MIX DESIGN AND WEATHER DURABILITY EVALUATION OF LOW-DENSITY CONCRETES

by

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ABSTRACT

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A large portion of the fatal accidents on the Interstate Highway System and freeways are attributed to vehicles colliding with stationary, unmovable objects along the roadside. One attempt to reduce this large number of fatalities has been to install impact attenuators around the stationary objects to absorb the energy of impact. One type of material suggested for use in constructing impact attenuators has been low-density, high energy absorbing concrete. Because impact attenuators constructed from low-density concretes would be exposed to the effects of weather, the low-density concretes must possess high resistance to the effects of a freezing and thawing environment.

This study investigated the actual effects of a freezing and thawing condition in the laboratory on several low-density concretes. The low density concretes tested for freeze-thaw effects in this study were perlite concrete, vermiculite concrete, foam concrete, and polystyrene concrete. Mix designs were made and mix design

procedures were established along with mixing and placing techniques for these low-density concretes.

ACKNOWLEDGEMENTS

This author would like to acknowledge the assistance of colleague Ron Rizzo for help in developing and evaluating the low-density concrete mixes. Also acknowledgements are due electrical technicians Mike Repetski and Jim Bolchak for maintaining the electrical equipment used in this study. Special acknowledgements are expressed to the parents of the author and Dr. Clara S. Crane, a personal friend of the author, for moral support and understanding through his academic career.

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SYMBOL	DEFINITIONS	UNITS OF REFERENCE
E	Dynamic Modulus of Elasticity	Lbs/In^2
f	Fundamental Frequency	Cyc./Sec
k	Constant	Sec Lbs/Cyc. In^2
Ex	Dynamic Modulus of Elasticity at x Cycles	Lbs/In^2
fx	Fundamental Frequency at x Cycles	Cyc/Sec
fo	Fundamental Frequency at Zero Cycles	Cyc/Sec
DF	Durability Factor	None
X	Number of Freeze-Thaw Cycles	None
M	Maximum Number of Freeze-Thaw Cycles	None
C	Constant	None
DF'	New Durability Factor	None

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CHAPTER I

INTRODUCTION

On the Interstate Highway System the leading source of fatal accidents has been attributed to single vehicles colliding with fixed roadside objects. Some examples of the fixed roadside objects are bridge supports, guard rail ends, posts, and light poles. These objects are familiar to every motorist traveling the Interstate Highway System and seem rather innocent as they perform their functions, but they are a deadly menace to the occupants of any vehicle colliding with them at a high rate of speed. When a vehicle collides with a fixed immovable roadside object all the energy the vehicle had before impact is, after impact, dissipated by the excessively deforming of the colliding vehicle. Needless to say, the individuals inside the vehicle experience severe deceleration.

Several methods have been proposed to deal with this problem. One simple solution is to place the fixed immovable objects in locations where vehicles could not possibly collide with them or eliminate the objects completely. These solutions are satisfactory but some roadside objects cannot be relocated or eliminated, i.e., bridge supports, sign posts, and light poles. Another solution to the problem is to make sign posts and light poles that break away when a vehicle collides into them, thus allowing the vehicle to continue on after collision to come to a safer stop, hopefully. This solution is also satisfactory, but bridge supports that break away upon collision is an impractical idea and what about the millions of non-breakaway posts currently in existance? A more feasible solution to this problem is to place an energy absorbing system, i.e., an impact attenuator, around the fixed immovable roadside object to absorb the energy of the vehicle upon collision. When a vehicle would collide with a fixed immovable roadside object with an impact attenuator protectively placed around it, the energy the vehicle had before impact would be, after impact, absorbed for the most part by the impact attenuator thereby reducing the number of fatalities attributed to this type of accident.

One material proposed for constructing these impact attenuators is low-density, high energy absorbing concrete. (Low-density concrete is considered to have a unit weight ranging from 20 to 50 lbs/ft^3 as opposed to normal concrete which has a unit weight ranging from 140 to 150 lbs/ft^3.) Because these impact attenuators would be exposed to the effects of weather, low-density concretes must be resistant to weathering effects. The most severe effects of weather in the Northern parts of the United States is that of freezing and thawing in the presence of water.

This study investigated the effects of a laboratory imposed freezing and thawing environment on several types of low-density concrete. In the literary search for this study, there were no articles or papers available on the effects of freezing and thawing of low-density concretes. The main use for this type of material has been for isolation where the effects of freezing and thawing in water was not considered to be a factor. Also, there were no criteria available for designing a mix of low-density concrete for a specific unit weight.

To accomplish the objective of this study, that being the effects of a freezing and thawing environment on low-density concrete, low-density concrete mixes were established and a mix design criteria was developed to design low-density concrete mixes with various unit weights. Mixes were designed for three types of low-density concrete; perlite concrete, vermiculite concrete, and foam concrete, and the material and mix proportions for polystyrene concrete were furnished by Koppers Co. of Pittsburgh. All the low-density concrete investigated in this study had oven dry unit weights ranging from 20 to 43 lbs/ft^3 and static compressive strengths ranging from 30 to 500 psi. Five mixes of perlite concrete were designed but only four of these mixes were tested for freeze-thaw effects because the perlite concrete mix with the highest oven dry unit weight (43 lbs/ft^3) had minimal energy absorbing properties and therefore, it was not useful for impact attenuators applications. Three mixes of vermiculite concrete and four mixes of foam concrete were designed and tested for freeze-thaw effects. Koppers Co. furnished three commercially available polystyrene mixes that were also tested for the effects of freezing and thawing. The procedure followed in this study and the results obtained are presented in the following chapters.

CHAPTER II
MIXED DESIGN PROCEDURES

2.1 MATERIALS AND EQUIPMENT

2.1.1 PERLITE AGGREGATE

Perlite is a natural occurring siliceous rock found in the Western United States. It has a unique property in that when it is heated to a suitable temperature in its softening range it expands anywhere from four to twenty times its original volume. This property makes it suitable for a low-density concrete aggregate.

The expanded perlite used in this study had a bulk unit weight of 8 pcf and a bulk specific gravity of 0.3868. A typical gradation for the perlite used is as follows:

Sieve Number	Percent Retained	Cumulative % Retained	Percent Finer
4	0.00	0.00	100.00
8	0.84	0.84	99.16
16	42.74	43.58	56.42
30	27.44	71.02	28.98
50	16.00	87.02	12.98
100	7.86	94.88	5.12
PAN	5.12	100.00	0.00

The perlite aggregate can be seen in Figure 2-1.

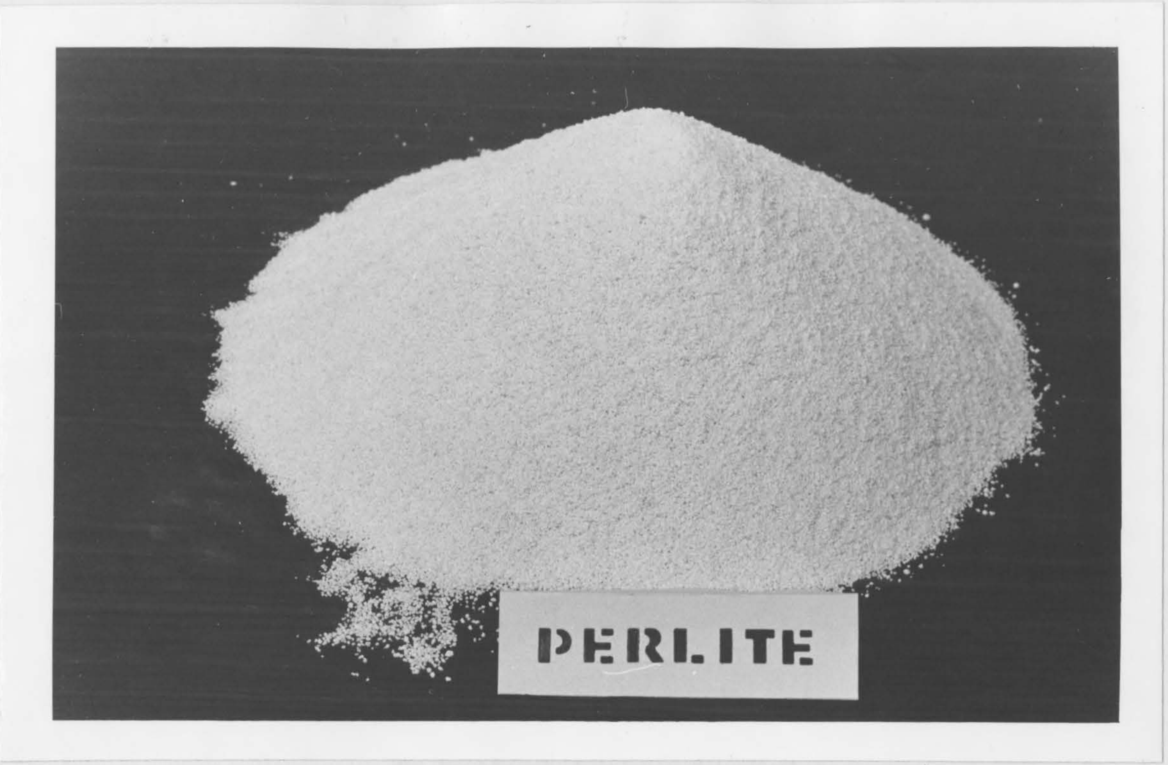


FIGURE 2-1. PERLITE AGGREGATE

2.1.2 VERMICULITE AGGREGATE

Vermiculite is a micaceous mineral which when subjected to intense heat forms millions of tiny air cells. This causes an intense expansion and thus a light-weight aggregate is formed.

The expanded vermiculite used in this study is sold under the trade name of Wyo-Lite and has a bulk unit weight of 7 to 10 pcf. The bulk specific gravity of Wyo-Lite is 0.569. A chart for the particle gradation of this aggregate follows:

Sieve Number	Percent Retained	Cumulative % Retained	Percent Finer
4	0.00	0.00	100.00
8	5.54	5.54	94.46
16	50.18	55.72	44.28
30	29.71	85.43	14.57
50	7.15	92.58	7.42
100	3.58	96.16	3.84
PAN	3.84	100.00	0.00

The vermiculite aggregate is shown in Figure 2-2.

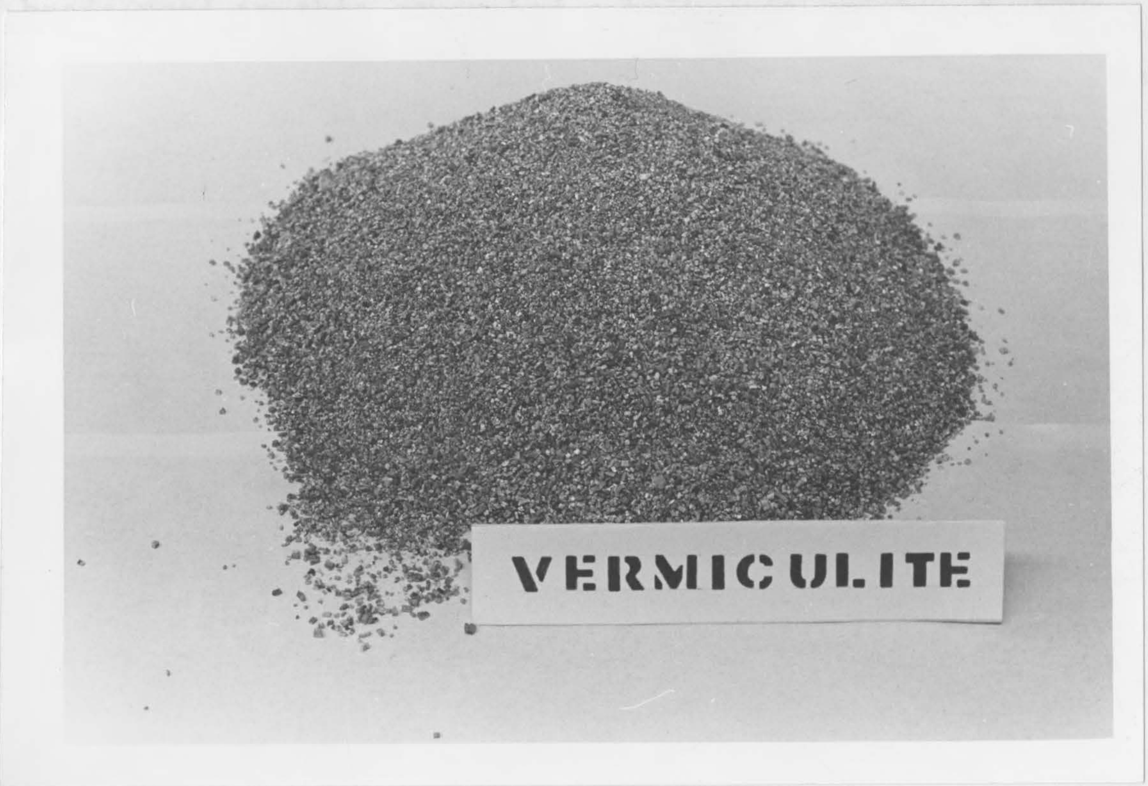


FIGURE 2-2. VERMICULITE AGGREGATE

2.1.2 POLYSTYRENE AGGREGATE

Expanded polystyrene consists of polystyrene particles which contain five to eight percent by weight of a volatile, saturated, paraffinic hydrocarbon. The hydrocarbon serves as a blowing agent, and with the application of heat the polystyrene expands into a bead shape. The degree of expansion can be controlled within the limits of two to fifty times the unexpanded volume. The bulk unit weight of the unexpanded polystyrene is about 30 pcf, while the expanded beads used in this study had a bulk unit weight of about 1 pcf. The polystyrene used in this study was produced and supplied by the Sinclair-Koppers Company, under the trade name of Dylite. The bulk specific gravity of Dylite is 0.016 and the size gradation ranges from 0.157 inches to 0.055 inches with the mean partical diameter of 0.109 in. The polystyrene aggregate is shown in Figure 2-3.

2.1.4 FOAMING AGENT AND EQUIPMENT

The foaming agent used in this study produced a stable air-bubble system for the fabrication of cellular concrete. A premixed solution of concentrated foaming agent and water was placed in a pressure tank under a controlled air pressure. The air pressure forced the solution out of the tank through a flexable tube into a blending nozzle. In the blending nozzle the solution was agitated and combined with compressed air to make a preformed foam which is similar

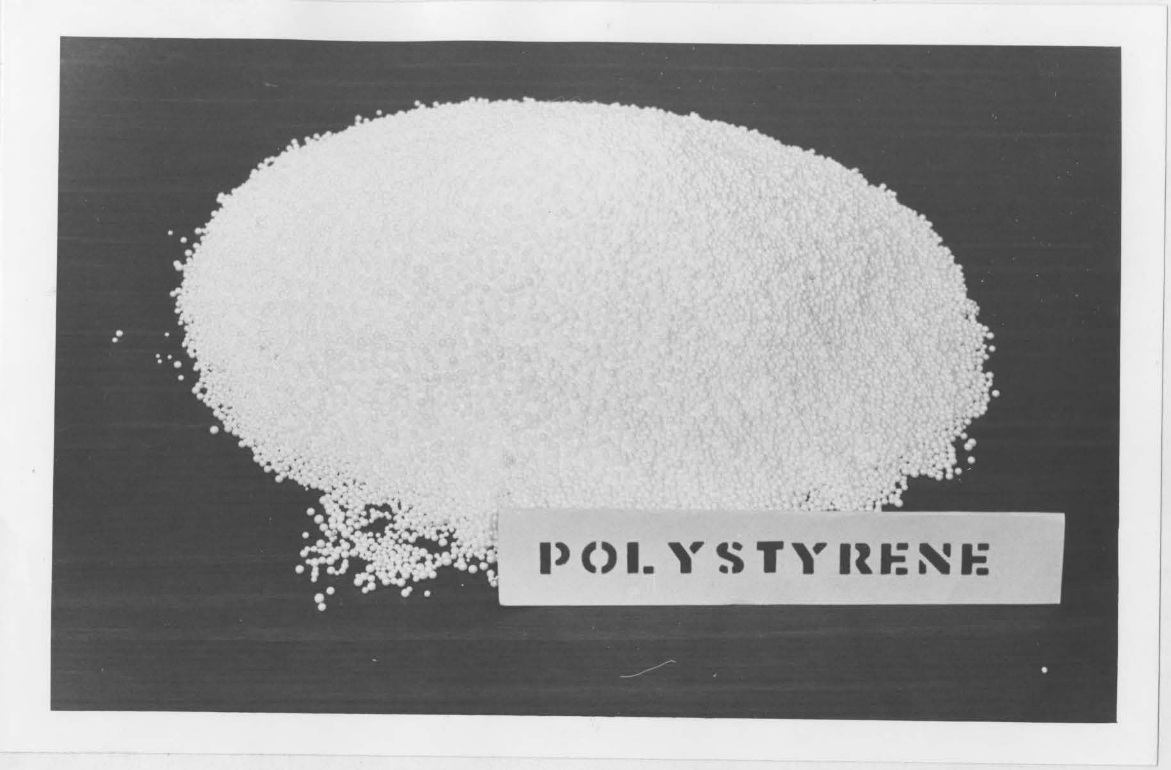


FIGURE 2-3. POLYSTYRENE AGGREGATE

in consistency to shaving cream taken from an aerosol can. The preformed foam was then mixed with cement and water to produce the cellular concrete. The foam producing equipment is shown in Figure 2-4 and a tray of preformed foam is shown in Figure 2-5.

The pressure tank and blending nozzle are available from the Mearl Corporation (220 W. Westfield Avenue, Roselle Park, New Jersey 07204) or can be constructed from specifications furnished by the Mearl Corporation. The concentrated foaming agent is also available at a nominal fee from the Mearl Corporation. The air compressor required

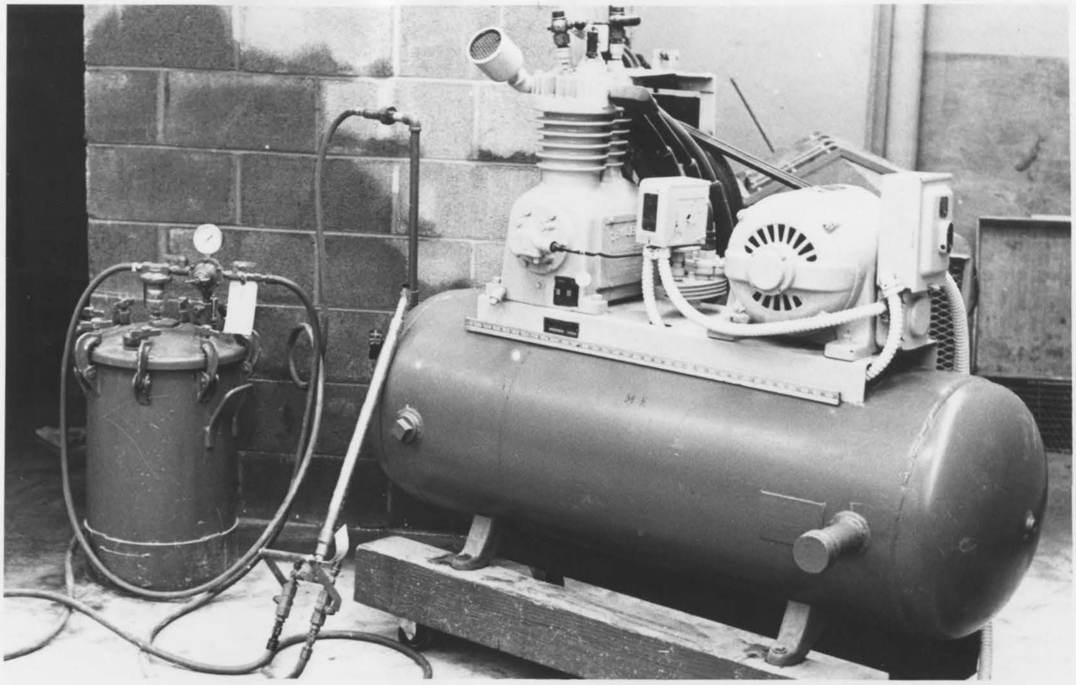


FIGURE 2-4. FOAM EQUIPMENT

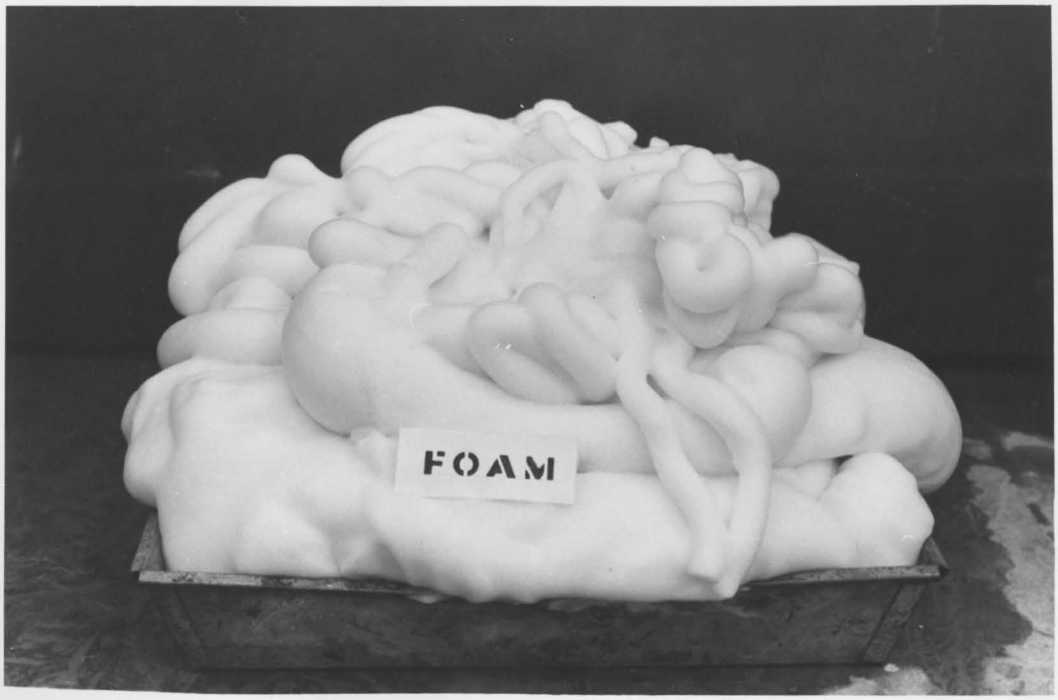


FIGURE 2-5. STABILIZED FOAM

to operate the foam generating system used in this study was of conventional variety and capable of delivering five cubic feet per minute of free air at a gage pressure of 80 psi.

2.1.5 THE MIXER

The mixer used to blend the low-density concrete mixtures was a conventional plaster and mortar mixer. Rubber blades were attached to the ends of the steel mixing arms to insure a more complete mixing. This type of mixer was chosen over the conventional concrete drum mixer to avoid the possibility of segregation of the low-density aggregate. In addition, this type of mixer was recommended by the various other investigators[1, 2] working in the low-density concrete area. The capacity of the mixer used was 3½ cubic feet with a blade rotation of 36 rpm. The mixer used for this study is shown in Figure 2-6.

2.1.6 THE AIR-ENTRAINING AGENT

The air-entraining agent used in this study was a commercially available product. The trade name of the air-entraining agent is Master Builder's Resin (MBVR).

2.2 MIXING; PROPORTIONS, PROPERTIES AND PROCEDURES

In developing the low-density concrete mixtures three items were considered; compressive strength, oven dry unit weight (between 20 to 50 pcf), and ability to reproduce the

FIGURE 2-6. PLASTER AND MORTAR MIXER

mix with similar properties.

First, trial mixes were made, based on previous work in the low-density concrete area. The oven dry unit weights and compressive strengths of these mixes were determined and new mixes were designed. The new mixes were designed by varying the aggregate-cement ratio as a means of varying the oven dry unit weight and by varying the water-cement ratio to alter the compressive strength.

After the trial mixing was completed, several mixes using each kind of aggregate were mixed again to determine the reproducibility of each mix. The results, to include both compressive strength and oven dry unit weight, were compared to the previous mixes and final mixes were selected for the study.

The mix proportions for each type of low-density concrete were different but the casting procedures were the same for each. The test specimens were cast by placing small amounts of the plastic low-density concrete into cylinder molds and vibrating the molds to fill all large air voids. The specimens were then placed in a moist cure room (100 percent humidity and 70°F) for the duration of the curing period.

All the trial mixing was accomplished by using Type III High Early Cement and the test specimens were moist cured for 14 days. The final test specimens were made with Type I Normal Cement and moist cured for 28 days before testing.

2.2.1 PERLITE CONCRETE MIX DESIGN

The trial mixes for the perlite concrete were taken from the perlite manufacturer's recommendations. Also, original trial mixes were designed and mixed. All results were evaluated, then final mixes were chosen based upon the criteria established earlier in Section 2.2.

Five final mixes of perlite concrete were selected from the trial mixes. The oven dry unit weights ranged from 22.3 to 43.13 pcf and the corresponding compressive strengths ranged from 41.6 to 636.3 psi.

