PERFORMANCE OF CAST STONE SUBJECTED TO RAPID FREEZING AND THAWING

Submitted by

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INTRODUCTION

Although quality has always been important when selecting construction materials, specifiers have embraced this as a paramount criterion in recent years. One very important aspect of construction material quality is its long-term durability. In climates which expose construction materials to cold temperatures and moisture, the resistance to cycles of freezing and thawing can be crucial. This study attempts to report the performance of a widely used architectural precast concrete product ca1led "cast stone."

Cast stone is a portland cement-based architectural precast product manufactured using fine aggregate, and sometimes coarse aggregate. The use of a high percentage of fine aggregate creates a very smooth, consistent texture for the building elements being cast, resembling natural cut stone. Other ingredients such as chemical admixtures, pozzolans, fiber reinforcement, and pigments, also may be added. Cast stone frequently is produced with a low water-to-cement ratio mixture with a “dry" (or "earth moist") consistency. The mixture is consolidated into a mold using an air or electrical1y - driven tamping device. Products manufactured in this manner are referred to as vibrant-dry-tamped (VDT) cast stone. For cast stone mixtures produced with a slumpable consistency mixture, the concrete typically is consolidated using internal or external vibration.

Through the decades, several investigations have been performed studying the durability of "wet cast" (or slumpable) concretes. However, on1ya limited amount of information is available in the U.S. for VDT concrete products such as cast stone, concrete masonry units, and paving stones (Refs. 1, 2, 3 and 4). In these earlier studies, it is reported that the durability of VDT concrete products is increased through the use of air entraining admixtures, higher density (increased compaction), and a sufficient quantity of cement per batch. Air entraining admixtures in dry cast concrete products were found to increase the compatibility of mixture ingredients instead of developing a uniformly distributed, spherical air void system as found in "wet cast" concretes. (See the increased densities in Ref. 4 when an air entrainer was used.)

This study was performed by the Lehigh Portland Cement Research Center to provide information to the Cast Stone Institute on the freeze 1 thaw durability of cast stone produced by manufacturers across the U.S. It is hoped that this information will provide further insight for producing durable cast stone, as well as assist in further refining ASTM specifications and test methods for these products.

OBJECTIVE

The objective of this study was to determine the performance of cast stone subjected to 5 to 7 cycles of freezing and thawing per day for a total of 300 cycles. Correlations were attempted between the durability results and compressive strength, product density, water absorption, cement content, water-to-cement ratio, combined aggregate fineness modulus, presence and type of admixtures, and several manufacturing process parameters.

SCOPE

A total of twelve sets of cast stone were submitted in the form of three beams for ASTM C-666 Procedure A, Freeze / Thaw Testing, and nine cubes foe compressive strength and absorption (cold and boiling water) measurements as described in ASTM C 1194 and 1 195. The Lehigh Portland Cement Research Center tested the beam specimens for freeze / thaw performance beginning at or near 14 days of age, and compression and absorption properties of the cubes were measured at 28 days of age. Mix designs including aggregate gradations are reported, along with other pertinent data collected from each cast stone manufacturer supplying specimens.

CAST STONE SAMPLE PRODUCTION

Each participating manufacturer produced a single unit of cast stone from which test specimens later were sawn. The unit of cast stone was requested to be cast in the dimensions of 4" x 18" x 24".

Each cast stone sample was cured for six days with the typical method used by the cast stone manufacturer. At 7 days of age, each cast stone producer was asked to submerge the sample in lime-saturated water which had a temperature between 75° and 85° F.

At 8 days of age, the sample was to be removed from the water bath and sawn to obtain three 3" x 4" x 16" beams, and nine 2" cubes. Special care was to be taken to prevent the cast stone surfaces from becoming dry by storing the specimens in water until they were prepared for shipment. Each specimen was to be sawn so that only one side remained which was origina1ly in contact with the mold (form). For the beams, the only molded side was to be a long side.

On the same day the specimens were sawn from the sample, the specimens were sent to the Lehigh Cement Research Center. Prior to shipment, each specimen was wrapped in damp towels and enclosed individually in plastic. Specimens were cushioned inside a wooden container to prevent damage during shipment. The specimens arrived at the Research Center on or before they were 14 days old.

TEST METHODS

Freeze / Thaw Durability Testing

On or about 14 days of age, each set of cast stone beams began freeze / thaw cycling as set forth in ASTM C - 666.92, Procedure A, "Standard Test Method for Resistance of Concrete to Rapid Freezing and Thawing (Ref. 5)." Procedure A requires rapid freezing and thawing in water, whereas Procedure B dictates rapid freezing in air and thawing in water. The fundamental transverse frequency was measured for each beam every 30 to 36 cycles per ASTM C 215-91 (Ref. 6). This is used to calculate the Relative Dynamic Modulus of Elasticity and the Durability Factor as described in ASTM C-666-92.

In addition to measuring the fundamental transverse frequency, all spalled material caused by freeze / thaw cycling was collected from the individual beams to monitor weight loss during testing. The spalled material was dried, weighed and recorded individually and cumulatively for each beam.

After the 300 freeze / thaw cycles were completed, each specimen was dried for 48 hours (or to constant weight). The initial dry weight of each beam was assumed to be the final dry weight of the specimen plus the amount of spalled material collected from the specimen throughout the test. Percent Weight Loss was calculated using this assumption. No specimen was oven dried before or during the rapid freeze / thaw testing since it might affect the results.

Compressive Strength, Absorption and Density Measurements

Cube specimens were moist cured at the Research Center until 27 days of age, and then processed for testing at 28 days of age, following ASTM C - 1194 - 91, "Standard Test Method for Compressive Strength of Architectural Cast Stone (Ref. 7)," and ASTM C - 1195 - 91, "Standard Test Method for Absorption of Architectural Cast Stone (Ref. 8)." Absorption was measured using Method A, the cold water test, and Method B, the boiling water test.

As a supplement, the oven dried bulk density was measured for the cold water absorption cube specimens as described in ASTM C - 140 - 94, "Standard Test Methods of Sampling and Testing Concrete Masonry Units (Ref. 9)."

RESULTS

Table 1 shows a summary of the test results obtained. Additional data collected for each set of cast stone is summarized in Table 2.

Appendix A shows Cumulative Percent Weight 1oss and Durability Factor versus Freeze / Thaw Cycles for each set of cast stone tested in this study.

ANALYSIS OF RESULTS

Unlike the other 10 cast stone samples, Projects J and M were produced using a "wet cast" procedure. These two products contained air entraining agents and high-range water reducers, which are common admixtures in high performance slumpable concrete mixtures. Product J developed a stable air void system which was well distributed for producing good freeze / thaw durability. However, Product M did not perform well. A petrographic analysis revealed that Product M contained an insufficient quantity of air entrainment (only approximately 2%). The dosage level of air entraining admixture may not have been adequate for the specific concrete mixture. The performance difference between Products J and M confirms that proper air entrainment provides an excellent freeze / thaw durability mechanism for wet cast concrete products. Since it is clear why Projects J and M performed as they did, and since they are wet cast concrete products, they are not analyzed in conjunction with the other cast stone samples in this study.

Figure 1 shows Durability Factor versus Cumulative Percent Weight Loss for each set of cast stone tested in this study. No correlation between the two measurements of durability is apparent. From the data, it appears that a cast stone unit may achieve a high Durability Factor (greater than a value of70[1]) and still experience a very high Weight Loss by the end of 300 freeze / thaw cycles. Therefore, Durability Factor calculations based on Relative Dynamic Modulus of Elasticity measurements, may not be a very sensitive test for differentiating between high durability cast stone and poor quality products.

In order to determine which of the two durability measurements is most appropriate, Durability Factor and Cumulative Percent Weight Loss are compared to several physical properties in the following paragraphs.

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[1] Asserted from the recommendation given by the Precast/Prestressed Concrete Institute Manual for Quality Control for a minimum acceptable level of 70 for ASTM 666, Procedure B. (Ref. 10).

Figures 2 through 6 show Durability Factor measured at the end of300 freeze / thaw cycles versus 28-day compressive strength, cold and boiling water absorptions, density, and combined aggregate fineness modulus. No correlation between these physical properties and Durability Factor was apparent.

Figures 7 through 11 present Cumulative Percent Weight Loss at the end of 300 freeze / thaw cycles versus 28-day compressive strength, cold and boiling water absorptions, density, and combined aggregate fineness modulus for each set of cast stone tested. It should be noted that one set of cast stone which bad a Cumulative Percent Weight Loss of 6.6% (product A) was found to have lost weight only 0n one side of each of the three specimens subjected to freezing and thawing. After investigating the procedures used by the producer of Product A, it is believed that water was sprayed on the cast stone before the mixture reached initial set. This would cause a higher water-to-cement ratio to occur on the top surface of the cast stone which dilutes the cement matrix, leading to higher porosity and weaker surface strength. This would account for the freeze / thaw beam specimens losing weight during freezing and thawing cycles on a single side. Another way in which a cast stone specimen might develop a weak surface would be for excessive water to be used during mixing which would tend to bleed toward the free surface of the cast stone. Therefore, the Cumulative Percent Weight Loss for Product A specimens is not representative of the bulk of that product.

In Figure 7, very low weight losses were observed when the 28-day compressive strength was greater than 6,000 psi. The only exception was the data for Product A, which was explained in the preceding paragraph.

Figure 8 shows cold water absorption versus weight loss. For cast stone exhibiting cold water absorptions less than 7.5%, weight loss is very low. Again, the only exception is the data for Product A (6.6% weight loss).

Figure 9 shows low weight loss percentages for cast stone produced with boiling water absorptions less than 12%, with the exception of the data for Product A.

Figure 10 also shows low weight loss percentages for cast stone produced with bulk densities greater than 125 pounds per cubic foot (product A again is the one exception). Figure 11 indicates that having a higher combined aggregate fineness modulus tends to reduce the percentage of weight loss for cast stone subjected to 300 freeze / thaw cycles. However, a combined aggregate fineness modulus of 1.6 to 2.2 can also provide very low weight loss.

Most of the cast stone products tested in this study contained air entraining admixtures with the exception of Products C, E, K and L. Products e, K and L had very good durability performances. The coarsely graded backing mixture used with Products e and L, and the cast stone's high density, are speculated to have helped their durability. This would correspond to greater compaction and higher strength.

Product K contained an acrylic latex which may have helped durability although density was low.

Product E had a very poor performance. It exhibited low density and strength as well as high absorption, even though it contained a water repellent admixture. This cast stone apparently was not properly consolidated. As expected, poor compaction leads to poor durability for VDT cast materials.

In order to ascertain the influence of air entraining agents on the durability of VDT concrete products, a petrographic analysis was performed on Products A, B, and F which showed good freeze / thaw durability and Product E which performed very poor1y. It was found that no spherica1 air void system was developed in any of the VDT concrete samples which incorporated an air entraining admixture. This is not surprising due to the lack of sufficient liquid in the mixture for developing such a system. Comparing the petrography results of the three well performing samples to Product E which had no air entraining admixture, it could readily be seen that Products A, B, and F were more efficiently compacted than Product E. Therefore, the durability of VDT concrete products such as cast stone seems to depend at least partially on the degree of consolidation (density).

It is important to note that VDT concrete products such as cast stone contain several angular voids which are caused by aggregates in contact with each other which form gaps between them. These were seen in the petrographic images for Products A, B, E, and F. The quantity of voids is known to range between 7 to 14%, depending on the degree of consolidation (Ref. 4). Since these voids are not spherical, uniformly distributed nor sufficiently small, they do not provide the classic mechanism for freeze / thaw durability which is commonly used in air entrained wet cast concretes. Therefore, use of air entraining admixtures and sufficient compaction energy apparently decreases the number of voids in VDT concretes.

The curing procedures catalogued in this study ranged from using air curing only, to mist curing with carbon dioxide being injected into the curing chamber. No correlation between the method of curing and durability was apparent; however, curing still should be recognized as being a very important issue for cast stone and all other concrete products to achieve sufficient strength gain at early ages.

No correlation between cement content and durability could be asserted in this study since each product was produced with a high percentage of cement (See Table 2). However, previous studies show the importance of having sufficient quantities of cement per batch for durability (Refs. 1, 2 and 3).

Other parameters recorded from each cast stone producer (Table 2) were investigated without finding a correlation with durability results.

CONCLUSIONS

From this study, the following conclusions can be made.

1. The cast stone samples investigated in this study performed well in regard to freeze / thaw durability with few exceptions. All VDT -produced cast stone performed similar to properly air-entrained wet cast concrete. Non-air-entrained wet cast concrete performed very poorly, as expected.

2. A general correlation can be drawn between 28-day compressive strength, absorption, and density with Cumulative Percent Weight Loss through 300 rapid freeze / thaw cycles per

ASTM C 666-92, Procedure A Evaluating cast stone using a weight loss criterion seems logical since it is a product often used for its aesthetic properties.

3. For VDT cast stone, no correlation was found between Durability Factor described in ASTM C 666-92 and Cumulative Percent Weight 1.oss, measured as described in this study.

4. Producing cast stone with a 28-day compressive strength of at least 6000 psi a cold water absorption of less than 8% and a dry bulk density greater than 125 pounds per cubic foot provided very low Cumulative Percent Weight 1.oss through 300 rapid freeze / thaw cycles. The only exception was caused when a sample of cast stone was mist cured before the mixture reached initial set (product A).

Note: **The Cast Stone Institute Standard Specification requires a minimum 28-day compressive strength of 6500 psi and a maximum cold water absorption of 6%. This criterion appears conservative and is supported by this study. By having such a conservative criterion, it could preclude the need for adding a costly freeze / thaw durability test method to the Cast Stone Standard Specification.**

5. In VDT concrete products, air entraining admixtures do not perform the same function as in wet cast (slumpable) concretes. Air entraining admixtures act as lubricating agents which allow the abrasive mixture particles (cement and aggregates) to slip and slide around each other

easier, thereby increasing the ease of compaction. This leads to higher density and strength, and generally lower absorptions.

