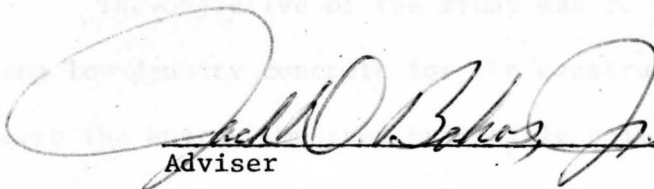
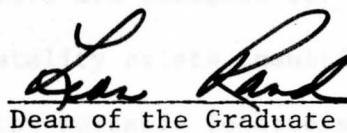


LOW-DENSITY CONCRETE IMPACT ATTENUATORS
(Freeze-Thaw Protection and Installation Techniques)

by
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ABSTRACT

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Masters of Science in Civil Engineering

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This thesis was performed in accordance with a research project undertaken by Jack D. Bakos, Jr., Ph.D. of the Civil Engineering department of Youngstown State University. The project was sponsored by the Ohio Department of Transportation in cooperation with the U.S. Department of Transportation, the Federal Highway Administration, and the Bureau of Public Roads.

The objective of the study was to determine the feasibility of using low-density concrete for the construction of crash attenuators to absorb the energy imparted by vehicle collision at a high rate of speed. The attenuators are intended for use in areas where high probability of passenger fatality exists resulting from a vehicle running off the roadway. The most suitable locations are near bridge abutments and exit ramp gore areas.

The following text deals with the protection of the attenuators from environmental effects and with economical installation techniques.

ACKNOWLEDGEMENTS

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CHAPTER I

INTRODUCTION

Vital to the development of a low-density concrete impact attenuator is the establishment of a means of protecting the concrete itself against the detrimental effects of the environment over its projected life-span. Historically, normal concrete has been particularly vulnerable to weathering, especially the effects of freeze-thaw cycling. This effect is compounded for the concretes considered in this study since these concretes have compressive strengths of 1/25 to 1/125 that of normal concrete and with air contents considerably greater. With this reduction in strength and increased air voids comes a greatly amplified reduction in resistance to freeze-thaw cycling.

Consistency is a key element in the success of highway impact attenuators. Herein lies the necessity for careful examination of the durability problem. In order for the attenuator's performance to be predictable and dependable, the parameters involved in its energy absorbing capabilities must remain relatively constant. Certainly, a prime factor is the concrete matrix structure. It is the collapse of the concrete matrix as well as the collapse of the concrete configuration which serves to absorb the energy imparted by an impacting vehicle. Repeated freezing and thawing of water trapped within the concrete will deteriorate the bridging network of the concrete matrix, thereby reducing its energy absorbing ability.

In a discussion of durability, freeze-thaw cycling is not the only element of concern. An outdoor structure, especially one located adjacent to a high vehicle traffic area, is subjected to many detrimental effects. Rain, snow, and hail, particularly when acting together with the freeze-thaw effect, will vastly complicate the durability problem. Snow can become piled upon the attenuator and upon melting can create a near submerged environment. Being adjacent to vehicular traffic, it is very likely that small stones and bits of metal will be ejected from the roadway against the attenuator. The concrete must be able to resist this particle bombardment without the need of repair. In addition, the concrete must also be resistant to the effects of deicing salts, asphaltic materials, road tars, and to the erosive effects of melting water.

The single most important factor necessary to insure weather durability is the elimination of water intrusion into the concrete. The role played by such intruded water in the mechanics of the freeze-thaw cycle will be discussed in detail later. Furthermore, low-density concrete saturated with frozen water during cold periods will grossly inhibit the energy absorbing capabilities of the attenuator. An attenuator which is capable of absorbing the energy of an impacting vehicle may become far too rigid when filled with frozen water. With the need to increase durability thus established, the question becomes one of how it can be accomplished.

Many additives and admixtures are available which can be valuable in improving the durability of normal concrete. These products, however, often do so by increasing the inherent strength of the mix

which in turn would reduce the energy absorbing nature of the low-density concretes. Other additives and admixtures are available, such as oils and soaps, which act to reduce the permeability of the concrete. Such substances may effectively increase the durability of concrete, but lack the ability to be consistent and thus are not as effective as other processes.

Air entrainment has long been considered extremely valuable in increasing concrete's resistance to freeze-thaw cycling. Normal air entrainment occupies approximately 5% to 10% of the concrete volume. The low-density concrete mixes considered herein already include considerably more air than this. Thus, further air entrainment would not be effective.

From the foregoing discussion, it would appear that some type of surface treatment could best solve the weather durability problem. In addition to solving the durability problem, a surface coating could also be somewhat effective in retaining any concrete spall in the event of a collision. If the concrete spall were not contained, large fragments of the attenuator could be ejected into the roadway upon impact, thereby creating a hazard, i.e., even though the fragments are easily crushable, they would still appear as "concrete" to oncoming motorists.

Criteria for a surface treatment or system is, therefore, as follows:

- (a) Increase the weather durability of a low-density concrete for a limited life-span.
- (b) Inhibit the concrete spall under impact.
- (c) Provide economy.
- (d) Provide ease of application.

CHAPTER II

PRELIMINARY STUDY OF CONCRETE TYPES

In 1974, a pilot study^{(1)*} evaluating various low-density concretes for use in an impact attenuator system was completed. The study assessed in great detail the applicable attributes of four basic types of low-density concrete: perlite concrete, polystyrene concrete, vermiculite concrete, and foam concrete, which utilized a foaming agent to produce a cellular concrete. Each concrete was evaluated for its relative energy absorbing abilities, its mix reproducibility, weather durability, and aggregate availability. After careful examination of these evaluated properties, vermiculite and foam concretes were excluded from further study. Since the time of the first study, another low-density concrete was found which exhibited excellent energy absorbing capabilities. Its evaluation was, therefore, included in the current study. The concrete, termed Dycon IV, can be classified as a polystyrene concrete, but as will be shown later, differs appreciably with those in the first study.

Five concretes in all were examined in this study. Two of them utilize perlite as the aggregate. Perlite is a naturally 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. The perlite used in this study had a bulk unit weight of 8 pcf and a bulk specific gravity of 0.3868. Mix proportions

*Number in parenthesis indicates reference cited.

along with batch yields, unit weights, and compressive strengths for the two perlite mixes, designated P2 and P4, are summarized in Table 2.1.

Mixing procedure was the same for both P2 and P4. First, all the water and air-entraining agent were placed in the mixer and mixed for 30 seconds. Secondly, 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.

Two other concretes carried over from the earlier study were of the polystyrene type. The aggregate used in this type of concrete was expanded polystyrene which consists of polystyrene particles containing 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 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 concrete produced by the use of this aggregate is also marketed by Koppers under the trade name of Dycon. One problem involved in using this type of concrete is the aggregate's tendency to segregate from the mix, i.e., the beads tend to float to the top of the form, yielding a non-homogeneous mix. Koppers' mix has an additive which prevents this problem. The two Dycon mixes, designated D2 and D3 are summarized in Table 2.2.

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 %	Average Oven Dry Unit Wt. Lb/Ft ³	Average Compressive Strength 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	31.750	49.10	26.9	121.8

*Master Builders Resin

TABLE 2.2
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
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

Mixing procedure for both D2 and D3 was the same and is as follows: All the water and polystyrene beads were placed in the mortar mixer (the polystyrene beads also contained air-entraining agent and desegregation agent) and mixed for two minutes. Next, the cement was added and mixing was continued for an additional five minutes to complete the mix procedure.

The fifth concrete type considered in this study was also of the polystyrene type, but differed appreciably from D2 and D3. This concrete contains a gradation of Dylite aggregate ranging from approximately 1/32" to 5/8" in diameter. The aggregate used to obtain this gradation is Dylite KFP-525. Dylite KFP-525 consists of relatively large, irregularly shaped particles of general purpose polystyrene containing a volatile hydrocarbon blowing agent which is expanded by conventional Rodman steam pre-expansion equipment. The expanded KFP-525 particles have a characteristic off-round shape, dimpled skin, and uniform, superfine internal cell structure. The concrete made by use of this aggregate was designated D4. At the time of this study, D4, which was developed by Koppers, was not ready for marketing. For this reason, mix proportions and yields will not be presented here. D4 is mixed at a water/cement ratio of 0.46. It has a wet density of 20 to 22 pcf, a cure density of 17.5 to 19.5 pcf, and its compressive strength ranges from 78 to 80 psi. The D4 concrete utilized in this study was mixed and cured by Koppers and shipped to the study location in large blocks where it was cut by conventional hand and power saws to the desired sizes.

Figure 2.1 shows a cross section of the three basic types of concrete: perlite, Dycon, and D4.

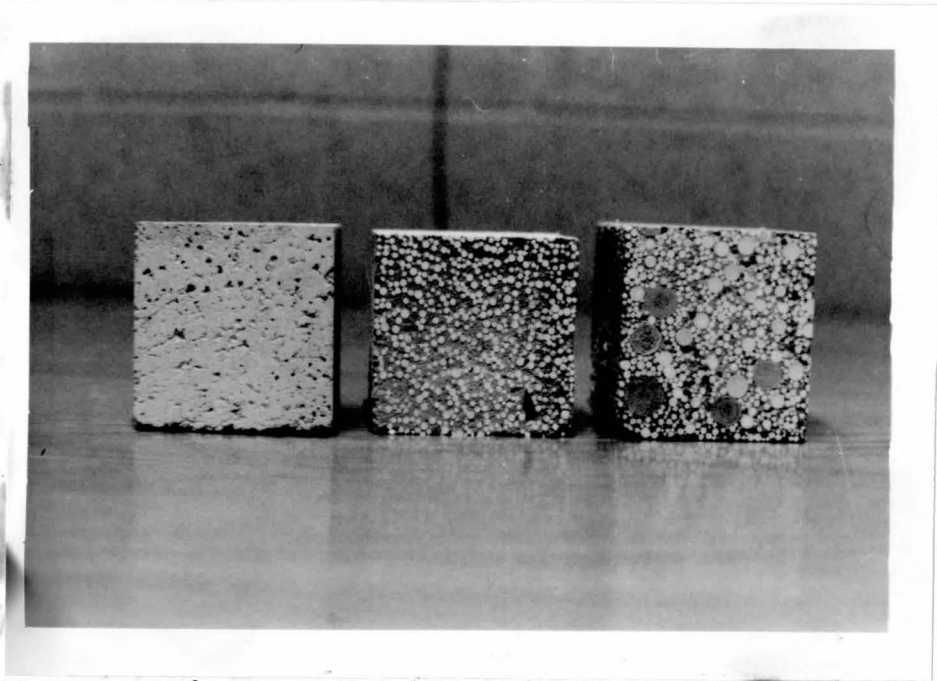


FIGURE 2.1
PERLITE, DYCON, D4

CHAPTER III

SURFACE TREATMENTS

With the criteria for a surface treatment established, a search was begun to identify particular treatments that would be effective. It was soon found that little, if any, of this kind of evaluation had been done with coatings on low-density concrete. Some work had been done, however, with coatings on normal concrete, but it is extremely difficult to draw a correlation between the behavior of normal concrete and that of low-density concrete. The evaluation, therefore, began with a study of applicable treatments. Table 3.1 summarizes the findings of the study.

In addition to the treatments listed in Table 3.1, some treatments, involving a combination of materials, have been used. These composite treatments are costly and time consuming to apply, but their superior durability warrants their mention.

The California Highway Department, in a search to find improved protective coatings for bridge decks, has tried several unique composite treatments.⁽²⁾ One treatment involved imbedment of fiber fabric in the second and fourth layers of a five layer, spray applied, coal tar emulsion. The system was found to be nearly perfect in its weather protecting efficiency.

A similar treatment involved precoating both sides of a glass fabric with the same coal tar emulsion. The road surface was primed for adequate bonding. This system was at least as good as the previous treatment.

TABLE 3.1
CONCRETE SURFACE TREATMENTS PRESENTLY IN USE

CLASSIFICATION	REFERENCES	FORMS	METHODS OF APPLICATION	ADVANTAGES	DISADVANTAGES
Bituminous Materials	(2) (3) (4) (5) (6) (7)	Coal Tar Pitch Asphaltic Emulsion Wax Bitumen Bitumen in Furnace Oil Bituminous Paint	Spray Squeegee Brush	High resistance to water Resistant to alcohols and polar solvents	Dissolvable by hydrocarbon solvents Slow in drying Emulsions may be inconsistent
Resin Latexes	(3) (4) (6)	Acrylics Polyvinyl Acetate Latex Alkyd Resin	Spray Brush	Acrylic latexes are resistant to heat, sunlight, weather. Polyvinyl acetate latexes are highly resistant to weathering. Fast drying Easily pigmented	Acrylic latexes cannot withstand continuous attack from acids, alkalis, and oils. Polyvinyl acetate latexes tend to soften in heat. Emulsions may be inconsistent.
Rubber	(3) (4) (6) (7) (8) (9)	Styrene-Butadiene Chlorinated Rubber Paint Neoprene Latex	Spray Squeegee Brush	Facilitates expansion and contraction of concrete High resistance to acids, alkali, oil, grease, and water.	Expansion and contraction may greatly exceed the concrete. Neoprene latex rubber is unstable in sunlight.

TABLE 3.1 (continued)

CLASSIFICATION	REFERENCES	FORMS	METHODS OF APPLICATION	ADVANTAGES	DISADVANTAGES
Vinyls	(3) (4) (8) (10)	Polyvinyl Alcohol Polyvinyl Chloride Polyvinyl Acetate Lacquer Polyvinyl Chloride Acetate Polyvinylidene Chloride Polyvinyl Butyral Polyvinyl Formal	Spray Brush	Highly resistant to water, acids petroleum products	Bond poorly with concrete
Polyethylenes	(3) (4) (6)	Most common is chlorosulfonated polyethylene	Spray Brush	Resistant to water, acids, and alkalies	Relatively unstable in sunlight Difficult to apply Costly
Linseed Oil	(3) (4) (11) (12)	Pure Linseed Oil Linseed Oil mixed with water, kerosene, or mineral spirits	Spray Brush	Effective in protecting concrete during periods of freeze and thaw and from the application of deicing salts Inexpensive Easily applied	Does not prevent the intrusion of water into the concrete Requires several coats An abundance of alkalies in concrete may dissolve the oil.

TABLE 3.1 (continued)

CLASSIFICATION	REFERENCES	FORMS	METHODS OF APPLICATION	ADVANTAGES	DISADVANTAGES
Urethanes	(2) (3) (4) (8)	Moisture Cured Urethane Oil Modified Urethane	Spray Brush	Highly resistant to water, acids, and alkalis, abrasion	Bond poorly with concrete
Epoxies	(2) (3) (4) (7) (8)	Epoxy Resins High-Build Epoxies Coal-Tar Epoxies	Spray Squeegee Brush	Highly resistant to abrasion, water, chemicals and oil Bond extremely well with concrete	High drying time Expensive Can be difficult to apply
Polymeric Concrete	(13) (14) (15) (16)	Cured by radiation, heat, or chemical catalyst	Spray Squeegee	Virtually eliminates water permeability Decreases water absorption up to 95 percent Resistance to many corrosive materials and conditions is high.	Increases strength properties of concrete so much that the energy absorbing characteristics are destroyed Difficult to apply Costly

Another, more difficult, treatment consisted of a primer followed by a coal-tar-base adhesive which was covered with a hand-placed thermoplastic sheet 30 mils thick. Heat was then applied to melt the plastic sheet. This treatment was also found to be very effective.