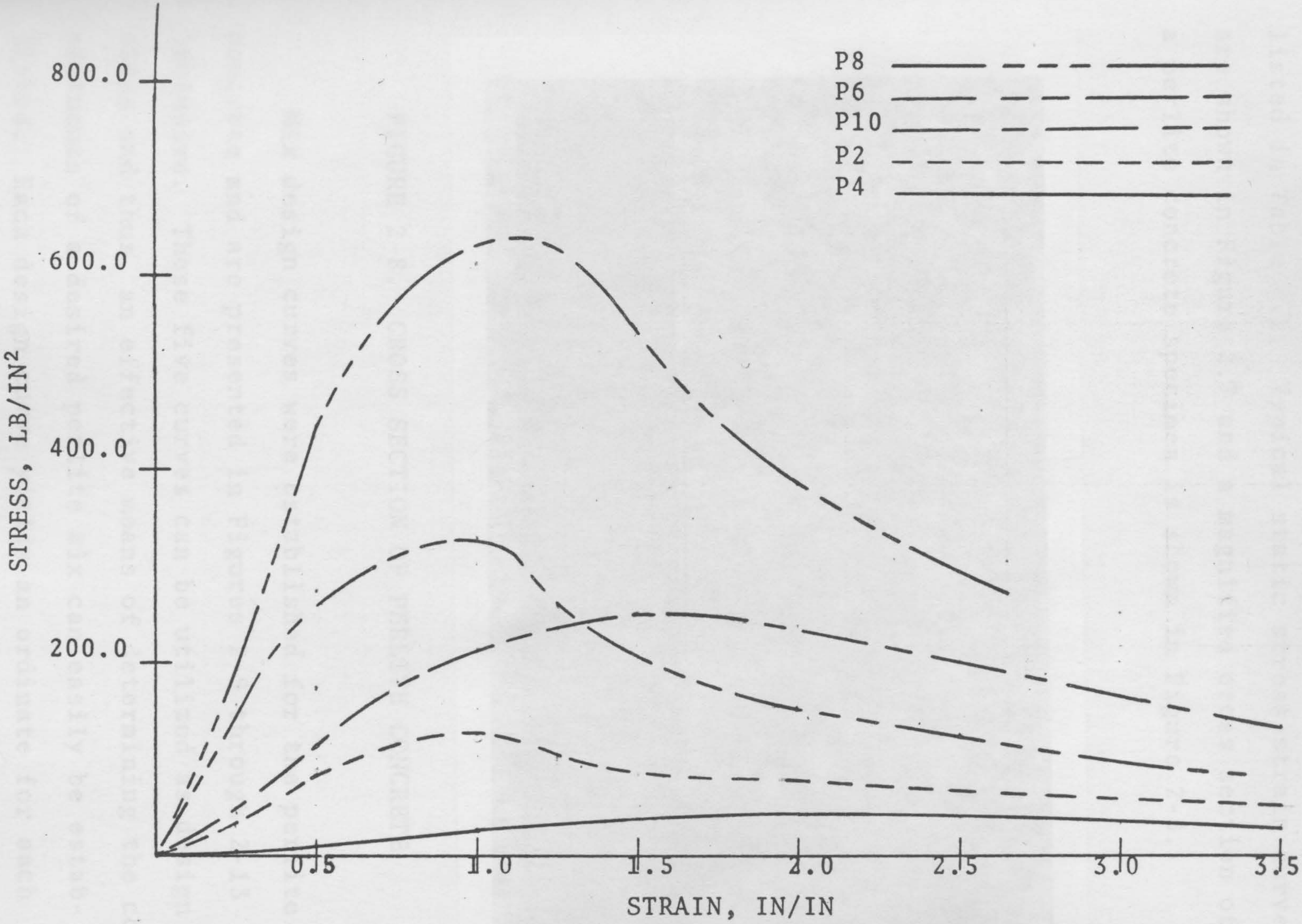


FIGURE 2-7. TYPICAL STATIC STRESS-STRAIN CURVES FOR PERLITE CONCRETE

These final mix proportions and properties are listed in Table 2.1. Typical static stress-strain curves are shown in Figure 2.7 and a magnified cross section of a perlite concrete specimen is shown in Figure 2-8.

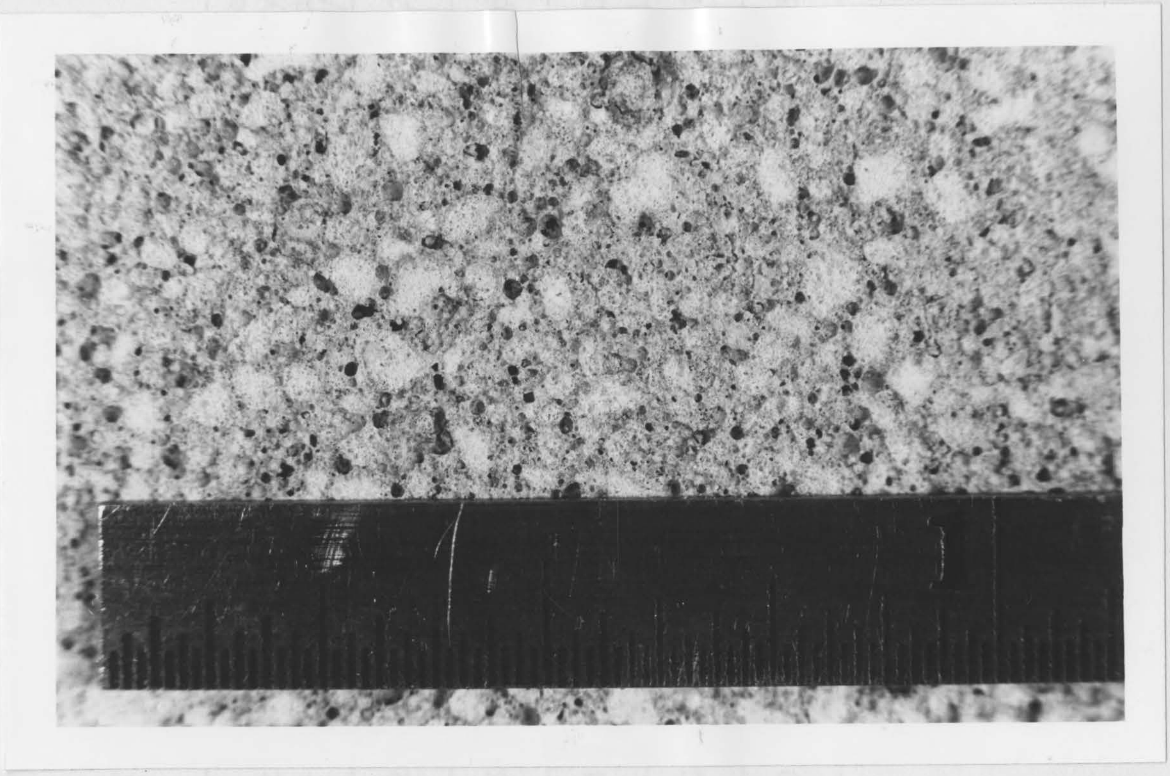


FIGURE 2-8. CROSS SECTION OF PERLITE CONCRETE

Mix design curves were established for the perlite concrete and are presented in Figures 2-9 through 2-13 inclusive. These five curves can be utilized as design aides and thus, an effective means of determining the constituents of a desired perlite mix can easily be established. Each design curve yields an ordinate for each

TABLE 2.1

PERLITE MIX PROPORTIONS AND PROPERTIES

Mix Designation Number	Cement Lbs.	Water Lbs.	Perlite Lbs.	Air Entr. Agent mls	Batch Yield Ft^3/Bag Cement	Fresh Unit Wt. Lb/Ft^3	Percent Air %	Ave.Ov. Dry Unit Weight Lb/Ft^3	Average Comp.Str. Lb/In^2
P4	14.24	19.32	8.42	124.9	9.596	28.875	49.49	22.3	41.6
P2	21.23	20.72	9.03	134.0	7.110	31.75	49.1	26.9	121.8
P10	34.85	27.19	9.44	193.8	4.345	44.375	37.41	30.4	251.0
P6	42.3	30.0	10.80	160.2	3.929	47.0	34.97	34.8	328.8
P8	52.22	31.33	9.40	139.4				43.13	636.3

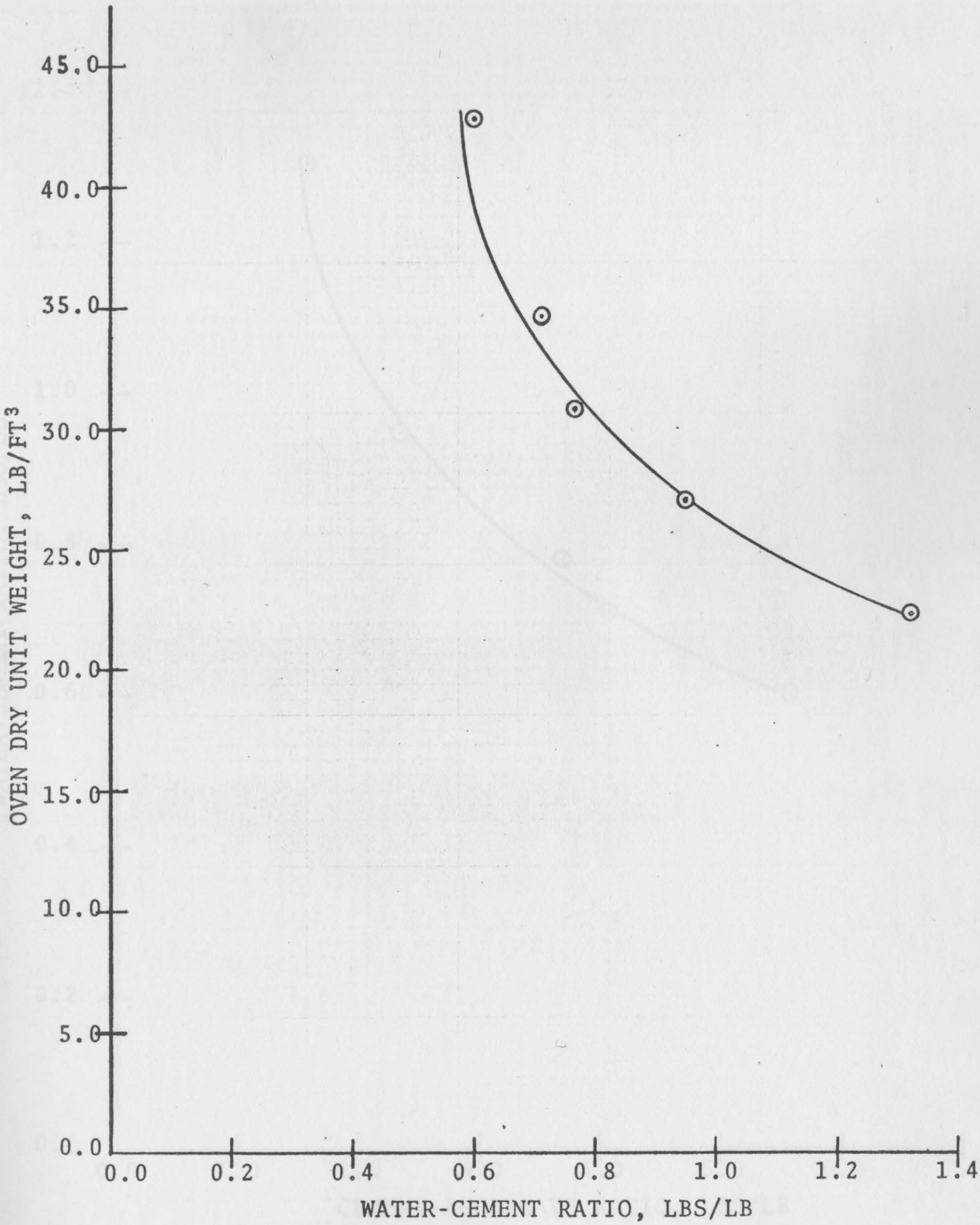


FIGURE 2-9. OVEN DRY UNIT WEIGHT VERSUS WATER-CEMENT RATIO FOR PERLITE CONCRETE

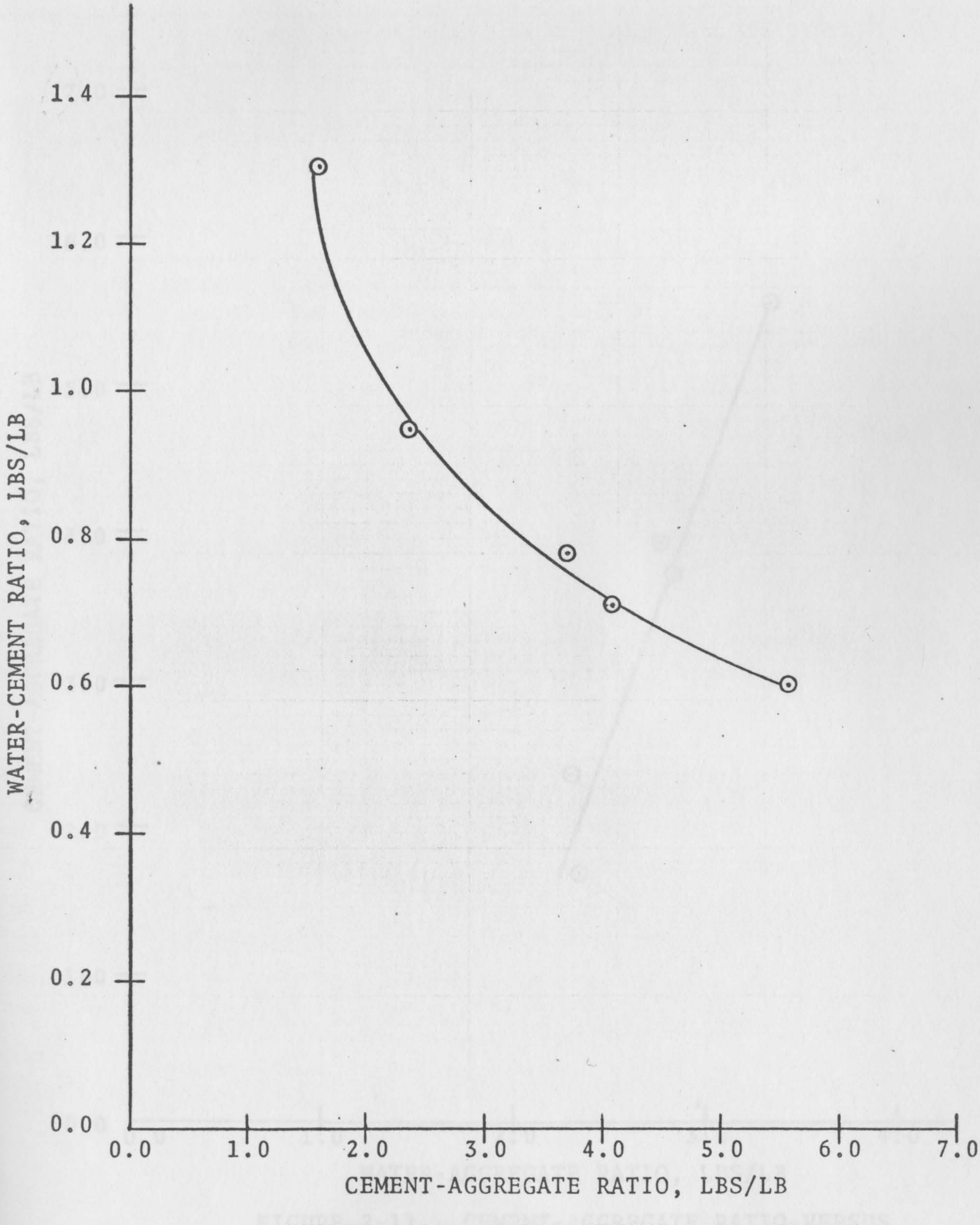


FIGURE 2-10. WATER-CEMENT RATIO VERSUS CEMENT-AGGREGATE RATIO FOR PERLITE CONCRETE

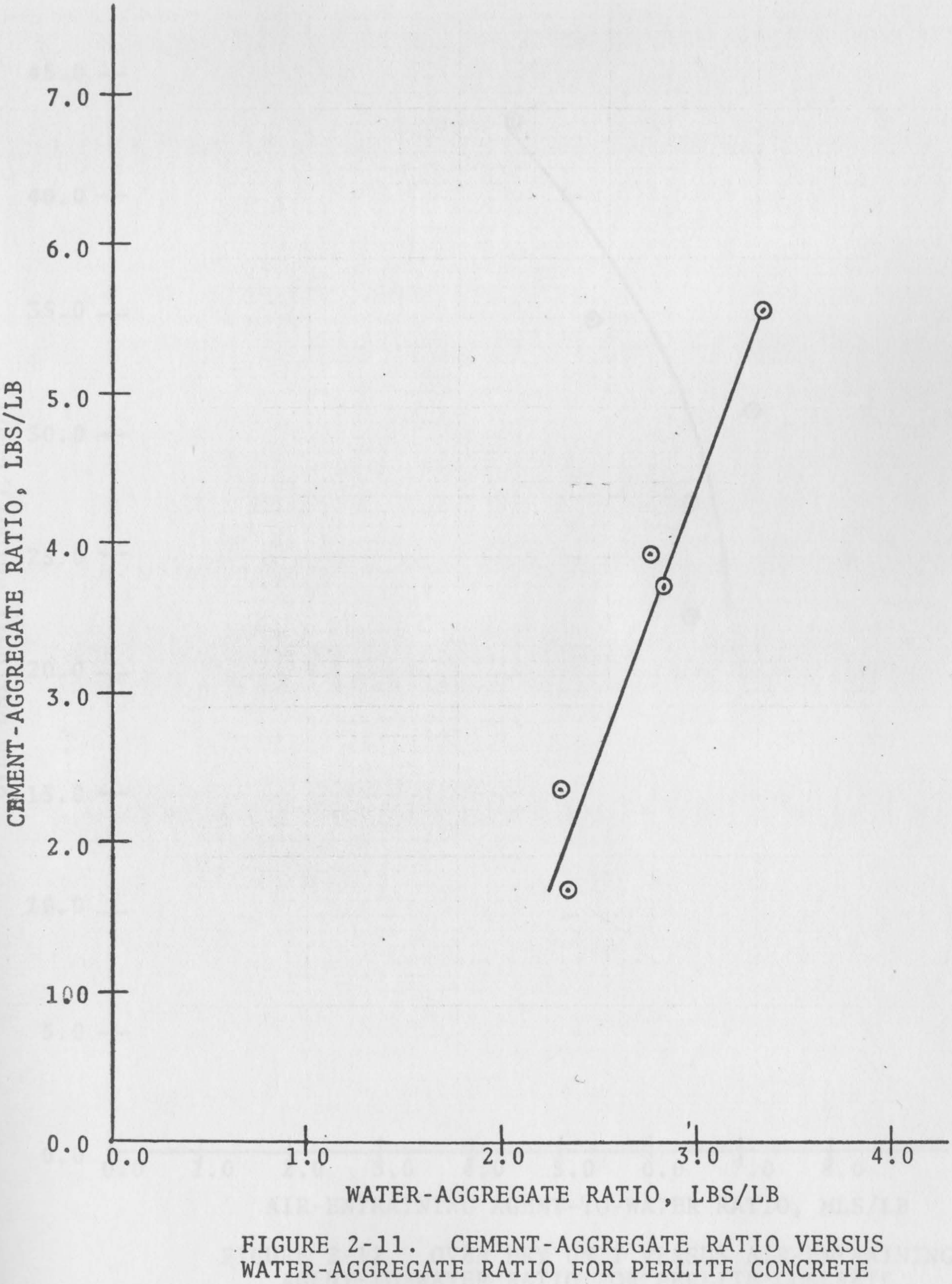


FIGURE 2-11. CEMENT-AGGREGATE RATIO VERSUS WATER-AGGREGATE RATIO FOR PERLITE CONCRETE

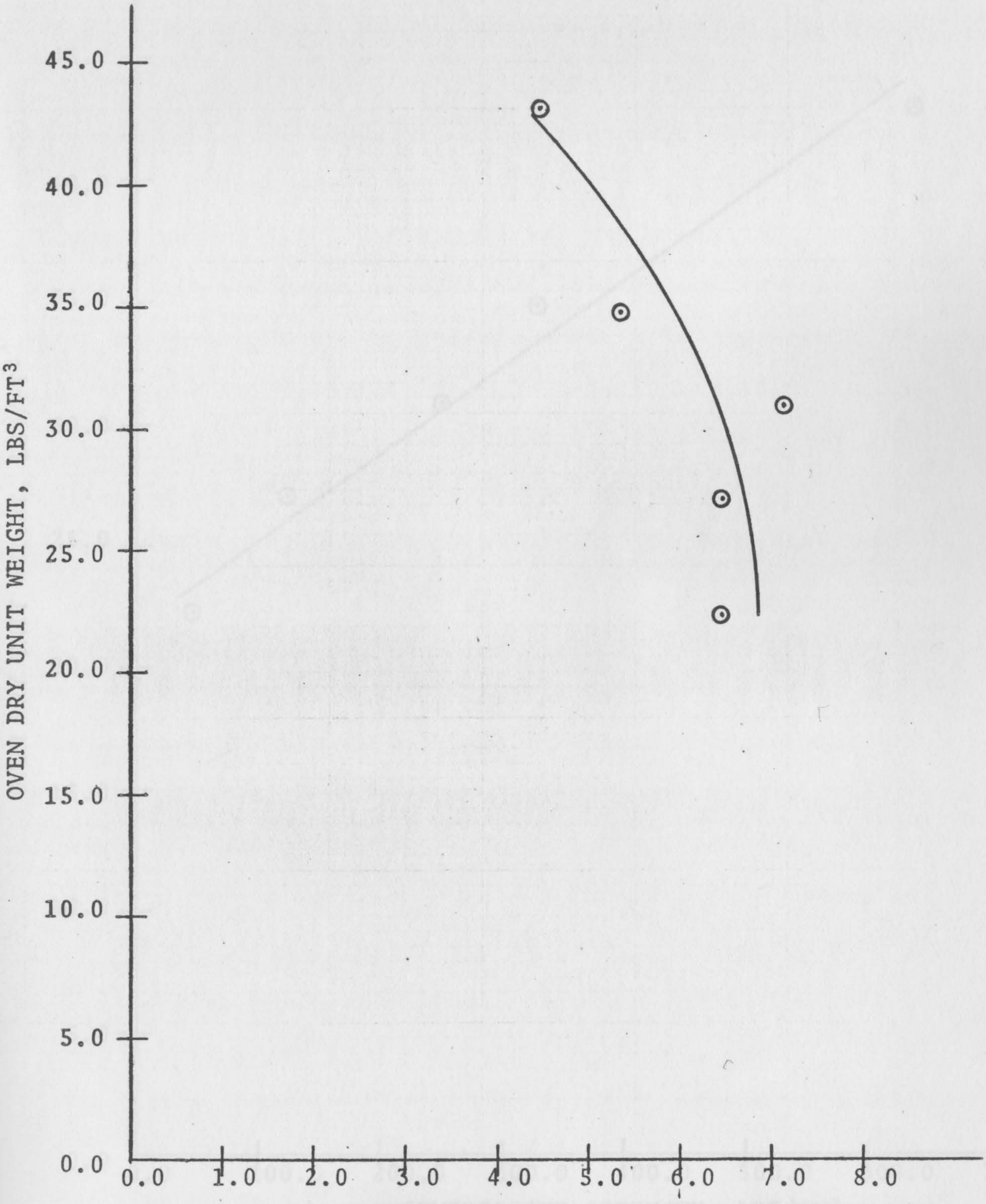


FIGURE 2-12. OVEN DRY UNIT VERSUS AIR-ENTRAINING AGENT-TO-WATER RATIO FOR PERLITE CONCRETE

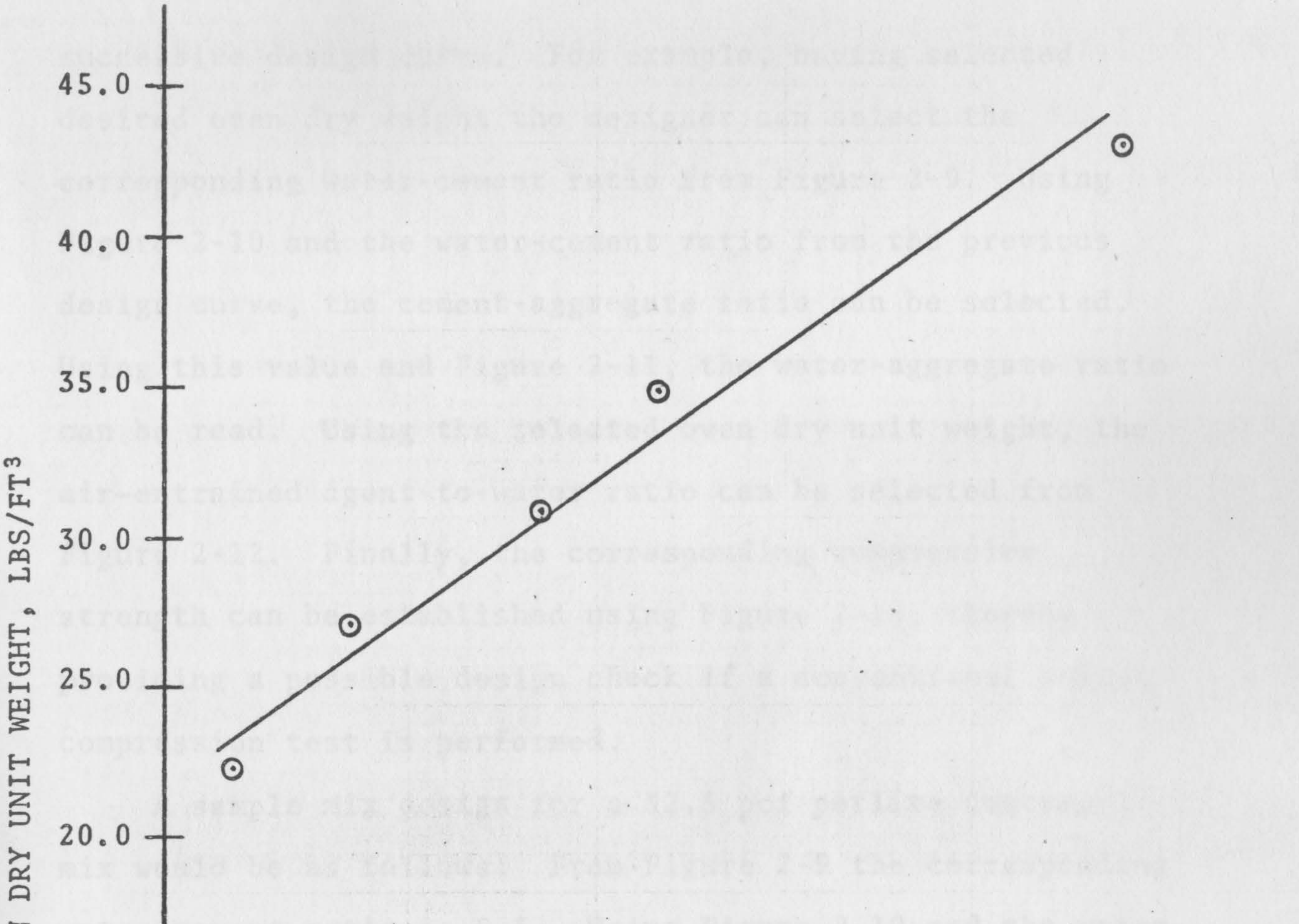


FIGURE 2-13. OVEN DRY UNIT WEIGHT VERSUS STATIC COMPRESSIVE STRENGTH FOR PERLITE CONCRETE

successive design curve. For example, having selected desired oven dry weight the designer can select the corresponding water-cement ratio from Figure 2-9. Using Figure 2-10 and the water-cement ratio from the previous design curve, the cement-aggregate ratio can be selected. Using this value and Figure 2-11, the water-aggregate ratio can be read. Using the selected oven dry unit weight, the air-entrained agent-to-water ratio can be selected from Figure 2-12. Finally, the corresponding compressive strength can be established using Figure 2-13, thereby providing a possible design check if a conventional static compression test is performed.