6. For wet cast concretes, air entraining admixtures should be used to obtain good freeze / thaw durability. When wet cast concretes are produced with a sufficient addition of air entraining agent, the air bubbles which are churned into the concrete during mixing are stabilized as very small spherica1 bubbles distributed throughout the concrete to provide a pressure relief mechanism for when water freezes in the pores and expands.

7. Although no specific curing method was found to be significantly better than the others in this study, early age curing is important for all concrete products.

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Table 1.

Summary of Cast Stone Durability Data													
Cast Stone Product	Durability Factor (300 Cycles)	Cum % Wt. Loss (300 Cycles)	Cement/ Aggregate Ratio by Wt. (%)	Combined Aggregate Fineness Modulus	Density (pcf)	Cold Water Absorption (%)	Boiling Water Absorption (%)	28-Day Comp. Strength	Was Mix Ever Fluid?	Air Entraining Admixture?	Water Repellent Admixture?	Other Admixture?	Other Info
A	93.4	6.6	33.6	1.64	133.3	2.9	8.7	7,430	Yes	Yes	Yes	No	
B	79.3	0.3	25.5	1.85	131.0	4.8	9.1	7,180	No	Yes	Yes	No	
C	91.4	0.1	33.3	3.11	138.8	4.3	4.7	9,290	No	No/No	No/No	WR*	Face Mix/Backing Mix
D	83.0	3.2	39.2	2.05	128.8	4.9	10.6	10,070	No	Yes	Yes	No	
E	87.1	15.5	33.3	1.97	117.6	9.8	15.2	3,790	No	No	Yes	No	
F	75.8	1.4	31.4	2.26	136.6	4.2	7.4	11,470	No	Yes	Yes	No	Fiber
G	93.1	1.2	31.4	2.20	133.3	4.9	8.7	9,680	No	Yes	Yes	No	Fiber
H	84.0	2.1	33.6	1.88	128.6	4.1	5.4	6,240	Yes	Yes	Yes	No	
J	94.7	0.1	23.6	4.82	144.9	4.6	4.8	9,020	Yes	Yes	No	HRWR**	Wet Cast w/Sufficient Air Entrainment
K	86.0	0.7	31.1	1.49	124.6	7.3	11.9	7,580	No	No	No	Acrylic Latex	
L	91.8	0.2	33.3	1.91/4.19	136.2	5.1	5.2	9,620	No	No/No	Yes/Yes	Retarder	Face Mix/Backing Mix
M	⊕	⊕	21.6	5.08	146.3	5.4	5.6	9,300	Yes	Yes	No	HRWR	Wet Cast w/o Sufficient Air Entrainment (2%)

* WR = Water Reducer
** HRWR = High Range Water Reducer
⊕ Severe Deterioration - No final measurement

Table 2.

Additional Cast Stone Durability Data							
Cast Stone Product	Approx. Water/Cmt Ratio	Batching Sequence	Total Mixing Time (Min.)	Mixing Time After Last Ingredient Added (Min.)	No. of Layers for Compaction	Compaction Time Per Layer (Sec.)	Curing
A	0.26	Aggs, H2O, Admix, Color, Cmt	10	5	3	30	Mist Cure 8 hrs; steam cure 8 hrs; let cool; shrink wrap.
B	0.27	Aggs, 1/2 H2O+Admix, Cmt, 1/2 H2O	7	3	2	10	Mist Cure for 2 days.
C	0.22-0.28	Aggs, 1/2 H2O, Admix,Cmt, 1/2 H2O	NR	NR	2	30	1 day in mold w/ mist curing followed by air curing.
D	0.28	Aggs, Admix, some H2O, Mix 1 Min, Cmt, Final H2O	6	5	2	17, 28	Mist cure 1 day, then air cure.
E	0.26-0.38	1/2 Aggs, 1/2 Cmt, 1/2 H2O; Repeat	3	1.25	3	180	Spray w/ water twice a day for 2 days; then air cure.
F	0.27	Aggs, Fiber, Cmt, 3/4 H2O,Admix, 1/4 H2O	5	0.5	3	30,30,15	Steam & CO2 12 hrs; 105 F & 100% humid for 24 hrs; then air cure.
G	0.27	Aggs, Fiber, Cmt, 3/4 H2O, Admix, 1/4 H2	5	0.5	3	30,30,15	Mist cure 2.5 hrs; 105 F steam & CO2 9.5 hrs; then air cure.
H	0.24	Aggs, H2O, Admix, Cmt	18	5	2	40	Mist cure 8 hrs @ 80 F; steam cure 8 hrs; air cure after 1 day.
J	0.44	1/2 Aggs, 1/4 Cmt, 1/4 H2O, HRWR Admix 1/2 Aggs, 3/4 Cmt, AE Admix	7	3	1	218	Stripped after 3 days and air cured.
K	0.3	Sand + Cmt, H2O w/admix	4	2	2	45	Mist cure 1 day, then air cure.
L	0.26	Agg, Cmt, H2O	2/4	1.25/0.75	2	360	Spray w/water twice a day for 2 days; then air cure.
M	0.4	Aggs, H2O, Admixes, Cmt	30	10	1	—	Air cured inside for 1 day; then wrapped in plastic & placed outside.