Another interesting protective system which may have potential is the use of a fiberglass cloth sandwiched between coatings of epoxy. The result is an extremely hard and durable surface treatment.

Based upon the review of pertinent literature as well as a consideration of the available treatments with respect to the unique problems associated with the low-density concrete, a group of coatings was chosen which was believed to be representative of the best and most suitable treatments. A brief description of each coating follows.

BITUPLASTIC NO. 28

Bituplastic No. 28 is a commercially available thixotropic coal tar emulsion. It is intended for use on steel and masonry surfaces for the purpose of preventing atmospheric corrosion in industrial environments and is manufactured by Koppers Company, Inc. In this study the coating was applied by brush in two coats. Bituplastic becomes touch dry in about two hours and dries completely in twelve to twenty-four hours.

BITUMASTIC 300-M

Bitumastic 300-M is a coal tar filled epoxy which was designed for use in marine environments. It is a two component system which is mixed in a 3½:1 ratio by volume. In this study a single application was applied by brush. The coating cure time is seven days, but it can be handled in twenty-four hours. Bitumastic 300-M is a commercially available product of Koppers.

SILICON MOISTURE REPELLANT

Silicon Moisture Repellant is also manufactured by Koppers and was specifically designed to waterproof masonry surfaces. Its consistency and appearance closely resembles

water. In this study two coats were applied liberally by brush. Although the coating dries to the touch in fifteen minutes, complete drying takes approximately four hours.

AQUA-BASE AND AQUA-TOP

These two treatments were developed by the Sika Chemical Corporation as a two part treatment for protecting structures in marine environments. In this study the two treatments were evaluated separately since the cost of using the two-part system would be prohibitive. Both Aqua-Base and Aqua-Top are two component systems; namely 100% solids, reactive epoxy resin based. The treatments are mixed in a 1:1 proportion. The mixed consistency of both coatings resembles that of heavy cream and both dry to a high gloss, tile-like finish. Both treatments were applied by brush using a single coat. Brush application was found to be quite difficult. Aqua-Base and Aqua-Top require at least five hours for touch drying. Final cure is accomplished in seven days.

SIKADUR LO-MOD AND SIKADUR HI-MOD

These treatments, developed by the Sika Chemical Corporation, are both two component, 100% solids, moisture-insensitive, epoxy-resin systems. Lo-Mod has a low modulus of elasticity which allows for variations in both stress and temperature. Hi-Mod has a high modulus of elasticity for added strength and bonding ability. Lo-Mod is mixed at a ratio of 2:1 by volume while Hi-Mod is mixed in a 1½:1 volumetric proportion. In this study both treatments were applied by brush using a single application. The mixed viscosity of both treatments is similar to that of heavy oil. Application was comparatively easy. Lo-Mod is tack free in seven hours and requires seven days for complete cure. Hi-Mod is tack free in five hours and requires three days for complete cure.

LINSEED OIL

The oil used was 100% boiled linseed oil since boiling acts to increase its drying capabilities. Linseed oil is a natural water barrier and tends to seal the pores in the concrete. Its consistency is comparable to that of cooking oil. In this study the oil was brushed on liberally using two coats. Drying was quite slow with the specimens usually requiring twenty-four to forty-eight hours for tack free drying.

LACQUER

The lacquer used herein was that typically used for wood finishing and consisted of about 78% hydrocarbons. Using a brush, the lacquer was applied liberally.

PARAFFIN

The paraffin used had a high melting temperature (in excess of 200°F). It was hoped that paraffin, being an excellent moisture barrier itself, would seal the pores of the concrete. The paraffin was melted to liquid form and pigmentation was added to aid in visual evaluation. The liquid paraffin was transferred to a flat tray which was preheated to maintain the paraffin in liquid form. Each face of the concrete specimen was then dipped into the paraffin and held there for about thirty seconds. The specimen was then pulled from the paraffin tray and allowed to dry. This procedure continued until the specimen was completely coated.

CONCRETE PAINT

The concrete paint used was identical to that used to waterproof cellar walls. It is available in dry form to which water is added. The paint has a high percentage of portland cement and is quite similar to grouting material. Application is extremely easy and was accomplished by two brush coats. The coating became touch dry in two hours.

EPOXY LAMINATING RESIN 1391

Epoxy Laminating Resin 1391 is a two component system, mixed 5:1 by weight, and was designed to produce extremely strong laminations with fiberglass cloth. The epoxy has a relatively low-viscosity and is very easily applied. In this study one coat of the epoxy was applied with a brush. It should be noted that working with Resin 1391 can be dangerous. It has a peak exotherm at the time of gellation of over 450°F and must be mixed in containers not exceeding one quart. Resin 1391 cures completely in twenty-four hours.

COMCOAT

Comcoat is a relatively new development of Commercial Shearing, Inc. Its principle use is as a sealant for tunnel linings. It is a 100% solids two component, elastomeric, cross-linked terpolymer which is mixed 1:1 by volume. Comcoat dries to an elastic, rubber-like substance and is an excellent moisture barrier. In this study Comcoat was squeegeed on in a single application. The coating was touch dry in three to four hours, but requires twenty-four hours for complete cure.

CHAPTER IV

MECHANISMS OF FREEZE-THAW DETERIORATION

The primary consideration when using any type of concrete in an outdoor environment is its durability with respect to temperature changes. In areas where temperatures fall below freezing, repeated changes from a frozen to a thawed condition are the worst enemies of a concrete structure. Therefore, before the results of the freeze-thaw tests are presented, and in order to better interpret the results, the mechanisms of freeze-thaw deterioration will be discussed.* Special emphasis will be put upon those mechanisms particularly applicable to low-density concrete.

Concrete is a heterogeneous material consisting of aggregate suspended in a cement gel. Cement gel is a widely used term for hardened cement paste. Throughout concrete are innumerable void spaces. There are many theories as to the causes of freeze-thaw deterioration in concrete, but common to most theories is the fact that the deterioration is caused by water, in some form, in the void spaces. The void spaces vary in size and nature and can be classified as gel pores, capillary cavities, or air voids.

Gel pores are the smallest and range from 15 to 20 angstroms in diameter. These microscopic pores usually contain water, but are only large enough for a few molecules. For this reason, the water is not capable of freezing at any normal climatic temperature. It is

*Most of the information in this section was acquired from Reference (17).

estimated that in order for the water contained in gel pores to freeze, consistent temperatures below -78°C are needed. Capillary cavities are much larger than gel pores although they are still microscopic. The average diameter of a capillary cavity is about 5,000 angstroms. Water may or may not exist in these spaces, depending upon the degree of saturation of the concrete. Water is capable of freezing in capillary cavities, but freezing may not begin until the temperature of the concrete is several degrees below 0°C .

From the preceding discussion, it may be concluded that the temperature at which freezing begins is a function of the size of the cavity and degree of saturation. Air voids are much larger than capillary cavities and range in diameter from a few microns to several centimeters in low-density concrete. These voids are usually caused by the entrainment or the entrapment of air in the concrete mix. These spaces are seldom completely water-filled unless pressurized.

Changes in temperature and humidity act to propel the water held in the void spaces of the concrete. Herein lies the basis of freeze-thaw deterioration. Concrete will usually not deteriorate drastically until it obtains a high degree of saturation known as the critical degree of saturation. This theory was presented in 1928 by Petry.⁽¹⁸⁾ The theory further states that concrete can be uniformly filled with water up to nine-tenths of its available void space without dramatic damage from freezing since, upon freezing, water expands by one-tenth of its original volume. In other words, the water contained in the concrete at the critical saturation (90%) could theoretically expand upon freezing to, at most, the full volume of the concrete void

space without exerting pressure within the concrete matrix. Degrees of saturation in excess of the nine-tenths level can then begin to cause severe deterioration as the size of the ice crystals begin to exceed the available space for growth.

There are three actions of freezing water in concrete which are believed to be the major contributors to deterioration of the concrete structure. These are as follows: Generation of hydraulic pressures due to the freezing of water in the internal capillaries, diffusion of and freezing of gel water in the capillaries, and the generation of osmotic pressures from salts and alkalies concentrated in the capillary water itself.

When water freezes in an air void or capillary cavity, and the size of the void cannot accommodate the growing ice crystal, hydraulic pressure is applied to the surrounding gel pores and capillaries. Generally speaking, this pressure increases as the square of the distance from the ice crystal. In concrete having a large number of air voids and a high degree of permeability, these hydraulic pressures are relatively low since the water can move freely through the concrete and can find unoccupied space. In denser concretes, having a small number of air voids, the hydraulic pressures can be as high as 1,200 psi. This mechanism is a strong argument for the use of air-entraining to increase the void space in concrete, thereby increasing its durability. Low-density concrete inherently has a large number of air voids and is quite permeable. Its strength properties, however, when compared to normal concrete, are drastically reduced. Thus, despite the fact that the hydraulic pressures developed are relatively

low, due to the close proximity of the large number of air voids, the amount of pressure required for deterioration is also very low. It is believed, therefore, that the development of even the slightest hydraulic pressure is effective in the deterioration of low-density concrete.

As was previously mentioned, ice crystals can easily form in capillary cavities, but cannot form in gel pores. The ice in the capillary cavities and the water in the gel pores are in thermodynamic equilibrium at the freezing point. When the temperature drops below the freezing point, this equilibrium is destroyed. The gel pore water now has a free energy higher than that of the capillary ice and is propelled from the gel pores into the capillary cavity, causing the ice crystal to grow beyond its available growth space.

Water also moves from the capillary cavities into the gel pores. This is accomplished by the introduction of osmotic pressure.

"When solutions of different concentrations of soluble materials are separated by a permeable barrier, the solvent particles move through the barrier toward the solution of greater concentration and a differential head is set up between the two solutions. This osmotic action increases the hydraulic pressure in cement paste as freezable water is forced from the capillaries into the gel pores."(17)

Suppose that the water present in the capillary cavities is concentrated with salts or alkalies. Upon freezing, the concentration is increased and the capillary water, having a concentration much greater than the water in the gel pores, is forced out of the capillaries into the gel pores increasing the moisture saturation of the concrete gel structure and creating destructive pressures therein. Because of the intended use of the low-density concrete, namely crash attenuators,

the concrete will be exposed to deicing salts and again, any developed pressures will have detrimental effects.

Another effect which may be detrimental when dealing with the particular concretes in this study is that of expansion and contraction. As previously mentioned, concrete is a heterogeneous material and because of the nature of the lightweight aggregates used, low-density concrete further qualifies in this respect. It may be that the hardened cement paste and the lightweight aggregates differ so drastically in their coefficient of expansion that differential expansion and contraction could cause internal ruptures in both the aggregate and cement gel structures.

Any applied protective coatings must also be compatible with the expansion and contraction of this concrete. A coating must be able to expand and contract compatibly with the structure on which it is overlaid. If the coating is too rigid and does not facilitate this action, the coating may pull away from the concrete or destroy the concrete gel structure in cold temperatures and split or destroy the gel structure in warm temperatures. It is also possible for the coating to be over-reactive to expansion and contraction which could result in the same adverse effects mentioned above. Idealistically, the coating should remain relatively elastic throughout the temperature range anticipated and at the same time minimize moisture absorption of the concrete.

CHAPTER V

TESTING

5.1 The Freeze-Thaw Test

The protection afforded by the various surface treatments to the low-density concretes was evaluated by testing via freeze-thaw cycling. There are several accepted freeze-thaw test procedures, the differences being in the specimen environment and cycle duration. It has historically been a difficult task to make any correlation between freeze-thaw tests in the laboratory and actual conditions in the field. Laboratory freeze-thaw testing can only yield relative information between the durability characteristics of the various types of concrete and, in this case, the effects of protective surface treatments. In other words, the observations made can only be compared to other observations in the laboratory since no direct relation can be made to field application. For example, laboratory testing may indicate that a given surface treatment is superior to all others similarly tested, but its field performance cannot be accurately predicted. Although a direct correlation cannot be made to field application, certain durability characteristics and modes of failure can be observed and thus, a prediction of the approximate service a system can give in the field is obtained.

With the aforementioned limitations in mind, it was determined to use ASTM C290-67; Rapid Freezing And Thawing In Water. This test procedure is most severe, thereby enabling the maximum amount of information to be gathered in the shortest possible time. ASTM C290-67

specifies that the freeze-thaw testing apparatus must contain suitable chambers in which each test specimen 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" of fresh water at all times while 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 $\pm 2^\circ\text{F}$.

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 ($\pm 3^\circ\text{F}$) and at the end of the heating period the center of the specimen must be at 40° ($\pm 3^\circ\text{F}$). 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 freeze-thaw apparatus used in this study was manufactured by Hogentogler & Company, Inc., and in accordance with ASTM C290-67. The deep-freezer-like cabinet has automatic cycling controls and a seven

day recorder to monitor temperature vs. time (see Figures 5.1, 5.2, and 5.3). The cabinet itself facilitates the testing of 17 3" x 3" x 15" specimens plus one control specimen. The specimens are stored in water-filled copper chambers oriented side-by-side and spaced by heating and cooling elements (see Figure 5.4). Thermocouples are inserted into the interior of the control specimen and sealed from intruding water.

5.2 Preparations of Specimens

As was previously mentioned, D4 was premixed and cured and shipped to the study location. The specimens used for freeze-thaw evaluation were also pre-cut to the 3" x 3" x 15" shape. The remaining concretes were mixed in accordance with the proportions and procedures given earlier in Chapter II. Type III, High Early Portland Cement, was used throughout the study. A 3½ cubic foot Muller mixer with rubber scrapers attached to the ends of the mixing blades was used for complete agitation of the mix. The wet mix was poured into a 30" x 3" x 48" plywood form and cured at 100 percent humidity for fourteen days. The cured 3" thick slab was then cut on a conventional concrete power saw to the desired specimen size. The specimens were then allowed to air dry.