A sample mix design for a 32.5 pcf perlite concrete mix would be as follows: From Figure 2-9 the corresponding water-cement ratio is 0.5. Using Figure 2-10 and the water-cement ratio of 0.5 a cement-aggregate ratio of 4.2 is selected. Employing Figure 2-11 with a cement-aggregate ratio of 4.2, a water-aggregate ratio of 3.0 is determined and from Figure 2-12 with the selected oven dry unit weight of 32.5 pcf, the air-entrained agent-to-water ratio is 6.0. From Figure 2-13, as a check on the design, the corresponding static compressive strength for the selected oven dry unit weight of 32.5 pcf is 300.0 psi.

The units for the water-cement ratio, cement-aggregate ratio and water-aggregate ratio are in pounds per pound. The ratio of air-entrained agent-to-water is in the units of milliliters per pound. Compressive strength is expressed in pounds per square inch and oven dry unit weight is expressed in pounds per cubic foot.

It should be noted that a trial mix should be made and tested as a check on the mix design. Due to the inconsistency displayed in Figure 2-12, some slight adjustments of the various ratios may be necessary to achieve the desired end result.

2.2.2 PERLITE CONCRETE MIX PROCEDURE

The mixing procedure followed was the same for all the perlite mixes. First, all the water and air-entraining agent were placed in the mixer and mixed for 30 seconds. Second, all the cement was added and mixed with the mixture of water and air-entraining agent for another 30 seconds. Finally, the perlite aggregate was added to the cement-water slurry and mixed for an additional two minutes. After this, the perlite concrete was ready for placing.

2.2.3 VERMICULITE CONCRETE MIX DESIGN

Three sources for trial mixes were consulted. They were: Hoff(2), Smith(1), and the manufacturer. Trial mixes were made from these three sources and additional original trial mixes were designed. The results from the trial mixes were evaluated and final mixes were selected based on the criteria set forth in Section 2.2.

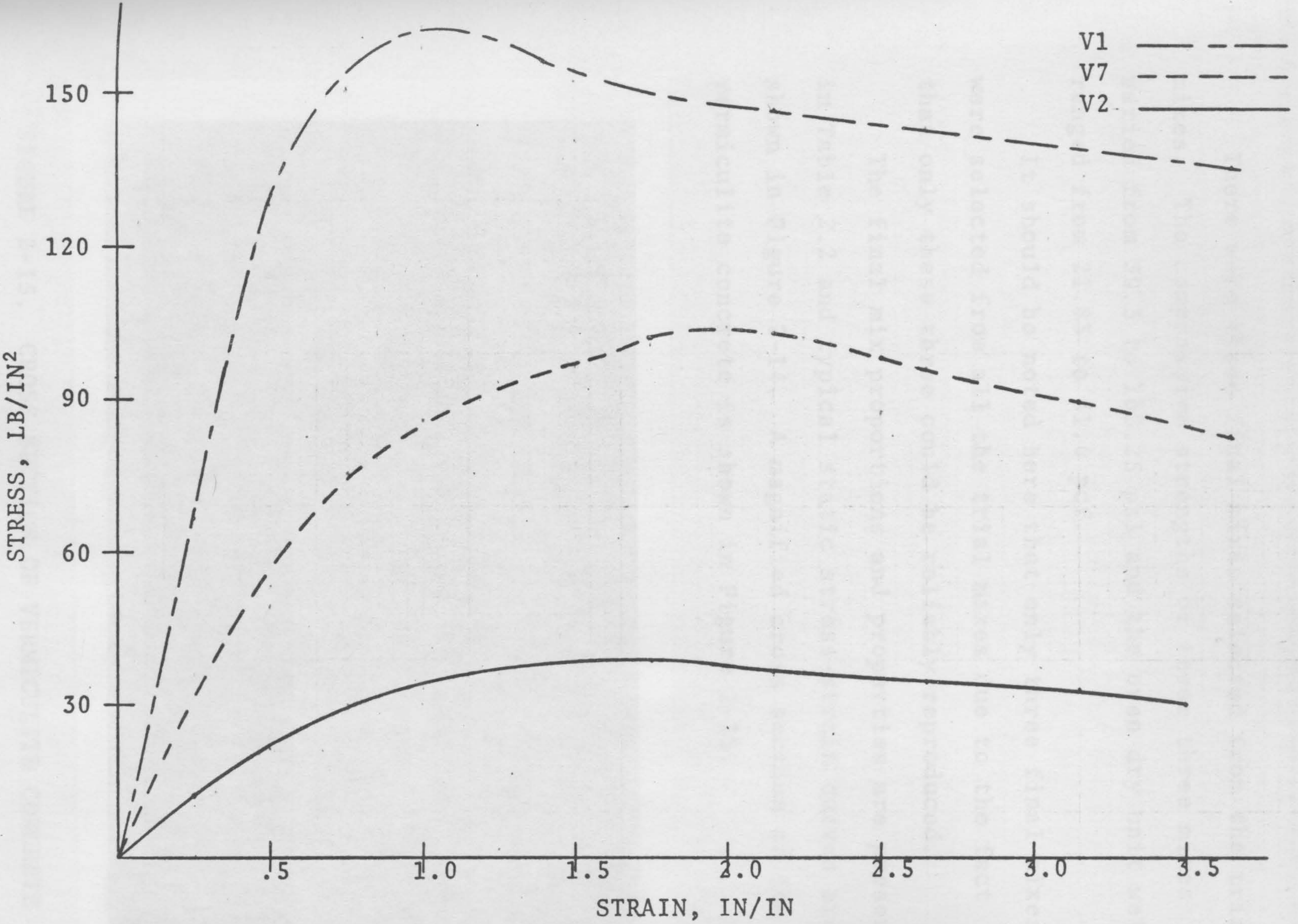


FIGURE 2-14. TYPICAL STATIC STRESS-STRAIN CURVES FOR VERMICULITE CONCRETE

There were three final mixes selected from the trial mixes. The compressive strengths of these three mixes varied from 39.3 to 165.25 psi and the oven dry unit weight ranged from 21.83 to 31.0 pcf.

It should be noted here that only three final mixes were selected from all the trial mixes due to the fact that only these three could be reliably reproduced.

The final mix proportions and properties are presented in Table 2.2 and typical static stress-strain curves are shown in Figure 2-14. A magnified cross section of the vermiculite concrete is shown in Figure 2-15.

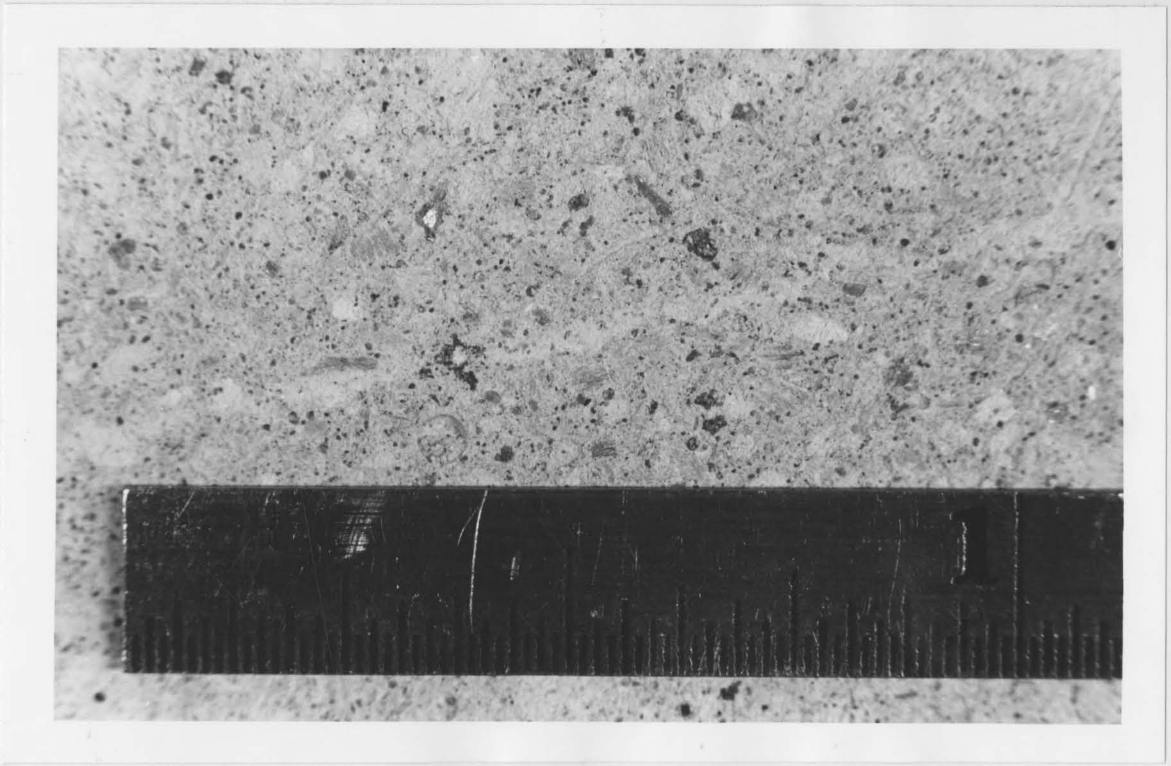


FIGURE 2-15. CROSS SECTION OF VERMICULITE CONCRETE

TABLE 2.2

VERMICULITE MIX PROPORTIONS AND PROPERTIES

Mix Designation Number	Cement Lbs.	Water Lbs.	Vermiculite Lbs.	Air Entr. Agent mls	Batch Yield Ft^3/Bag Cement	Fresh Unit Wt. Lb/Ft^3	Percent Air %	Ave. Ov. Dry Unit Weight Lb/Ft^3	Average Comp.Str. Lb/In^2
V2	32.4	82.5	22.0	107.0	8.28	48.0	25.7	21.83	39.3
V1	36.9	62.0	20.0	80.6	6.44	47.0	31.0	27.58	164.25
V7	18.2	60.8	19.8	100.0	10.10	50.5	16.9	29.29	102.9