NR = Not Reported

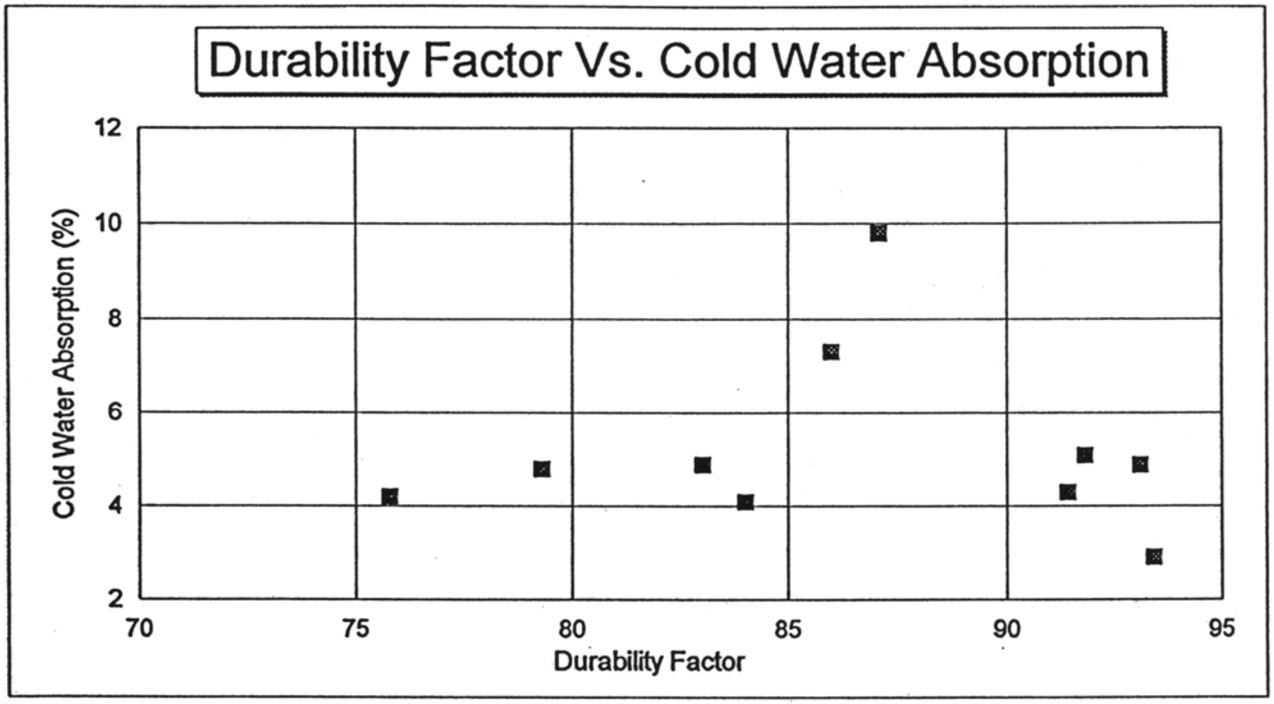


Figure 3. Durability Factor vs. Cold Water Absorption

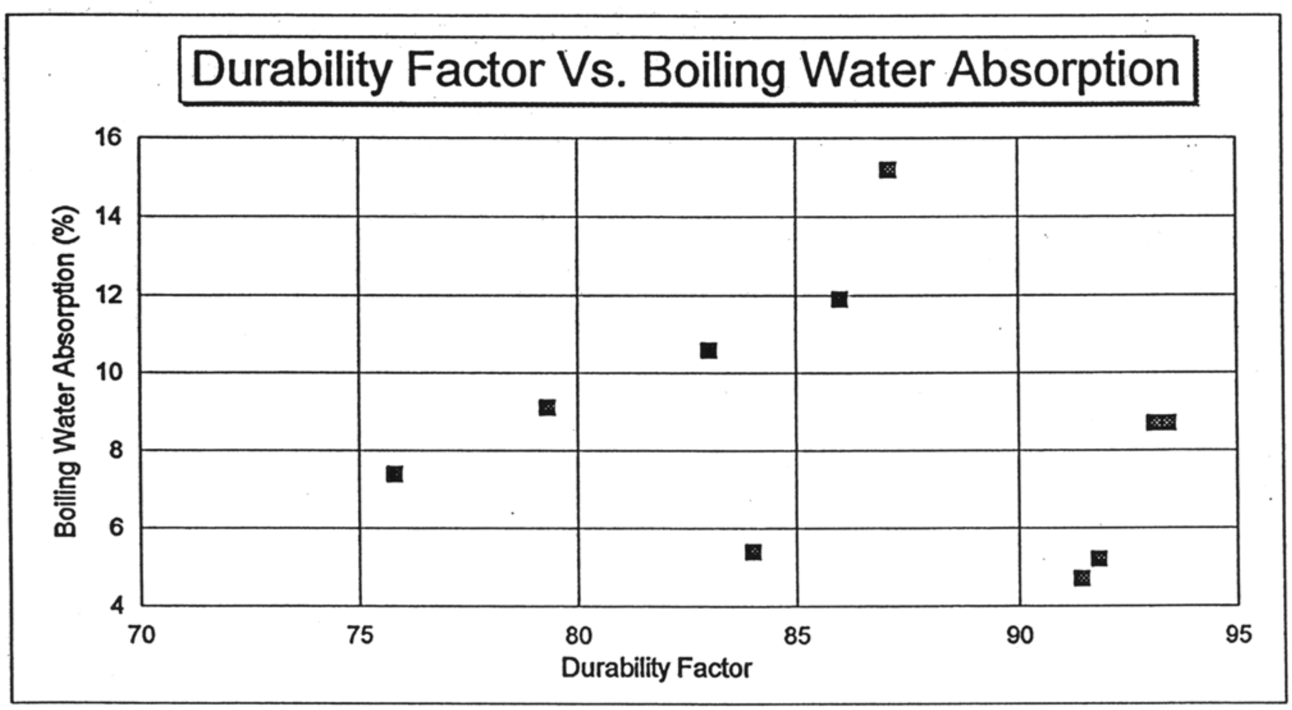


Figure 4. Durability Factor vs. Boiling Water Absorption

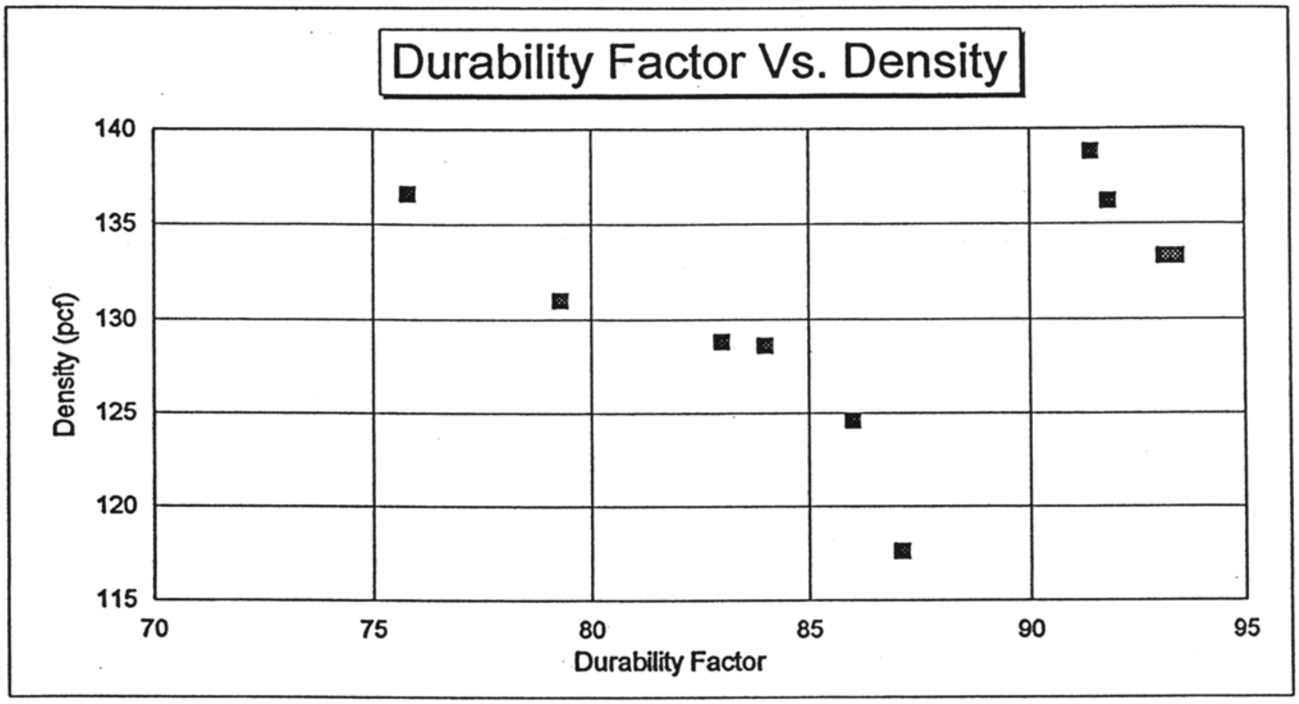


Figure 5. Durability Factor vs. Density

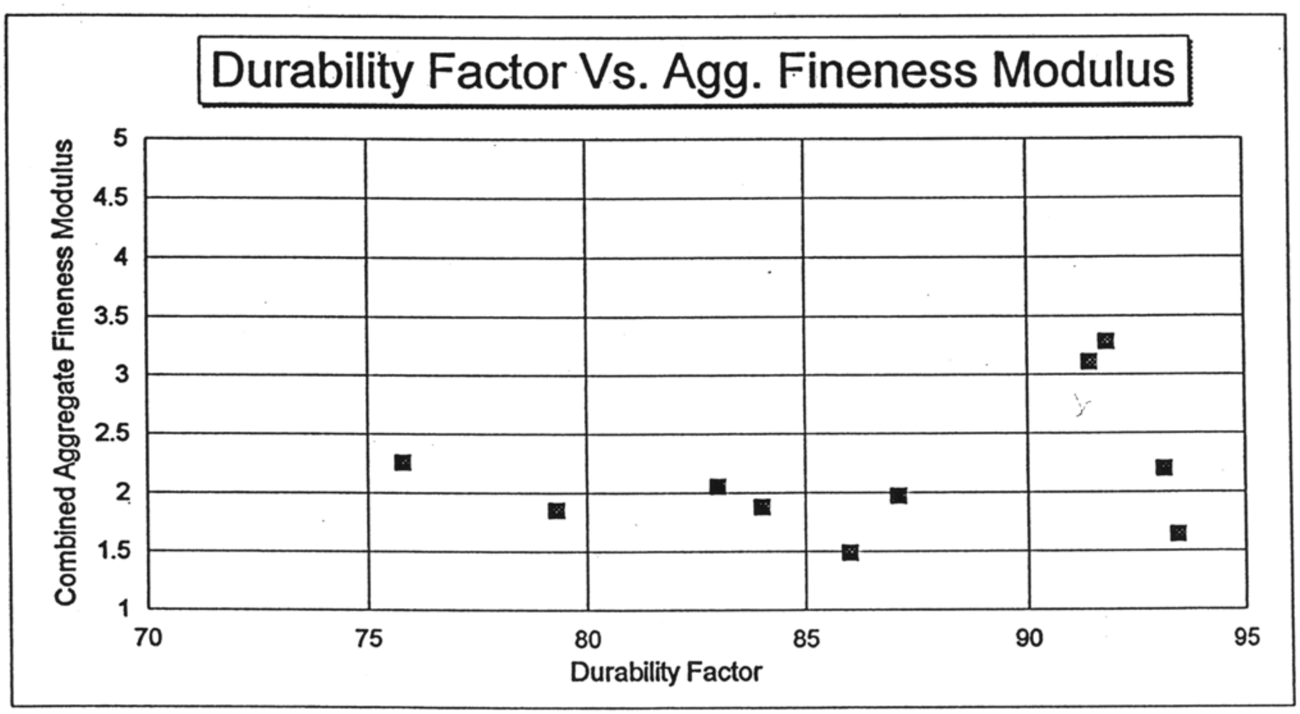


Figure 6. Durability Factor vs. Combined Aggregate Fineness Modulus

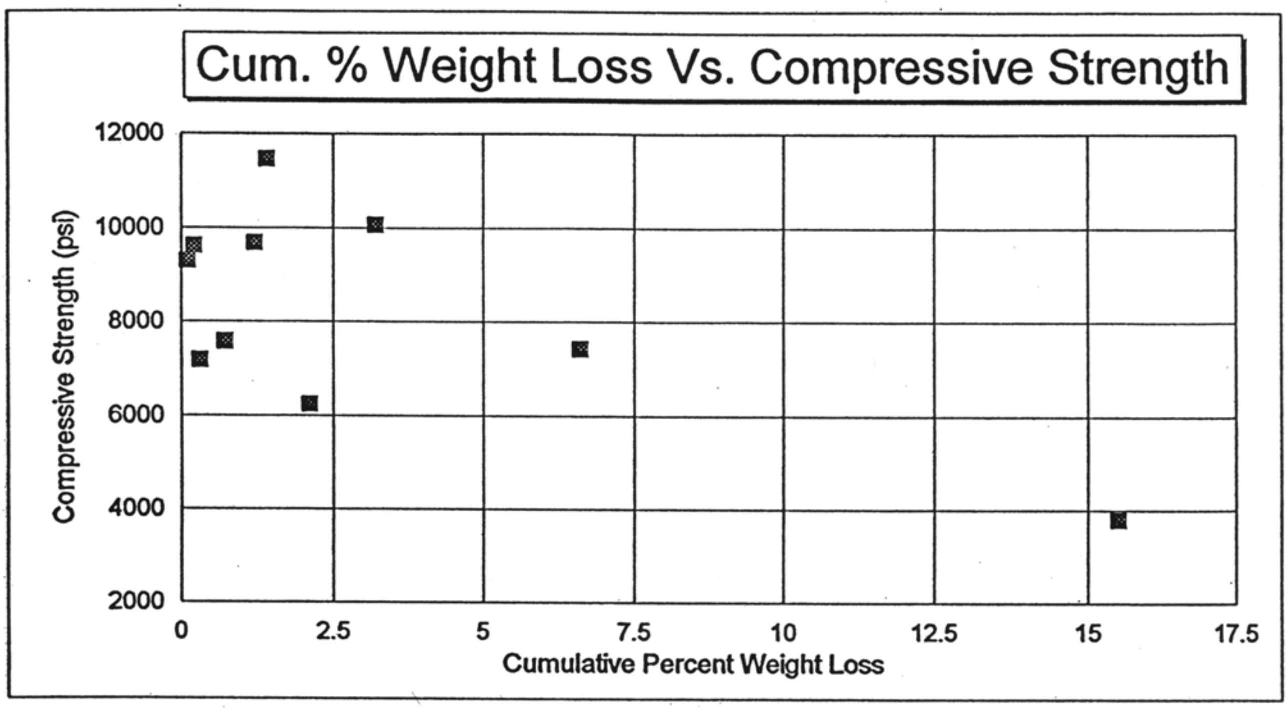


Figure 7. Cumulative Percent Weight Loss vs. 28-Day Compressive Strength

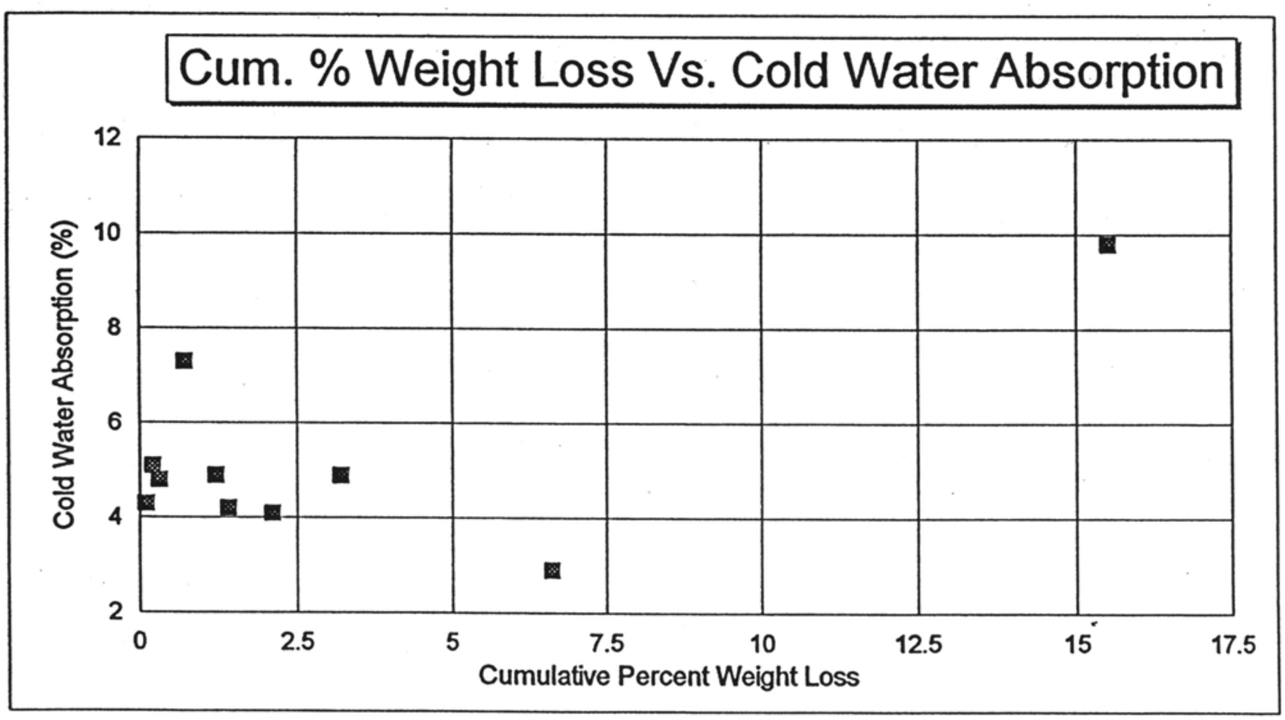


Figure 8. Cumulative Percent Weight Loss vs. Cold Water Absorption