In preparation for coating, the concrete specimens were checked for surface voids and flaws and cleaned of any surface residue. The specimens were then coated. Table 5.1 summarizes the number of applications and approximate drying times for each of the treatments examined. For the most part, only a single coat of the treatments was applied since further applications would be too costly and time



FIGURE 5.1
THE FREEZE-THAW APPARATUS

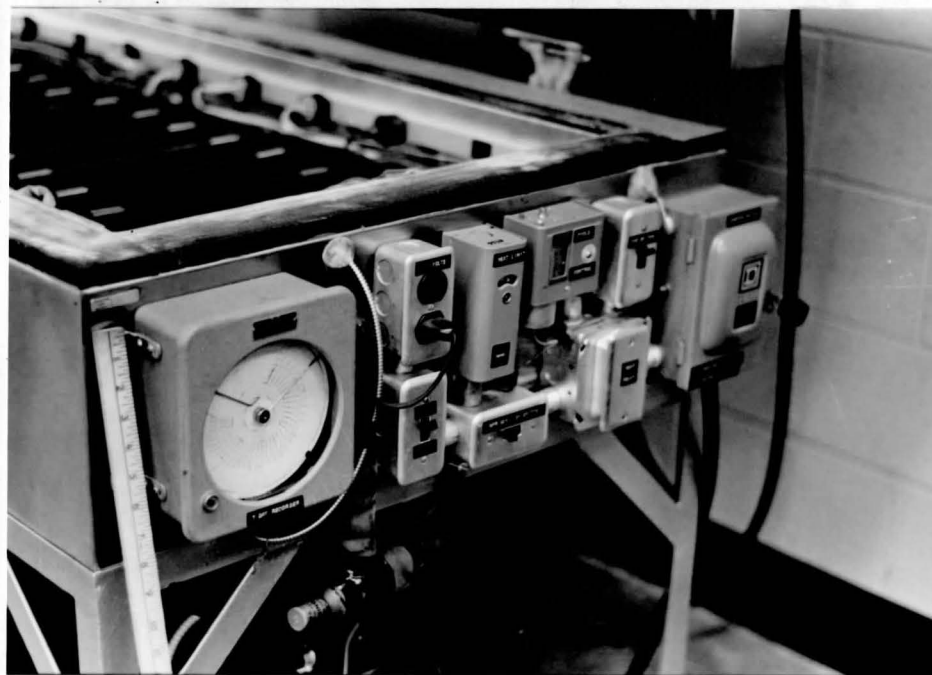


FIGURE 5.2
THE AUTOMATIC TEMPERATURE CONTROL SYSTEM
FOR THE FREEZE-THAW APPARATUS

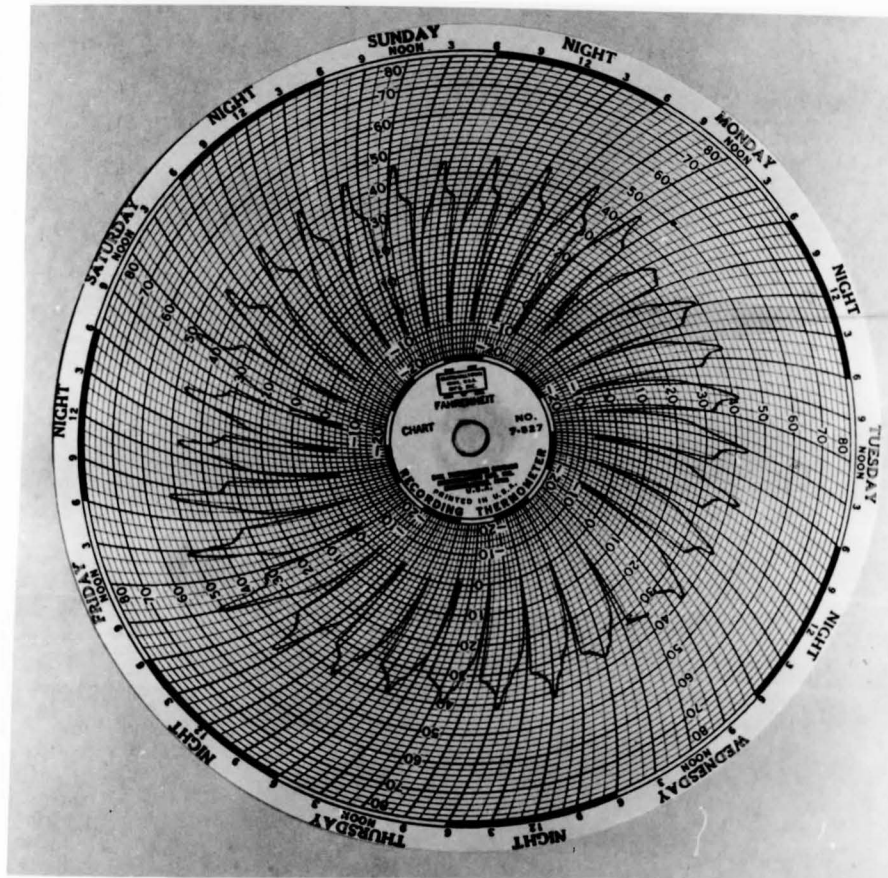


FIGURE 5.3
TYPICAL SEVEN DAY TEMPERATURE RECORD

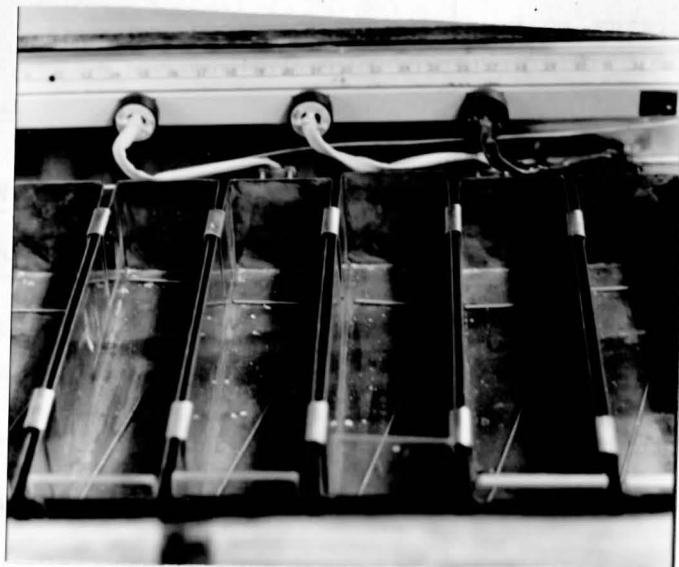


FIGURE 5.4
COPPER SPECIMEN CHAMBERS
IN THE FREEZE-THAW APPARATUS

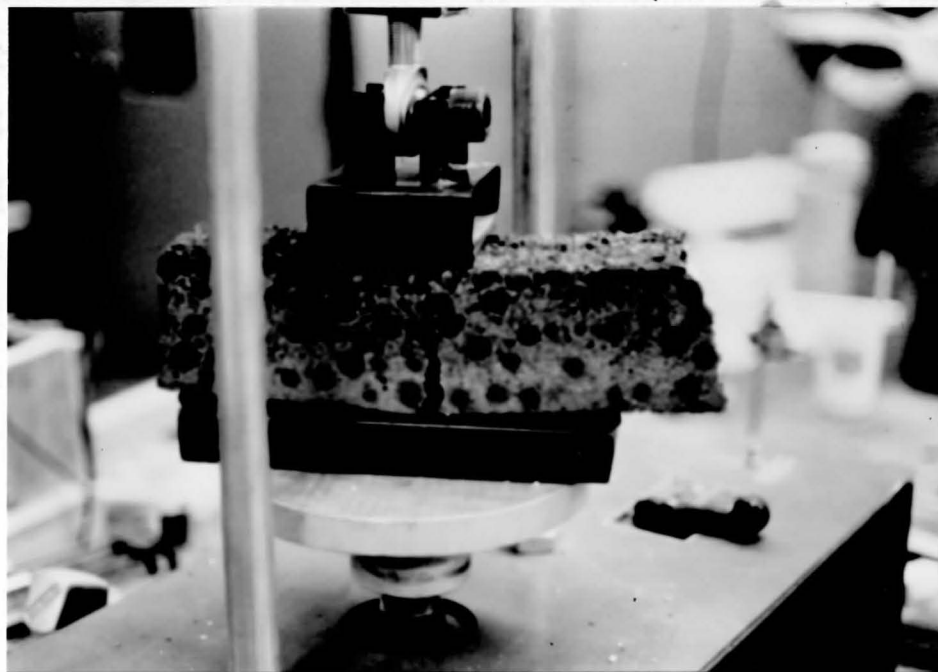


FIGURE 5.5
MODULUS OF RUPTURE APPARATUS
WITH SPECIMEN IN PLACE

SURFACE TREATMENT	NUMBER OF APPLICATIONS (coats)	TACK FREE DRYING TIME	COMPLETE CURE TIME
Bituplastic No. 28	2	2 Hours	24 Hours
Bitumastic 300-M	1	24 Hours	7 Days
Silicon Moisture Repellant	2	15 Min.	4 Hours
Aqua-Base	1	5 Hours	7 Days
Aqua-Top	1	5 Hours	7 Days
Lo-Mod	1	7 Hours	7 Days
Hi-Mod	1	5 Hours	3 Days
Linseed Oil	2	24-48 Hrs.	48 Hours
Lacquer	2	1 Hour	3 Hours
Paraffin	1	Few Seconds	1 Minute
Concrete Paint	2	2 Hours	24 Hours
Epoxy Resin 1391	1	6 Hours	24 Hours
Comcoat	1	3-4 Hours	24 Hours

TABLE 5.1
NUMBER OF TREATMENT
APPLICATIONS AND DRYING TIMES

consuming for the intended use. In some cases, however, a second application was used. These were cases when it was evident that a single application would not be effective. In these cases, the cost of the coating was relatively low.

Four specimens of P2, D2, and D4 were coated on all surfaces with each of the treatments. P4 and D3, differing from P2 and D2, respectively, only in the water-cement ratio, were to be examined after selection of the most suitable treatments. Three of the four specimens coated were then subjected to freeze-thaw cycling. The fourth specimen became the uncycled specimen which was later used for a basis of comparison and evaluation. It should be noted that one of the treatments, lacquer, could only be applied to the perlite specimens as it tended to dissolve the polystyrene aggregate.

5.3 Data Collection and Test Procedure

Upon complete drying, the specimens were ready for testing. It was determined that because of the many parameters involved in the durability of the specimens and because of the inability to directly link the test results to field performance, it would be most beneficial to run the tests for a large number of cycles in order to fully exercise all parameters. It was, therefore, decided to cycle the specimens 100 times. After 25, 50, 75, and 100 cycles, the specimens were removed from the test cabinet and inspected.

The procedure for executing and evaluating the tests is as follows. The three specimens to be cycled were weighed and the weights were recorded to the nearest gram. The fourth specimen was stored for future use. Color slides were also taken to visually document the

tests. The three specimens were then placed in the freeze-thaw cabinet and each chamber was filled with water. The cabinet was activated to begin the cycling. Each series of tests consisted of five different coatings in sets of three, one uncoated temperature control specimen, and two uncoated control specimens for comparison with the coated specimens. At the end of each 25 cycle period, the specimens were taken out of the freeze-thaw cabinet, weighed, recorded, photographed and replaced into their respective chambers. Note was also made of the condition of each specimen.

At the end of 100 cycles, the specimens were permanently removed from the freeze-thaw cabinet and final documentation was made. The specimens were then allowed to dry in air for approximately 48 hours. At this time modulus of rupture tests were performed to determine the loss in strength of the specimen with respect to the uncycled specimen that had been stored. A photograph was taken of a typical cross-section of the cycled specimen along side of a cross-section of the uncycled specimen. Also, any extreme damage due to cycling was also documented pictorially. This completed the testing procedure.

The normal method of evaluating the results of freeze-thaw cycling, as specified in ASTM 290-67, is the determination of the loss in the dynamic modulus of elasticity. This is accomplished by determining the fundamental transverse frequency of a specimen using ultrasonic techniques. This method is only applicable, however, to homogeneous materials. The effect of the large water absorption by the uncoated control specimen as well as the water absorption experienced after failure of a surface treatment further limited this

method. The use of this test procedure was thought, therefore, to yield erroneous results. It was decided, therefore, that the third-point modulus of rupture test (ASTM C78-64) would be used for determining the strength loss due to freeze-thaw cycling. Because of the size of the specimens to be tested (3" x 3" x 15") and the low flexural strength of low-density concrete, conventional universal testing machines were found to be far too insensitive. A special apparatus was, therefore, contrived. A Soiltest AP-170A Stability Compression Machine (see Figure 5.5) was utilized for this purpose. The machine was modified (in accordance with ASTM C78-64) by fabricating both support and applied load apparatus. Figure 5.6 is a diagrammatic view of this modified apparatus. The load was applied by slowly rotating a hand crank which in turn moved the specimen upward against the loading points. Applied load was determined from the deflection of the proving ring at the top of the apparatus. The load was applied until the concrete fractured. This rupture was noted by a severe drop in the applied load while the crank was still being rotated. According to ASTM C78-64, the modulus of rupture is calculated in the following manner:

- (a) If the fracture occurs within the middle third of the span length, i.e., between the two loading points, the modulus of rupture is calculated by:

$$R = \frac{Pl}{bd^2} \quad \text{where:}$$

R = modulus of rupture, psi,

P = maximum applied load, lbs.,

l = span length, in.,

b = average width of specimen, in.,

d = average depth of specimen, in.

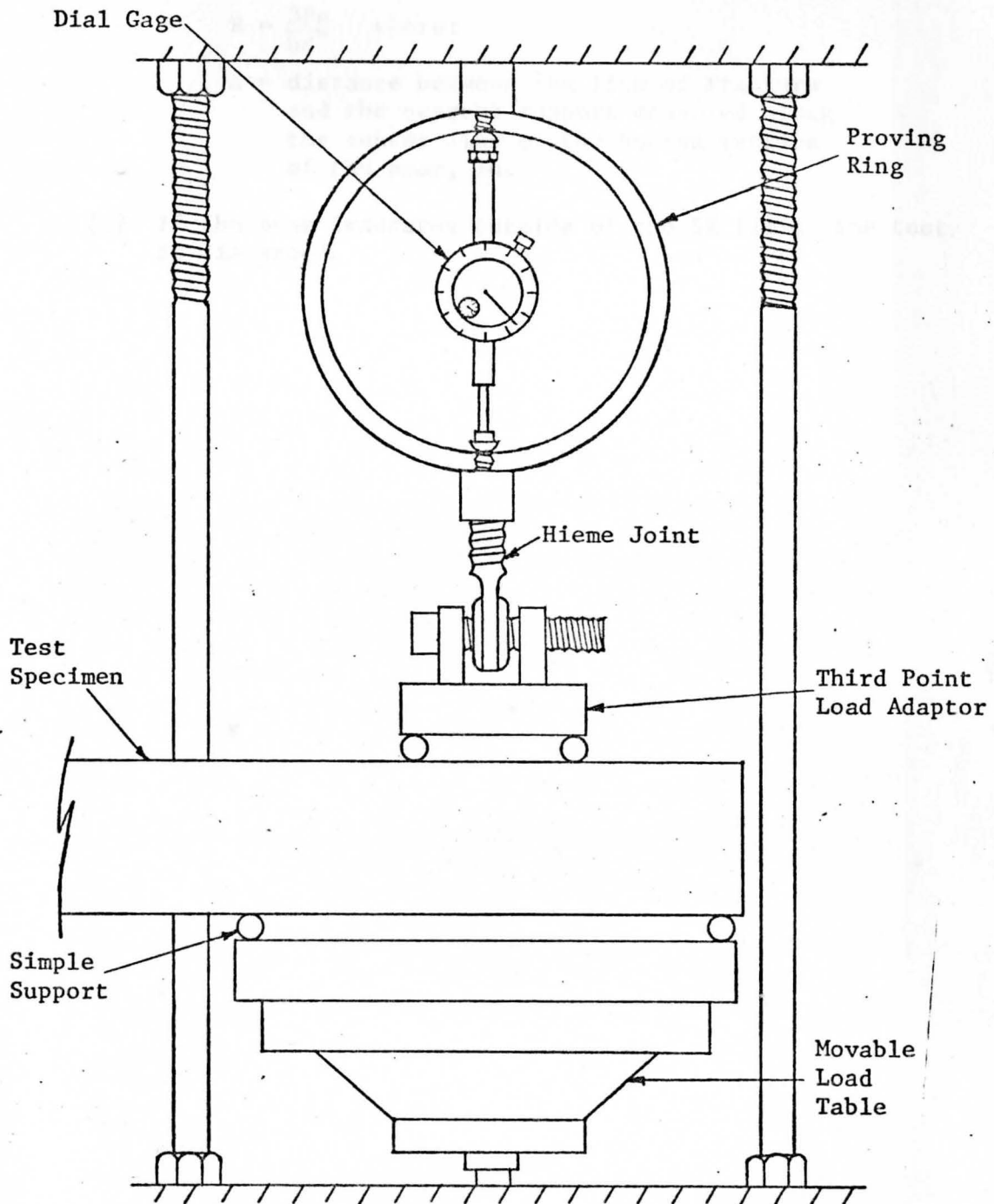


FIGURE 5.6
MODULUS OF RUPTURE APPARATUS

- (b) If the fracture occurs outside the middle third of the span by not more than 5% of the span length, the modulus of rupture is calculated by:

$$R = \frac{3Pa}{bd^2} \quad \text{where:}$$

a = distance between the line of fracture and the nearest support measured along the center line of the bottom surface of the beam, in.