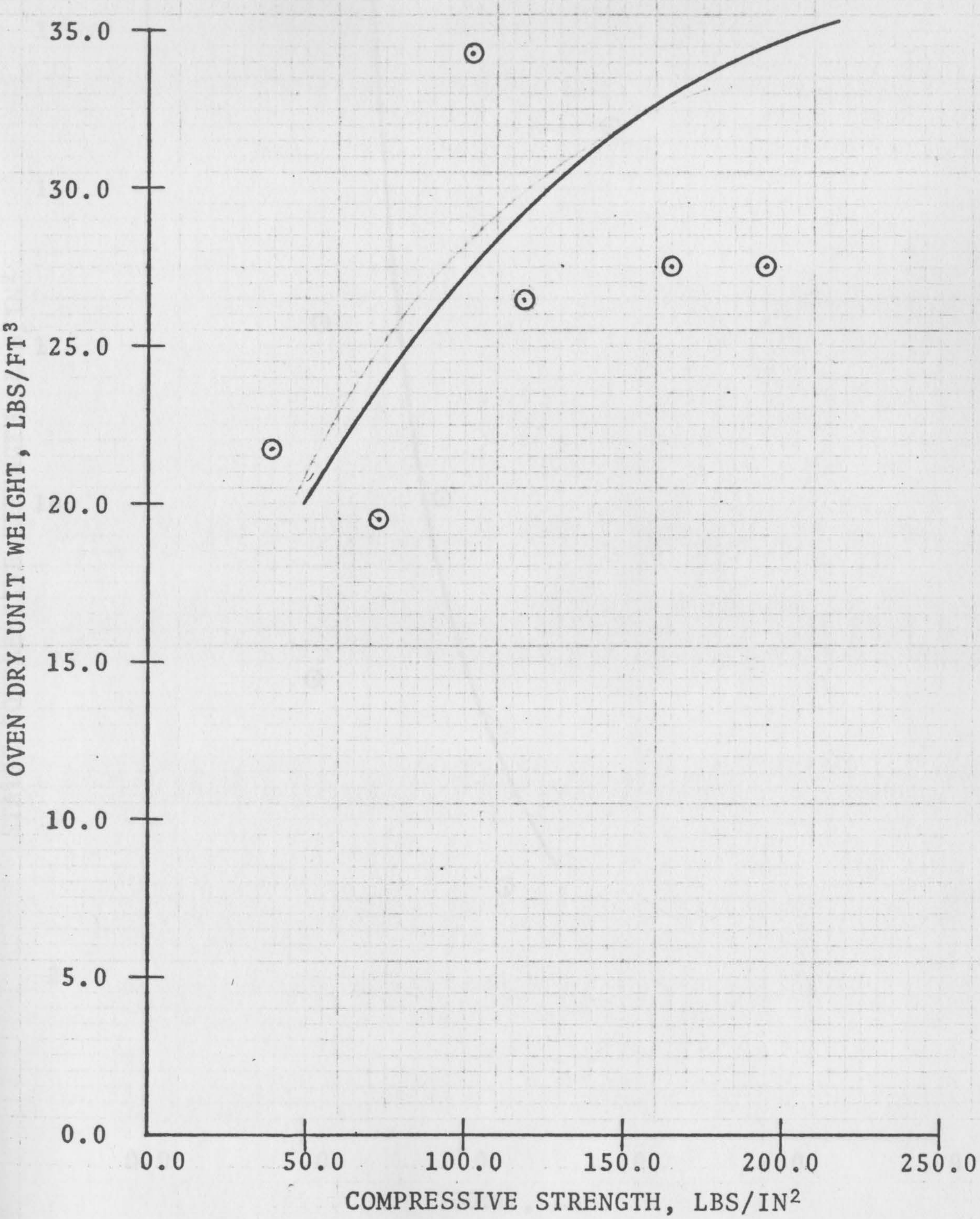


FIGURE 2-16. OVEN DRY UNIT WEIGHT VERSUS STATIC COMPRESSIVE STRENGTH FOR VERMICULITE CONCRETE

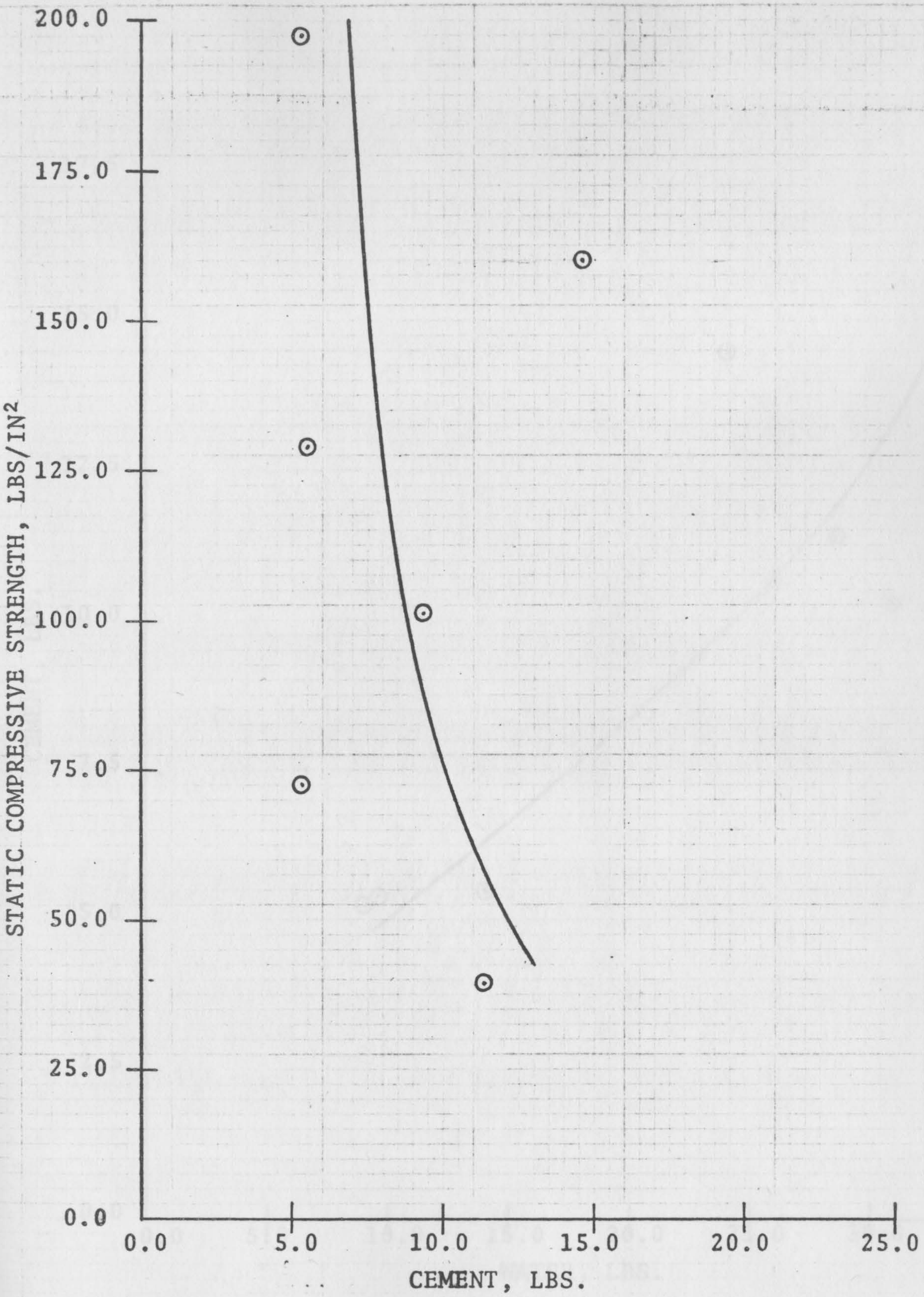


FIGURE 2-17. STATIC COMPRESSIVE STRENGTH VERSUS CEMENT FOR VERMICULITE CONCRETE

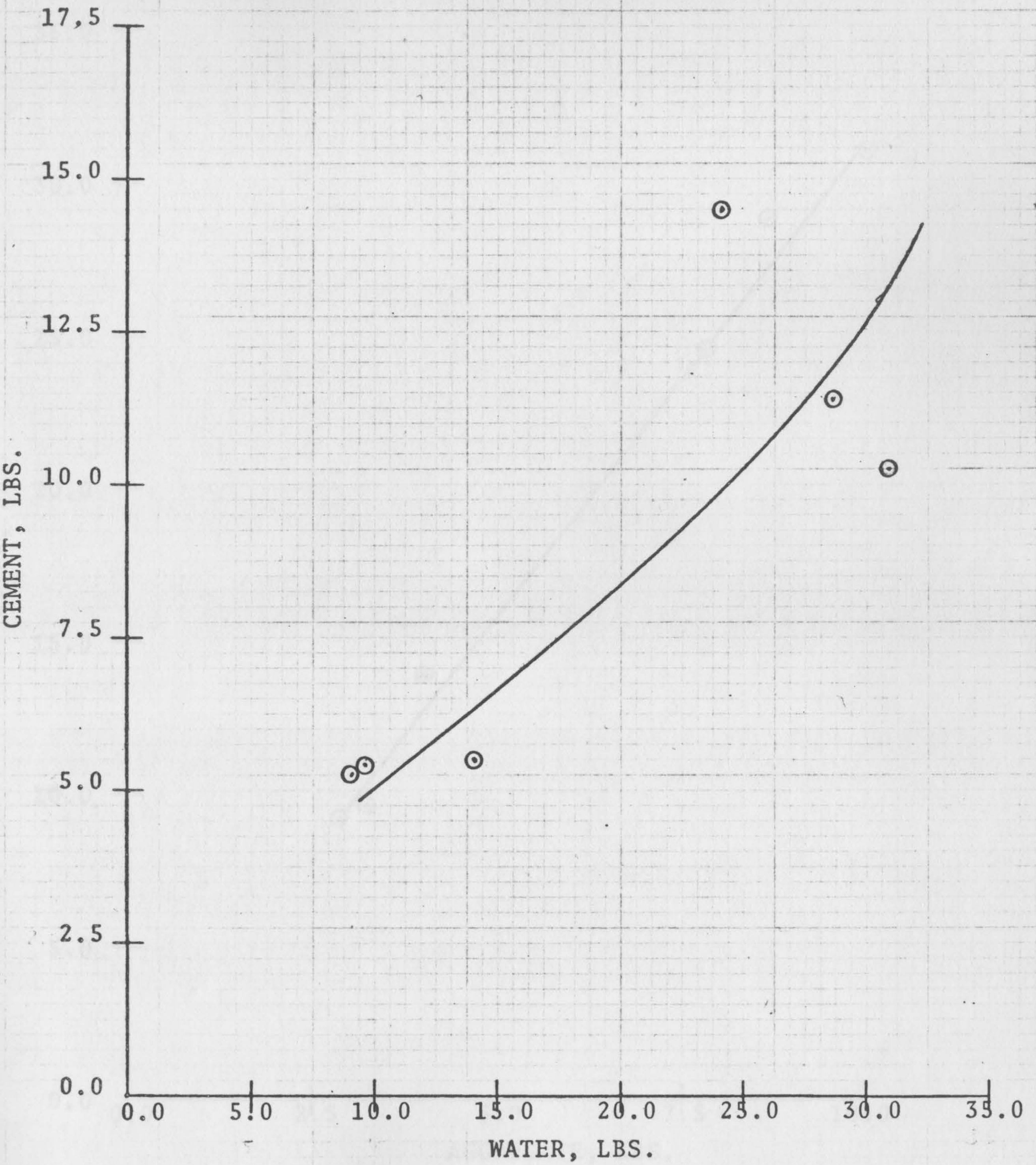


FIGURE 2-18. CEMENT VERSUS WATER FOR VERMICULITE CONCRETE

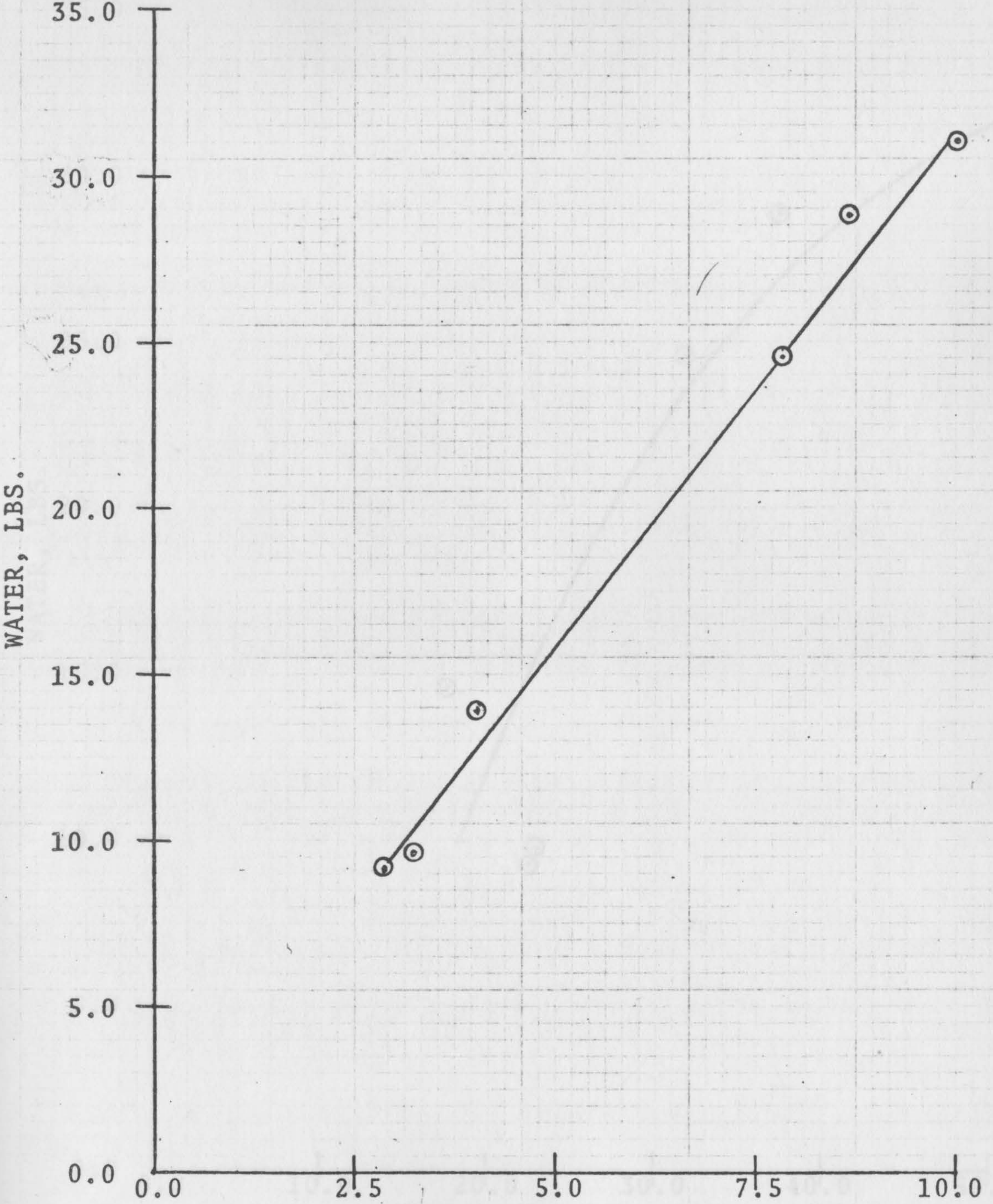


FIGURE 2-19. WATER VERSUS AGGREGATE FOR VERMICULITE CONCRETE

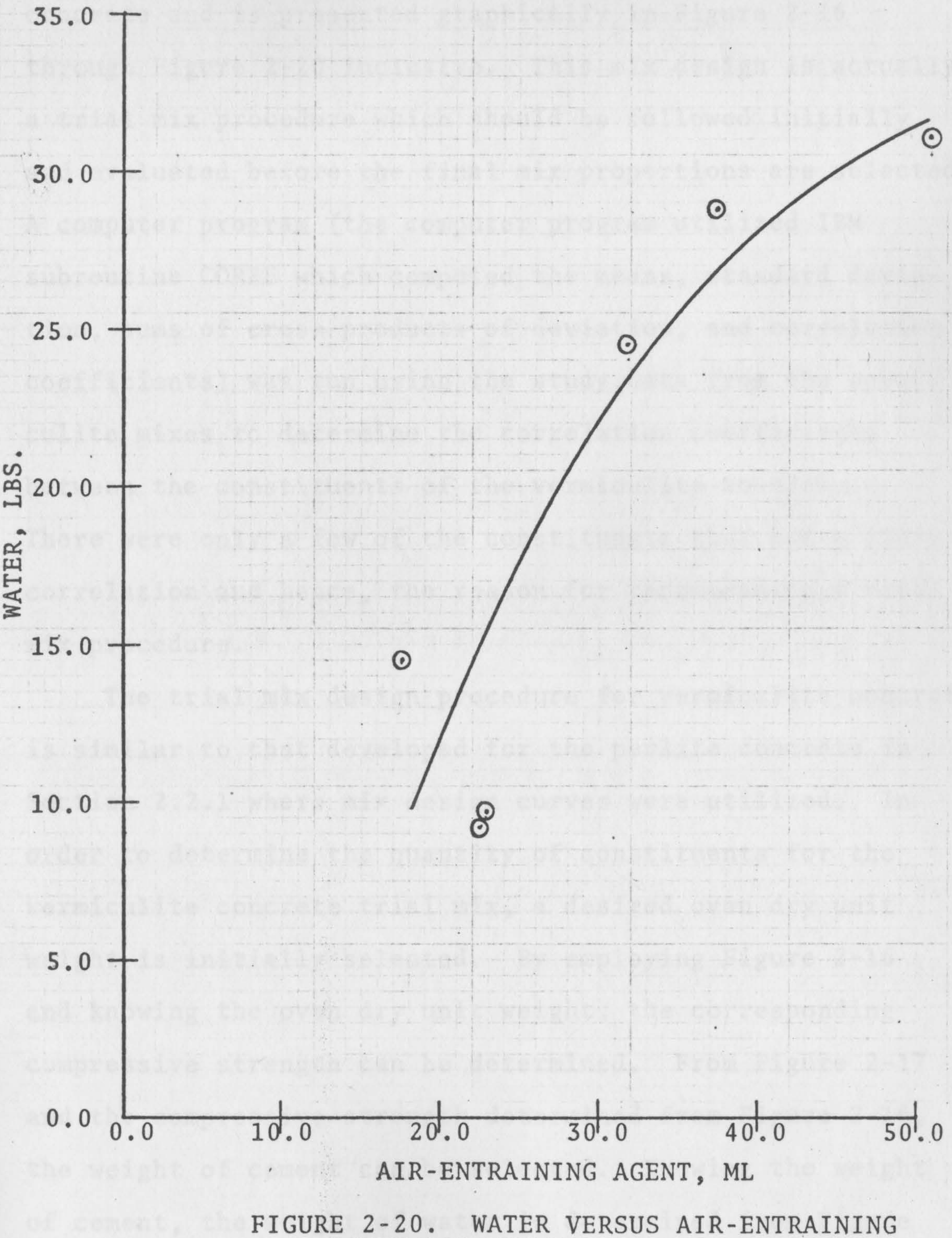


FIGURE 2-20. WATER VERSUS AIR-ENTRAINING AGENT FOR VERMICULITE CONCRETE

A mix design procedure was developed for vermiculite concrete and is presented graphically in Figure 2-16 through Figure 2-20 inclusive. This mix design is actually a trial mix procedure which should be followed initially and evaluated before the final mix proportions are selected. A computer program (the computer program utilized IBM subroutine CORRE which computed the means, standard deviation, sums of cross-products of deviation, and correlation coefficients) was run using the study data from the vermiculite mixes to determine the correlation coefficients between the constituents of the vermiculite concrete. There were only a few of the constituents that had a close correlation and hence, the reason for recommending a trial mix procedure.

The trial mix design procedure for vermiculite concrete is similar to that developed for the perlite concrete in Section 2.2.1 where mix design curves were utilized. In order to determine the quantity of constituents for the vermiculite concrete trial mix, a desired oven dry unit weight is initially selected. By employing Figure 2-16 and knowing the oven dry unit weight, the corresponding compressive strength can be determined. From Figure 2-17 and the compressive strength determined from Figure 2-16, the weight of cement can be selected. Knowing the weight of cement, the weight of water is determined from Figure 2-18. With the weight of water selected from Figure 2-18, the weight of aggregate can be selected from Figure 2-19. Finally, entering Figure 2-20 with the required weight of water, the milliliters of air-entrainment agent can be determined.

An example trial mix of vermiculite concrete with an oven dry unit weight of 24 pcf would be as follows: From Figure 2-16 with an oven dry unit weight of 24 pcf, the corresponding compressive strength is 75.0 psi. Using Figure 2-17 and the compressive strength of 75.0 psi, the weight of cement required is 10.0 lbs. With a weight of cement of 10.0 lbs. and Figure 2-18, the weight of water is determined to be 24.5 lbs. Entering Figure 2-19 with the required weight of water, the corresponding weight of vermiculite is 7.6 lbs. Lastly, from Figure 2-20 with the previously determined weight of water, the milliliters of air-entraining agent needed is 33.5 ml. This trial mix will yield approximately one cubic foot of fresh vermiculite concrete but a fresh batch unit weight should be determined to calculate the actual batch yield and air content. It should be noted that some adjustments in the trial mix proportions may be necessary to achieve the desired oven dry unit weight.

2.2.4 VERMICULITE MIX PROCEDURE

The mixing procedure was standardized for all the vermiculite concrete mixtures and was as follows: First, the water and air-entraining agent was mixed in the mixer for 1½ minutes. Next, the vermiculite aggregate was added and mixed for an additional 1½ minutes. Finally, the cement was added and the whole mixture was blended for five additional minutes.

2.2.5 FOAM CONCRETE MIXES

The manufacturer or developer, i.e., Mearl Corporation, suggested several mixes utilizing foam, cement, and water and foam, cement, sand, and water. The oven dry unit weights of the mixes containing sand were considerably higher than the ranges considered in this study and thus, a decision to use only the mixtures without sand was made. Trial mixes were made with the foam, cement, and water ingredients and final mixes were selected.

The final mixes for foam concrete numbered four in all, with oven dry unit weights ranging from 25.6 to 35.35 pcf. The corresponding compressive strengths ranged from 44.8 to 153.45 psi. The final foam mix proportions and properties are listed in Table 2-3 with typical static stress-strain curves shown in Figure 2-21. A magnified cross section of the foam concrete can be seen in Figure 2-22.

Mix design curves were established for the foam concrete and are presented in Figures 2-23 and 2-24. These curves are to be used as design aids in determining the proper proportions of foam, cement, and water to achieve a desired oven dry unit weight. To design a foam concrete

TABLE 2.3

FOAM MIX PROPORTIONS AND PROPERTIES

Mix Designation Number	Cement Lbs.	Water Lbs.	Foam Ft^3	Batch Yield Ft^3/Bag Cement	Fresh Unit Weight Lb/Ft^3	Percent Air %	Average Oven Dry Unit Wt. Lb/Ft^3	Average Compressive Strength Lb/In^2
F1	37.9	20.2	1.2	4.059	35.5	68.4	25.6	44.8
F2	44.2	23.6	1.14	3.94	36.6	67.4	28.1	82.2
F3	50.9	27.0	1.1	3.21	44.8	60.3	31.8	110.3
F4	57.7	30.8	1.02	2.84	50.8	54.8	35.35	153.45

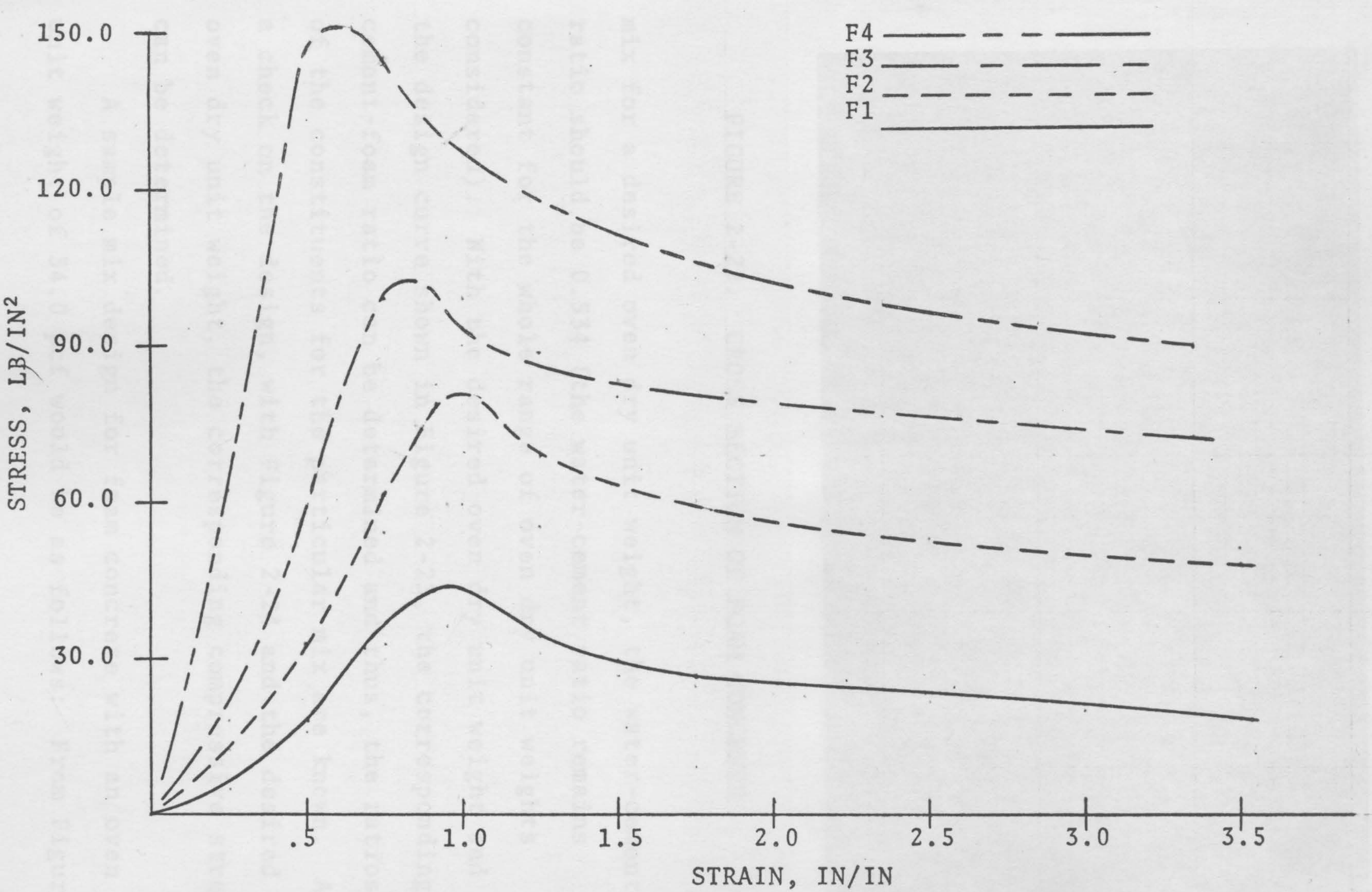


FIGURE 2-21. TYPICAL STATIC STRESS-STRAIN CURVES FOR FOAM CONCRETE

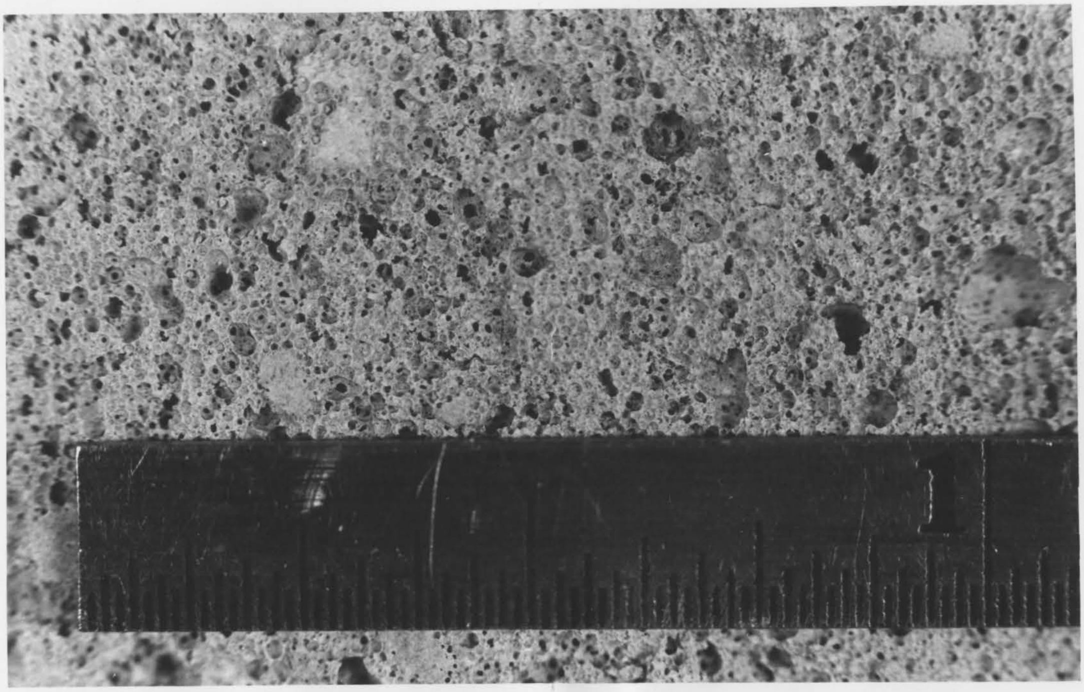


FIGURE 2-22. CROSS SECTION OF FOAM CONCRETE

mix for a desired oven dry unit weight, the water-cement ratio should be 0.534 (the water-cement ratio remains constant for the whole range of oven dry unit weights considered). With the desired oven dry unit weight and the design curve shown in Figure 2-23, the corresponding cement-foam ratio can be determined and thus, the ratios of the constituents for the particular mix are known. As a check on the design, with Figure 2-24 and the desired oven dry unit weight, the corresponding compressive strength can be determined.

A sample mix design for foam concrete with an oven dry unit weight of 34.0 pcf would be as follows: From Figure

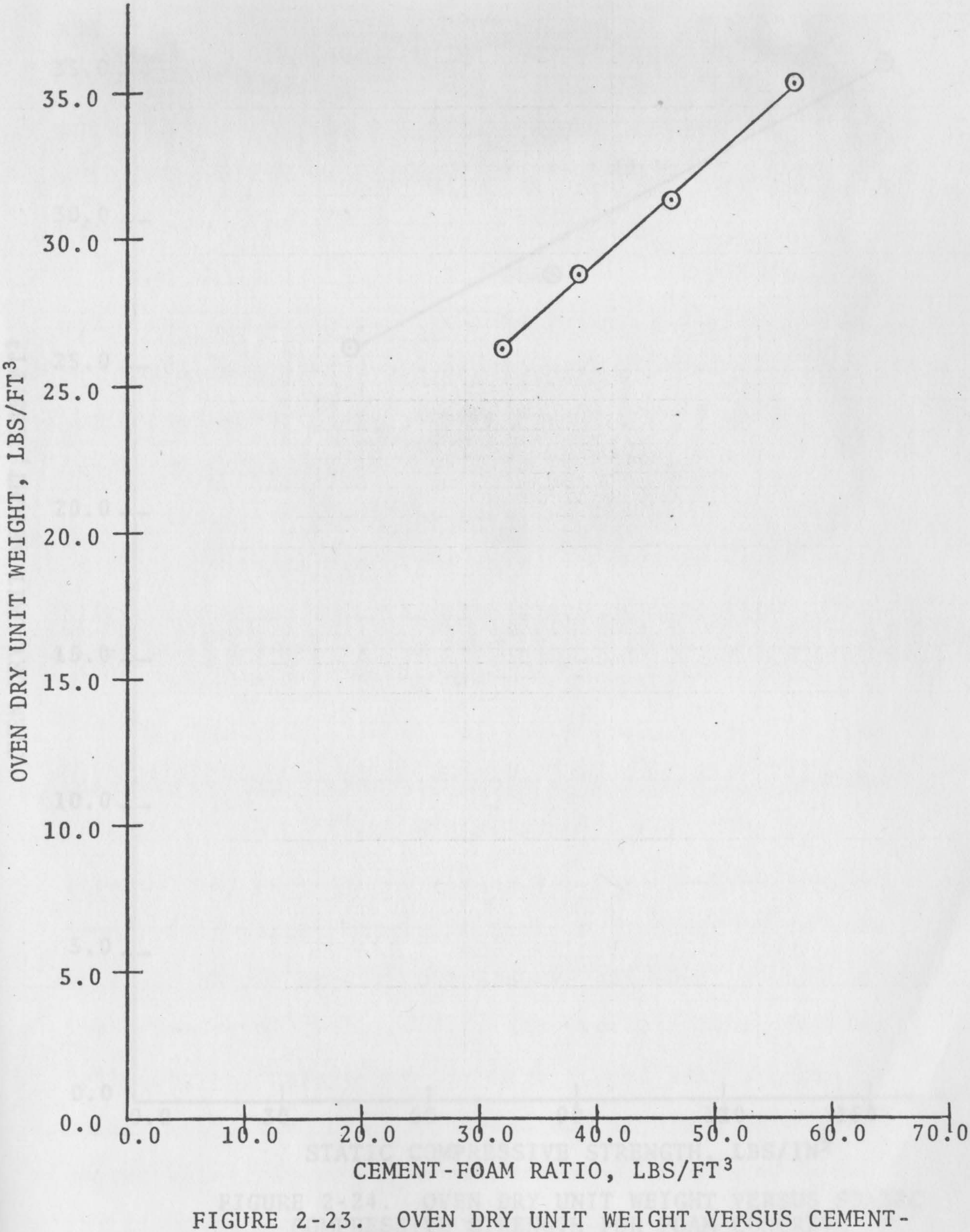


FIGURE 2-23. OVEN DRY UNIT WEIGHT VERSUS CEMENT-FOAM RATIO FOR FOAM CONCRETE

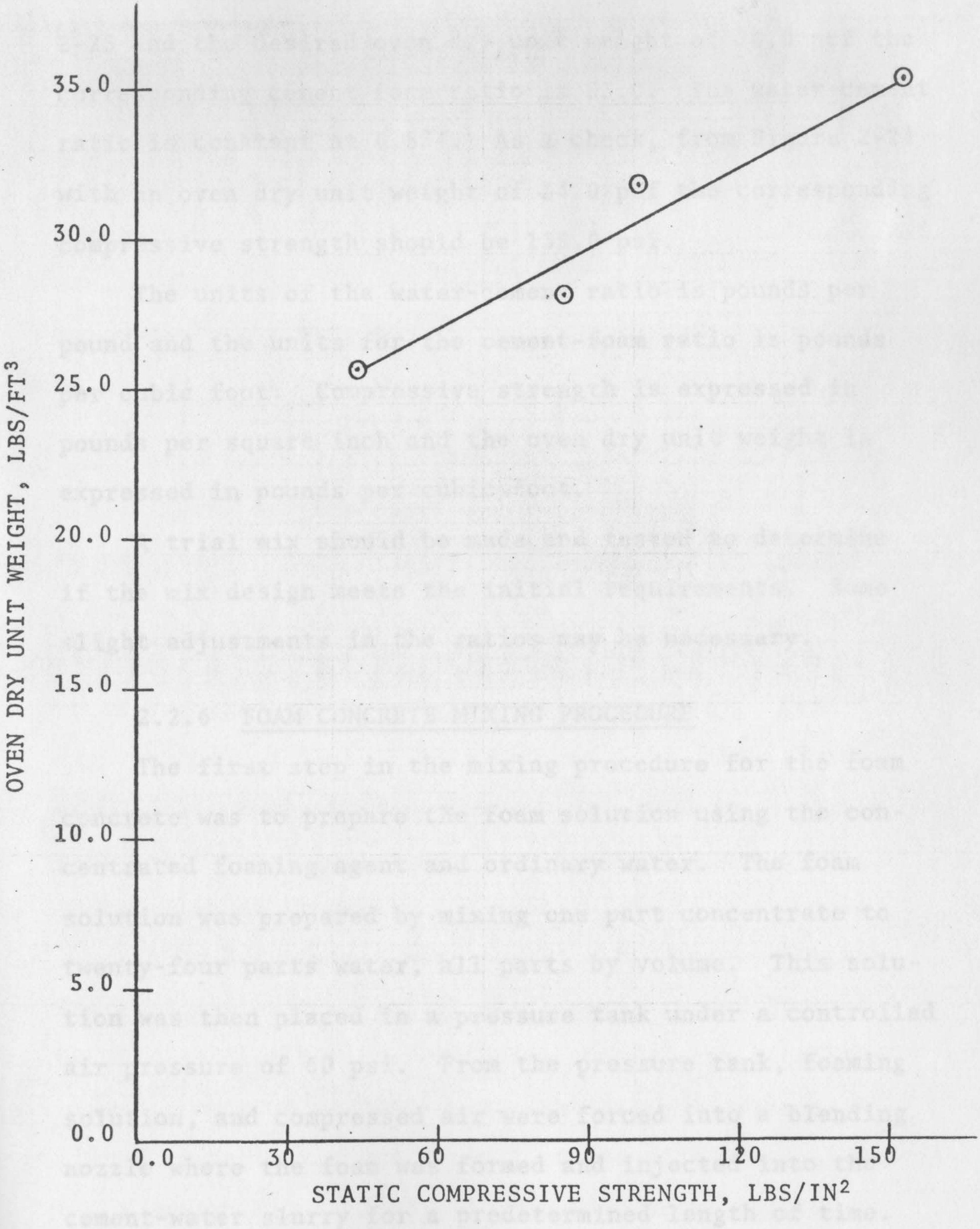


FIGURE 2-24. OVEN DRY UNIT WEIGHT VERSUS STATIC COMPRESSIVE STRENGTH FOR FOAM CONCRETE

2-23 and the desired oven dry unit weight of 34.0 pcf the corresponding cement-foam ratio is 53.0. The water-cement ratio is constant at 0.534. As a check, from Figure 2-24 with an oven dry unit weight of 34.0 pcf the corresponding compressive strength should be 135.0 psi.