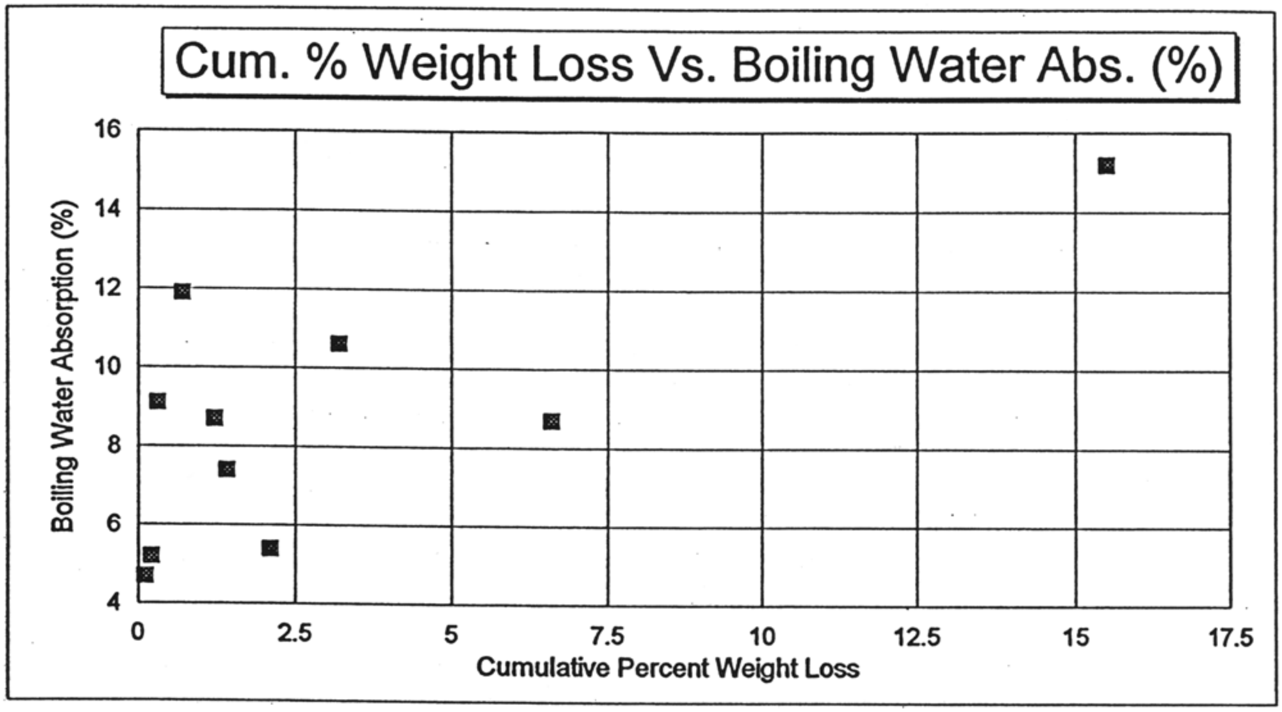


Figure 9. Cumulative Percent Weight Loss vs. Boiling Water Absorption

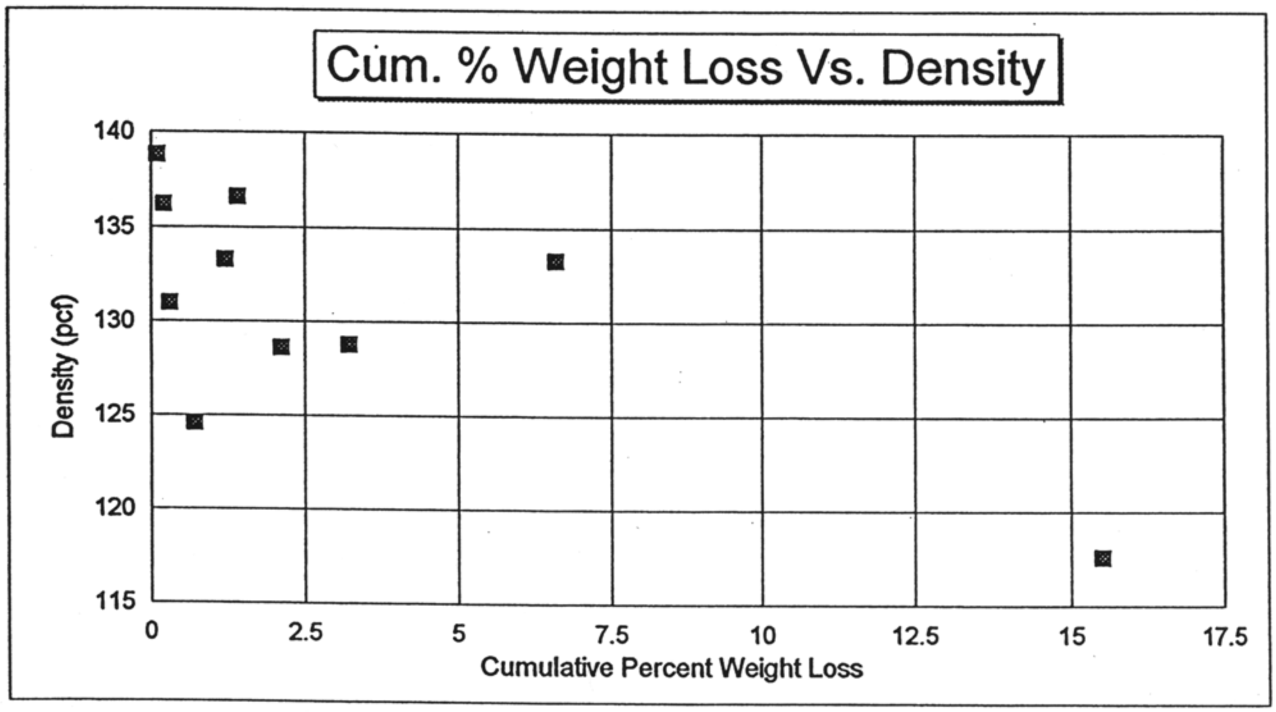


Figure 10. Cumulative Percent Weight Loss vs. Density

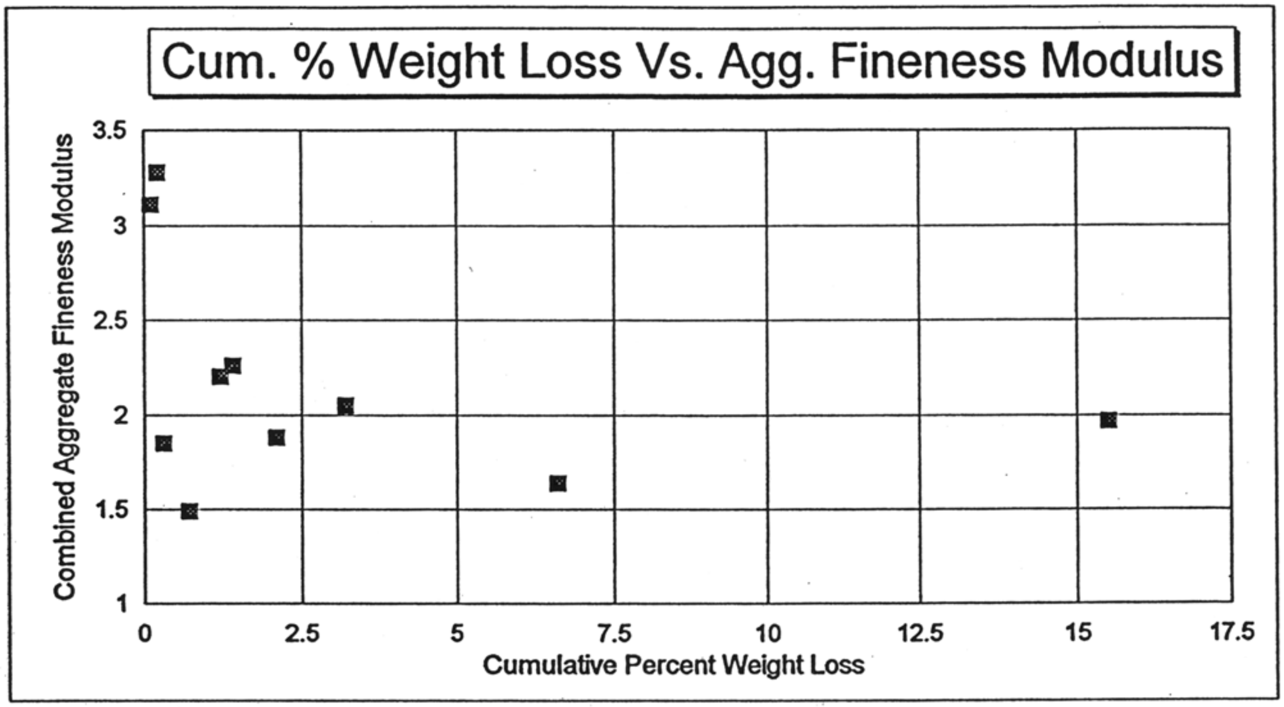
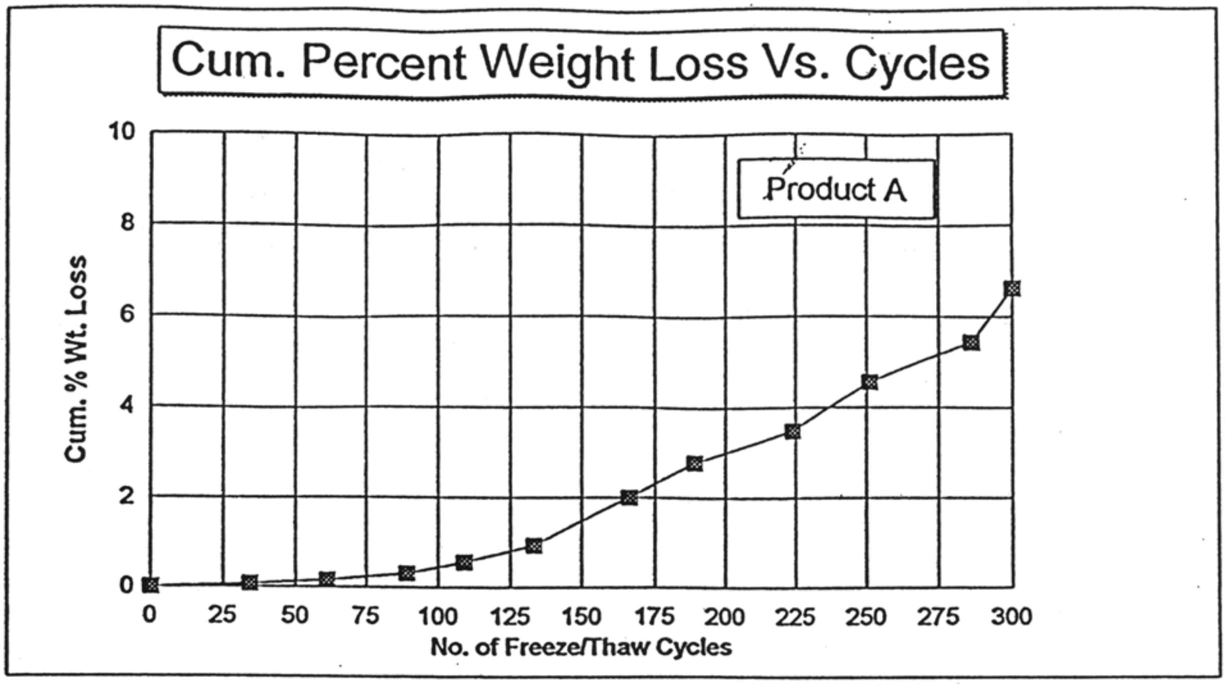
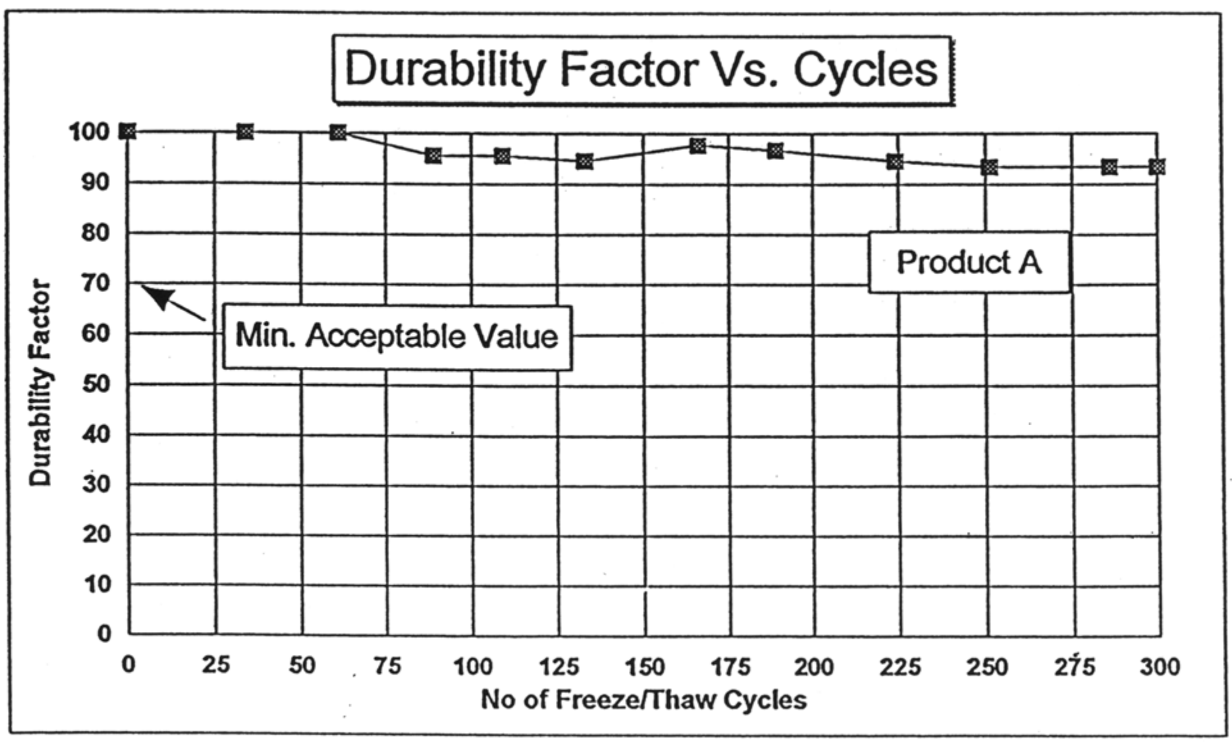


Figure 11. Cumulative Percent Weight Loss vs. Combined Aggregate Fineness Modulus

Appendix A
Cumulative Percent Weight Loss and Durability Factor vs. Freeze / Thaw Cycles





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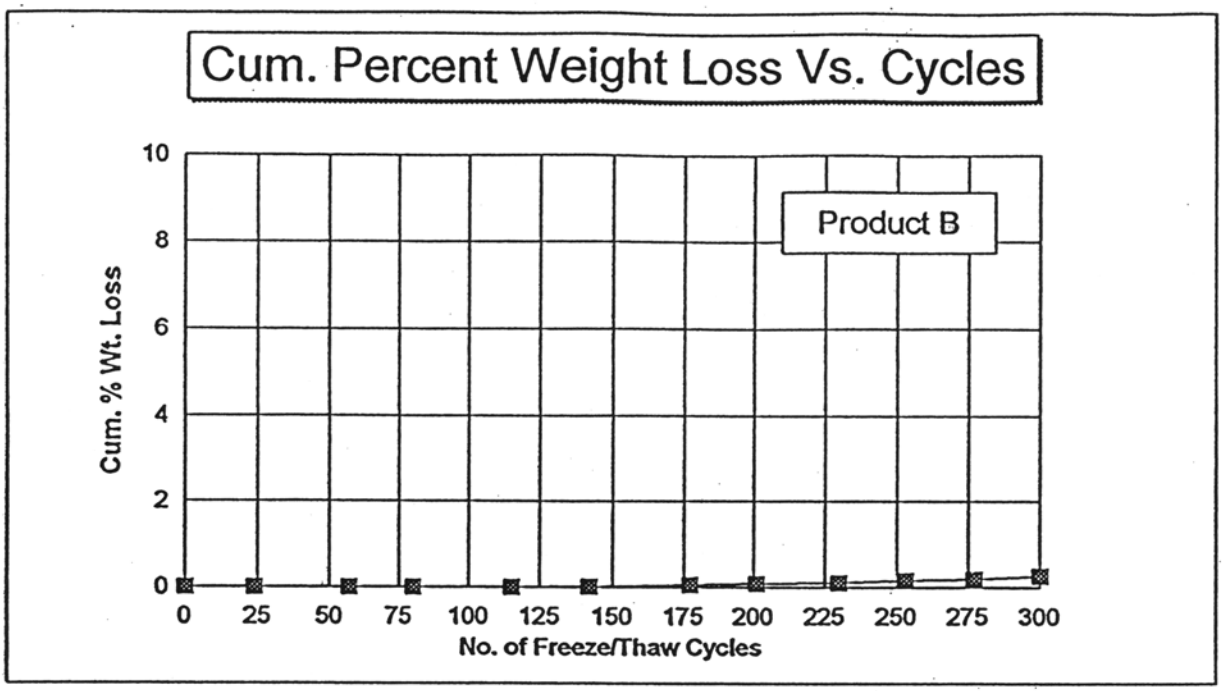