- (c) If the beam fractures outside of the 5% limit, the test is discarded.

CHAPTER VI

TEST DATA AND EVALUATION

The freeze-thaw tests were performed over a period of nine months of continuous testing in accordance with the procedure set forth in Chapter V. The time necessary to complete the tests was longer than originally anticipated because of the large number of freeze-thaw cycles evaluated and the length of time required for a single cycle. As was stated in Chapter V the desired length of time to complete a single freeze-thaw cycle, according to ASTM C290-67, is two to four hours. Because of the excellent insulating properties inherent to low-density concrete, the time required for a single cycle was found to be six to eight hours.

There were various types of failure observed with the mode of failure depending upon the type of concrete and the surface treatment used. Each type of failure will be discussed individually. The most common type of failure observed for the epoxy coatings was splitting or cracking of the coating. This splitting can be attributed to several different factors. Most of the epoxy treatments produce a hard, non-yielding shell around the specimens which is tightly bonded to the concrete. As the specimen was cycled, the expansion and contraction of the concrete and the coating may have differed appreciably, thereby establishing stress in the coating. In such a non-elastic coating, these stresses may have been sufficient to cause a crack in the coating. Once a crack is initiated, it will inevitably propagate and severe splitting will continue with intrusion

of water around the crack and its subsequent freezing. Splitting of the coatings may also have been caused by thermal shock due to the accelerated freeze-thaw rate. A common household dish which has been in a freezer for a period of time will crack if held over a flame immediately after removal from the freezer. The rate at which the coated specimens were cycled may have been such so as to cause a similar sudden rupture in the brittle coating. Another possible cause of splitting may have been the build-up of ice in a particular area of the specimen. Intrusion of water through a pinhole or flaw in the coating creates high stresses in the coating upon freezing which in turn could have produced rupture. Figures 6.1 through 6.3 illustrate some of the severe splitting encountered during the testing.

On the specimens coated with stronger and more elastic materials the most common type of failure was heaving. Heaving is caused by the accumulation of large amounts of moisture and its subsequent freezing in an isolated area of the concrete. In all cases, the moisture accumulation was either directly beneath the coating or not more than $\frac{1}{4}$ " below it. This water accumulation occurred in the same manner as that previously described in the splitting mode of failure. The distinction between the two failure modes is that in the case of heaving the coating is strong enough or elastic enough to prevent splitting. The damage is, therefore, directed toward the concrete. In the case of an elastic coating, the growing ice mass pushes up on the coating causing it to deform considerably. The coating, however, is bonded to the concrete and one of two actions will result. Either the bond between the coating and the concrete is destroyed, or a layer



FIGURE 6.1
SPLITTING OF BITUMASTIC 300-M
ON P4 AFTER 100 CYCLES

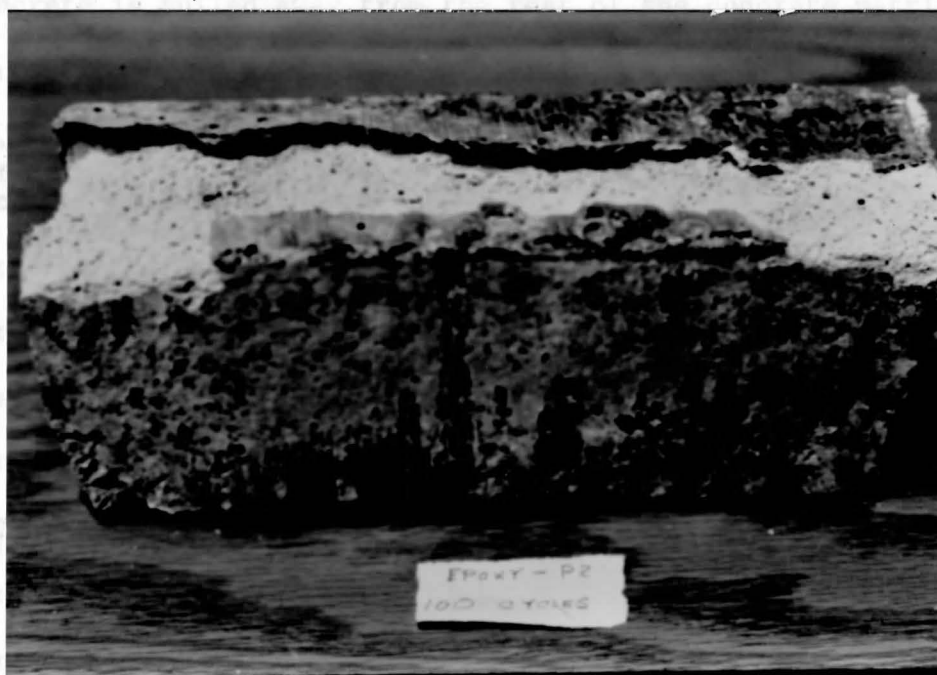


FIGURE 6.2
SPLITTING OF EPOXY RESIN 1391 ON P2
AFTER 100 CYCLES (A PORTION OF THE
COATING HAS BEEN REMOVED TO SHOW THE
DISINTEGRATION OF THE UNDERLYING CONCRETE)

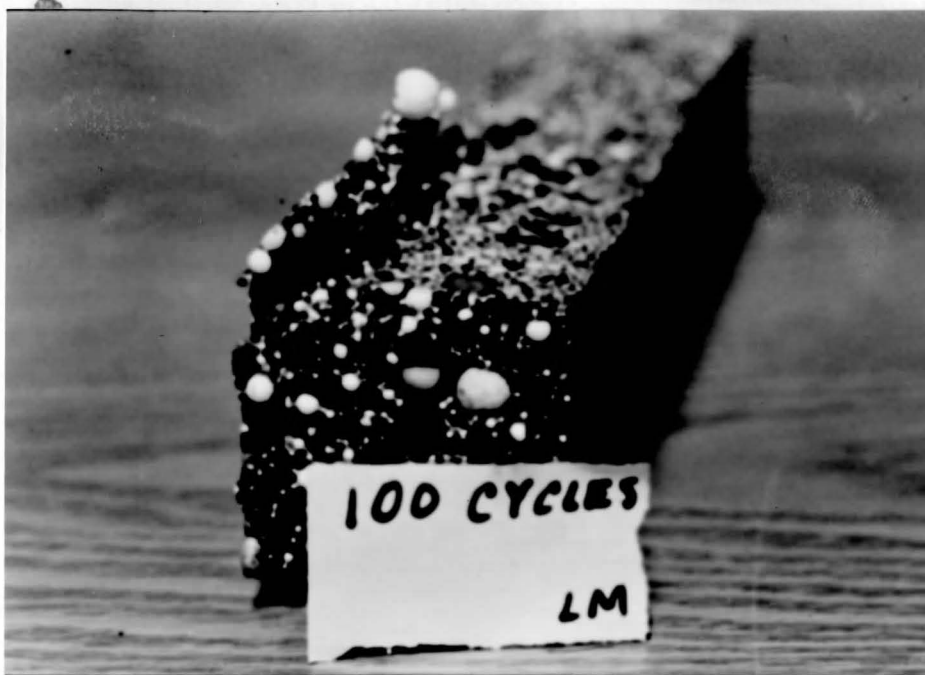


FIGURE 6.3
SPLITTING OF LO-MOD
ON D4 AFTER 100 CYCLES

of concrete is pulled away from the rest of the concrete matrix. In either case, room is made for the accumulation of more water and hence, further deterioration. In the case of a strong, non-elastic coating underlied by a growing ice mass, the concrete gel structure is destroyed since only limited yielding of the coating is permitted. This deterioration is evidenced by a spongy structure below the coating rather than a noticeable bulge in the coating. Examples of heaving can be seen in Figures 6.4 and 6.5.

The non-epoxy coatings which act to saturate the top layer of the concrete rather than form a protective shell around the concrete had unique mannerisms of failure. On these types of specimens, namely those treated with linseed oil, Silicon Moisture Repellant, etc., slight surface scaling was the predominant mode of failure up to a

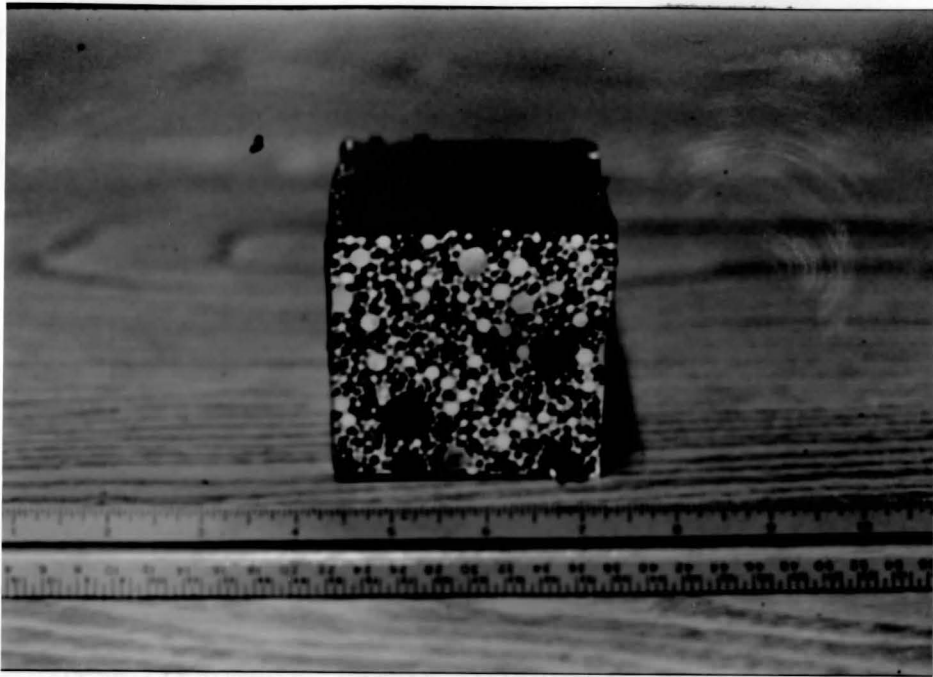


FIGURE 6.4
HEAVING OF AQUA-BASE ON D4

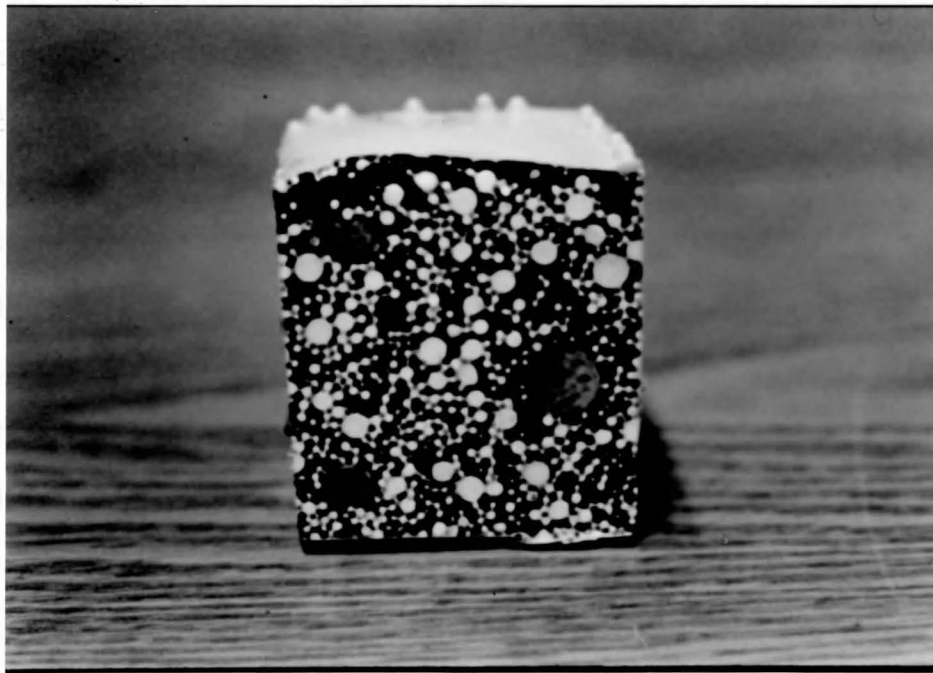


FIGURE 6.5
HEAVING OF AQUA-TOP ON D4

point at which the specimens began to spall completely, i.e., large layers of concrete separated from the specimen (see Figure 6.6). Water absorption was usually extremely high and sometimes exceeded that of uncoated specimens. This can be explained by the fact that these types of treatments do not prevent water from intruding into the concrete, but create a layer of dense treatment saturation which may, to a certain degree, trap the water within the specimen (see Figure 6.7).

A few of the treatments were considered completely inadequate as the coating almost totally disintegrated after twenty-five or less cycles. These treatments, namely Bituplastic No. 28, lacquer, concrete paint, and paraffin, were excluded from further evaluation after limited testing.

For the sake of comparison, the type of failure encountered with the uncoated specimens must be noted. Failure of the uncoated specimens was drastic. Deterioration began after only a few cycles and was marked by surface scaling of the specimens. Scaling proceeded rapidly and a loss of approximately one-third of the volume of the specimen was sometimes encountered over the 100 cycle test period. Often uncoated specimens became so weak that crumbling occurred in an attempt at removal from the freeze-thaw cabinet.