The units of the water-cement ratio is pounds per pound and the units for the cement-foam ratio is pounds per cubic foot. Compressive strength is expressed in pounds per square inch and the oven dry unit weight is expressed in pounds per cubic foot.

A trial mix should be made and tested to determine if the mix design meets the initial requirements. Some slight adjustments in the ratios may be necessary.

2.2.6 FOAM CONCRETE MIXING PROCEDURE

The first step in the mixing procedure for the foam concrete was to prepare the foam solution using the concentrated foaming agent and ordinary water. The foam solution was prepared by mixing one part concentrate to twenty-four parts water, all parts by volume. This solution was then placed in a pressure tank under a controlled air pressure of 60 psi. From the pressure tank, foaming solution, and compressed air were forced into a blending nozzle where the foam was formed and injected into the cement-water slurry for a predetermined length of time. The blending nozzle was calibrated to deliver 3.9 ft^3

of foam per minute which thus established the time frame of the foam injections.

In preparing the actual foam concrete, all the water and cement were placed in the mixer and mixed for one minute. Next, the foam was injected into the cement-water slurry and mixing was continued for an additional minute to complete the mixture.

2.2.7 POLYSTYRENE CONCRETE MIXES

The polystyrene concrete constituents used in this project were supplied by the Koppers Company of Pittsburgh, Pennsylvania. Koppers owns the rights to this particular concrete and markets it under the trade name of Dycon. The advantage in using Koppers' polystyrene concrete is that no segregation of the polystyrene beads occur. Hoff(14) experienced problems of this nature, i.e., the polystyrene beads floated to the top of his cast specimens, thereby yielding a non-homogeneous mix. Koppers' mix has an additive which prevents this problem.

Three Dycon mixes were supplied by Koppers Company. The oven dry unit weight of these mixes ranged from 18.9 to 26.8 pcf and the corresponding compressive strengths ranged from 89.6 to 236.3 psi. The mix proportions are listed in Table 2.4 and typical static stress-strain curves are shown in Figure 2-25. A magnified cross section of Dycon concrete is shown in Figure 2-26.

TABLE 2.4

DYCON MIX PROPORTIONS AND PROPERTIES

Mix Designation Number	Cement Lbs.	Water Lbs.	Dylite Ft^3	Batch Yield Ft^3/Bag Cement	Fresh Unit Weight Lb/Ft^3	Percent Air %	Average Oven Dry Unit Wt. Lb/Ft^3	Average Compressive Strength Lb/In^2
D1	28.0	12.5	0.9	3.9	34.9	54.3	26.8	236.3
D2	13.0	7.5	0.5	4.9	31.1	56.0	23.3	159.9
D3	10.4	7.0	0.5	5.9	27.2	57.9	18.9	89.6

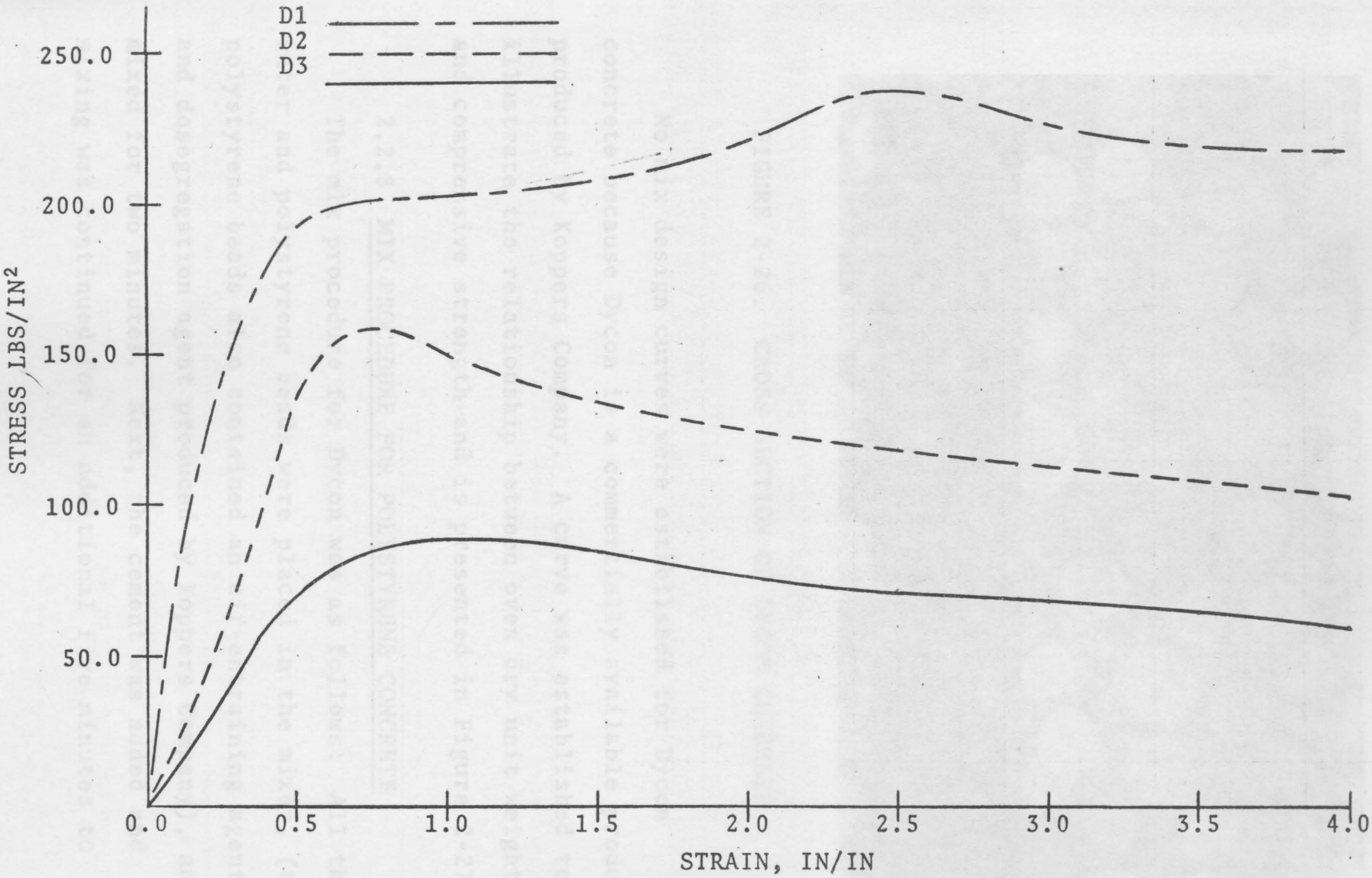


FIGURE 2-25. TYPICAL STATIC STRESS-STRAIN CURVES FOR DYCON CONCRETE

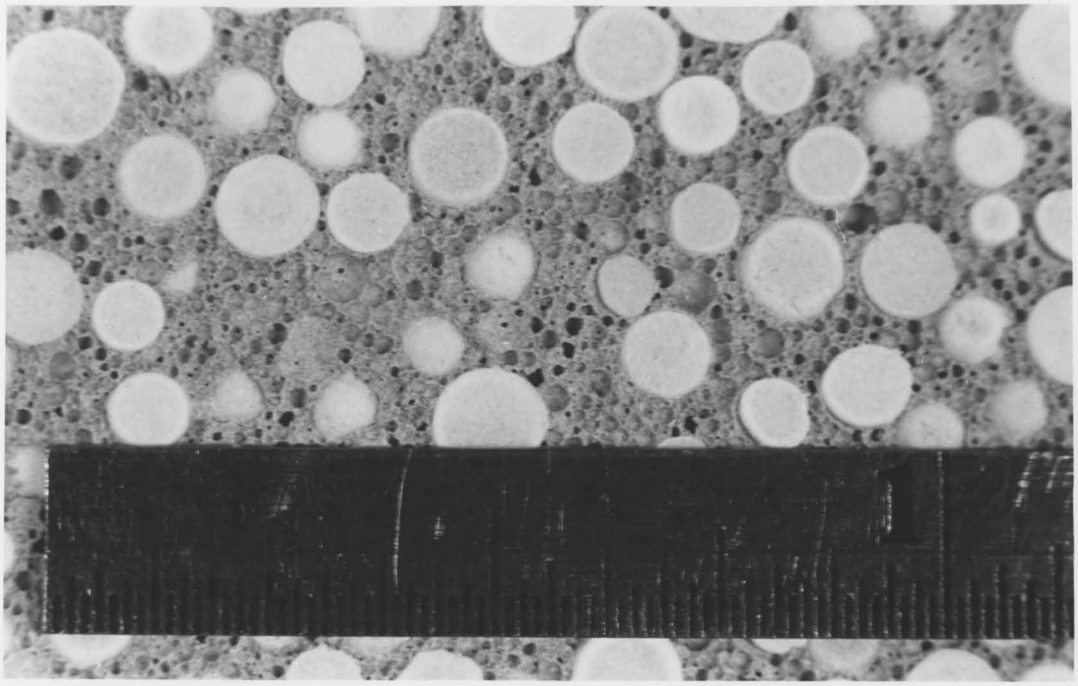


FIGURE 2-26. CROSS SECTION OF DYCON CONCRETE

No mix design curves were established for Dycon concrete because Dycon is a commercially available product produced by Koppers Company. A curve was established to illustrate the relationship between oven dry unit weight and compressive strength and is presented in Figure 2-27.

2.2.8 MIX PROCEDURE FOR POLYSTYRENE CONCRETE

The mix procedure for Dycon was as follows: All the water and polystyrene beads were placed in the mixer, (the polystyrene beads also contained an air-entraining agent and desegregation agent produced by Koppers Company), and mixed for two minutes. Next, the cement was added and mixing was continued for an additional five minutes to

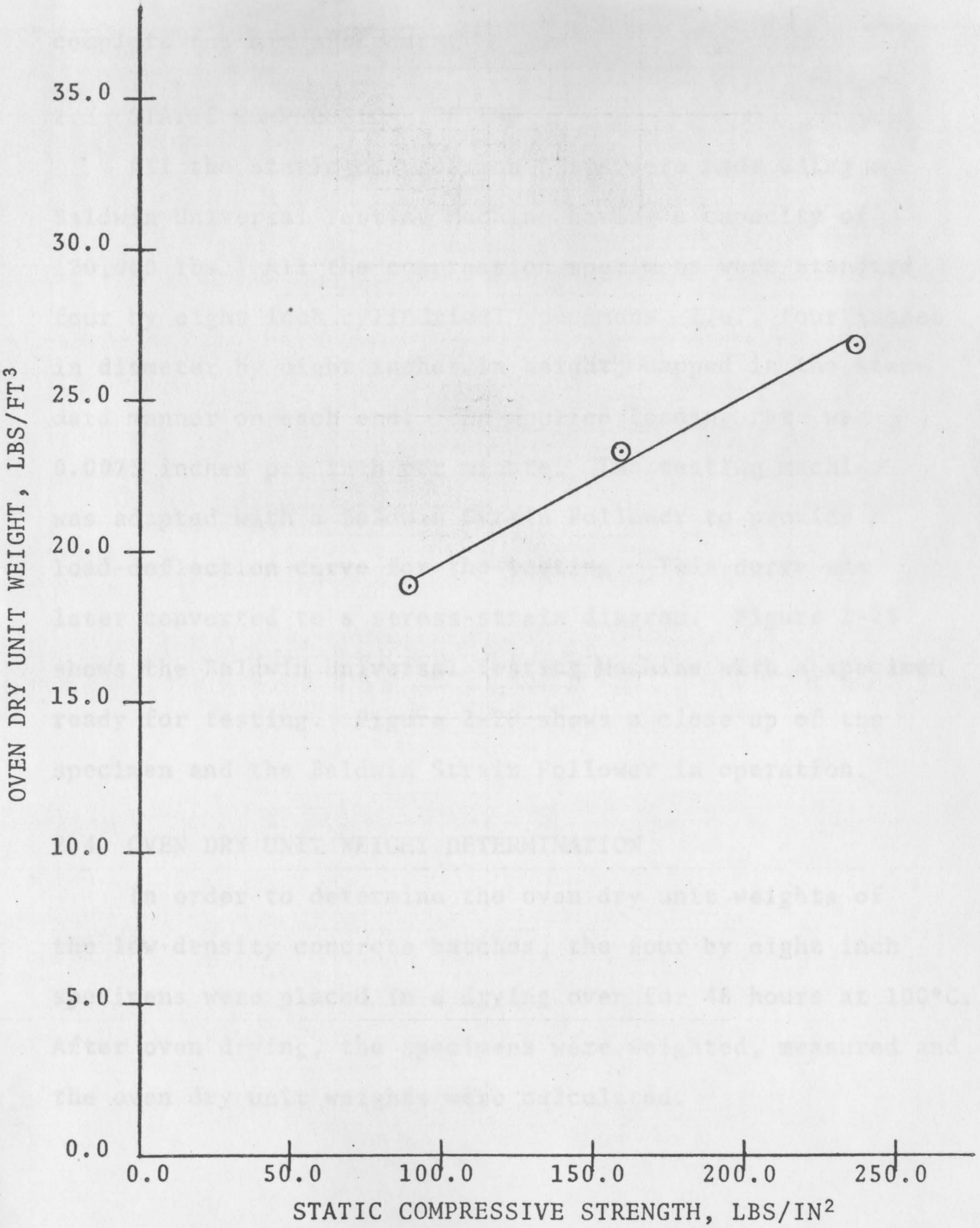


FIGURE 2-27. OVEN DRY UNIT WEIGHT VERSUS STATIC COMPRESSIVE STRENGTH FOR DYCON CONCRETE

complete the mix procedure.

2.3 STATIC COMPRESSION TESTING

All the static compression tests were made using a Baldwin Universal Testing Machine having a capacity of 120,000 lbs. All the compression specimens were standard four by eight inch cylindrical specimens, i.e., four inches in diameter by eight inches in height, capped in the standard manner on each end. The applied loading rate was 0.0075 inches per inch per minute. The testing machine was adapted with a Baldwin Strain Follower to provide a load-deflection curve for the testing. This curve was later converted to a stress-strain diagram. Figure 2-28 shows the Baldwin Universal Testing Machine with a specimen ready for testing. Figure 2-29 shows a close up of the specimen and the Baldwin Strain Follower in operation.

2.4 OVEN DRY UNIT WEIGHT DETERMINATION

In order to determine the oven dry unit weights of the low-density concrete batches, the four by eight inch specimens were placed in a drying oven for 48 hours at 100°C. After oven drying, the specimens were weighted, measured and the oven dry unit weights were calculated.

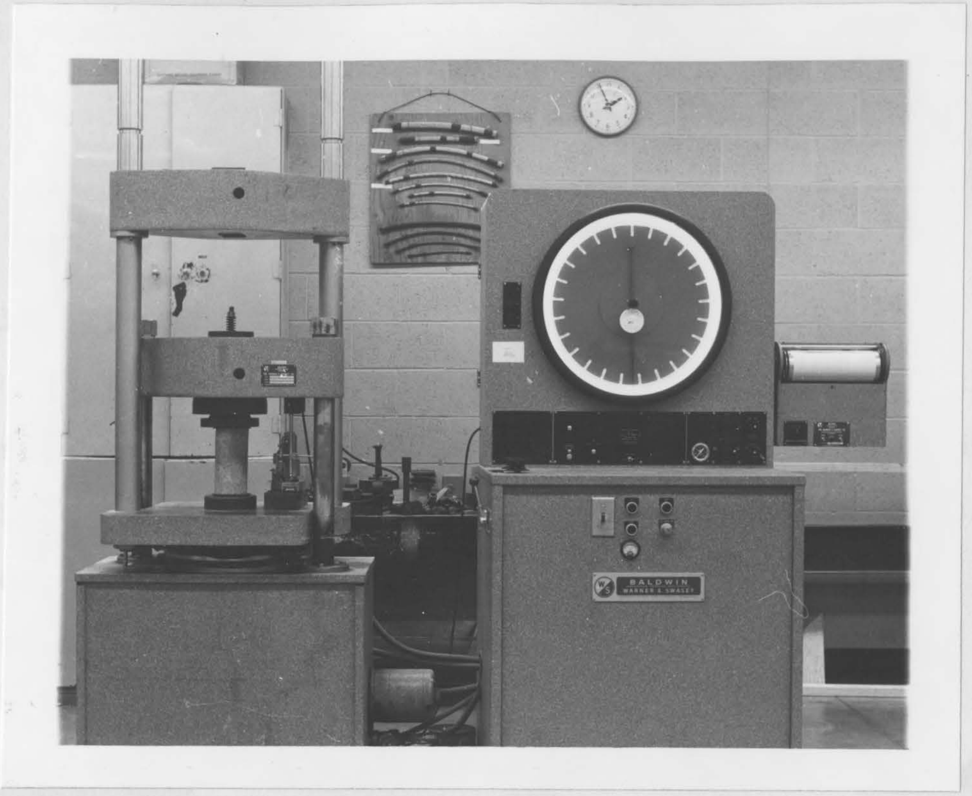


FIGURE 2-28. BALDWIN
UNIVERSAL TESTING MACHINE

FIGURE 2-29. BALDWIN
STRAIN FOLLOWER

CHAPTER III

FREEZE-THAW TESTING PROCEDURES

3.1 FREEZE-THAW SPECIMENS

The test specimens used throughout the freeze-thaw tests were 15 inches long and their cross section measured 3 inches square. Some typical freeze-thaw specimens can be seen in Figure 3-1.

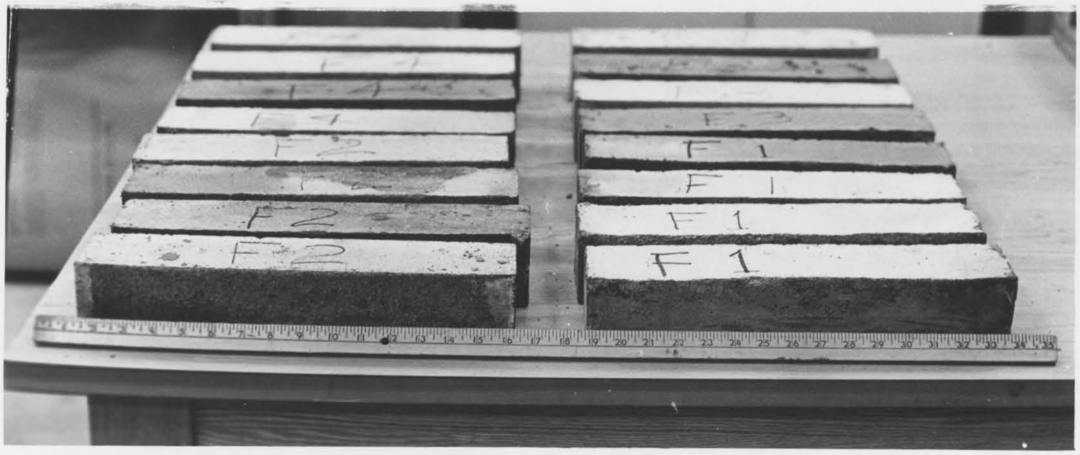


FIGURE 3-1. FREEZE-THAW SPECIMENS

This rectangular prism shaped specimen met with the requirements of ASTM Designation: C 290-67, Resistance of Concrete Specimens to Rapid Freezing and Thawing in Water. (ASTM Designation: C 290-67 test specifications are presented in Section 3-2 of this report.) The length-to-width ratio of the specimens satisfied the requirements of ASTM Designation: C 215-60, Test of Fundamental Transverse, Longitudinal, and Torsional Frequencies of Concrete Specimens. (ASTM Designation: C 215-60 test specifications are presented in Section 3-3 of this report.)

Molds for the freeze-thaw specimens were constructed from a resin coated plywood material which made it possible to reuse the molds. The various sections of the molds were fastened together by bolts to expedite assembly and disassembly of the molds. The interior of the molds were covered with a thin layer of heavy grease to ease the separation of the molds from the cast specimens and also to provide water proofing for the molds, thereby preventing any loss of water during curing. A typical specimen mold is shown in Figure 3-2.

3.2 FREEZE-THAW TEST PROCEDURE

Currently only two procedures are specified by ASTM for conducting freeze-thaw testing of concrete, ASTM Designation: C 290-67, Resistance of Concrete Specimens to Rapid Freezing and Thawing in Water, and ASTM Designation C 291-67, Resistance of Concrete Specimens to Rapid Freezing in Air and Thawing in Water. The freezing and thawing in water procedure is usually more severe, causing scaling of most normal concrete by 100 cycles.(3) Because of this increased severity and due to the climatic conditions in the

FIGURE 3-2. FREEZE-THAW SPECIMEN MOLD

anticipated area of implementation, i.e., Ohio, ASTM Designation: C 290-67 was selected as the study test procedure. ASTM Designation: C 290-67 test procedure specifies that the freeze-thaw apparatus must contain suitable chambers in which the test specimens may be subjected to a freeze-thaw cycle. Also, the freeze-thaw apparatus must have refrigerating and heating equipment with automatic controls, thereby permitting the concrete specimens to be cycled within the specified temperature limits. It is also required that specimens be completely surrounded by approximately 1/8 inch of fresh water at all times while they are being subjected to the freeze-thaw cycles. The difference in temperature of the specimen's interior and exterior must be no greater than 6°F except during the transition period between freezing and thawing and thawing and freezing. The temperature measuring equipment must be capable of measuring temperatures at the center of the specimen to within ±2°F.

The dynamic testing procedure and apparatus used to determine the fundamental transverse frequencies of the specimens must conform to the ASTM Designation: C 215-60 test procedure which is described later in Section 3.3.

The normal freeze-thaw cycle starts by lowering the interior temperature of the specimens from 40°F to 0°F and then raising the interior temperature of the specimens from 0°F to 40°F. This constitutes one cycle. The time required for one cycle must not be less than two hours and not more than four hours, with not less than 25 percent of the time used for thawing. At the end of the cooling period, the center of the specimens must be at 0°F (±3°F) and at the end of the heating period the center of the specimen must be 40°F (±3°F). The difference between the temperature at the center of the specimens and the temperature at the surface of the specimens must not exceed 50°F. The test specimens must be rectangular prisms made and cured in accordance with ASTM Designation: C 192, Method of Making and Curing Concrete

Test Specimens in the Laboratory.

After the curing and before the freeze-thaw tests are started, the specimens must be weighted, measured, and the fundamental transverse frequency determined in accordance with ASTM Designation: C 215-60 test specifications.

The freeze-thaw tests are started by placing the specimens in the freeze-thaw apparatus at the end of a thaw period of a cycle. The specimens must be removed in a thawed condition at intervals no greater than 30 cycles of exposure to freezing and thawing. At these intervals, the fundamental natural frequency must be determined and the specimens must be weighted. Each time the specimens are tested for fundamental frequency a note should be made on any change in the visual appearance of the specimens. The freeze-thaw tests should be terminated when the relative dynamic modulus of elasticity of a specimen reaches 60 percent of its initial relative dynamic modulus of elasticity or after 300 cycles of exposure to freezing and thawing, whichever comes first. It should be emphasized that these specifications are for normal weight concrete specimens and thus, are not necessarily mandatory for low-density concretes which have no freeze-thaw testing guidelines.

The freeze-thaw apparatus used in this study was built in accordance with the specifications of ASTM Designation: C 290-67 previously discussed. The freeze-thaw apparatus contained 18 copper specimen chambers with one chamber to be utilized by a control specimen. Thermocouples were installed in the center of the control specimen to record the interior temperature of the control specimen and also to operate the automatic temperature control system. A seven day recorder monitored the temperature as a function of time for the interior of the control specimen. The automatic temperature control system simultaneously turned the heating system off and the refrigeration system on at the beginning of a cooling period and turned the refrigeration system off and the heating system on at the beginning of a heating period. Temperatures at which the heating and cooling periods began could be varied by adjustment of the automatic temperature control system. Also incorporated in the automatic temperature control system was a heat limit unit which limited the exterior temperature of the specimens.

The freeze-thaw apparatus is shown in Figure 3-3 and the copper specimen chambers are shown in Figure 3-5. The automatic temperature control system along with the seven day temperature recorder is shown in Figure 3-4.