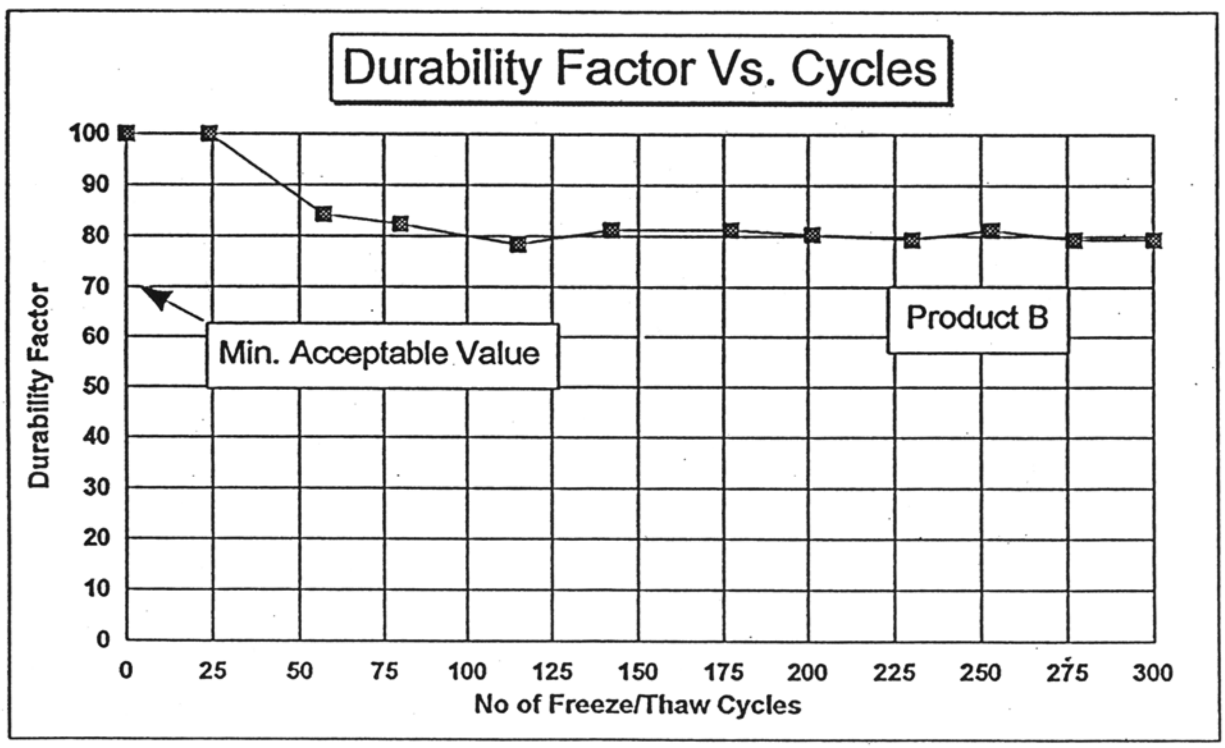

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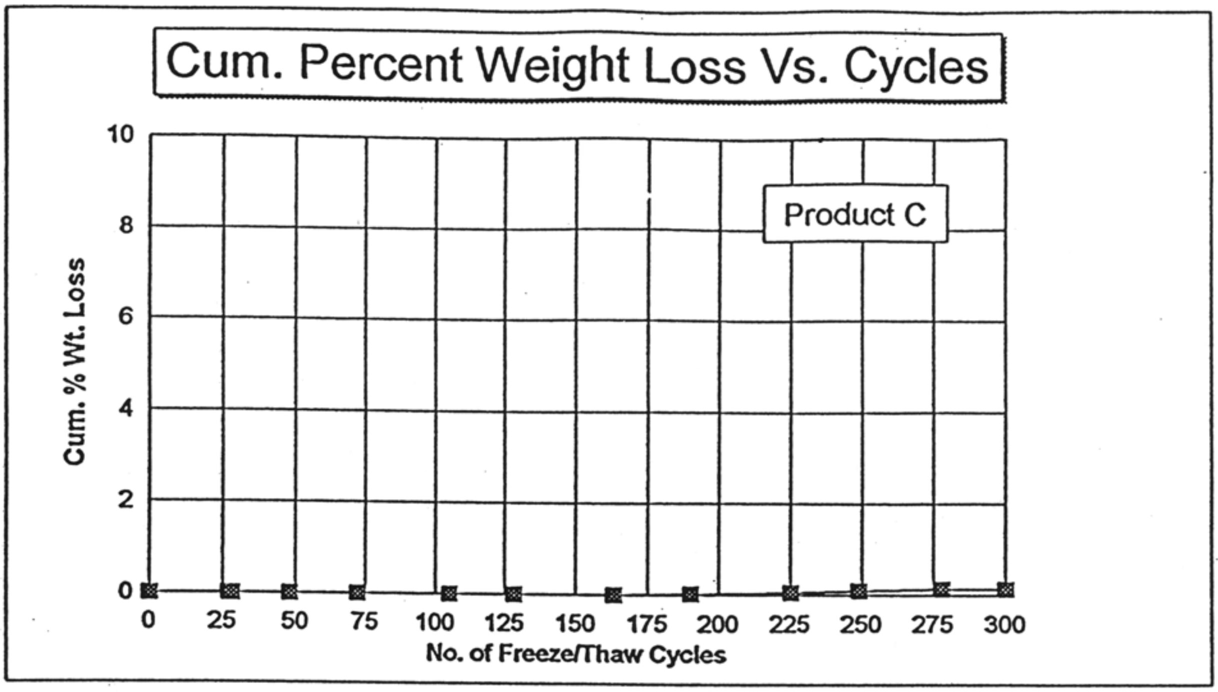
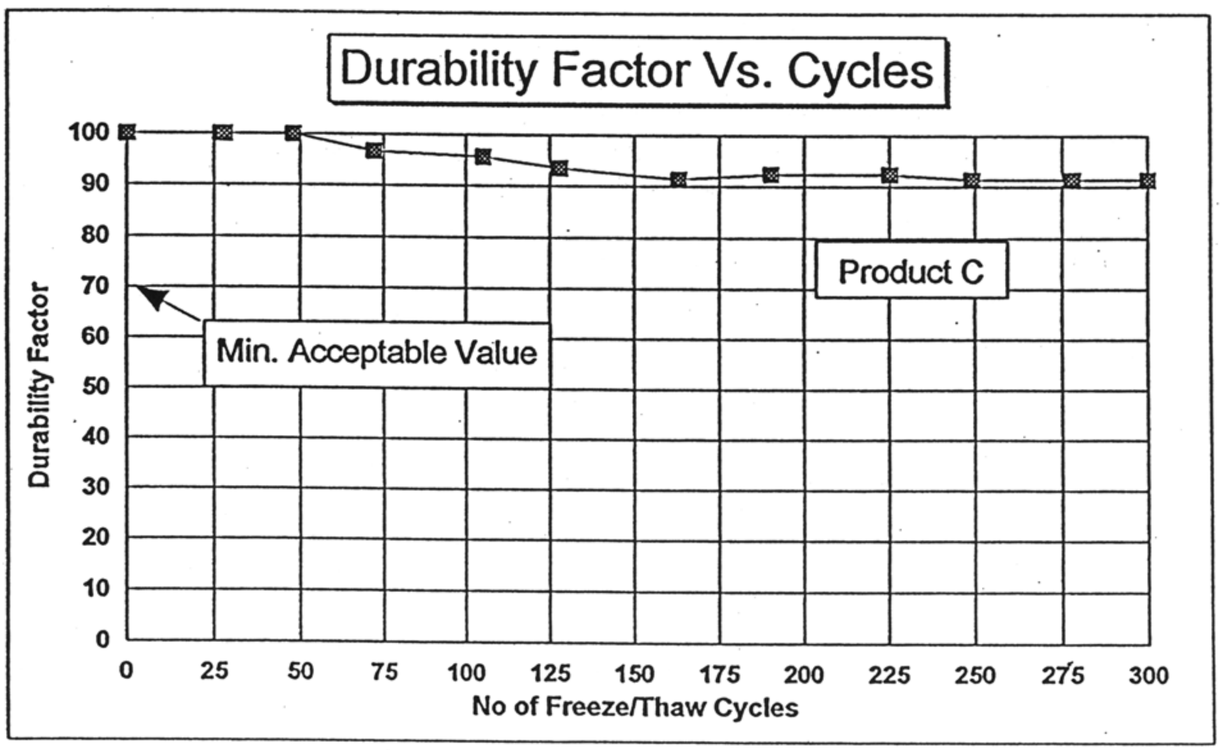
Cumulative Percent Weight Loss and Durability Factor vs. Freeze / Thaw Cycles





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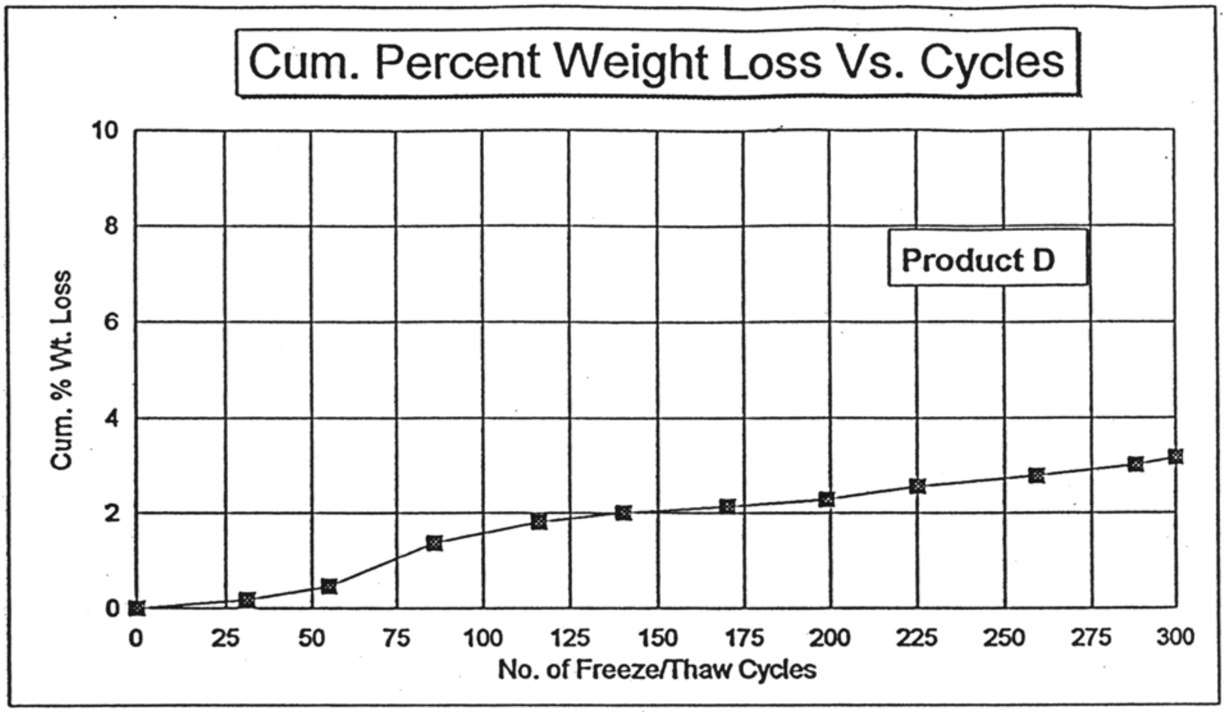