With a discussion of the types of failure in mind, the specific test results will now be presented. Table 6.1 is a listing of the deterioration encountered for all the cycled specimens. It can be seen that some of the categories have a listing of "not evaluated". Such an entry indicates that those particular treatments were

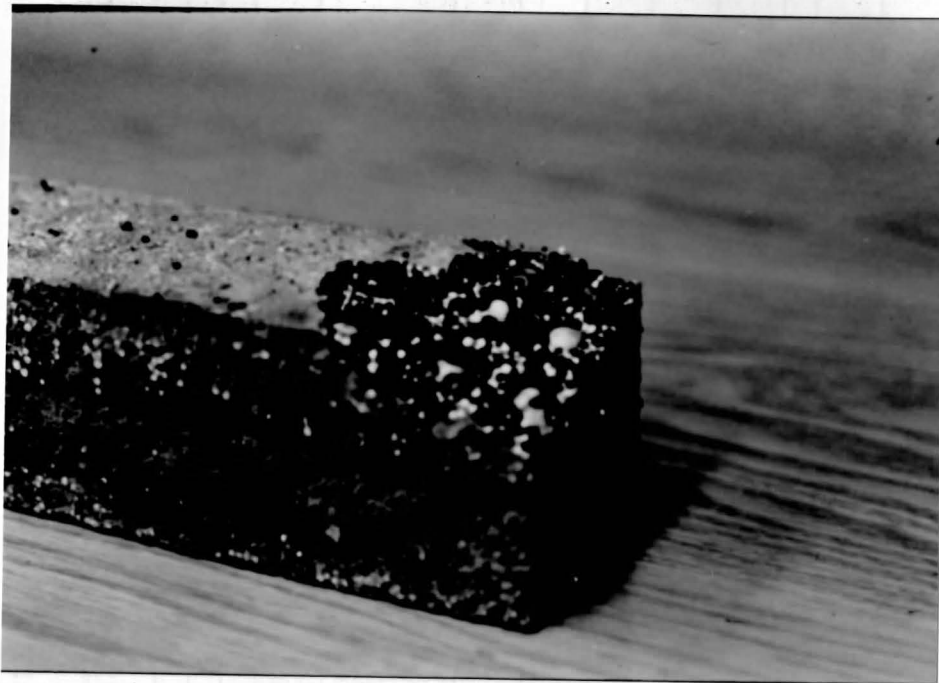


FIGURE 6.6
SPALLING OF LINSEED OIL ON D4



FIGURE 6.7
SPALLING OF LINSEED OIL ON P2
(NOTE LAYERED EFFECT)

TABLE 6.1
VISUAL DETERIORATION OF FREEZE-THAW SPECIMENS

SURFACE TREATMENT	NO. OF FREEZE-THAW CYCLES	EFFECT ON D4	EFFECT ON D2	EFFECT ON P2
Bituplastic No. 28	25	Severe scaling of coating Test discontinued	Not evaluated	Severe scaling of coating Test discontinued
	50	--	--	--
	75	--	--	--
	100	--	--	--
Bitumastic 300-M	25	No deterioration	Cracking and spalling of coating	Not evaluated
	50	No deterioration in Spec. 1 and 2 Spec. 3 developed small crack in coating	Severe deterioration Coating poorly bonded to concrete Test discontinued	--
	75	Cracking of coating on all Spec.	--	--
	100	Severe heaving and cracking of coating	--	--
Silicon Moisture Repellant	25	No apparent deterioration Large water absorption	Slight scaling	No deterioration
	50	Moderate deterioration	Severe scaling Test discontinued	Severe scaling Test discontinued
	75	Spec. crumbled to the touch	--	--
	100	Total deterioration	--	--
Aqua-Base	25	No deterioration Some pinholing	Not evaluated	Not evaluated
	50	No deterioration Water absorption through pinholes	--	--
	75	No deterioration in Spec. 2 and 3 Large heave of	--	--

TABLE 6.1 (Continued)

SURFACE TREATMENT	NO. OF FREEZE-THAW CYCLES	EFFECT ON D4	EFFECT ON D2	EFFECT ON P2
Aqua-Base (cont'd)	75	coating on Spec. 1		
	100	Severe heaving of coating on Spec. 1 and 3	--	--
Aqua-Top	25	No deterioration	Cracking of coating on all Spec.	No deterioration
	50	No deterioration of Spec. 1 and 2 Crack in coating on Spec. 3	Slight cracking of coating on Spec. 1 Severe cracking and heaving of coating on Spec. 2 and 3	Coating slightly cracked on all Spec. Coating heaved slightly on Spec. 3
	75	No deterioration of Spec. 2 Coating heaved on Spec. 1 Coating cracked on Spec. 3	Severe splitting of coating on all Spec. Tests discontinued	Coating cracked and heaved on all Spec.
	100	No change	--	Coating severely cracked and heaved on all Spec.
Lo-Mod	25	No deterioration	No deterioration	No deterioration
	50	No deterioration	No deterioration	No deterioration
	75	No deterioration of Spec. 1 and 2 Coating cracked and slightly heaved on Spec. 3	No deterioration of Spec. 1 and 2 Slight cracking of coating on Spec. 3	Coating slightly cracked and heaved on all Spec.
	100	Coating cracked and heaved on all Spec.	Slight flaking of coating on all Spec. Slight cracking of coating on Spec. 3	Coating flaked on all Spec. Coating severely cracked on Spec. 3
Hi-Mod	25	No deterioration	Not evaluated	Not evaluated
	50	No deterioration of Spec. 3 Coating slightly cracked on Spec. 1 and 2	--	--

TABLE 6.1 (Continued)

SURFACE TREATMENT	NO. OF FREEZE-THAW CYCLES	EFFECT ON D4	EFFECT ON D2	EFFECT ON P2
Concrete Paint (cont'd)	75	--	--	--
	100	--	--	--
Epoxy Resin 1391	25	No deterioration	No deterioration	No deterioration
	50	No deterioration	Slight flaking of coating	No deterioration
	75	No deterioration	Coating flaked and cracked on all Spec.	No deterioration of Spec. 2 and 3 Coating cracked on Spec.1
	100	No deterioration	Coating severely flaked and cracked on all Spec.	Coating slightly cracked and flaked on all Spec.
Comcoat	25	No deterioration	No deterioration	No deterioration
	50	No deterioration	No deterioration of Spec. 1 Coating slightly heaved on Spec. 2 and 3	No deterioration of Spec. 1 and 2 Slight separation of coating from concrete in Spec. 3
	75	No deterioration	Same as at 50 cycles	Separation of coating from concrete on all Spec.
	100	No deterioration	Same as at 50 cycles	Coating intact but nearly complete separation from concrete on all Spec.
Uncoated	25	Slight scaling	Slight scaling	Scaling
	50	Scaling Spec. 2 spalled upon removal from chamber	Severe scaling	Severe scaling
	75	Severe spalling	Severe spalling Test discontinued	Severe scaling
	100	Severe spalling	--	Severe surface scaling but no large segment heaving or cracking

TABLE 6.1 (Continued)

SURFACE TREATMENT	NO. OF FREEZE-THAW CYCLES	EFFECT ON D4	EFFECT ON D2	EFFECT ON P2
Hi-Mod (cont'd)	75	Coating cracked and heaved on all Spec.	--	--
	100	Coating severely cracked and heaved on all Spec.	--	--
Linseed Oil	25	No deterioration	No deterioration	No deterioration
	50	Slight scaling	No deterioration	Slight scaling
	75	Slight scaling A layer of concrete heaved in Spec. 3	No deterioration of Spec. 1 and 2 Spec. 3, slight deterioration	Severe damage High water absorption Coating heaved on all Spec.
	100	Spec. 3 spalled where heave had previously occurred Moderate scaling on Spec. 1 and 2	Moderate deterioration on Spec. 1 and 2 Spec. 3, severe spalling	Spec. spalled upon removal from chambers
Lacquer	25	Not evaluated	Not evaluated	Coating deteriorated Concrete slightly scaled
	50	--	--	Scaling
	75	--	--	Severe scaling
	100	--	--	Concrete severely spalled
Paraffin	25	Coating deteriorated on all Spec.	Not evaluated	Coating severely scaled Test discontinued
	50	Coating severely deteriorated Concrete scaled	--	--
	75	Severe scaling of concrete Concrete heaved on Spec. 3	--	--
	100	Further scaling	--	--
Concrete Paint	25	Severe scaling of coating Test discontinued	Not evaluated	Severe scaling of coating Test discontinued
	50	--	--	--

determined unsatisfactory in the initial tests and thus, did not warrant further evaluation on other types of concrete. Table 6.2 is a listing of the moisture absorption characteristics of all the specimens. The moisture absorption is presented in terms of the percentage of increased weight over the initial air dry weight of the specimens, i.e., the weight before initiation of freeze-thaw testing. The results of the modulus of rupture tests are given in Table 6.3. Results are tabulated only for those treatments which survived the complete 100 cycles of testing. Modulus of rupture figures are listed for both cycled and uncycled specimens along with the percent reduction in the modulus of rupture.

It was stated in Chapter V that complete durability testing was to be performed on D4, D2, and P2 and that D3 and P4, which differ from D2 and P2 only by water/cement ratios, were to be evaluated to a lesser degree in order to determine if a significant difference in durability existed. The water/cement ratio is considered to be a prime factor in the freeze-thaw resistance of concrete.⁽¹⁷⁾ The lower the water/cement ratio, the higher the resistance to freeze-thaw cycling. This is attributed to decreased capillary void space within the concrete which in turn reduces the hydraulic pressures developed by capillary ice growth. All of the low-density concretes considered in this study are highly susceptible to freeze-thaw cycling effects. It is clear that none of the concretes could survive for any length of time in Northern climates without some protective treatment. The object of this study was to find those coatings which will enable the concretes to be used in attenuator construction. D3 and P4 have

TABLE 6.2
AVERAGE MOISTURE ABSORPTION FOR CYCLED SPECIMENS

SURFACE TREATMENT	NO. OF FREEZE-THAW CYCLES	AVERAGE MOISTURE ABSORPTION AS PERCENTAGE OF INITIAL WEIGHT		
		ON D4 (%)	ON D2 (%)	ON P2 (%)
Bituplastic No. 28	25	*	--	*
	50	--	--	--
	75	--	--	--
	100	--	--	--
Bitumastic 300-M	25	63.50	76.37	--
	50	68.98	*	--
	75	72.70	--	--
	100	*	--	--
Silicon Moisture Repellant	25	98.97	47.27	44.77
	50	114.43	*	*
	75	122.90	--	--
	100	*	--	--
Aqua-Base	25	31.03	--	--
	50	40.60	--	--
	75	48.20	--	--
	100	48.60	--	--
Aqua-Top	25	33.43	65.17	39.03
	50	51.43	85.00	50.73
	75	56.30	96.30	63.57
	100	56.70	--	72.27
Lo-Mod	25	54.77	56.22	49.73
	50	64.37	69.98	59.90
	75	70.47	71.15	71.10
	100	72.63	72.86	79.30
Hi-Mod	25	57.37	--	--
	50	66.90	--	--
	75	72.70	--	--
	100	76.67	--	--
Linseed Oil	25	20.93	38.50	30.60
	50	57.07	56.33	44.80
	75	65.70	71.40	54.70
	100	67.30	72.95	*
Lacquer	25	--	--	43.53
	50	--	--	46.63
	75	--	--	*
	100	--	--	*
Paraffin	25	33.57	--	*
	50	47.87	--	--
	75	48.40	--	--
	100	50.83	--	--
Concrete Paint	25	*	--	*
	50	--	--	--
	75	--	--	--
	100	--	--	--

*Scaling too severe for accurate weight calculations

TABLE 6.2 (Continued)

SURFACE TREATMENT	NO. OF FREEZE-THAW CYCLES	AVERAGE MOISTURE ABSORPTION AS PERCENTAGE OF INITIAL WEIGHT		
		ON D4 (%)	ON D2 (%)	ON P2 (%)
Epoxy Resin 1391	25	19.00	57.37	28.80
	50	25.60	58.00	36.90
	75	26.20	60.30	40.53
	100	27.70	61.60	43.77
Comcoat	25	2.40	20.30	32.00
	50	5.73	35.43	47.90
	75	6.70	40.87	55.90
	100	7.33	46.70	67.23
Uncoated	25	62.30	83.25	31.95
	50	73.50	90.70	36.35
	75	*	*	40.70
	100	*	--	*

TABLE 6.3
AVERAGE MODULUS OF RUPTURE FOR
CYCLED AND UNCYCLED SPECIMENS

SURFACE TREATMENTS	TYPE OF CONCRETE	AVERAGE MODULUS OF RUPTURE (PSI)		
		UNCYCLED SPECIMENS	CYCLED SPECIMENS (100 CYCLES)	% REDUCTION
Bitumastic 300-M	D4	102.79	41.94	59.2
	D2	--	--	--
	P2	--	--	--
Silicon Moisture Repellant	D4	81.97	9.18	88.8
	D2	--	--	--
	P2	--	--	--
Aqua-Base	D4	172.88	81.16	53.1
	D2	--	--	--
	P2	--	--	--
Aqua-Top	D4	187.51	144.14	23.1
	D2	--	--	--
	P2	77.00	50.23	34.8
Lo-Mod	D4	142.34	45.08	68.3
	D2	87.62	34.36	60.8
	P2	78.40	58.30	25.6
Hi-Mod	D4	114.80	34.45	70.0
	D2	--	--	--
	P2	--	--	--
Linseed Oil	D4	80.50	23.87	70.3
	D2	129.53	34.92	73.0
	P2	118.42	52.36	55.8
Lacquer	D4	--	--	--
	D2	--	--	--
	P2	114.33	73.65	35.6
Paraffin	D4	94.51	24.99	73.6
	D2	--	--	--
	P2	--	--	--
Epoxy Resin 1391	D4	129.56	82.63	36.2
	D2	80.20	27.25	66.0
	P2	131.60	122.45	7.0
Comcoat	D4	63.70	48.42	24.0
	D2	68.05	36.05	47.0
	P2	89.60	69.15	22.8

water/cement ratios higher than those of D2 and P2, respectively, indicating that D3 and P4 are more susceptible to freeze-thaw damage. The treatments, therefore, which are most effective on D4, D2, and P2 can be assumed to be the ones most effective on D3 and P4. In order to determine the effect of the water/cement ratio, two of the coatings, Comcoat and Epoxy Resin 1391, were evaluated by a 50 cycle freeze-thaw test on both D3 and P4. Table 6.4 is a comparative tabulation of these results with those obtained in similar tests with D2 and P2. It can be seen that a change in water/cement ratio has a dramatic effect upon the absorption of water. The added amount of capillary void space due to the increased water/cement ratio increases the ease with which water can travel through the concrete, thereby making much more total void space available for occupation with water. The freezing of this large quantity of water, particularly in concretes having an extremely weak gel structure, is extremely damaging. It is highly recommended, therefore, that the low-density concrete mixes used for attenuator construction be of the lowest possible water/cement ratio. It should be noted that no change was observed in the behavior of the coatings due to the change in water/cement ratio. It is believed that effects caused by a change in water/cement ratio are best described by moisture absorption.

Care must be taken when examining all the data presented. No one method of examination, i.e., visual, moisture absorption, or reduction in modulus of rupture, can be used to choose the best treatments. All observations must be considered, bearing in mind the mechanisms of freeze-thaw damage and the criteria established in Chapter I.