In calibrating the automatic temperature control systems, several trial freeze-thaw tests were run. It became evident that because of the thermal insulating properties inherent to the low-density concretes, the time for one freeze-thaw cycle, as specified in ASTM Designation: 290-67 to be two to four hours, had to be extended to six to eight hours. A typical seven day temperature chart, as recorded

FIGURE 3-3. THE FREEZE-THAW APPARATUS

FIGURE 3-4. THE AUTOMATIC TEMPERATURE CONTROL SYSTEM FOR THE FREEZE-THAW APPARATUS

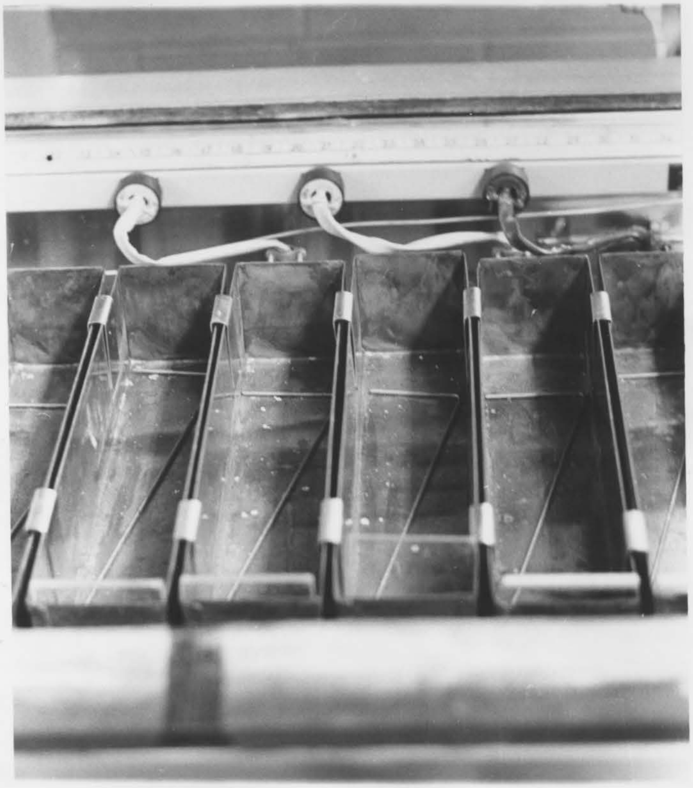


FIGURE 3-5. COPPER SPECIMEN CHAMBERS
IN THE FREEZE-THAW APPARATUS

by the seven day temperature recorder, is shown in Figure 3-6. Also from the trial freeze-thaw tests it was discovered that the air-dried, low-density concrete specimens absorb large quantities of water in the test chamber in a relatively short period of time. Because of the large amount of water absorption in the specimens, the fundamental transverse frequency of the specimens was greatly effected due to the water absorption and not the freeze-thaw cycling. To minimize the effect of water absorption, the freeze-thaw test specimens were submerged in water for 48 hours.

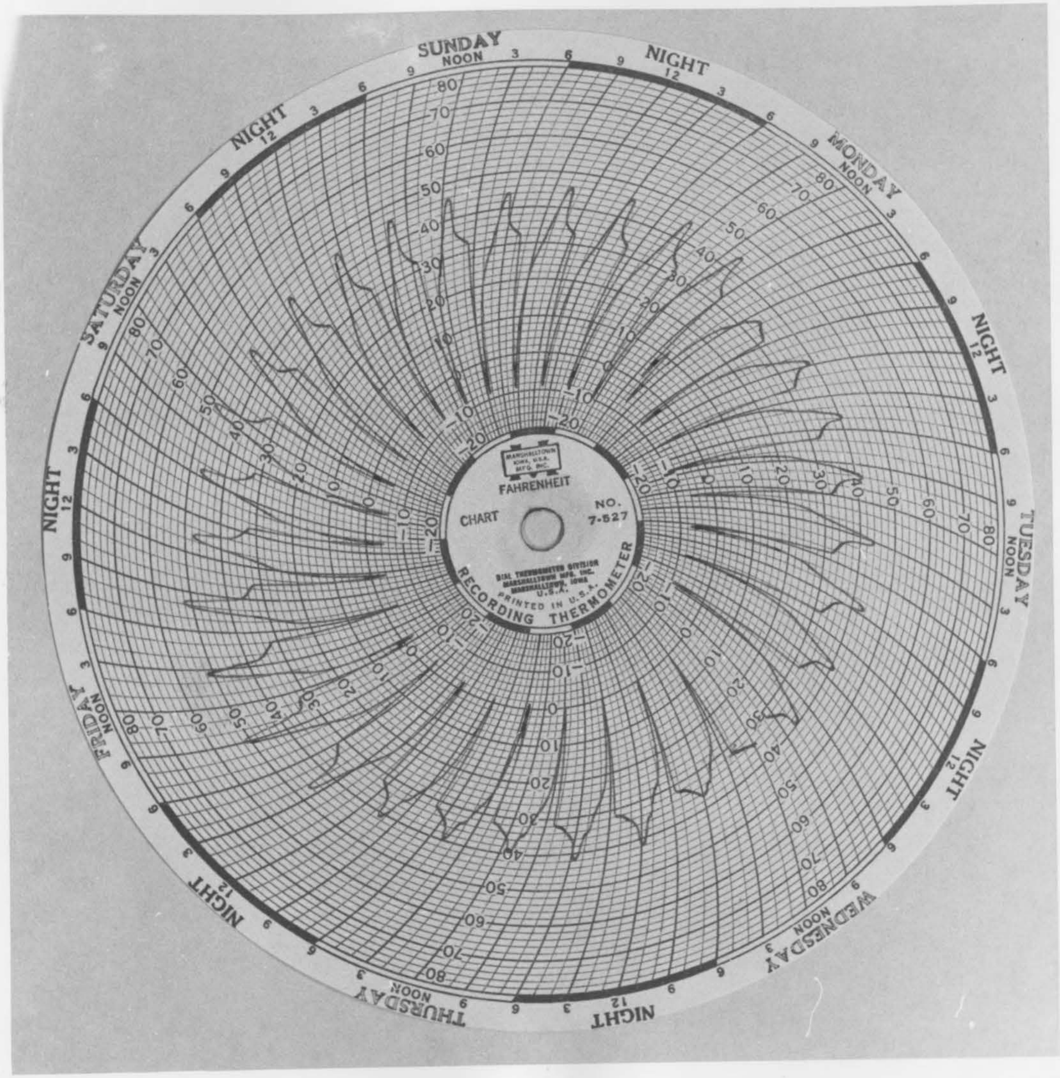


FIGURE 3-6. TYPICAL SEVEN DAY TEMPERATURE RECORD

After being submerged for this period of time, the specimens were weighted and their fundamental transverse frequency was determined. The freeze-thaw specimens were then immediately placed in the freeze-thaw apparatus and the freeze-thaw tests were started. The freeze-thaw specimens were tested for their fundamental transverse frequency at intervals of approximately 20 cycles of exposure to freezing and thawing.

3.3 NONDESTRUCTIVE TESTING

Since it is not practical to fabricate sufficient specimens to define properly the relationship between strength loss and cycles of exposure to freezing and thawing by destructive testing, a nondestructive test or dynamic test is used periodically during the freeze-thaw test to determine the strength loss of the specimens. This nondestructive test, ASTM Designation: C 215-60, Fundamental Transverse, Longitudinal, and Torsional Frequencies of Concrete Specimens, is accomplished by vibrating the specimen and determining its fundamental frequency. The percent strength loss can then be determined by the relationship

$$E = kf^2 \qquad (3\text{-}1)$$

where

E = modulus of elasticity, assumed to vary linearly with strength

f = fundamental frequency

k = constant depending on the dimensions and weight of the specimen and on the type of material tested

This equation relates the fundamental frequency to the modulus of elasticity which is assumed to vary linearly with the strength of the specimen. Thus, the percent strength loss after any given cycle can be calculated by (3)

$$\%E_x = \frac{f_x{}^2}{f_o{}^2} \times 100\% \qquad (3\text{-}2)$$

where

E_x = modulus of elasticity at x cycles

f_x = fundamental frequency at x cycles

f_o = fundamental frequency at zero cycles

It should be noted that the freeze-thaw cycling has a detrimental effect on the strength of the specimens. With increasing cycles of freezing and thawing, the fundamental frequency decreases and therefore, its strength decreases. Thus, by examining Equation 3-2 it is evident that the percent loss of strength will always be less than 100% which means there will be a net decrease in strength.

The procedure used to determine the fundamental transverse frequency of the freeze-thaw specimens is specified in ASTM Designation: C 215-60. This test procedure states that the apparatus for this test must consist of a driving circuit, a pickup circuit, and a specimen support system. The driver circuit must consist of a variable frequency audio oscillator, an amplifier, and a driving unit. The oscillator must be calibrated to read within ±2 percent of the true frequency over the range of use, and the combined oscillator and amplifier must have sufficient power output to vibrate the test specimen at frequencies other than the fundamental frequency. The driving unit must be capable of creating the vibration in the specimen and should be capable of handling the full power output of the oscillator and amplifier. Furthermore, the pickup circuit must consist of a pickup unit, an amplifier, and an indicator. The pickup unit must generate a voltage proportional to the amplitude of the vibrating test specimen. The amplifier must have a controllable output of sufficient magnitude to activate the indicator and the indicator must be a voltmeter, a milliammeter, or an oscilloscope. The specimen support system must also permit the specimen to vibrate without significant restraint. In this study, the specimen was supported by two thin wires located at the nodal points of the specimen, i.e., 0.224 times the length of the specimen measured from each end of the specimen. The nodal points are two points on the specimen that do not translate when the specimen is vibrating at its fundamental transverse frequency. Figure 3-7 shows a drawing of a specimen supported at its nodal points vibrating at its fundamental transverse frequency.

The specification dictating specimen shape specifies that the ratio of the length-to-maximum-transverse-dimension should be between three and five.

The nondestructive testing apparatus used in this study is shown in Figure 3-8. This apparatus was equipped with a digital frequency counter which determined the frequency of vibration of the specimen to the tolerances required by ASTM Designation C 215-60. The driver unit was equipped with a probe which made contact with the specimen and

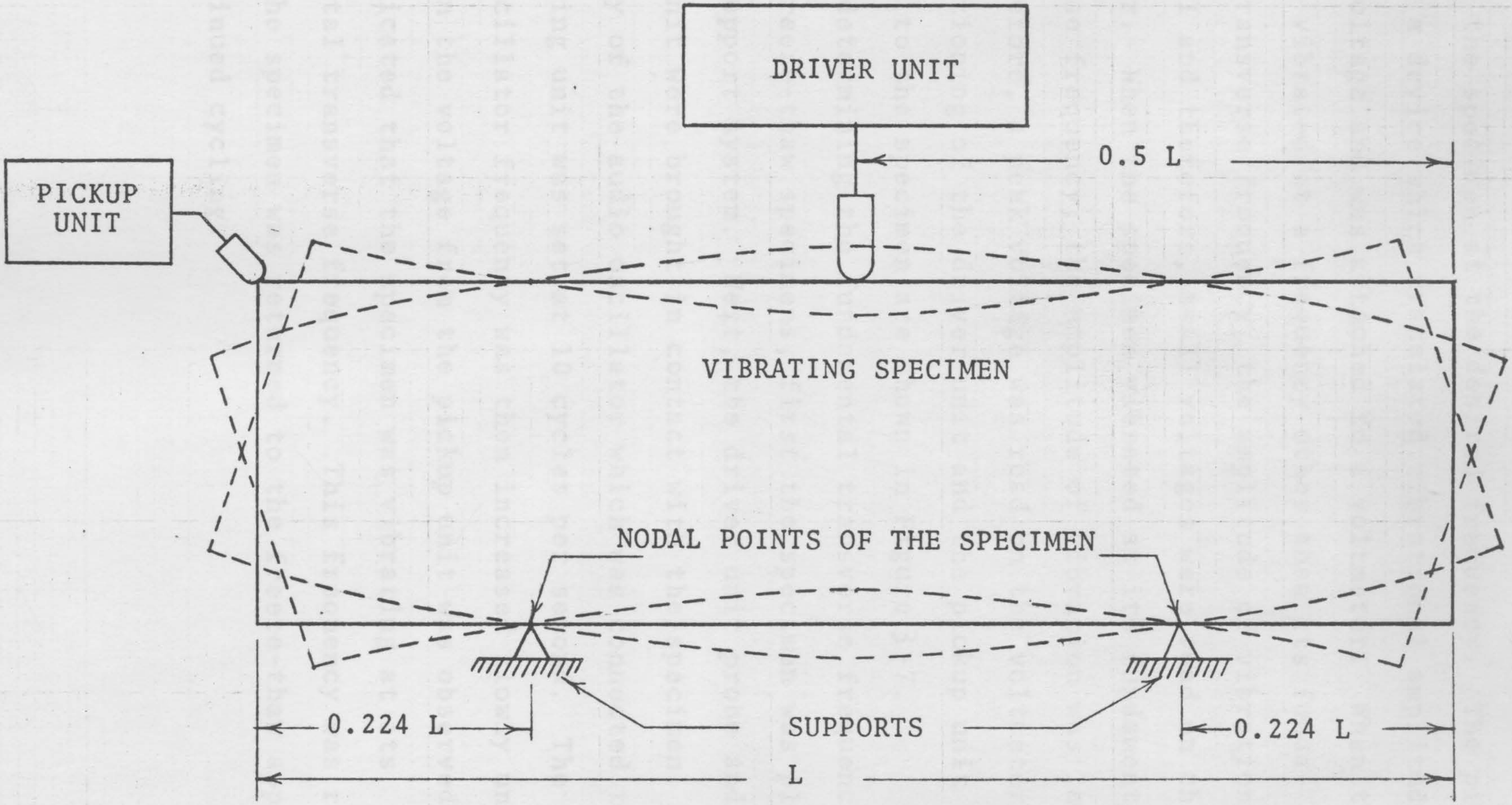


FIGURE 3-7. VIBRATIONAL MODE FOR THE FUNDAMENTAL TRANSVERSE FREQUENCY OF A FREEZE-THAW SPECIMEN

vibrated the specimen at the desired frequency. The pickup unit was a device which translated vibrational amplitude into a voltage and was attached to a voltmeter. When the specimen vibrated at a frequency other than its fundamental transverse frequency, the amplitude of vibration was small and therefore, small voltages were read on the voltmeter. When the specimen vibrated at its fundamental transverse frequency, the amplitude of vibration was large and therefore, a peak voltage was read on the voltmeter. The positioning of the driver unit and the pickup unit relative to the specimen are shown in Figure 3-7.

In determining the fundamental transverse frequency of the freeze-thaw specimens, first the specimen was placed on the support system. Next, the driver unit probe and pickup unit were brought in contact with the specimen. The frequency of the audio oscillator which was connected to the driving unit was set at 10 cycles per second. The audio oscillator frequency was then increased slowly until a peak in the voltage from the pickup unit was observed. This indicated that the specimen was vibrating at its fundamental transverse frequency. This frequency was recorded and the specimen was returned to the freeze-thaw apparatus for continued cycling.

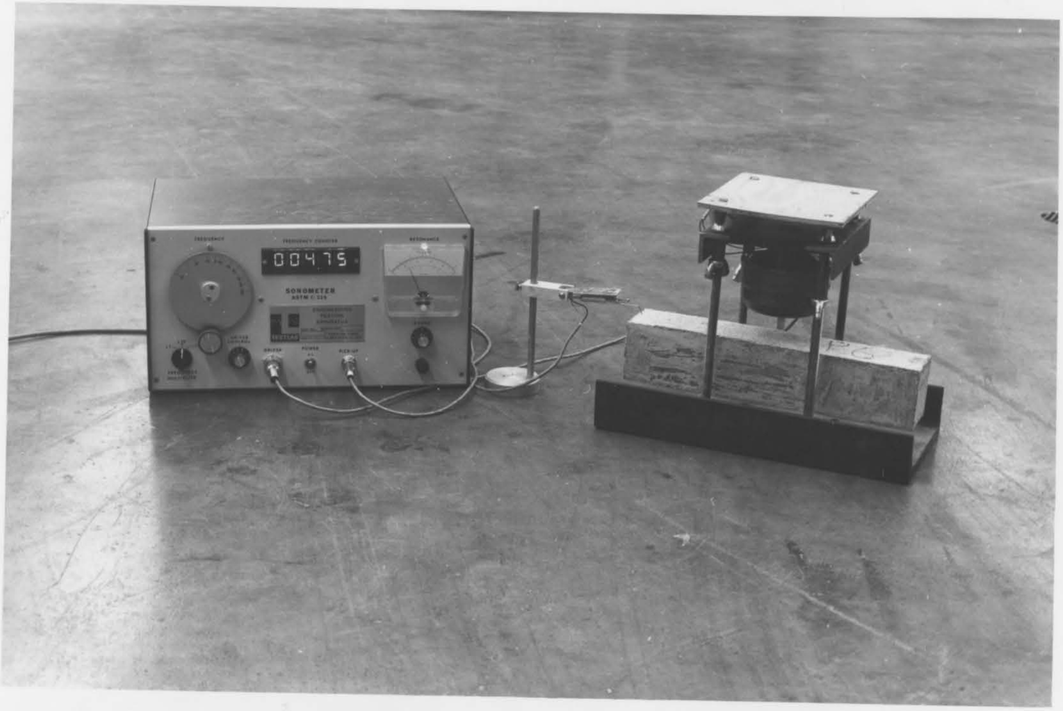


FIGURE 3-8. THE NONDESTRUCTIVE TESTING APPARATUS

CHAPTER IV

FREEZE-THAW TEST RESULTS AND DISCUSSION OF RESULTS

4.1 FREEZE-THAW TEST CRITERIA

The limits, set forth by ASTM Designation C 290-67 (ASTM Designation C 290-67 is described in Section 3-2), were adhered to in this investigation. Briefly, these limits are that the freeze-thaw testing should be terminated after 300 cycles of freezing and thawing or when the relative dynamic modulus of elasticity of the specimen reaches 60% of the initial relative dynamic modulus, whichever occurs first. This specification was originally designated for normal concrete (γ = 150 pcf) which has properties quite dissimilar from those of the low-density concretes investigated in this study. In addition, a structure built of normal concrete and exposed to a severe freezing and thawing environment would be required to have a longer life expectancy than an impact attenuator constructed from low-density concrete. (At this point it is assumed that there is a linear relationship between freeze-thaw cycles experienced in the laboratory and those experienced during a normal life expectancy.) If a structure built of normal concrete has a life expectancy of say 25 years and if the life expectancy of a highway impact attenuator is assumed to be about 5 years, a tentative ratio may be established as follows:

$$\frac{\text{Life Expectancy Of Attenuator}}{\text{Life Expectancy Of Structure}} = \frac{\text{Lab Cycles For Low-Density Concrete}}{\text{Lab Cycles For Normal Concrete}}$$

or

$$\frac{5}{25} = \frac{\text{X Cycles}}{300}$$

$$X = 60 \text{ Cycles}$$

Thus, if a low-density concrete specimen withstands 60 cycles of freezing and thawing in the laboratory test, a highway impact attenuator constructed of the same low-density concrete should have a life expectancy of 5 years. Therefore, the criterion thus established will be used in this study as the limiting values for the freeze-thaw tests, i.e., 60 cycles of freezing and thawing or when the relative dynamic modulus of elasticity reaches 60% of the initial relative dynamic modulus, whichever comes first. The relative dynamic modulus was previously calculated by Equation 3-2 and the durability factor of the test specimens was calculated by Equation 4-1 as

$$DF = \frac{E_X X}{M} \qquad (4-1)$$

where DF = durability of the test specimen

E_X = relative dynamic modulus of elasticity at x cycles of freezing and thawing calculated by Equation 3-2

X = number of cycles at which E_x reaches 60% of the initial relative dynamic modulus of elasticity (E_o) or 60 cycles, whichever occurs first

M = the specified number of cycles at which the freeze-thaw test is to be terminated (60 cycles)

4.2 TEST RESULTS

Three specimens made from each mix of low-density concrete investigated in this study (see Chapter 2) were tested for freeze-thaw effects. The results of the freeze-thaw tests are presented in Table 4-1. Graphs depicting the relationship of the average durability factor of the specimens to the oven dry unit weight of the specimens are presented in Figures 4-1, 4-2, 4-3, and 4-4 for the respective types of low-density concrete. Figures 4-5 and 4-6 show representative visual effects of the freezing and thawing cycles on the test specimens.

It was previously mentioned that a large amount of water was absorbed by the freeze-thaw specimens. In order to evaluate the effects of this water absorption on the durability of the specimens during the freeze-thaw tests, plots were drawn showing the relationship of the average durability factor to the average percent increase in weight (due to water absorption) for each mix. The percent increase in weight was calculated based on the initial air dry weight of each specimen and the weight of each specimen

TABLE 4-1

FREEZE-THAW TEST RESULTS

Mix Designation Number	Physical Condition At Termination Of Freeze-Thaw Test	Average Number Of Freeze-Thaw Cycles At Termination	Average Durability Factor
Perlite			
P4	Severe Spalling	22	22.0
P2	Severe Spalling	46	48.3
P10	Spalling	52	52.2
P6	Slight Spalling	60	70.3
Vermiculite			
V2	Spalling	17	17.0
V1	Spalling	25	24.6
V7	Spalling	60	67.3
Foam			
F1	Severe Spalling	23	22.6
F2	Severe Spalling	46	46.4
F3	Severe Spalling	55	54.6
F4	Spalling	58	69.3
Dycon			
D1	Slight Spalling	51	54.8
D2	Spalling	58	63.4
D3	Spalling	37	37.0

Slight Spalling was considered to be when small amounts of the surface of the specimen crumbled off.

Spalling was considered to be when considerable amounts of the surface of the specimen crumbled off.

Severe Spalling was considered to be when large amounts of the surface of the specimen crumbled off.