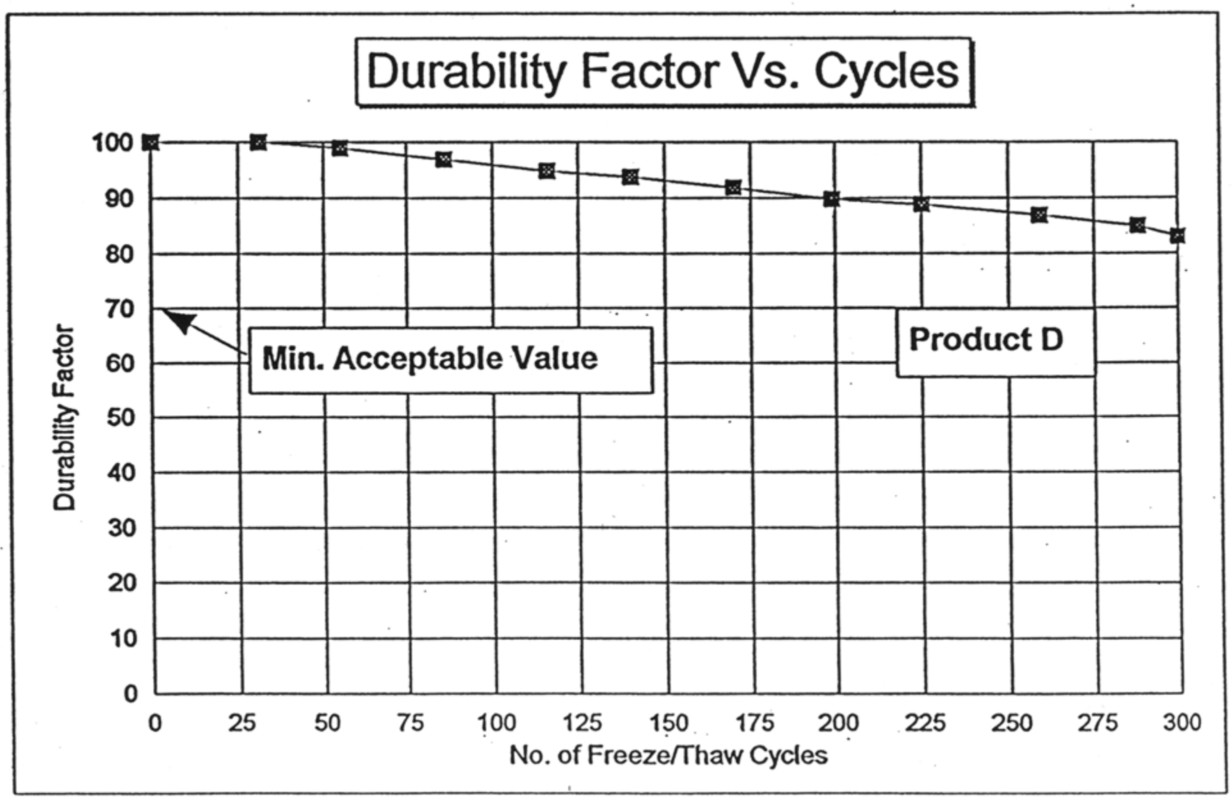

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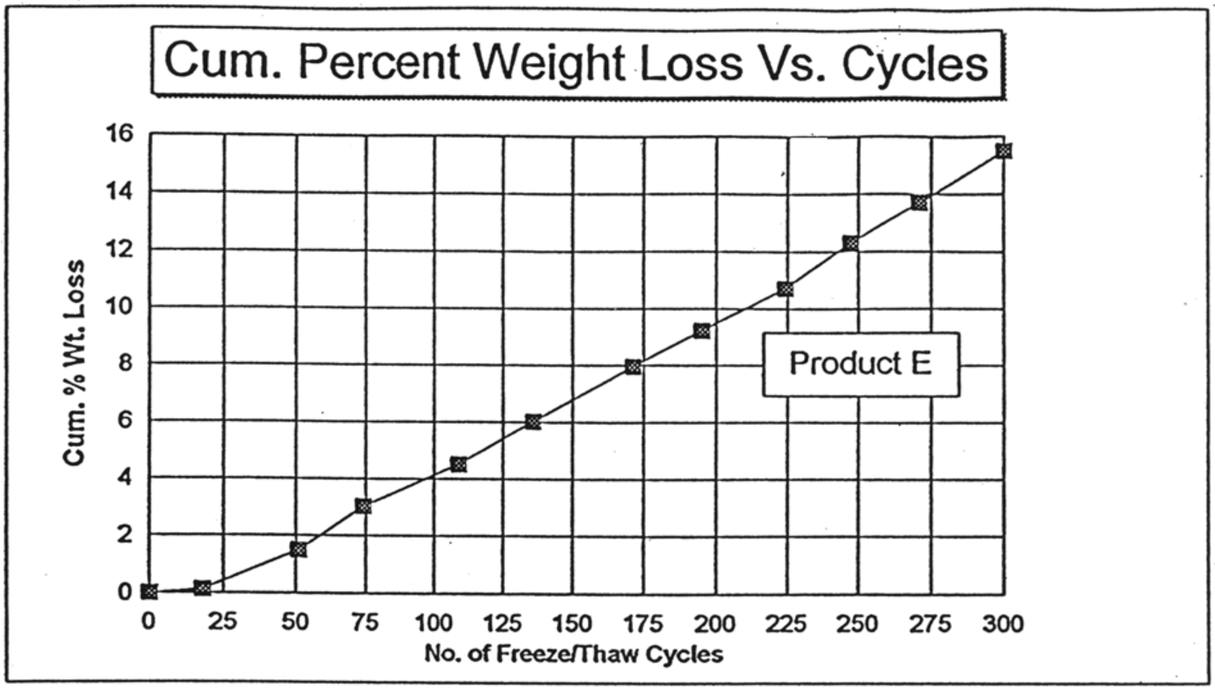

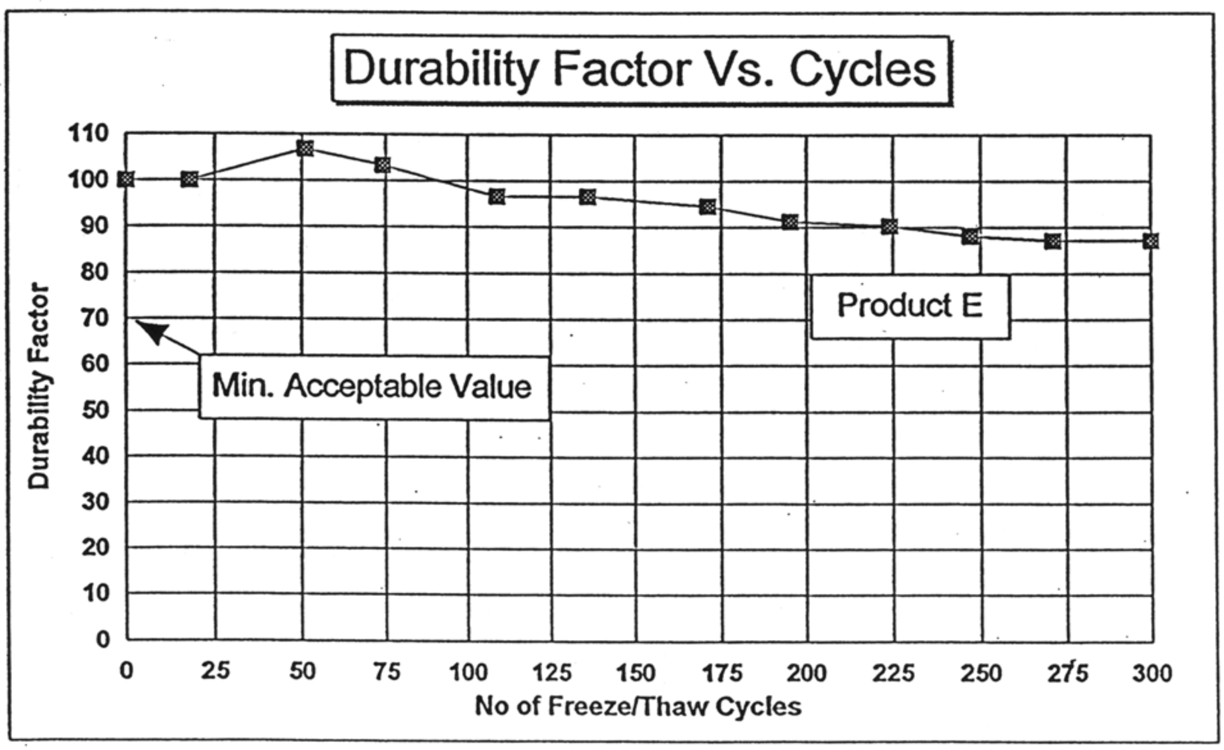

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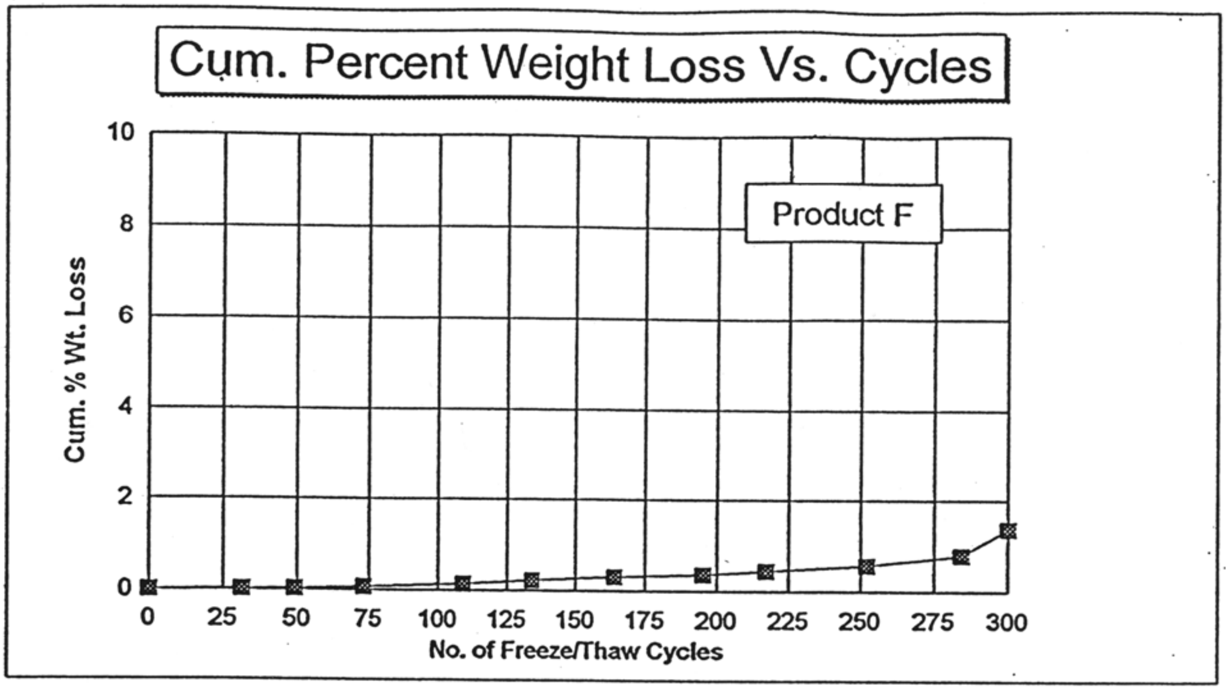
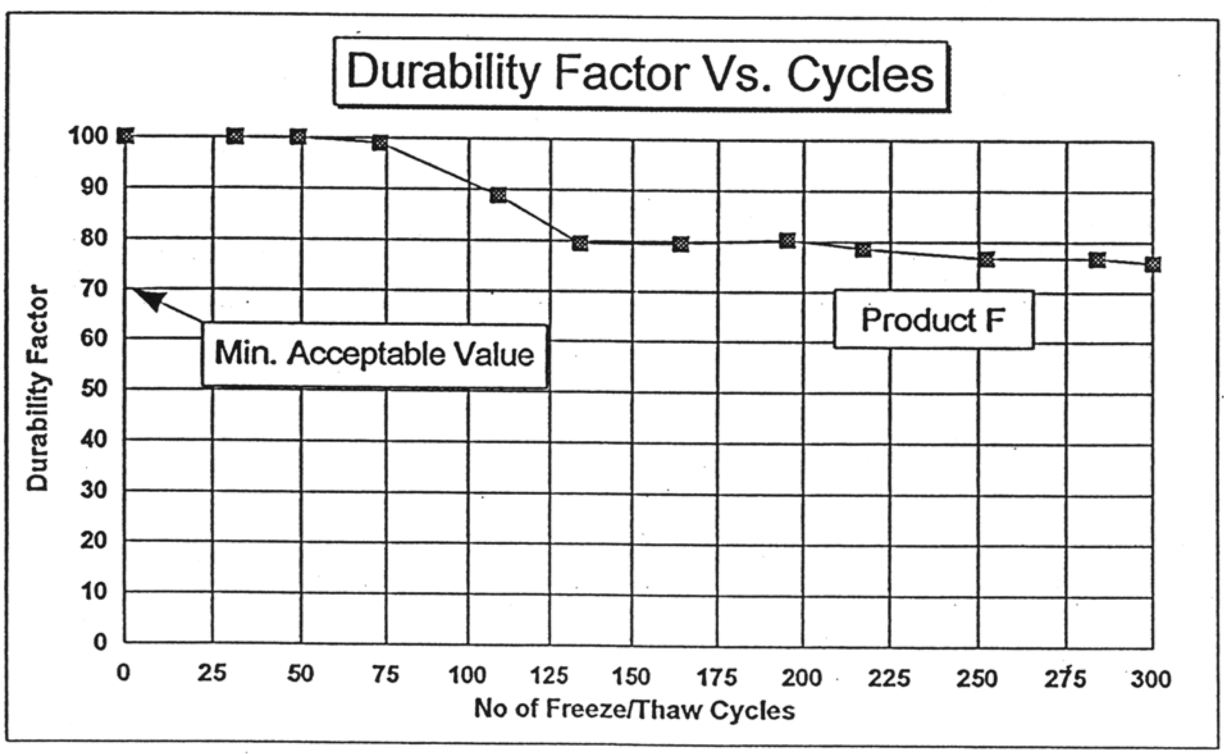
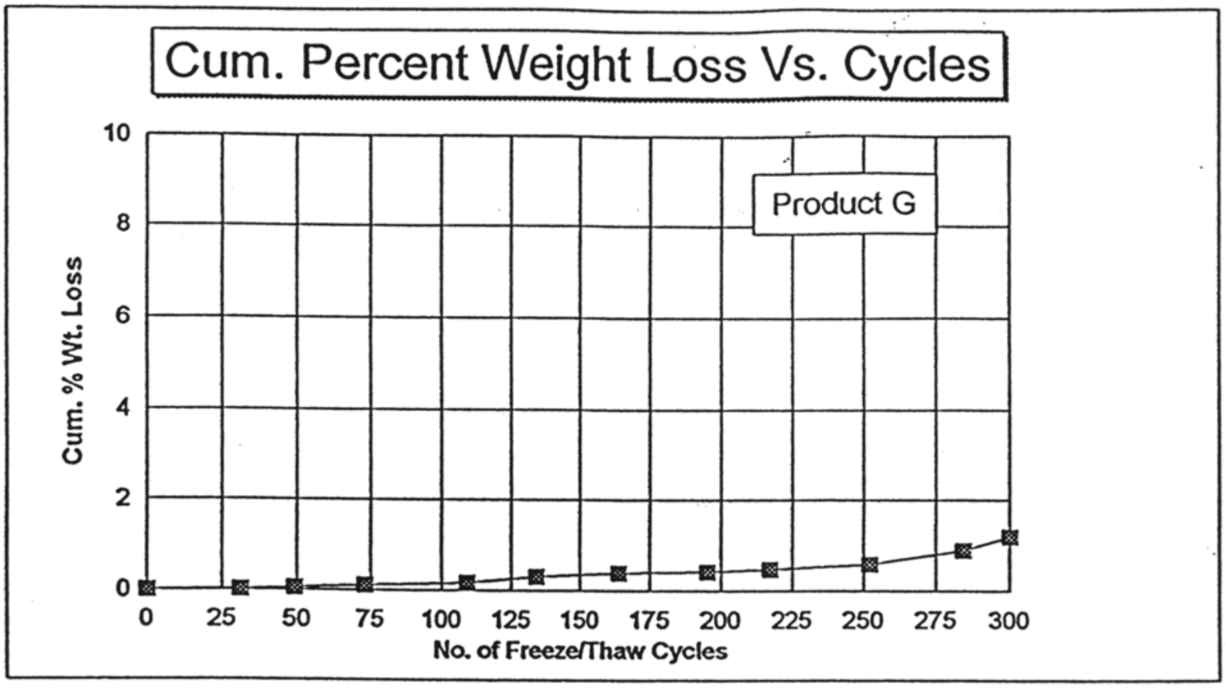
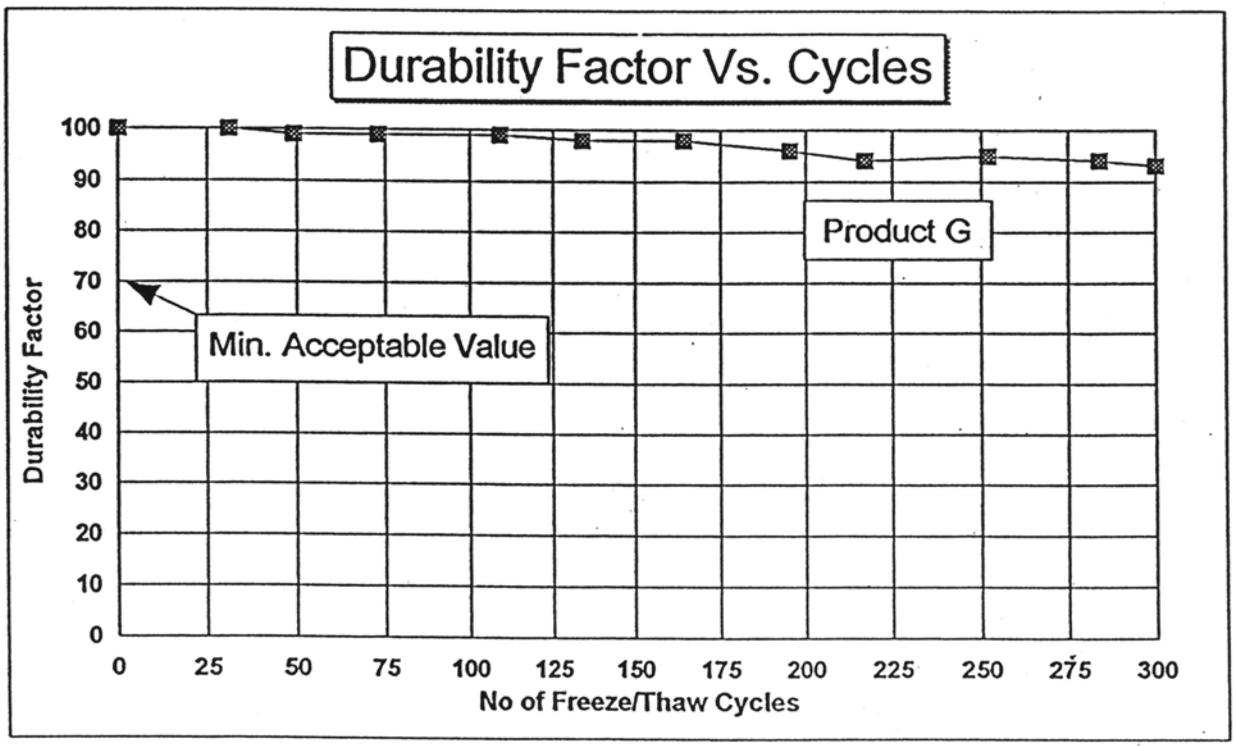
Cumulative Percent Weight Loss and Durability Factor vs. Freeze / Thaw Cycles