TABLE 6.4
 MOISTURE ABSORPTION COMPARISON WITH RESPECT TO
 A CHANGE IN WATER/CEMENT RATIO

	TYPE OF SPECIMEN							
	EPOXY RESIN 1391				COMCOAT			
	ON D2	ON D3	ON P2	ON P4	ON D2	ON D3	ON P2	ON P4
Water/Cement Ratio	0.58	0.67	0.98	1.36	0.58	0.67	0.98	1.36
Average Water Absorption After 25 Cycles (%)	57.37	76.40	28.80	72.30	20.30	35.68	32.00	52.30
Average Water Absorption After 50 Cycles (%)	58.00	116.50	36.90	106.20	35.43	76.45	47.90	91.30

Tables 6.5 and 6.6 rank the evaluated treatments with respect to their effectiveness in preventing moisture absorption in each type of concrete at 50 cycles and 100 cycles respectively. Table 6.7 ranks the evaluated treatments with respect to the lowest reduction in the modulus of rupture. Examination of Tables 6.5 and 6.6 reveals that the lowest rates of water absorption were obtained with use of Comcoat and Epoxy Resin 1391. Linseed oil was also quite effective in preventing water absorption to 50 cycles or more. It should be further noted that the water absorption encountered by using Comcoat on D4 was significantly lower than that obtained from any other test specimen/coating combination. The specimens of D4 coated with Comcoat were, by far, the most effectively protected specimens. Figures 6.8, 6.9, 6.10, and 6.11 are photographs of these specimens coated with Comcoat and after 25, 50, 75, and 100 freeze-thaw cycles compared to uncoated specimens after the same number of cycles. Figure 6.12 shows typical cross-sections of these specimens along with identical uncycled specimens. The Comcoat applied on D4 was of a much thicker consistency and as such yielded a thicker coating than that applied on the other types of concrete. It is believed that if a similar consistency of Comcoat was uniformly used throughout the testing similar results would have been obtained. It is, therefore, recommended that Comcoat be applied to a thickness of approximately 4 mm which results from the thick consistency mentioned earlier.

Comparing the results obtained from Tables 6.5 and 6.6 to the reduction in the modulus of rupture presented in Table 6.7, the effectiveness of Comcoat and Epoxy Resin 1391 is further emphasized.

TABLE 6.5

RANKING OF SURFACE TREATMENTS ACCORDING TO THE AVERAGE AMOUNT OF WATER ABSORPTION AFTER 50 CYCLES (AS PERCENTAGE OF INITIAL WEIGHT)					
ON D4	%	ON D2	%	ON P2	%
Comcoat	5.73	Comcoat	35.43	Epoxy Resin 1391	36.90
Epoxy Resin 1391	25.60	Linseed Oil	56.33	Linseed Oil	44.80
Aqua-Base	40.60	Epoxy Resin 1391	58.00	Lacquer	46.63
Paraffin	47.87	Lo-Mod	69.98	Comcoat	47.90
Aqua-Top	51.43	Aqua-Top	85.00	Aqua-Top	50.73
Linseed Oil	57.07			Lo-Mod	59.90
Lo-Mod	64.37				
Hi-Mod	66.90				
Bitumastic 300-M	68.93				
Silicon Moisture Repellant	114.43				

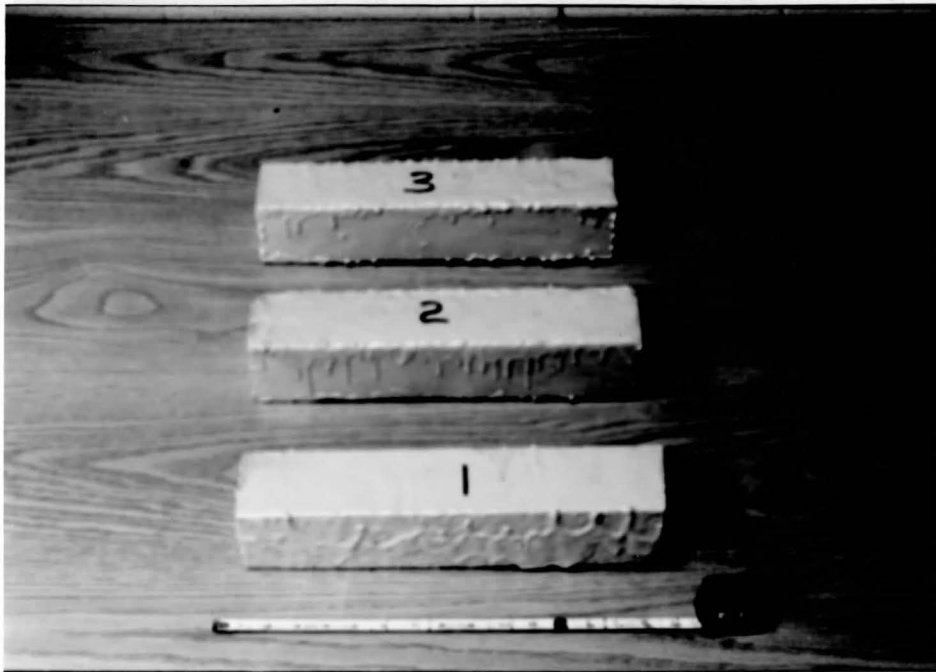
TABLE 6.6

RANKING OF SURFACE TREATMENTS
ACCORDING TO THE AVERAGE AMOUNT
OF WATER ABSORPTION AFTER 100 CYCLES
(AS PERCENTAGE OF INITIAL WEIGHT)

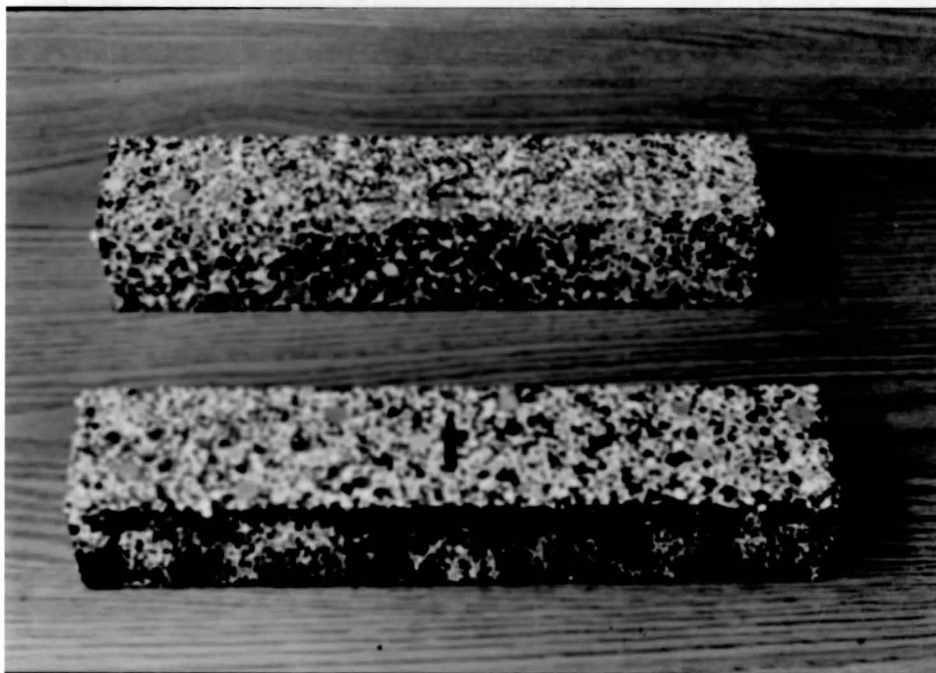
ON D4	%	ON D2	%	ON P2	%
Comcoat	7.33	Comcoat	46.70	Epoxy Resin 1391	43.77
Epoxy Resin 1391	27.70	Epoxy Resin 1391	61.60	Comcoat	67.23
Aqua-Base	48.60	Lo-Mod	72.86	Aqua-Top	72.27
Paraffin	50.83	Linseed Oil	72.95	Lo-Mod	79.30
Aqua-Top	56.70				
Linseed Oil	67.30				
Lo-Mod	72.63				
Hi-Mod	76.67				

TABLE 6.7
RANKING OF SPECIMENS ACCORDING TO
REDUCTION IN MODULUS OF RUPTURE

TYPE OF SPECIMEN	PERCENT REDUCTION IN MODULUS OF RUPTURE
Epoxy Resin 1391 on P2	7.0
Comcoat on P2	22.8
Aqua-Top on D4	23.1
Comcoat on D4	24.0
Lo-Mod on P2	25.6
Aqua-Top on P2	34.8
Lacquer on P2	35.6
Epoxy Resin 1391 on D4	36.2
Comcoat on D2	47.0
Aqua-Base on D4	53.1
Linseed Oil on P2	55.8
Bitumastic 300-M on D4	59.2
Lo-Mod on D2	60.8
Epoxy Resin 1391 on D2	66.0
Lo-Mod on D4	68.3
Hi-Mod on D4	70.0
Linseed Oil on D4	70.3
Linseed Oil on D2	73.0
Paraffin on D4	73.6
Silicon Moisture Repellant	88.8



(a)

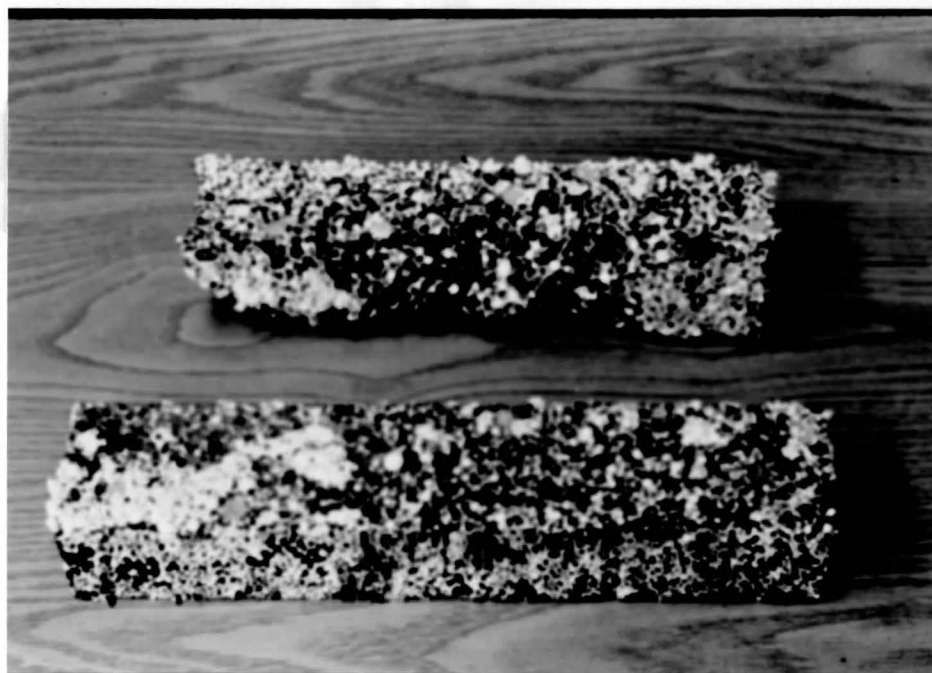


(b)

FIGURE 6.8
COMCOAT ON D4 (a) AND
UNCOATED D4 (b) AFTER 25 CYCLES

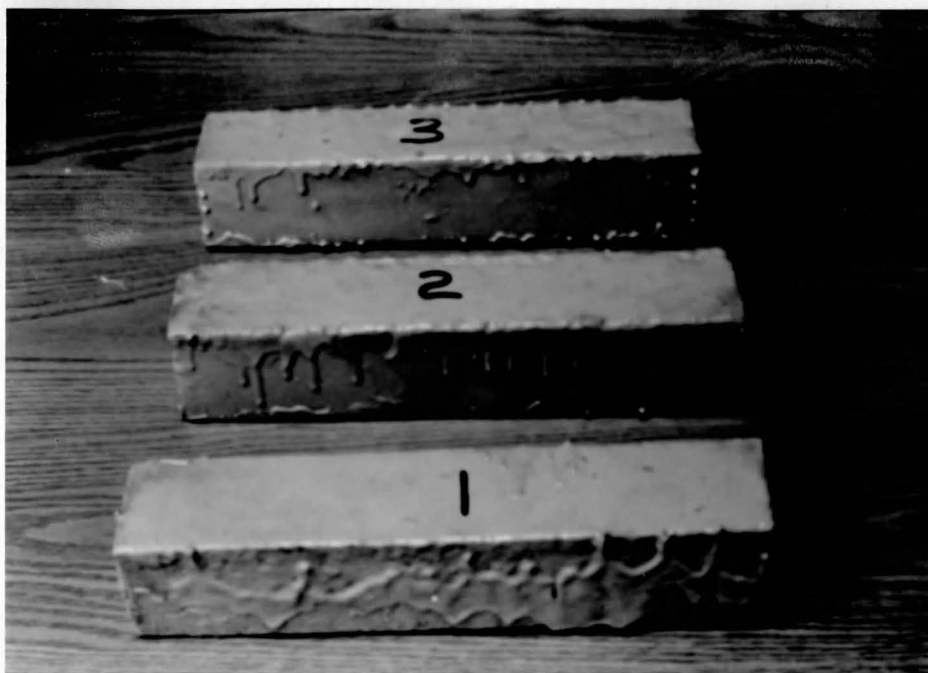


(a)

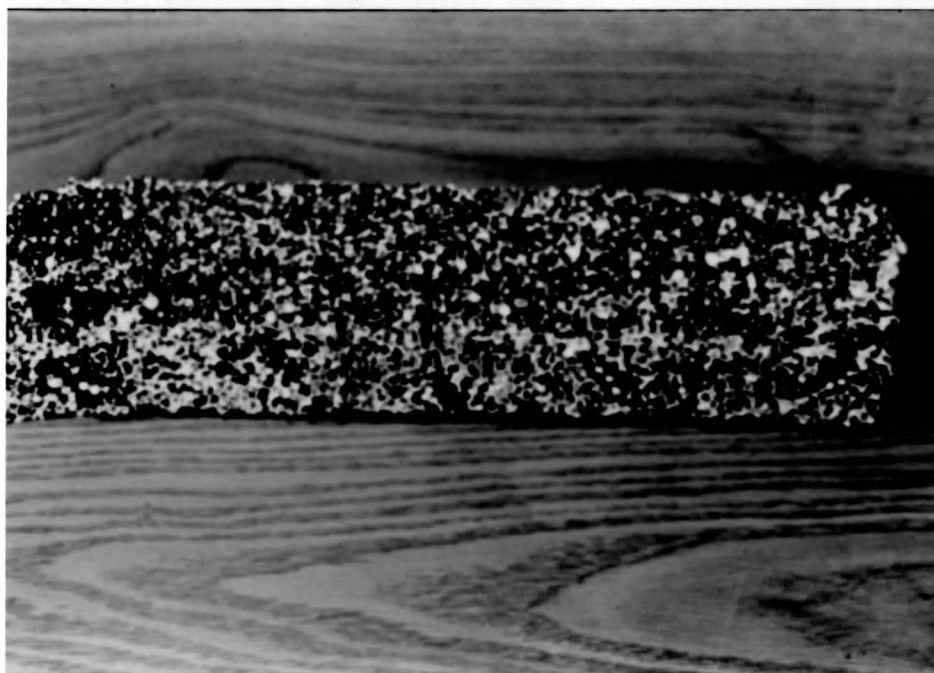


(b)