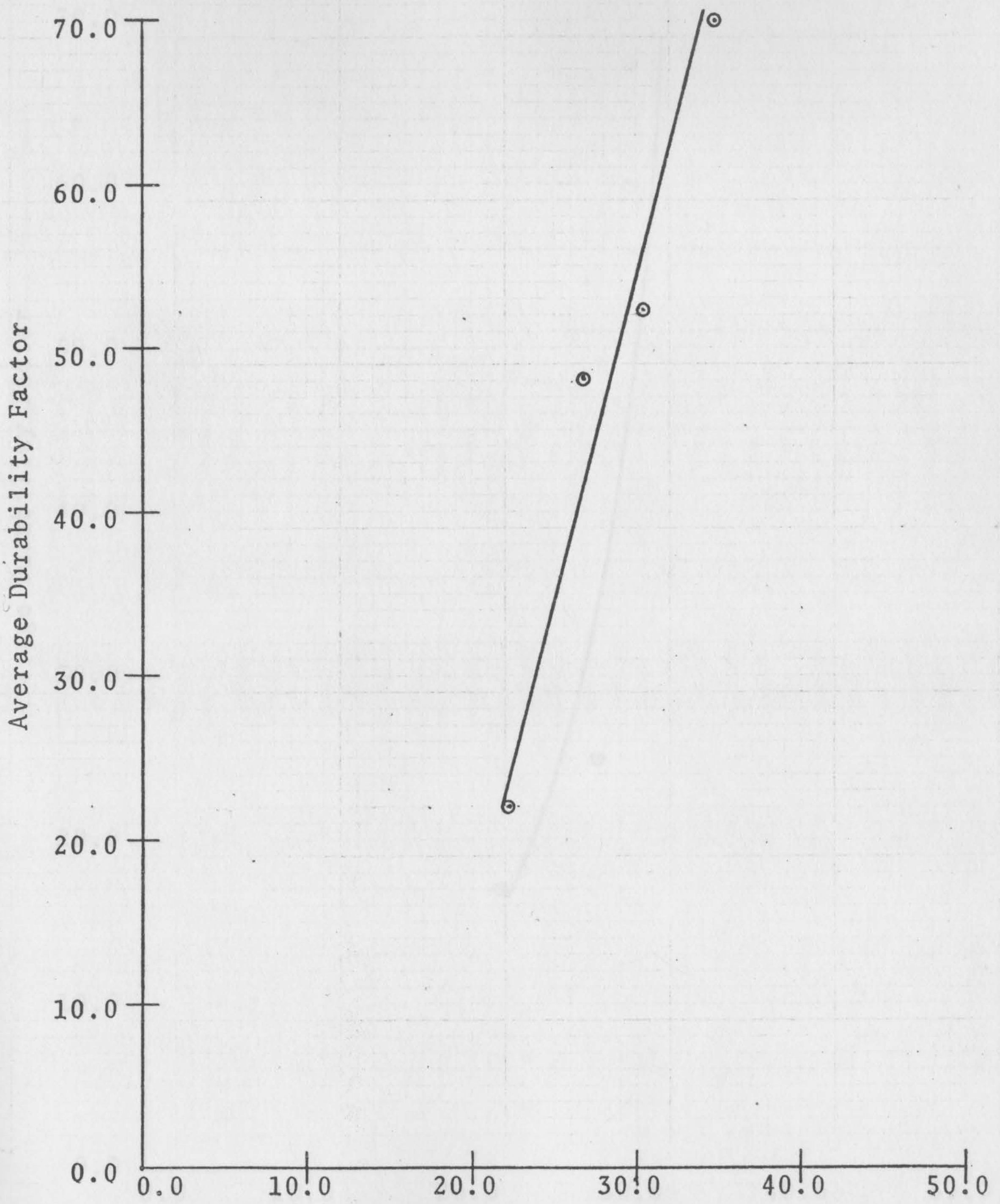


FIGURE 4-1. AVERAGE DURABILITY FACTOR VERSUS OVEN DRY UNIT WEIGHT FOR PERLITE CONCRETE

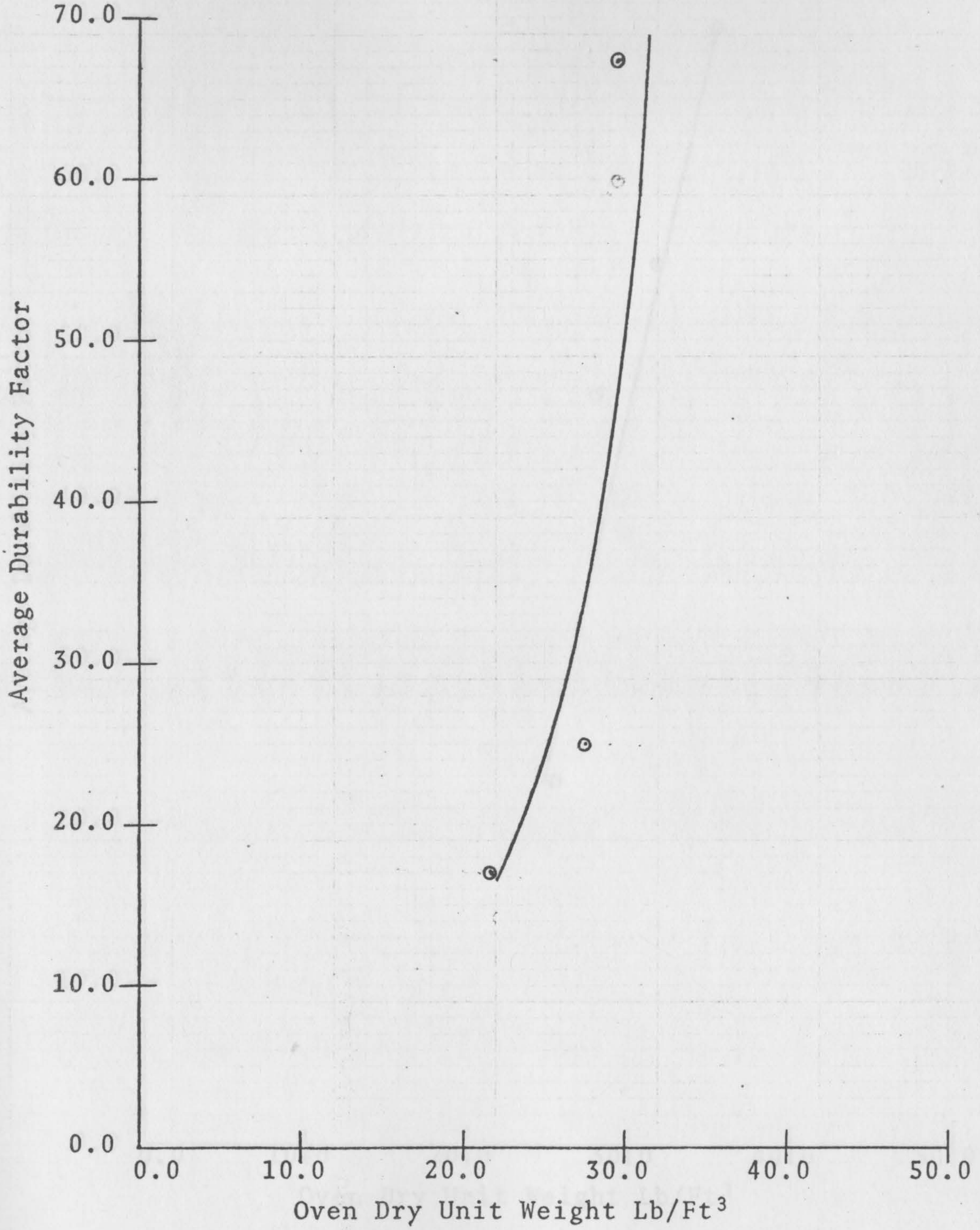


FIGURE 4-2. AVERAGE DURABILITY FACTOR VERSUS OVEN DRY UNIT WEIGHT FOR VERMICULITE CONCRETE

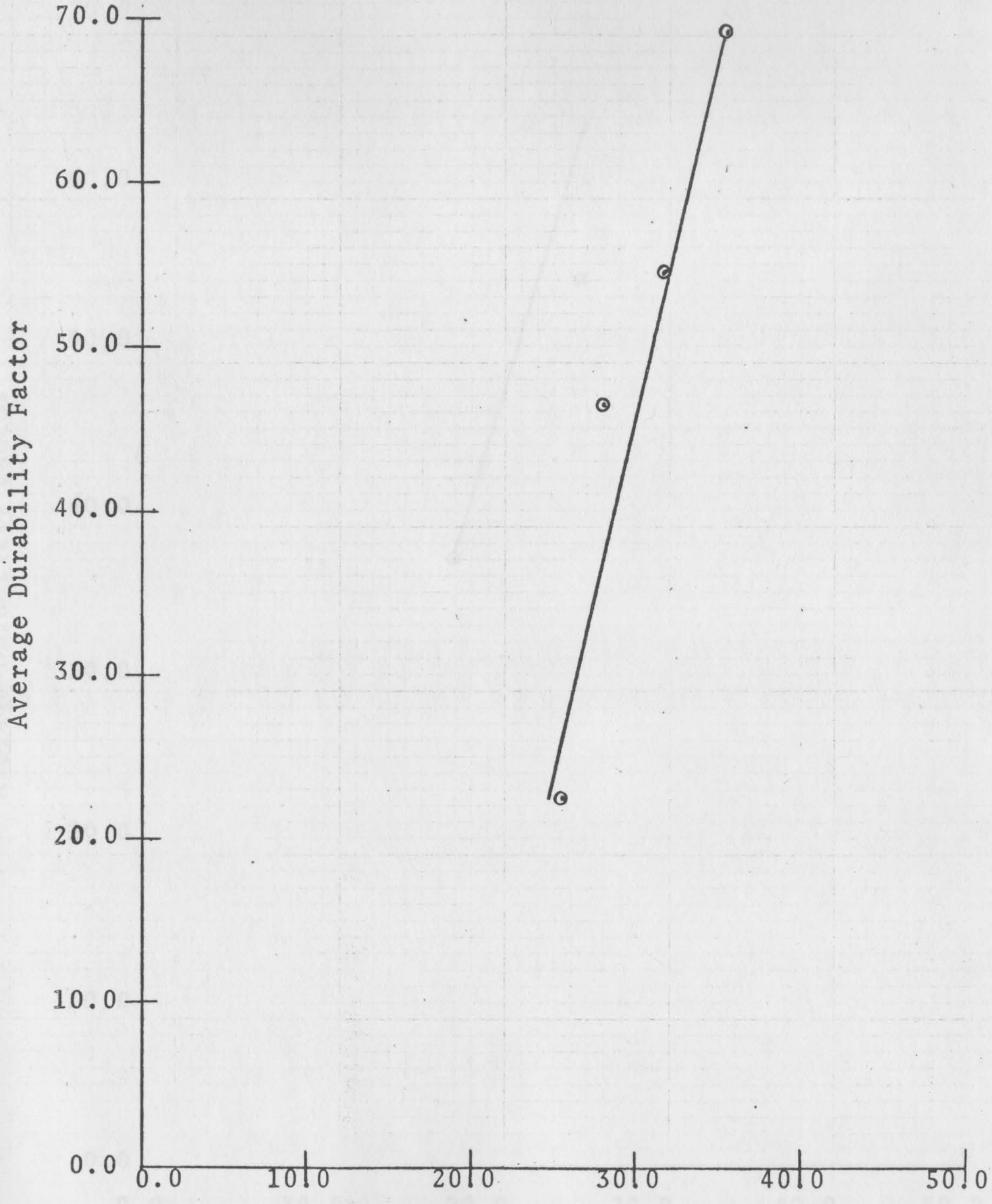


FIGURE 4-3. AVERAGE DURABILITY FACTOR VERSUS OVEN DRY UNIT WEIGHT FOR FOAM CONCRETE

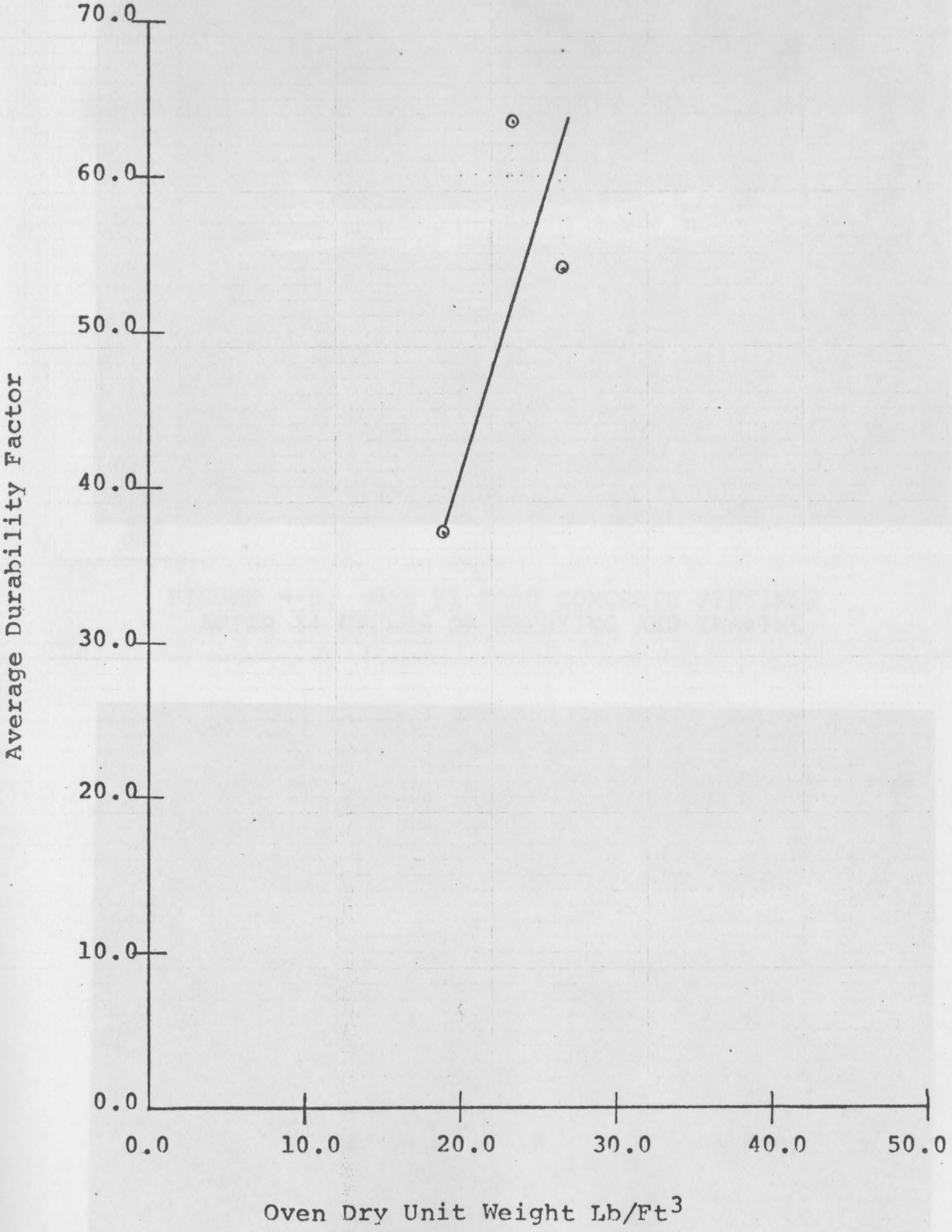


FIGURE 4-4. AVERAGE DURABILITY FACTOR VERSUS OVEN DRY UNIT WEIGHT FOR DYCON CONCRETE

FIGURE 4-5. MIX F1 FOAM CONCRETE SPECIMEN
AFTER 34 CYCLES OF FREEZING AND THAWING

FIGURE 4-6. MIX P6 PERLITE CONCRETE SPECIMEN
AFTER 104 CYCLES OF FREEZING AND THAWING

at the termination of the freeze-thaw tests. These graphs are presented in Figures 4-7, 4-8, 4-9, and 4-10. It should be noted that the actual percent increase in weight of the specimens would be slightly larger because of the reduction of weight of the specimen due to spalling after exposure to the cyclic freezing and thawing.

4.3 DISCUSSION OF FREEZE-THAW RESULTS

Historically it has been a very difficult task to relate the durability of a material in a freezing and thawing environment to freezing and thawing cycles produced in a laboratory. In the freeze-thaw test utilized in this study, the low-density specimens were submerged in water at all times but an impact attenuator constructed from this low-density concrete would not be continually submerged and would experience gravitational drainage. Also, an impact attenuator constructed from these low-density concretes would experience drying periods. This implies that the laboratory test for freeze-thaw durability is much more severe than the actual environment conditions. This is accounted for by limiting the number of laboratory freeze-thaw cycles, i.e., 300 cycles for normal concrete and 60 cycles (a tentative assumption) for low-density concretes.

The freeze-thaw tests indicate that the durability factor for the low-density concrete specimens is increased when the oven dry unit weight of the low-density concrete

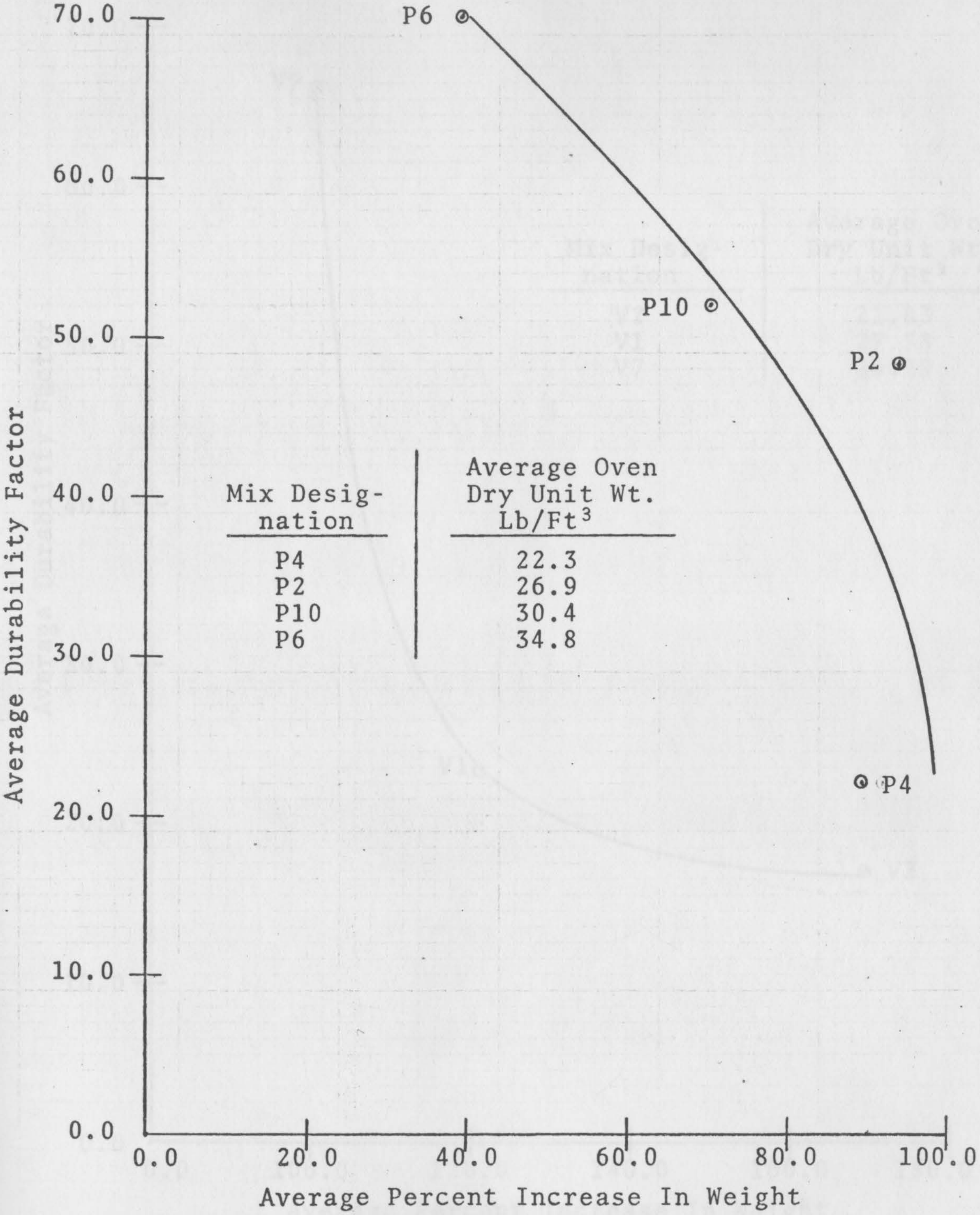
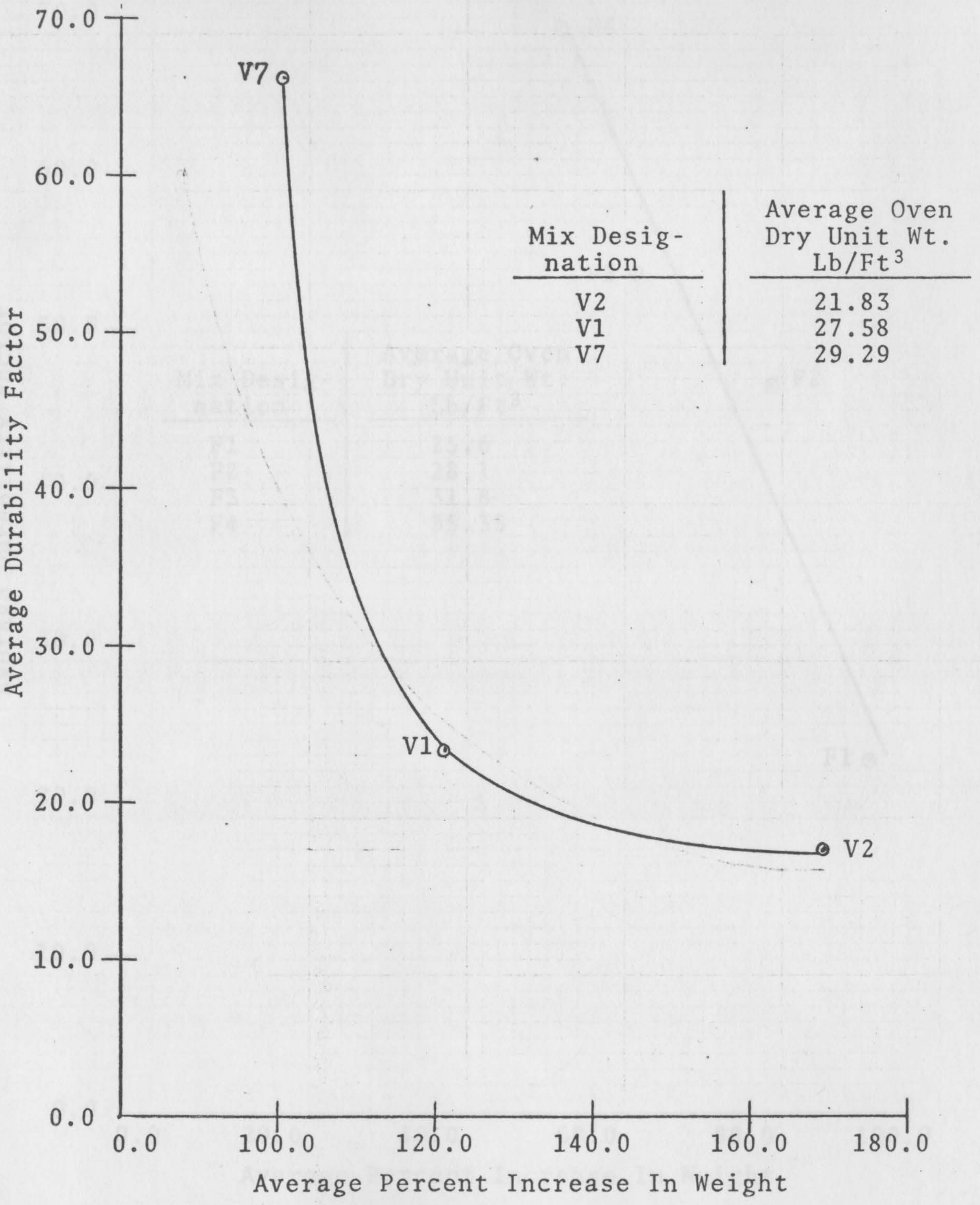


FIGURE 4-7. AVERAGE DURABILITY FACTOR VERSUS AVERAGE PERCENT INCREASE IN WEIGHT FOR PERLITE CONCRETE



Mix Designation	Average Oven Dry Unit Wt. Lb/Ft^3
V2	21.83
V1	27.58
V7	29.29

FIGURE 4-8. AVERAGE DURABILITY FACTOR VERSUS AVERAGE PERCENT INCREASE IN WEIGHT FOR VERMICULITE CONCRETE

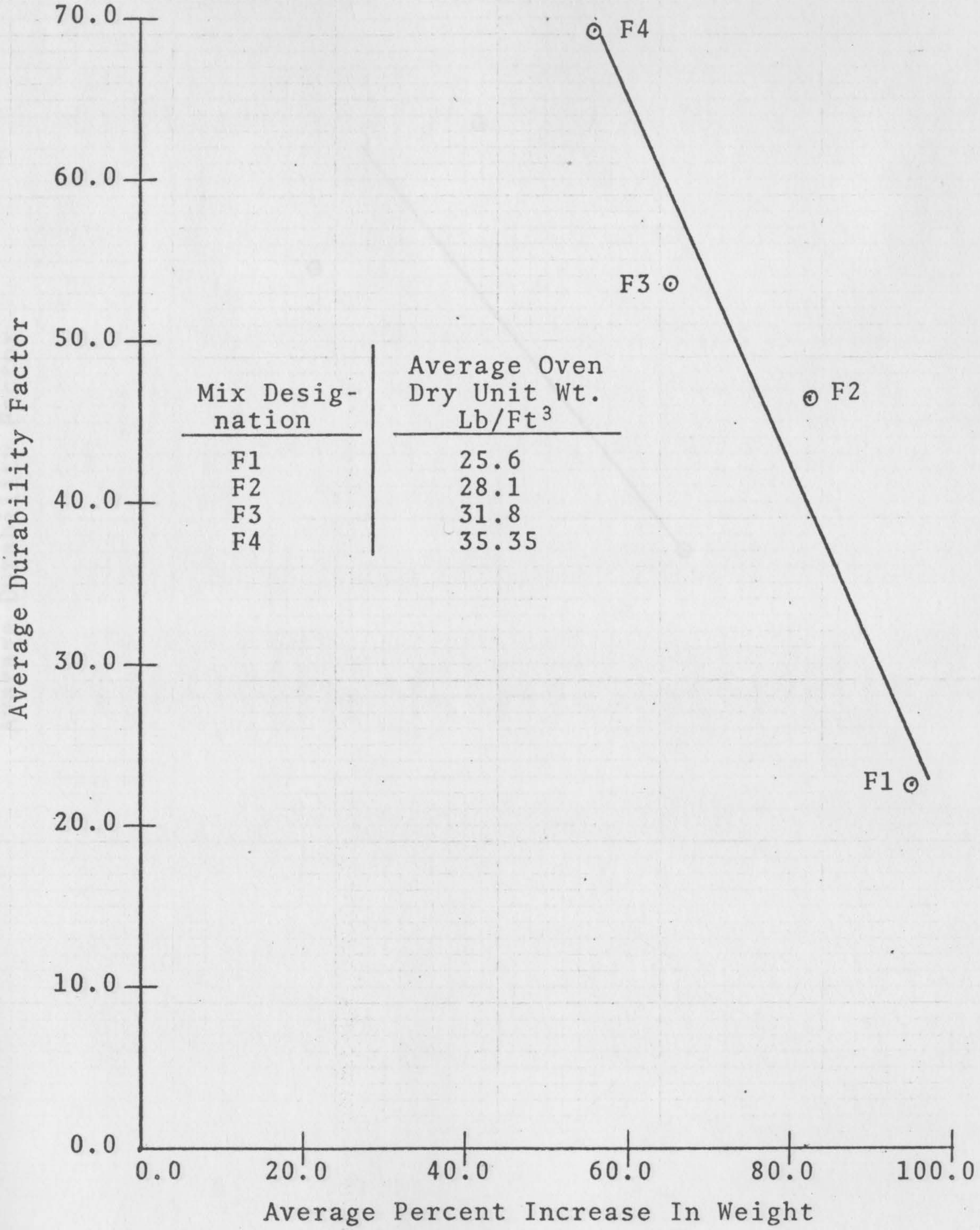


FIGURE 4-9. AVERAGE DURABILITY FACTOR VERSUS AVERAGE PERCENT INCREASE IN WEIGHT FOR FOAM CONCRETE

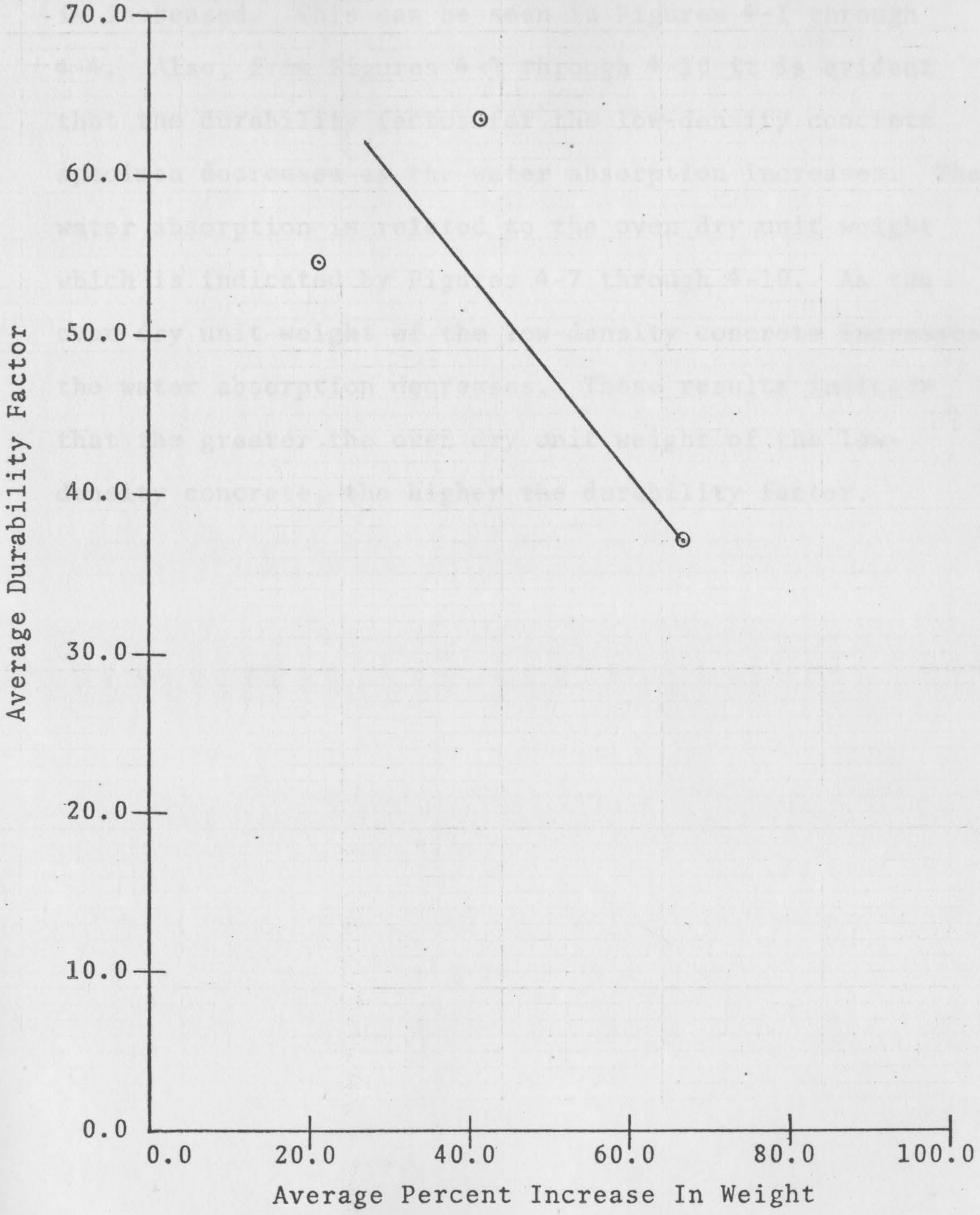


FIGURE 4-10. AVERAGE DURABILITY FACTOR VERSUS AVERAGE PERCENT INCREASE IN WEIGHT FOR DYCON CONCRETE

is increased. This can be seen in Figures 4-1 through 4-4. Also, from Figures 4-7 through 4-10 it is evident that the durability factor for the low-density concrete specimen decreases as the water absorption increases. The water absorption is related to the oven dry unit weight which is indicated by Figures 4-7 through 4-10. As the oven dry unit weight of the low-density concrete increases, the water absorption decreases. These results indicate that the greater the oven dry unit weight of the low-density concrete, the higher the durability factor.