Appendix A
Cumulative Percent Weight Loss and Durability Factor vs. Freeze / Thaw Cycles





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Cumulative Percent Weight Loss and
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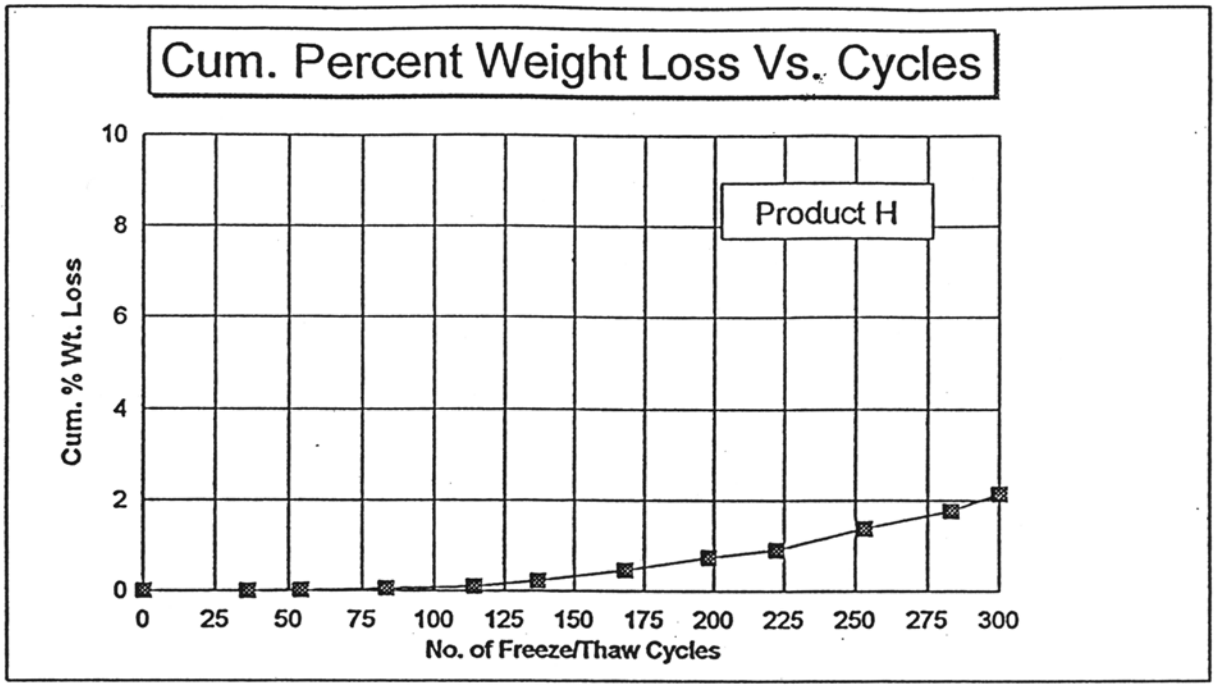
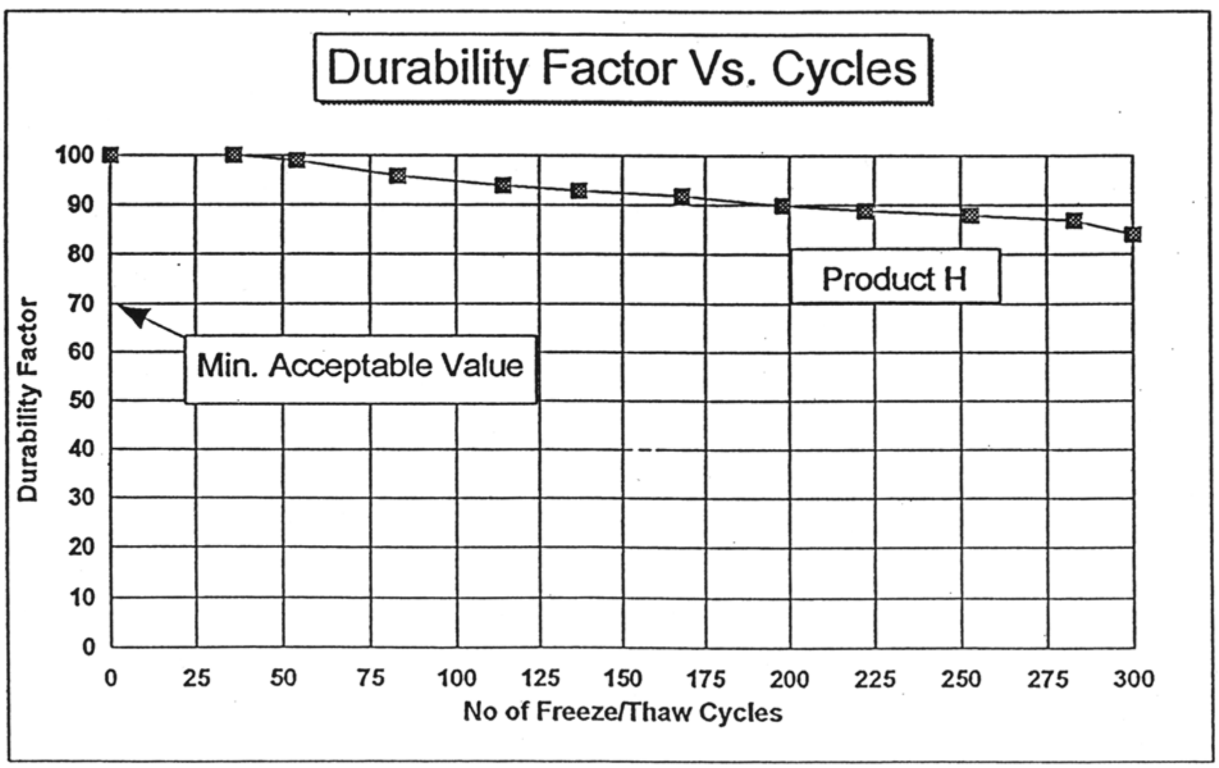
Freeze / Thaw Cycles