FIGURE 6.9
COMCOAT ON D4 (a) AND
UNCOATED D4 (b) AFTER 50 CYCLES

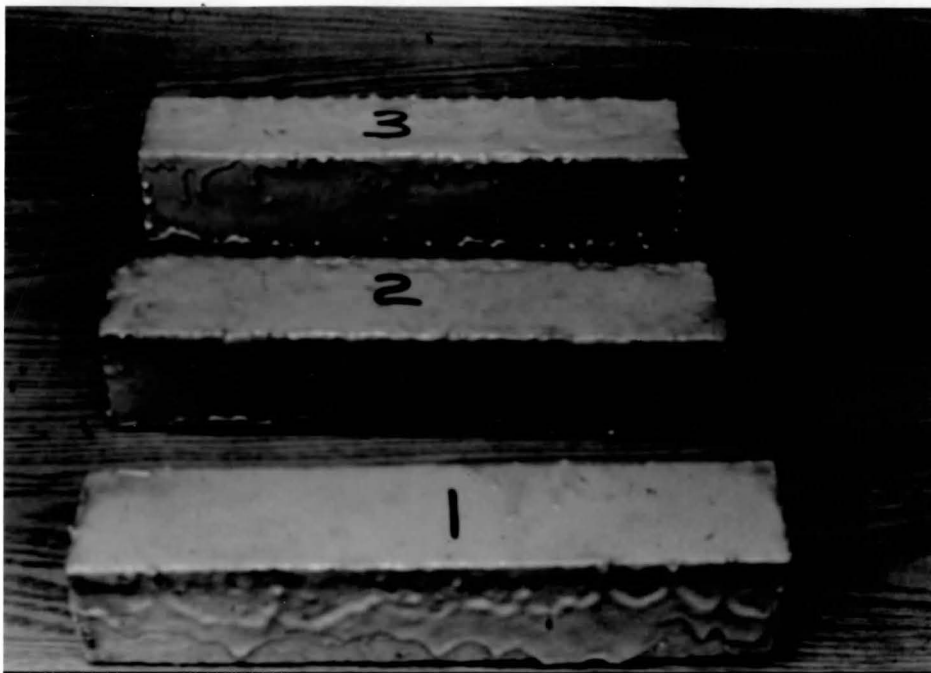


(a)

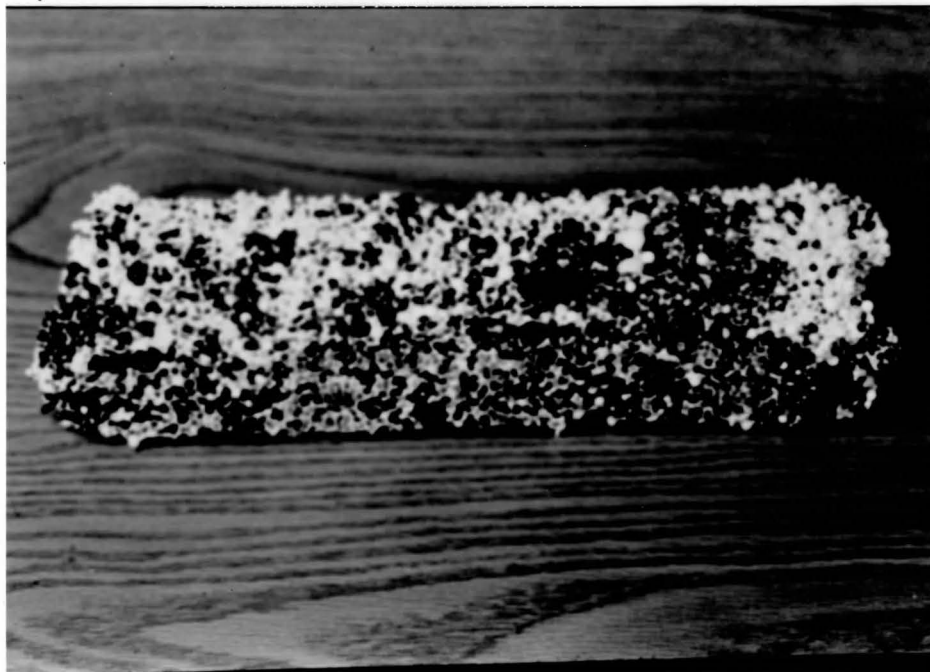


(b)

FIGURE 6.10
COMCOAT ON D4 (a) AND
UNCOATED D4 (b) AFTER 75 CYCLES

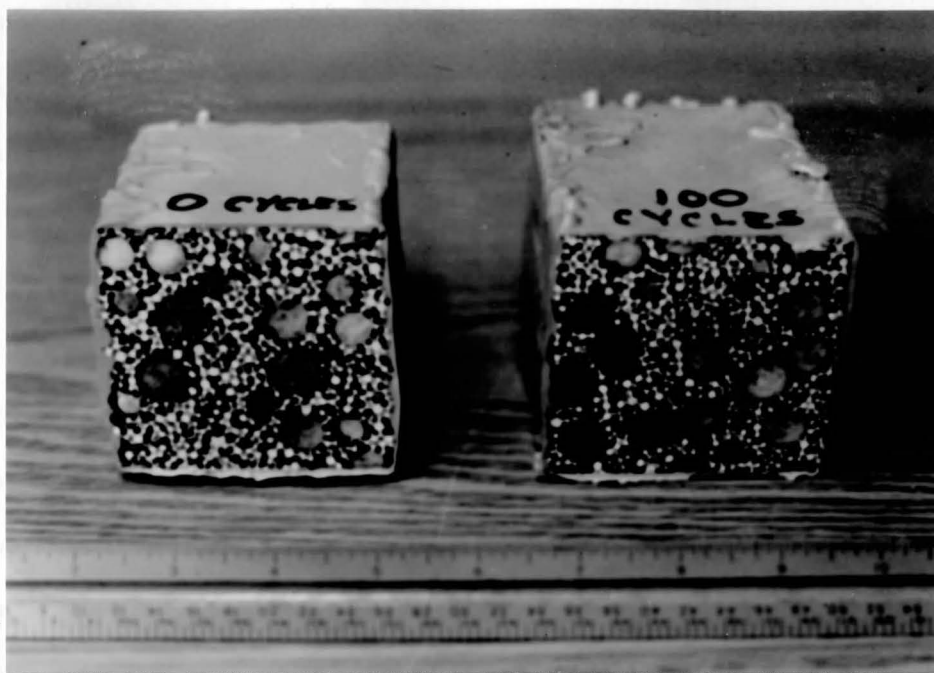


(a)

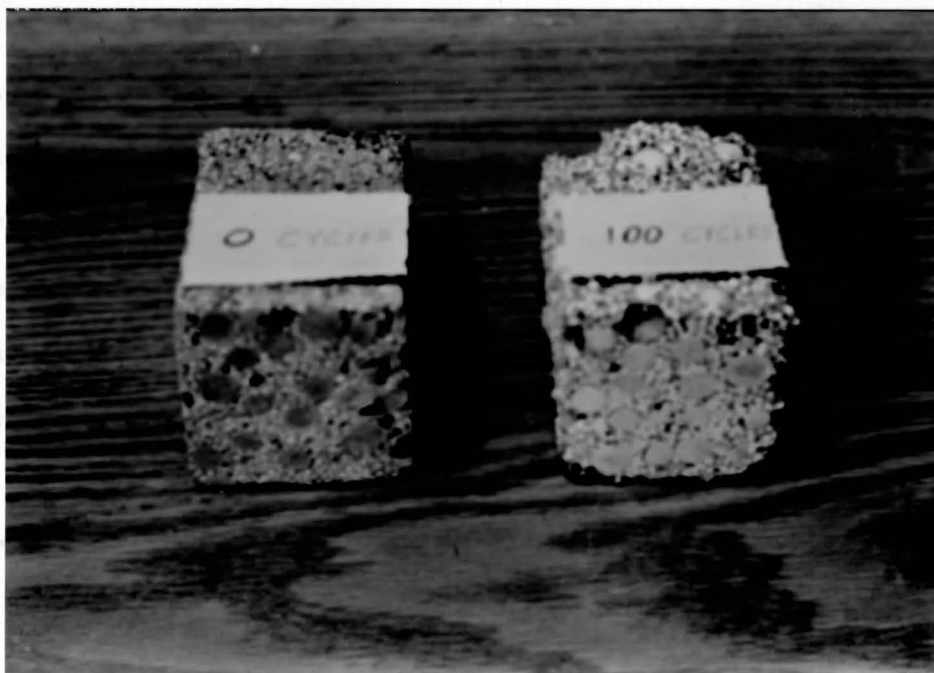


(b)

FIGURE 6.11
COMCOAT ON D4 (a) AND
UNCOATED D4 (b) AFTER 100 CYCLES



(a)



(b)

FIGURE 6.12
TYPICAL CROSS-SECTION OF
CYCLED AND UNCYCLED COMCOAT ON P4 (a) AND
CYCLED AND UNCYCLED UNCOATED P4 (b)

Linseed oil, however, appears much lower in the rankings. This may be clarified by a closer examination of the behavior of the linseed oil treated specimens. Linseed oil was quite effective in protecting the concrete from deterioration up to 50 cycles. The modulus of rupture data, obtained after 100 cycles, was collected in the later, more drastic stages of the deterioration of the linseed oil specimens. In other words, the modulus of rupture data evaluates the damage done to a specimen after 100 freeze-thaw cycles, but reveals nothing about the rate of deterioration. A treatment effective up to 50 cycles may very well be effective for use in the attenuator installations. It was mentioned previously that 100 cycles was initially chosen as the maximum number of test cycles in order to fully exercise all the parameters involved in the durability evaluation of the specimens. This is not to imply that a crash attenuator is expected to experience such a large number of severe cycles since there exists no known correlation between laboratory cycling and field performance. The 100 cycle treatment in the laboratory was felt to represent the most severe field conditions that an attenuator with a short field life would ever experience.

If a structure having a short life-span is indeed being considered, one of the main considerations should be its cost. Structures with a minimal service-life do not warrant excessive initial costs. The cost of the surface treatment should, therefore, be as low as possible. Table 6.8 is a listing of the cost of each of the more effective coatings. The right-hand column of this table presents the estimated cost of the material for coating a field installation and is based upon 900 sq. ft. of adequate coverage.

TABLE 6.8
COST OF SURFACE TREATMENTS

SURFACE TREATMENT	COST/GAL	RECOMMENDED COVERAGE PER GALLON (Sq Ft/Gal)	APPROXIMATE COST OF TREATMENT FOR FIELD USE
Bitumastic 300-M	\$10.20	100	\$91.80
Silicon Moisture Repellant	2.20	175	11.30
Aqua-Top	27.00	125	194.40
Lo-Mod	27.00	125	194.40
Linseed Oil	6.00	175	30.90
Epoxy Resin 1391	15.00	100	135.00
Comcoat	20.00	10	1800.00

It can be seen that Comcoat, which is perhaps the most effective treatment available, is much too costly at this time to be applicable. It is, therefore, felt that the treatments which are most suitable for use with respect to protecting the attenuator from freeze-thaw effects and with respect to the cost involved are Epoxy Resin 1391 and linseed oil.

The criteria established in Chapter I for a surface treatment must be adhered to for maximum crash attenuator effectiveness. Criteria (a) and (c), freeze-thaw durability and cost, have already been discussed. Criteria (d), ease of application, is also met by both of these treatments since either can be easily applied by brush or conventional spray equipment. The cost of treatment for field use, given in Table 6.7, is based upon a two-coat application of both Epoxy Resin 1391 and linseed oil since it was recommended earlier that two coats of both of these treatments be used for full effectiveness.

Epoxy Resin 1391 produces a hard protective finish on the concrete and becomes, therefore, resistant to both puncture and chemical attack. Conversely, linseed oil does little to change the surface structure of the concrete other than give it a yellow tint. Criteria (e), (h), and (i) will, therefore, be maximized by use of Epoxy Resin 1391. The use of linseed oil will not increase the concrete's effectiveness with respect to these criteria, i.e., (e), (h), and (i).

Both Epoxy Resin 1391 and linseed oil are translucent coatings. Although linseed oil yellows the concrete to a certain degree, the structure maintains a "concrete" appearance with application of both treatments.

One of the most important of the criteria has yet to be discussed; i.e., criteria (b), prevention of spall under impact. The importance of this criteria has been further emphasized by the scale model tests of highspeed impacts. The model attenuators have demonstrated a tendency to spall dramatically under impact. Uncontained, flying concrete fragments could turn a single vehicle crash into a potential roadway hazard, since oncoming motorists might mistakenly interpret these spall fragments as normal concrete rather than easily crushable low-density fragments. Epoxy Resin 1391, as stated in Chapter III, has been specially developed to create extremely high bonding with fiberglass cloth. It is recommended that this cloth be used between coatings of the resin on the outer surfaces to prevent spalling under impact. If linseed oil is used, concrete spall may be contained by positioning light gage chicken wire or hardware cloth within the outer concrete walls of each module of the attenuator. This is, of course, only a recommendation which has no test results for confirmation. Recommendations such as this can only be substantiated by full scale tests or field evaluation of the prototype designs.

Epoxy Resin 1391 and linseed oil, although not ideal in their effectiveness, have been found to be the most practical treatments evaluated for use on low-density impact attenuators.

CHAPTER VII

IMPACT ATTENUATOR CONSTRUCTION

A highway impact attenuator should be a low-cost, easily constructed facility. Ideally, it should lend itself to easy fabrication and assembly. Hopefully, sections could be stockpiled at a central location and shipped to the erection site for installation or replacement in a minimal amount of time. The impact attenuator design presented in this study meets this criteria. The attenuator can be prefabricated in 40" x 20" x 36" modules which can easily be handled by two men. These modules can then be taken to the erection site and hand placed in the prescribed design configuration. Each attenuator consists of a total of sixteen of these modules which are bolted together with conventional stove bolts.

There are two proposed installation plans recommended. Figure 7.1 shows the temporary installation and although the name temporary implies a short lifespan, this configuration is recommended for sites of relatively low accident occurrence or in areas where attenuator usage may ultimately be discontinued. In other words, this installation is intended for use in areas where replacement of the attenuator is expected to be infrequent. The cost of this installation was kept to a minimum.