CHAPTER V

CONCLUSIONS AND RECOMMENDATIONS

In order to evaluate the results of the freeze-thaw testing Table 5-1 was constructed. This table lists the various low-density concrete mixes in order of decreasing durability factor. (The higher the durability factor the better resistance severe weathering effects.)

TABLE 5-1

AVERAGE DURABILITY FACTORS FOR VARIOUS LOW-DENSITY CONCRETES

Mix Designation	Average Durability Factor
P6	70.3
F4	69.3
V7	67.3
D2	63.4
D1	54.8
F3	54.6
P10	52.2
P2	48.3
F2	46.4
D3	37.0
V1	24.6
F1	22.6
P4	22.0
V2	17.0

The ranking displayed in Table 5-1 indicates which low-density concrete mixtures are best suited for a severe freezing and thawing environment. This ranking is based on the freeze-thaw testing executed in the laboratory and using the assumed evaluation criteria set forth in Chapter 4.

Evaluating the data presented in Table 5-1, it is evident that all the low-density concrete mixes from Dycon 2, D2, to the top of the chart have a durability factor equal or greater than 60. This means that freezing and thawing cycles had minimal effect on these low-density concretes based on the criteria established in Chapter 4. Therefore, these mixes P6, F4, V7, and D2 would be adequate for use in the construction of impact attenuators exposed to a severe freezing and thawing environment.

Reconsidering the criteria set forth in Chapter 4, it was assumed that an impact attenuator would have a life expectancy of five years. This means that the attenuator would be expected to endure a freezing and thawing environment for five years to perform its function, ie., being able to absorb the energy of a colliding vehicle. If, however, the frequency of an expected collision with the impact attenuator is less than five years, ie., a high accident location, the material used in construction of the attenuator would not need as great a resistance to the effects of freezing and thawing. Therefore, it would be feasible that other low-density concrete mixes, other than the four mixes previously stated, would be adequate for construction of impact attenuators in high accident locations. In order to determine which mixes would be acceptable for construction of an attenuator with a life expectancy less than say five years, a ratio can be established and set equal to a constant C.

$$\frac{\text{5 Years}}{\text{Life Expectancy of Attenuator in years (less than 5 years)}} = C$$

Multiplying this constant by a durability factor listed in Table 5-1, ie., less than 60, for a particular mix a new durability factor DF' can be determined. If this new durability factor DF' is 60 or greater then that particular low-density concrete mix is adequate for construction of an impact attenuator with the life expectancy in years used to calculate the constant C. For example, Dycon 1, D1, has a durability factor of 54.8 (From Table 5-1), based on a five year life expectancy. If an impact attenuator is to be placed in a location where the expected frequency of collision is four years or less, is this mix, D2, adequate for the construction of the attenuator? Preceding with the calculations previously described:

$$C = \frac{\text{5 Years}}{\text{4 Years}} = 1.25$$

$$DF' = 1.25\ (54.8) = 68.5$$

The new durability factor DF' is 68.5 which is greater than 60 therefore Dycon 1, D1, would be an adequate low-density concrete mix for construction of the impact attenuator with a life expectancy of four years.

By setting DF' equal to 60 and back calculating for the life expectancy of an attenuator constructed from the various low-density concrete mixes, Table 5-2 was constructed. (These calculations were also extended to the four mixes previously determined to be adequate for a five-year life expectancy.)

TABLE 5-2

LIFE EXPECTANCY OF IMPACT ATTENUATOR
BASED ON DF' EQUAL TO 60

Mix Designation	Life Expectancy in Years
P6	5.85
F4	5.77
V7	5.60
D2	5.28
D1	4.56
F3	4.55
P10	4.35
P2	4.02
F2	3.86
D3	3.08
V1	2.05
F1	1.88
P4	1.83
V2	1.42

Table 5-2 shows the life expectancy of impact attenuators constructed with the various low-density concrete mixes based on a new durability factor of 60.

It should again be noted that all the calculations and results presented in this chapter are based on the test criteria presented in Chapter 4 where it was assumed the life expectancy of an impact attenuator was five years which would be equivalent to 60 cycles of freezing and thawing in the laboratory. If, however, another life expectancy is assumed, other than five years, a new number of equivalent freezing and thawing cycles can be determined from the ratio presented in Chapter 4. With this new criteria, the new number of equivalent freezing and thawing cycles, and the freeze-thaw data presented in Appendix C the relative dynamic modulus of elasticity and the durability factor for each mix can be revaluated by the use of Equations 3-2 and 4-1. The results would be a new set of durability factors relative to another assumed life expectancy of the impact attenuator.

It was shown earlier that if the water absorption of the specimens could be reduced, the durability factor would increase correspondingly. If the freeze-thaw specimens, or a prototype attenuator for that matter, were coated with a waterproofing agent, this would tend to decrease the amount of water absorbed by the specimen thereby increasing its resistance to freezing and thawing which in turn would increase its durability factor. This, of course, would be a detailed study in itself.

It should be emphasized again that the specifications set forth in ASTM Designation C290-67 are not adequate for the low-density concretes investigated in this study. It would be advisable, therefore, to develop a standard freeze-thaw test procedure for low-density concrete and that a correlation between the laboratory tests results and actual freezing and thawing environment be made. This would be helpful in predicting more accurately the life expectancy of low-density concrete in the actual freezing and thawing environment from data collected from freeze-thaw tests conducted in the laboratory.

APPENDICIES

APPENDIX A

PROCEDURE USED FOR DETERMINING THE WET SPECIFIC GRAVITY AND ABSORPTION OF A LIGHTWEIGHT AGGREGATE AT ANY TIME

The procedure described in this Appendix is a modification of that described in a previous University of Texas report (1) for determining the SSD specific gravity and absorption of a lightweight aggregate. However, before making these determinations, it is suggested that the entire procedure be read thoroughly.

The apparatus required for determining the wet specific gravity and absorption values (analogous to SSD specific gravity and absorption values) is a large wide-mouthed, straight-sided jar (coffee jar), two caps for the jar, a wire screen with approximately 1/32-in.-square openings, a 1-lb steel weight, and an accurate balance. A data sheet similar to the one given later in this Appendix can be used to record the data as the procedure is followed. The step-by-step procedure is as follows:

1. Cut a circular hole in one jar cap by a lathe such that a lip of 1/4-in. still remains in the cap. Cut a circular wire screen the same size as the jar opening. (The screen minimizes the loss of fine aggregate particles.) Place the wire screen in the cap in such a manner that it is held securely when the cap is tightened on the jar.

2. Make a stirring rod out of stiff wire and kink it in several places. Place it in the jar (at the appropriate time in step 7) in such a manner that a handle extends through the center of the wire screen when the cut-out cap and screen is secured in place.

3. Fill the jar with water, secure the cap and screen on the jar, and suspend the jar from the hook on the balance by a wire bail. Place the filled jar in the large bucket (also containing water) and, with the scoop on the balance, zero the balance.

4. Place a 1-lb steel weight (used for ballast to offset the negative buoyancy force of the aggregate sample) in the scoop and determine the exact weight (in grams) of the steel weight in air. Place the steel weight in the filled jar and determine the weight (in grams) of the steel weight in water. Remove the steel weight from the filled jar and set it aside temporarily.

5. Use enough aggregate to fill the jar approximately two-thirds full, place the aggregate in the scoop, and weigh the aggregate sample accurately. (An 80-gram sample was found to be sufficient for vermiculite aggregate.)

6. Remove the filled jar from the large bucket and place it on a table. Remove the cut-out cap and screen and pour out the water. Place the 1-lb steel weight and the aggregate sample in the unfilled jar, and fill the remaining space in the jar with water. Secure the solid

cap on the jar. Turn the jar upside down two times (only) with moderate speed. (This helps to eliminate the entrapped air between the aggregate particles.)

7. Remove the solid cap. Insert the stirring rod through the wire screen, and replace the solid cap with the cut-out cap, wire screen, and stirring rod.

8. With the scoop on the balance, place the jar with the aggregate sample (and water) in the large bucket. Suspend the jar from the hook by the wire bail. It should be emphasized that the hook should be free to move.

9. Working rapidly, record the weight of the (submerged jar and) aggregate sample.

10. After stirring the aggregate particles, record the weight of the (submerged jar and) aggregate sample at the desired times. (It is suggested the weight be recorded at times similar to those shown on the following data sheet.)

11. Stir the aggregate particles with the stirring rod continuously between each recorded weight up to 30 minutes.

12. Using the procedure outlined on the following data sheet, calculate the wet specific gravity and absorption of the lightweight aggregate at the desired times.

SAMPLE DATA SHEET FOR BULK WET SPECIFIC GRAVITY AND ABSORPTION DETERMINATIONS OF LIGHTWEIGHT AGGREGATES WITH BULK SPECIFIC GRAVITIES LESS THAN 1.0

MATERIAL__________ DATE__________ TEMPERATURE__________ °F

	Weight(grams)
a. Weight of ballast (in air)	________
b. Weight of aggregate sample (in air)(80 grams, generally)	________
c. Weight of ballast (in water)	________
d. Weight of water displaced by ballast (a - c)	________
e. Weight of ballast & aggregate (in air) (a + b)	________

TIME AND DATE (All weights in grams)

________	f. Weight of ballast and aggregate (in water)	________
________	g. Initial weight of displaced water (e - f)	________

h. Weight of ballast and aggregate (in water) after:	j. Weight of water displaced (e - h) after:	k. Weight of water absorbed (g - j) after:
2 min ________	2 min ________	2 min ________
5 " ________	5 " ________	5 " ________
10 " ________	10 " ________	10 " ________
15 " ________	15 " ________	15 " ________
20 " ________	20 " ________	20 " ________
25 " ________	25 " ________	25 " ________
30 " ________	30 " ________	30 " ________
24 hrs ________	24 hrs ________	24 hrs ________

l. Bulk Wet Specific Gravity [(b + k)/(g - d)] after:	m. Per Cent Absorption (by Wet Weight) (100)[(k)/(k + b)] after:
0 min	0 min
2 " ________	2 " ________
5 " ________	5 " ________
10 " ________	10 " ________
15 " ________	15 " ________
20 " ________	20 " ________
25 " ________	25 " ________
30 " ________	30 " ________
24 hrs ________	24 hrs ________

APPENDIX B

METHOD FOR FINDING THE CAST DENSITY, YIELD, AND AIR CONTENT OF CONCRETE

B.1 Introduction

Since difficulty was encountered in measuring air content in the standard manner, i.e., with an Air Meter or Pressure Meter, the researcher had to resort to a "Gravimetric" method. The description herein is a brief summary of ASTM Designation: C138-63. For further information, refer to this designation.

This method of testing covers the procedure for determining the weight per cubic foot of freshly mixed low-density concrete and gives the necessary relationships for calculating the volume of concrete produced from a mixture of known quantities of the component materials, the yield, i.e., the volume of concrete per unit volume of cement, and the air content of the low-density concrete. These determinations are as follows:

B.2 Weight Per Cubic Foot

1) With a balance or scale, weigh a standard cylindrical measure as described in ASTM C138-63, Section 2.

2) After calibrating the measure in the prescribed manner, fill the measure in three equal lifts. Each lift shall be rodded or vibrated in the same manner as described

in Chapter 2 of this report. Depending on the type of low-density concrete being tested, the rodding or vibrating will be adjusted respectively.

3) After consolidation of the concrete, strike off the top surface and finish smoothly and carefully. Be certain to clean off any excess concrete from the outside of the measure.

4) Weigh the filled measure to the nearest 0.1 pound.

5) Calculate the net weight of the concrete by subtracting the weight of the measure from the gross weight. Calculate the weight per cubic foot by multiplying the net weight by the factor for the measure used. (See ASTM C138, Section 3.)

B.3 Volume of Concrete

1) Calculate the volume of concrete produced per batch as follows:

$$S = \frac{(N \times 94) + W_{AG} + W_W}{W}$$

where:

S = volume of concrete per batch, in cubic feet

N = number of bags of cement in the batch

94 = net weight of a bag of cement, in pounds

W_{AG} = total weight of lightweight aggregate used (if any), in pounds

W_W = total weight of mixing water added to batch, in pounds, and

W = weight of low density concrete, in pounds per cubic foot

B.4 Yield

1) Calculate the yield as follows:

$$Y = \frac{S}{N}$$

where:

Y = yield of low-density concrete produced per 94 pound bag of cement, in cubic feet

S = volume of low-density concrete produced per batch, in cubic feet, and

N = number of bags of cement in the batch

B.5 Air Content

1) Calculate the air content as follows:

$$A = \frac{S - V}{S} \times 100$$

where:

A = air content (percentage of voids) in the concrete

S = volume of low-density concrete produced per batch, in cubic feet, and

V = total absolute volume* of the component ingredients in the batch, in cubic feet

*NOTE: The absolute volume of each ingredient is equal to the weight of that ingredient divided by the product of its specific gravity times 62.4.

APPENDIX C

FREEZE-THAW TEST DATA

Specimen Size-15 In. Long by 3 In. Square

PERLITE CONCRETE

Freeze-Thaw Cycles	Weight Gr.	Transverse Frequency Cyc./Sec.	Visible Condition
P4, Specimen #1 Air Dry Weight = 1096 Gr.			
0	1846	425	
3	1911	415	
12	1986	418	Slight Spalling
24	2087	330	Slight Spalling
40	2125	261	Spalling
67	2076	142	Severe Spalling
P4, Specimen #2 Air Dry Weight = 1104 Gr.			
0	1926	430	
3	1977	422	
12	2052	421	Slight Spalling
24	2163	336	Slight Spalling
40	2200	268	Spalling
67	2200	142	Severe Spalling
P4, Specimen #3 Air Dry Weight = 1151 Gr.			
0	1806	440	
3	1986	430	
12	2064	412	Slight Spalling
24	2140	278	Spalling
40	2148	201	Severe Spalling
67	2064	155	Severe Spalling

Freeze-Thaw Cycles	Weight Gr.	Transverse Frequency Cyc./Sec.	Visible Condition
P2, Specimen #1 Air Dry Weight = 1138 Gr.			
0	1610	624	
30	2001	524	Spalling
61	2412	425	Severe Spalling
86	2387	328	Severe Spalling
P2, Specimen #2 Air Dry Weight = 1187 Gr.			
0	1452	655	
30	1908	598	Spalling
61	2364	544	Severe Spalling
86	2173	478	Severe Spalling
P2, Specimen #3 Air Dry Weight = 1194 Gr.			
0	1470	645	
30	1914	479	Spalling
61	2357	313	Severe Spalling
86	2085	225	Severe Spalling
P10, Specimen #1 Air Dry Weight = 1280 Gr.			
0	1490	750	
30	1912	646	Slight Spalling
61	2334	533	Spalling
86	2290	457	Spalling
P10, Specimen #2 Air Dry Weight = 1259 Gr.			
0	1461	724	
30	1870	643	Slight Spalling
61	2281	562	Spalling
86	2247	490	Spalling

Freeze-Thaw Cycles	Weight Gr.	Transverse Frequency Cyc./Sec.	Visible Condition
P10, Specimen #3 Air Dry Weight = 1250 Gr.			
0	1490	747	
30	1896	649	Slight Spalling
61	2302	551	Spalling
86	2270	441	Spalling
P10, Specimen #4 Air Dry Weight = 1260 Gr.			
0	1455	776	
30	1859	656	Slight Spalling
61	2264	529	Spalling
86	2239	425	Spalling
P6, Specimen #1 Air Dry Weight = 1485 Gr.			
0	1571	812	
30	1833	753	Slight Spalling
61	2136	693	Slight Spalling
86	2130	565	Slight Spalling
P6, Specimen #2 Air Dry Weight = 1507 Gr.			
0	1572	830	
30	1815	757	Slight Spalling
61	2059	675	Slight Spalling
86	2032	546	Slight Spalling
P6, Specimen #3 Air Dry Weight = 1501 Gr.			
0	1574	847	
30	1843	780	Slight Spalling
61	2112	713	Slight Spalling
86	2095	630	Slight Spalling

VERMICULITE CONCRETE

Freeze-Thaw Cycles	Weight Gr.	Transverse Frequency Cyc./Sec.	Visible Condition
V2, Specimen #1 Air Dry Weight = 810 Gr.			
0	1978	390	
20	2215	281	Spalling
40	2233	187	Severe Spalling
V1, Specimen #1 Air Dry Weight = 1052 Gr.			
0	2000	588	
20	2282	481	Slight Spalling
40	2244	354	Spalling
V1, Specimen #2 Air Dry Weight = 1030 Gr.			
0	2000	553	
20	2313	461	Slight Spalling
40	2358	225	Spalling
V1, Specimen #3 Air Dry Weight = 1067 Gr.			
0	2086	558	
20	2396	470	Slight Spalling
40	2440	364	Spalling
V7, Specimen #1 Air Dry Weight = 1033 Gr.			
0	2215	456	
20	2280	419	Slight Spalling
40	2264	415	Slight Spalling
57	2188	419	Slight Spalling
82	2000	407	Slight Spalling

Freeze-Thaw Cycles	Weight Gr.	Transverse Frequency Cyc./Sec.	Visible Condition
V7, Specimen #2 Air Dry Weight = 1055 Gr.			
0	2260	454	
20	2326	408	Slight Spalling
40	2278	385	Slight Spalling
57	2204	381	Slight Spalling
82	2087	255	Slight Spalling
V7, Specimen #3 Air Dry Weight = 1061 Gr.			
0	2260	473	
20	2335	410	Slight Spalling
40	2208	373	Slight Spalling
57	2156	351	Slight Spalling

FOAM CONCRETE

Freeze-Thaw Cycles	Weight Gr.	Transverse Frequency Cyc./Sec.	Visible Condition
F1, Specimen #1 Air Dry Weight = 1135 Gr.			
0	2093	549	
15	2272	397	Spalling
34	2320	307	Severe Spalling
50	2008	153	Severe Spalling
F1, Specimen #2 Air Dry Weight = 1183 Gr.			
0	2126	484	
15	2265	431	Spalling
34	2280	283	Severe Spalling
50	2000	231	Severe Spalling

Freeze-Thaw Cycles	Weight Gr.	Transverse Frequency Cyc./Sec.	Visible Condition
F1, Specimen #3 Air Dry Weight = 1154 Gr.			
0	2096	422	
15	2300	393	Spalling
34	2226	321	Severe Spalling
50	2000	184	Severe Spalling
F2, Specimen #1 Air Dry Weight = 1257 Gr.			
0	2089	370	
15	2343	395	Slight Spalling
34	2364	334	Spalling
50	2239	265	Severe Spalling
70			Destroyed
F2, Specimen #2 Air Dry Weight = 1354 Gr.			
0	2228	397	
15	2457	407	Slight Spalling
34	2492	345	Spalling
50	2275	281	Severe Spalling
70	2000	181	Severe Spalling
F3, Specimen #3 Air Dry Weight = 1419 Gr.			
0	2268	459	
15	2560	418	Slight Spalling
34	2604	387	Spalling
50			Destroyed

Freeze-Thaw Cycles	Weight Gr.	Transverse Frequency Cyc./Sec.	Visible Condition
F3, Specimen #1 Air Dry Weight = 1409 Gr.			
0	2300	540	
4	2465	539	
15	2496	486	Slight Spalling
34	2467	475	Spalling
50	2308	425	Severe Spalling
70	2173	402	Severe Spalling
F3, Specimen #2 Air Dry Weight = 1398 Gr.			
0	2320	478	
4	2446	452	
15	2478	420	Slight Spalling
34	2433	420	Spalling
50	2262	367	Severe Spalling
70	2108	313	Severe Spalling
F3, Specimen #3 Air Dry Weight = 1385 Gr.			
0	2171	456	
4	2450	400	
15	2489	390	Slight Spalling
34	2510	364	Spalling
50	2399	363	Severe Spalling
70			Destroyed

Freeze-Thaw Cycles	Weight Gr.	Transverse Frequency Cyc./Sec.	Visible Condition
F4, Specimen #1 Air Dry Weight = 1517 Gr.			
0	2268	644	
15	2459	609	
34	2461	590	Slight Spalling
50	2393	478	Spalling
70	2368	273	Spalling
F4, Specimen #2 Air Dry Weight = 1529 Gr.			
0	2124	694	
15	2480	657	
34	2500	628	Slight Spalling
50	2416	592	Spalling
70	2362	539	Severe Spalling
F4, Specimen #3 Air Dry Weight = 1496 Gr.			
0	2082	657	
15	2430	644	
34	2435	610	Slight Spalling
50	2342	559	Spalling
70	2316	474	Severe Spalling

DYCON CONCRETE

Freeze-Thaw Cycles	Weight Gr.	Transverse Frequency Cyc./Sec.	Visible Condition
D1, Specimen #1 Air Dry Weight = 1181 Gr.			
0	1311	149	
17	1411	140	
42	1435	133	Slight Spalling
60	1437	125	Slight Spalling

Freeze-Thaw Cycles	Weight Gr.	Transverse Frequency Cyc./Sec.	Visible Conditions
D1, Specimen #2 Air Dry Weight = 1154 Gr.			
0	1278	183	
17	1387	152	
42	1407	141	Slight Spalling
60	1405	140	Slight Spalling
D1, Specimen #3 Air Dry Weight = 1199 Gr.			
0	1361	173	
17	1447	165	
42	1472	139	Slight Spalling
60	1474	132	Slight Spalling
D2, Specimen #1 Air Dry Weight = 900 Gr.			
0	1073	165	
17	1269	154	Slight Spalling
42	1286	134	Spalling
60	1264	132	Spalling
D2, Specimen #2 Air Dry Weight = 897 Gr.			
0	1062	152	
17	1254	125	Slight Spalling
42	1275	139	Spalling
60	1261	130	Spalling
D2, Specimen #3 Air Dry Weight = 899 Gr.			
0	1111	150	
17	1303	154	Slight Spalling
42	1319	139	Spalling
60	1298	115	Spalling

Freeze-Thaw Cycles	Weight Gr.	Transverse Frequency Cyc./Sec.	Visible Conditions
D3, Specimen #1 Air Dry Weight = 786 Gr.			
0	977	180	
17	1322	128	Slight Spalling
42	1351	126	Spalling
60	1347	120	Spalling
D3, Specimen #2 Air Dry Weight = 773 Gr.			
0	977	141	
17	1319	123	Slight Spalling
42	1352	114	Spalling
60	1377	92	Spalling
D3, Specimen #3 Air Dry Weight = 754 Gr.			
0	929	150	
17	1246	137	Slight Spalling
42	1237	135	Spalling
60	1243	98	Spalling