 (7 days cure)	1	4.30	5.53	0.54	"
	2	5.90	5.46	0.54	

Table 9. Specific Gravity Analysis of Chert Aggregate (F-2) by Heavy Liquid Separation

Sp. Gravity	1/4"-1/2" Weight in gms.	%age	1/2"-3/4" Weight in gms.	%age	3/4"-1" Weight in gms.	%age
Less than 2.3	53	6.5	100	3.7	100	1.9
2.3 to 2.4	142	17.6	290	10.9	369	7.2
2.4 to 2.5	334	41.3	790	29.6	2063	40.3
2.5 to 2.6	280	34.6	1475	55.3	2442	47.7
Greater than 2.6	--	--	15	0.5	150	2.9
Total	809	100.0	2670	100.0	5124	100.0

ABSTRACT

Freeze-thaw tests were conducted to determine the usefulness of different treatments for improving the durability of concrete having poor quality chert aggregates.

Cherts were separated by heavy liquid media into two groups of specific gravities +2.5 and 2.4 to 2.5. A blend of 50 percent from each group (1"-1/2" size) with that of high quality aggregate (1/2"-1/4" size) was tried. Another treatment, having a similar combination, was applied but the cherts were not separated as before. The improvement, though somewhat greater with the heavier group of separated cherts, was still below fair field performance in either case indicating that separation is not economical for the particular aggregate studied.

In the third treatment chert percentages varied from 20, 12 to 8 (1"-1/4" size), half of which in each case was between 1"-1/2" size. All the three combinations produced concrete which was classified under good field performance group. Concrete with 20 percent cherts gave just above fair durability while reduction below 12 percent did not cause any further improvement.

Correlation of durability results from plots of dynamic E, length change, and weight change against freeze-thaw cycles was found not reliable as compared to durability factor at 100 cycles.