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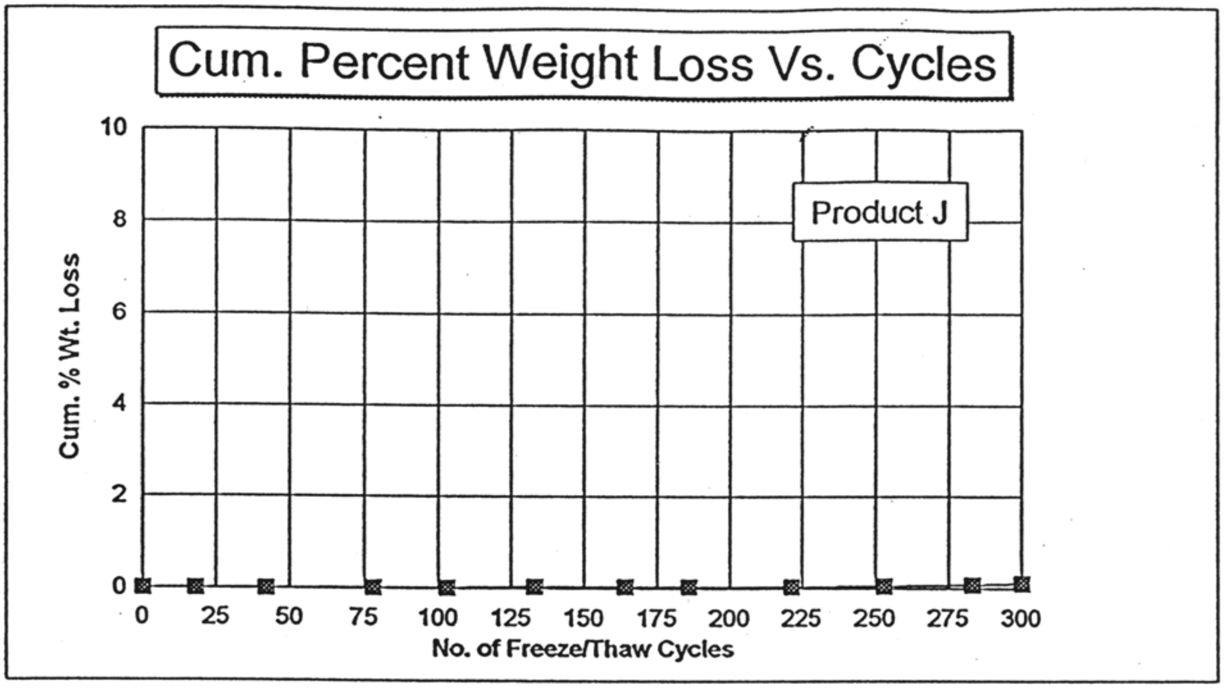
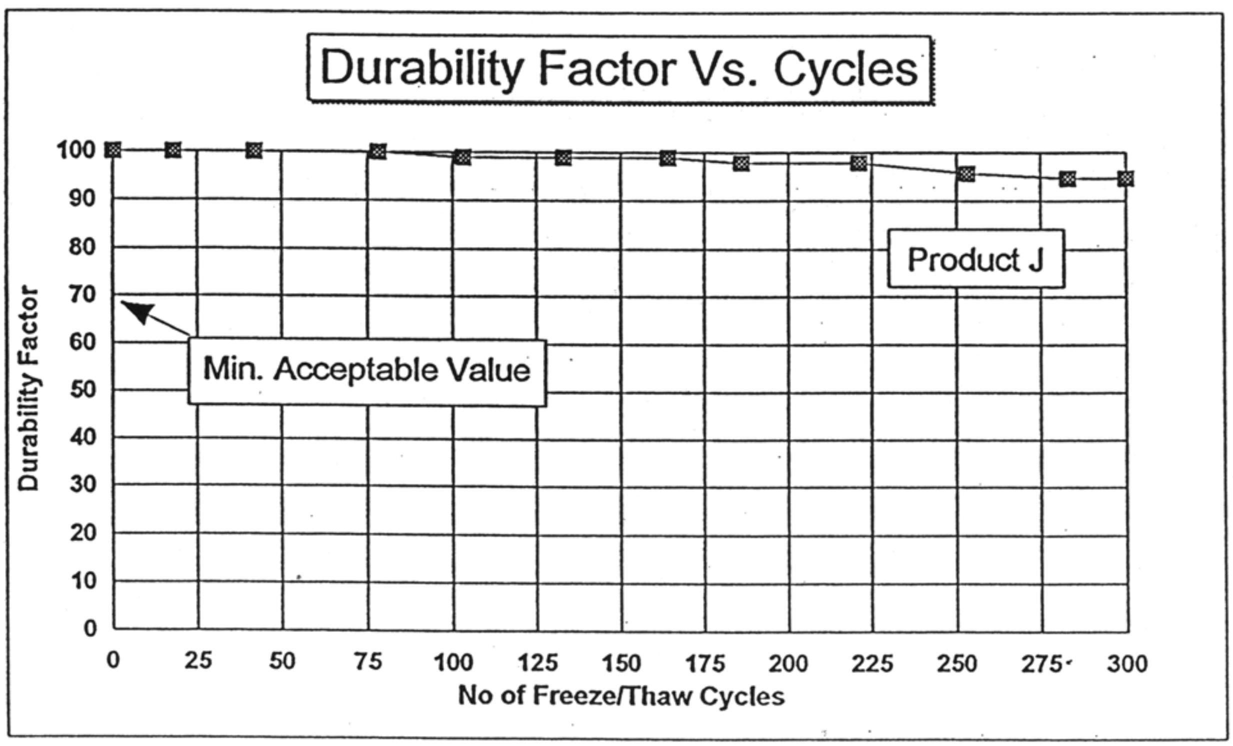
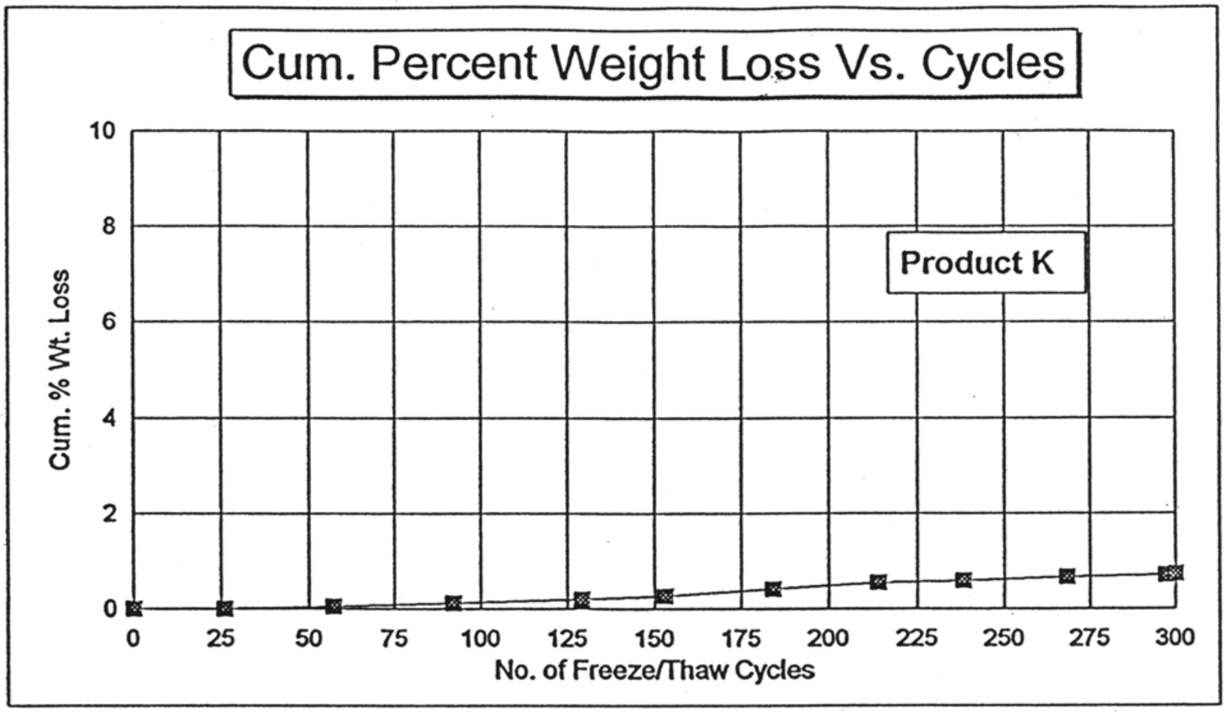
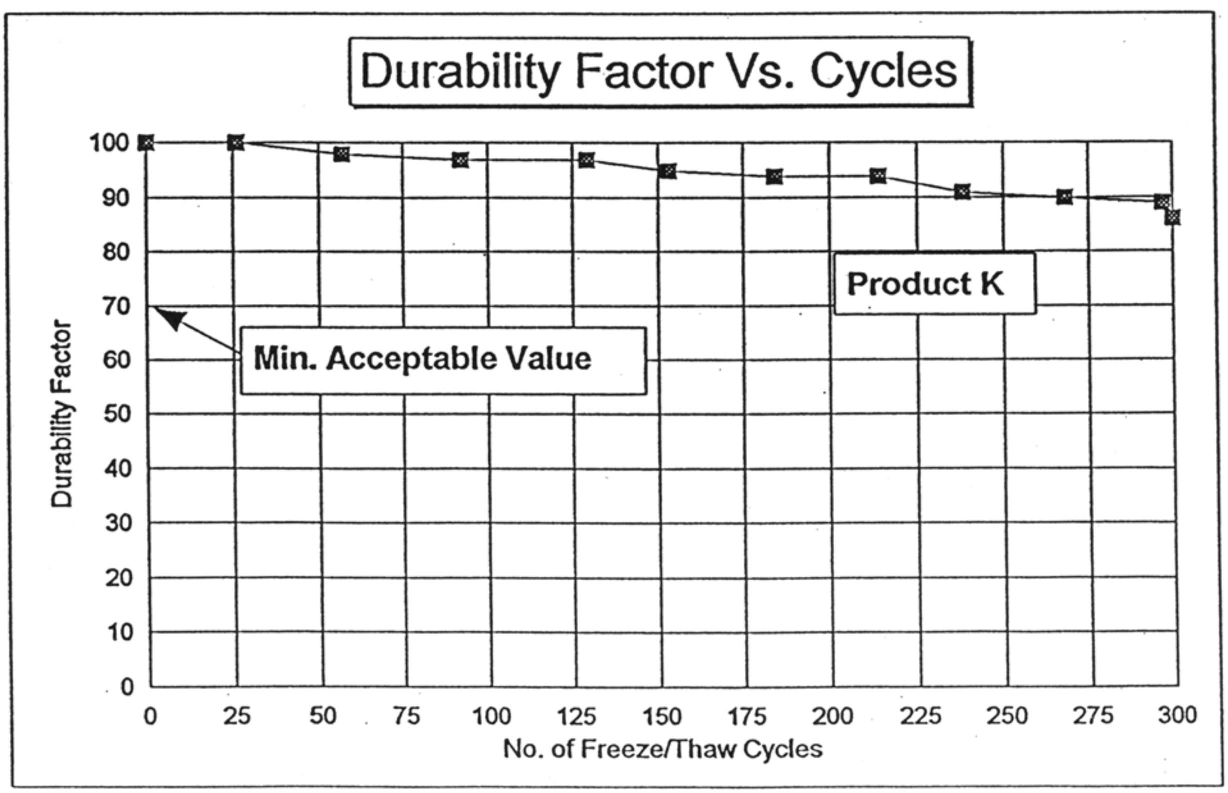
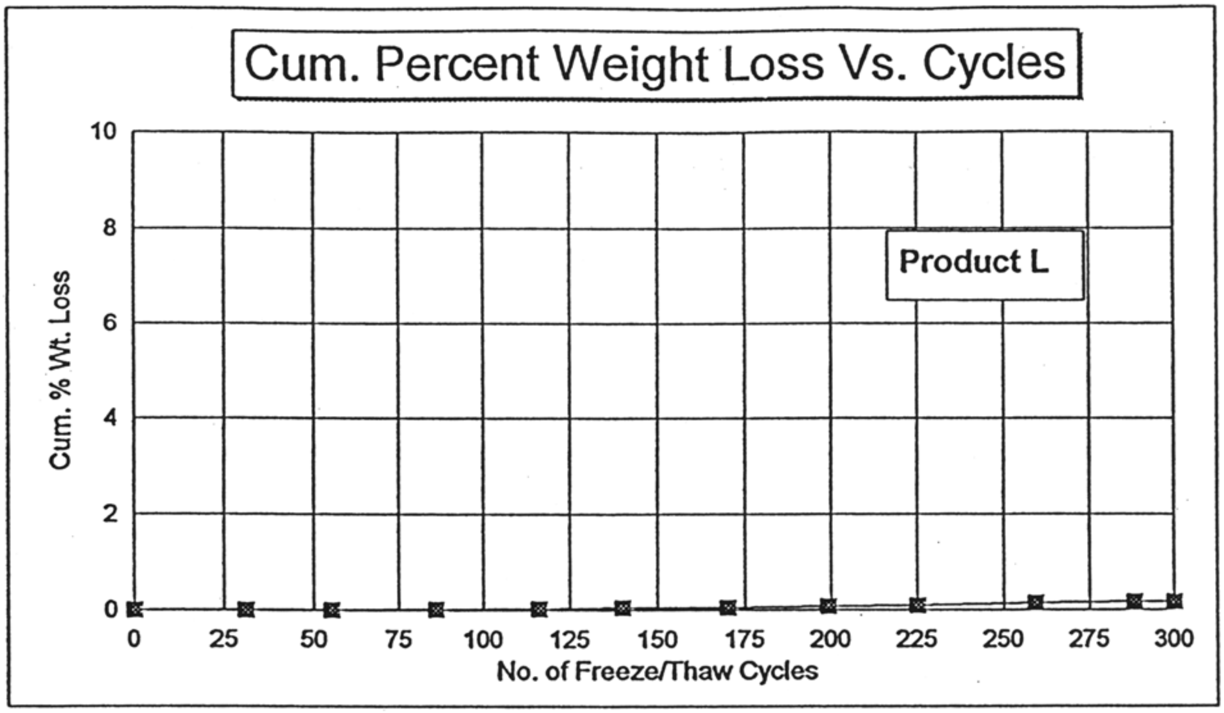


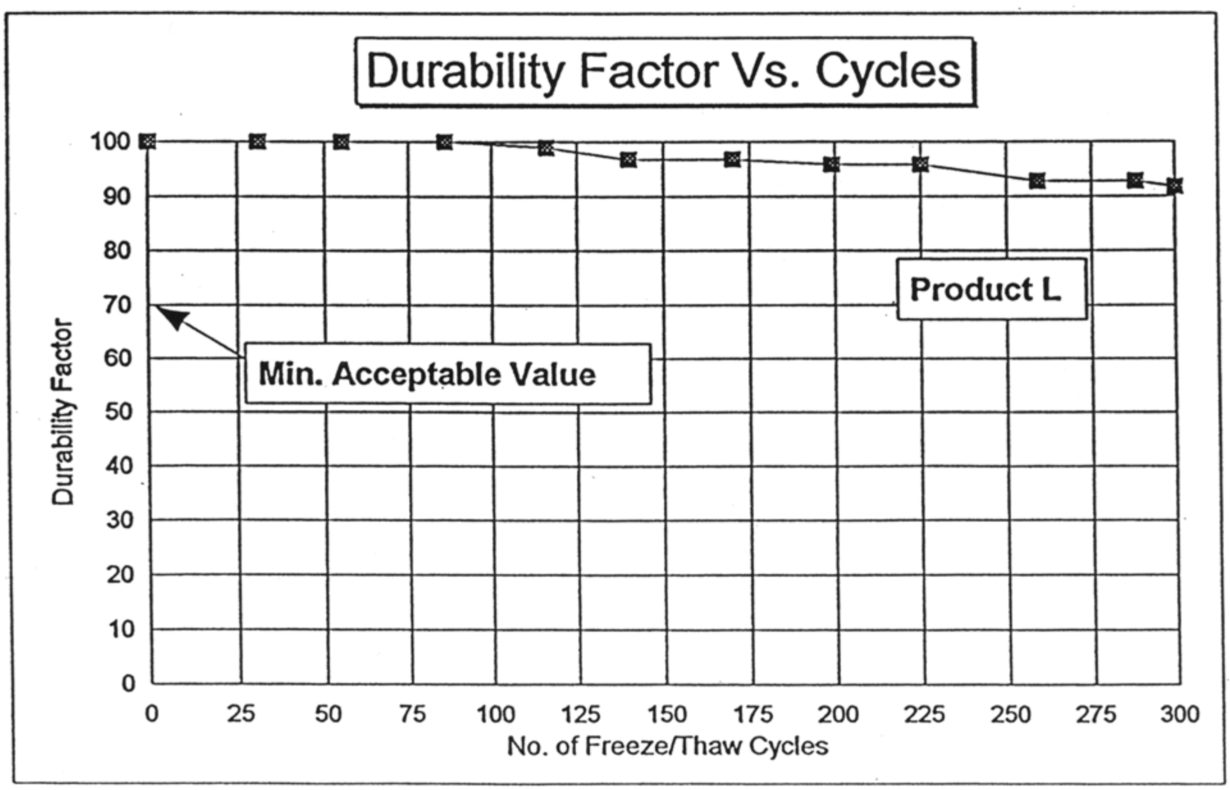



Cum. Percent Weight Loss Vs. Cycles
Product K
Cum. % Wt. Loss
10
8
6
4
2
0
0
25
50
75
100
125
150
175
200
225
250
275
300
No. of Freeze/Thaw Cycles


Durability Factor Vs. Cycles
Product K
Min. Acceptable Value
Durability Factor
100
90
80
70
60
50
40
30
20
10
0
0
25
50
75
100
125
150
175
200
225
250
275
300
No. of Freeze/Thaw Cycles

Appendix A
Cumulative Percent Weight Loss and Durability Factor vs. Freeze / Thaw Cycles





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