In areas of high collision expectancy, it is recommended that the permanent installation be used (see Figure 7.2). The permanent installation differs from the temporary installation only in the foundation or pad assembly and preparation. The temporary installation has

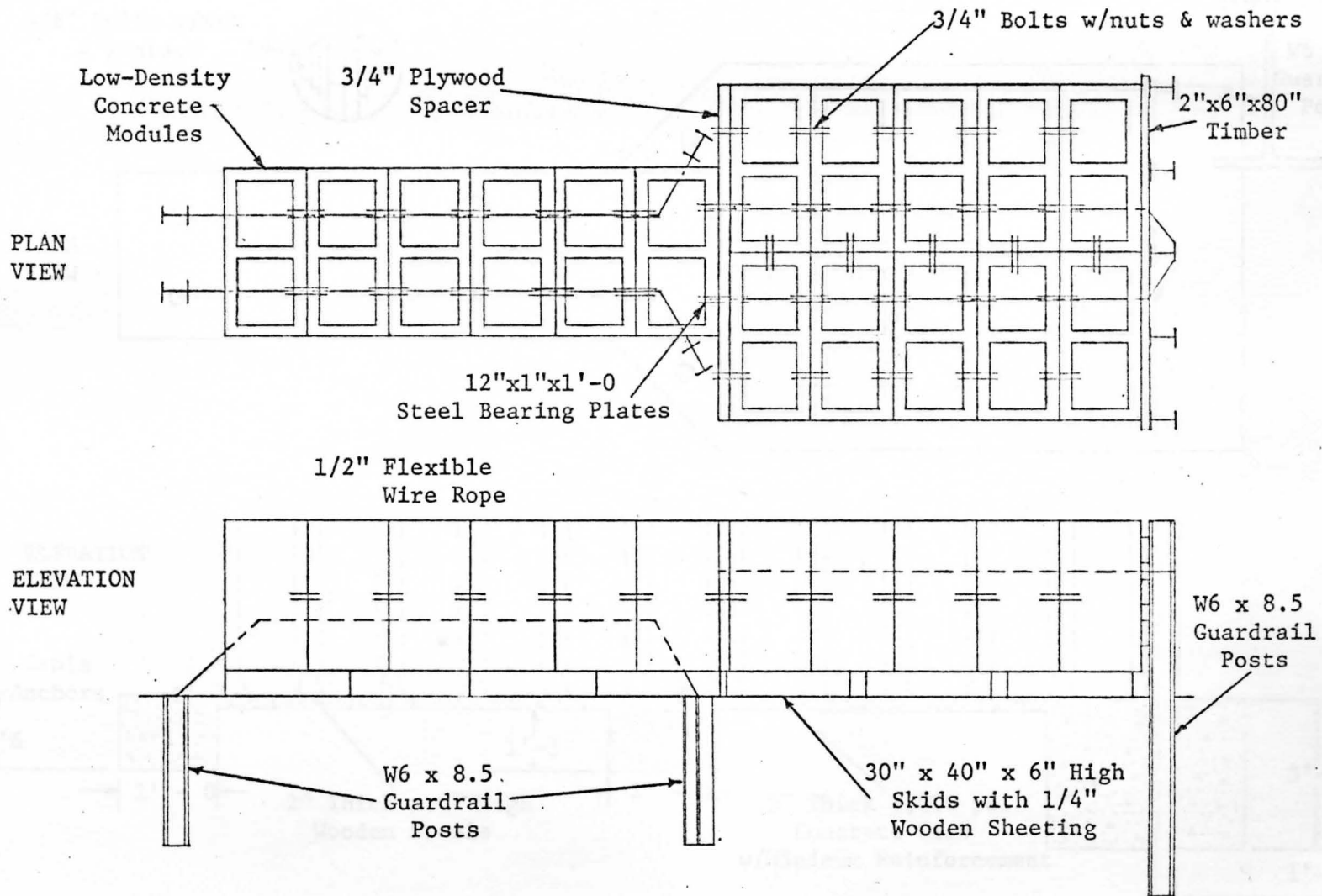


FIGURE 7.1
TEMPORARY ATTENUATOR INSTALLATION

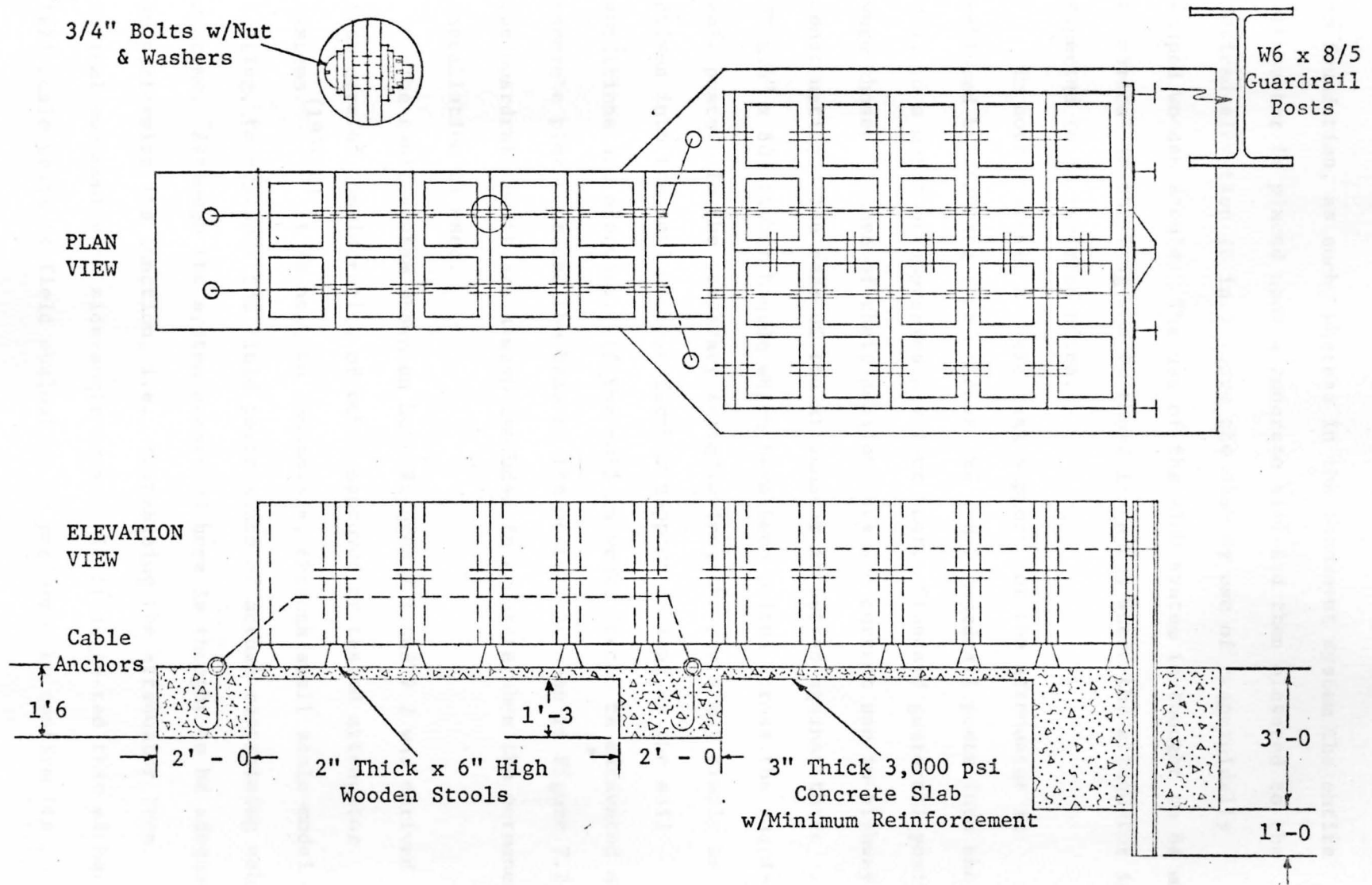


FIGURE 7.2
PERMANENT ATTENUATOR INSTALLATION

no foundation, as such, whereas in the permanent system the entire attenuator is placed upon a concrete slab and then elevated to the desired elevation (6 in.) above the slab by use of trapezoidally shaped wooden stools. The use of the slab system is thought to be more economical in the long run in those instances where the attenuator is expected to be replaced often.

In both systems, a rigid back support for the attenuator is achieved by securing five standard W6 x 8.5 guardrail posts into the soil to a depth of approximately four feet. Standard guardrail posts were chosen because of their availability and current use in highway construction. The rear of the attenuator is butted against three 2" x 6" x 80" timber boards which have been bolted across the guardrail posts. In the temporary installation, the posts may simply be driven into the soil without further support as long as the soil conditions are adequate. If the soil is weak, it can be excavated and concrete placed around the base of the posts. As seen in Figure 7.2, the guardrail posts are always imbedded in concrete when the permanent installation is used.

The cable system shown on both Figures 7.1 and 7.2 was derived from careful consideration of other approved or tested attenuator systems.⁽¹⁹⁾⁽²⁰⁾ It is next to impossible, through small scale-model testing, to evaluate the field performance of actual restraining cable systems. Although the system presented here is thought to be adequate in performing its function, i.e., restraining the attenuator from radical movement upon side-angle impact, it is suggested that either full scale tests or field evaluation be performed to confirm its

performance.

Having discussed some of the aspects of the attenuator's construction, a procedure for its construction will now be presented. The following is a step-by-step description of the construction of the impact attenuator.

Shop Work

- (a) The individual modules of the attenuator are fabricated, properly cured, and stockpiled.
- (b) The inside surfaces, only, of each module are coated with the desired surface treatment.
- (c) The modules are loaded on a truck for shipment to the erection site.

Field Work

- (d) Prior to the arrival of the modules, the site should have been prepared and should now be ready for installation of the attenuator. If a temporary installation, all guardrail posts should have been driven in place and the rear support structure erected. If a permanent installation, the concrete pad should have been poured and cured with cable anchors and back support in place.
- (e) Placement of the modules proceeds from rear to front. As the modules are placed, holes (using conventional hand tools) are drilled to facilitate the cables and the connecting bolts.
- (f) The cable is threaded through the modules as each module is placed and bolted to those already in place. Through the cable holes a short piece of PVC, or similar pipe, should be inserted to keep the cable from cutting through the concrete upon a side-angle collision.
- (g) After the rear (wide) portion of the attenuator is in place, the plywood spacer is positioned and bolted to the attenuator using the outermost two bolts.
- (h) A single module is centered in front of the spacer. The rear cables are threaded through the back wall of

this module, bearing plates are attached, and the cable is tied off.

- (i) The front cables are secured to the rear anchors located to the sides of the single module already positioned.
- (j) Installation of the front portion of the attenuator proceeds.
- (k) After the last module is secured, the cables are tied to the front anchors.
- (l) The outside and top surfaces of the attenuator are coated with the surface treatment, and the top joints (see plan views in Figures 7.1 and 7.2) are sealed.

It can be seen that the installation of the low-density concrete impact attenuator can be accomplished in a simple fashion, in a minimum of time, and without the need of special equipment or crews. Furthermore, its installation can be accomplished with a minimum of three men which in turn gives rise to low labor costs. In addition, the *cost of the materials* used to construct and install the attenuator is also low. Table 7.1 is a tabulation of approximate material costs for Perlite and Dycon attenuators and for both temporary and permanent installations. It should be noted that initial costs such as concrete forms, spray equipment, etc., along with labor costs, will amplify substantially the final cost of using these crash attenuators, but the total cost anticipated for construction and installation of these crash attenuators is low when compared to some of the attenuators currently in use.

Lastly, some mention must be made with respect to the mixing, casting, and handling of the modules. Throughout this study, inexperienced crews conducted these operations with minimal problems and

TABLE 7.1
MATERIAL COSTS FOR ATTENUATOR CONSTRUCTION

MATERIAL FOR DYCON ATTENUATOR	COST (\$)	MATERIAL FOR PERLITE ATTENUATOR	COST (\$)	MATERIAL FOR TEMPORARY INSTALLATION	COST (\$)	MATERIAL FOR PERMANENT INSTALLATION	COST (\$)
4.52 cu. yd. Dycon Concrete	163	4.52 cu. yd. Perlite Concrete	127	Ten 30"x40"x6" high Wooden Skids	30	4.78 cu. yd. 3000psi Concrete	143
Hardware	40	Hardware	40	5-7' W6 x 8.5 and 4-3' W6 x 8.5 Guardrail Posts	154	5-7' W6 x 8.5 Guardrail Posts	110
Coating*	135	Coating*	135	3 Pieces of 2"x6"x80" Timber	7	3 Pieces of 2"x6"x80" Timber	7
50 Yd. of Fiberglass Cloth	200	50 Yd. of Fiberglass Cloth	200	55 Ft. of 1/2" Flexible Wire Rope	32	55 Ft. of 1/2" Flexible Wire Rope	32
				Misc. Hardware	20	Misc. Hardware	20
TOTAL	538	TOTAL	502	TOTAL	243	TOTAL	312
Total Material Cost of Dycon Attenuator with Temporary Installation							780
Total Material Cost of Dycon Attenuator with Permanent Installation							849
Total Material Cost of Perlite Attenuator with Temporary Installation							744
Total Material Cost of Perlite Attenuator with Permanent Installation							813

*Cost for use of Epoxy Resin 1391

with a high degree of success with respect to the degree of consistent reproducibility. The shape of the module lent itself well to the construction of the forms. Handling of the modules presented no problems due to the low module weight and stiffness of the module walls. These attributes can be taken advantage of by most highway departments since their fabrication and erection crews will have no prior experience with these modules and attenuators.

CHAPTER VIII

CONCLUSIONS AND RECOMMENDATIONS

The use of low-density concrete for the construction of a highway impact attenuator has distinct advantages over other materials in that it is relatively easy to cast the desired configuration, it is lightweight, and it is efficient. More importantly, it is much less expensive than most other materials used in attenuator construction. The major drawback to using low-density concrete, which must be seriously considered, is its susceptibility to freeze-thaw cycling. The study revealed that all the low-density concretes considered deteriorated substantially after only a low number of freeze-thaw cycles. It must be recommended, therefore, that low-density concrete can only be employed as an attenuator material when proper freeze-thaw protection, as evaluated in Chapter VI, has been provided.

This study has dealt with some of the problems involved in the construction of and the freeze-thaw protection of highway impact attenuators. Feasible solutions to the major problems, namely low-cost durability protection through surface treatment of the concrete and construction and installation techniques, have been presented. Other problems exist, however, which cannot be evaluated in the laboratory or assessed by small scale model testing. Spalling of the concrete under impact, for example, presents one such problem which has not been completely evaluated. The spall prevention systems proposed, i.e., the use of fiberglass cloth or light-gage wire mesh, are impossible to effectively evaluate by small scale model tests. The

suggestions presented herein were based solely upon intuition, the experience obtained by working with the material, and observations made during the scale model attenuator tests. For these reasons, the proposed spall protection schemes are believed to be effective. The full effectiveness of these schemes, nevertheless, can only be evaluated by performance in the field or by full-scale testing.

Other problems which demand further consideration through field performance or full scale testing are: the relationship between the laboratory freeze-thaw test results and actual freeze-thaw deterioration; performance of the suggested cable restraining system; effectiveness of some aspects of the installation system such as the rear support device, bolting patterns, etc.; the ease with which the attenuator modules can be mass-produced; and the effect of roadside vibrations upon the proposed design.

The final conclusion of this study is that none of the aforementioned problems present serious drawbacks. It is believed that low-density concrete can be used to construct effective and low-cost highway impact attenuators and that when adequately protected can be utilized in adverse environmental conditions.

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