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Final Report

Assessing the Use of Mid-Range Water Reducers to Improve Constructability of Bridge Decks in Alabama

Submitted to

Highway Research Center
Auburn University

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on

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Assessing the Use of Mid Range Water Reducers to Improve Constructability of Bridge Decks in Alabama

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ABSTRACT

The two main sets of criteria that must be considered when developing a concrete mixture are the long-term requirements of the concrete as well as the short-term requirements during placement. A key ingredient in determining how both sets of requirements will perform is the amount of water present in the concrete mixture. The addition of too much water into the concrete mixture will lower the overall long-term performance of the concrete, such as low compressive strength, high volume change which leads to excessive drying shrinkage cracking, and poor durability. However, not enough water in the initial concrete mixture causes difficulties in placement, consolidation and finishing the concrete for contractors and this usually results in poor quality concrete.

Laboratory and field experimentations with concrete mixtures for bridge decks containing mid-range water reducers (MRWR), along with ALDOT standard bridge deck mixture for comparison, were conducted. The concrete mixtures included an improved bridge deck mixture containing MRWR as well as a 30% class "C"-fly ash replacement. Fresh and hardened properties were observed for concrete mixtures for both the laboratory and field experimentation, as well as the "workability" of the concrete mixtures tested in the field experiments.

Laboratory testing of the "improved" bridge deck mixture employing the use of MRWR displayed improved results relative to the ALDOT standard mixture, in both the fresh and hardened properties. However, the improvements were not significant enough to warrant further testing. The MRWR concrete mixtures did show some promise in effectively reducing the *w/c* ratio, which aids in the reduction of drying shrinkage.

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1. INTRODUCTION

1.1 Statement of Problem

There are two sets of criteria that must be considered when developing a concrete mixture:

1. Long-term requirements of the hardened concrete such as strength, durability, and volume stability, and
2. Short-term requirements, while the concrete is still in the plastic state, which are generally lumped together under the term "workability".

Unfortunately these two sets of requirements are not complementary, and a compromise is needed between them. However, the development of water reducing admixtures and the more recent development of superplasticers show great promise in overcoming the heretofore conflicting mixture requirements to attain good workability during placement, and good strength and durability in the hardened concrete. Indeed, high-range water reducing (HRWR) admixtures, or superplasticizers, appear to be the single biggest innovation in the concrete industry over the past couple of decades. They are known to allow reductions in water content, and the accompanying increase in strength and reductions in permeability and drying shrinkage, while at the same time increasing the workability and in-place quality and durability of concrete. Thus they can help in resolving the age-old conflict between owners wanting little water in their concrete (for improved hardened properties), and contractors wanting a lot of water (for improved workability).

The Alabama Department of Transportation (ALDOT) experimented with using Super-P concrete mixtures to improve constructability of bridge decks in Summer 1999 and unfortunately the results were not good. In the experimentation, some concrete producers and bridge contractors could not handle providing and/or working with Super-P concrete in an effective and reliable manner. Since mid-range water reducers (MRWR) are reported to be more user friendly, the ALDOT would like to see some laboratory and field experimentation with MRWR concrete mixtures for bridge decks. This was the impetus and purpose of this research.

1.2 Research Objectives

The objectives of this research were as follows:

- Conduct field experimentations with the use of MRWR in ALDOT's standard bridge deck concrete mixture to assess its construction friendliness and effect on pertinent hardened properties of the concrete.
- Identify an improved concrete mixture employing MRWR and perform laboratory testing to evaluate its fresh and hardened properties

1.3 Work Plan

A brief outline and discussion of the work plan to accomplish the project objectives is presented below:

1. Review the literature on concrete admixtures and water-reducers and talk with admixture suppliers to learn of the capabilities and sensitivities of these admixtures when used in Alabama's climate and with Alabama aggregates.
2. Assist the ALDOT as needed to arrange the placement of three bridge deck test spans employing the MRWR and concrete mixture designs as indicated in Fig. 1.1. The test spans will be placed during the Summer 2001, and will probably be located in the Birmingham area.

3. Monitor and document the construction friendliness of each of concrete mixture during placement.

4. Assist the ALDOT in performing standard fresh concrete testing on site along with preparing and later testing concrete cylinders for compressive strength. The ALDOT will perform the following testing.

    - Concrete Temperature
    - Unit Weight
    - Air content
    - Slump
    - Compressive strength (7, 28,56 days)

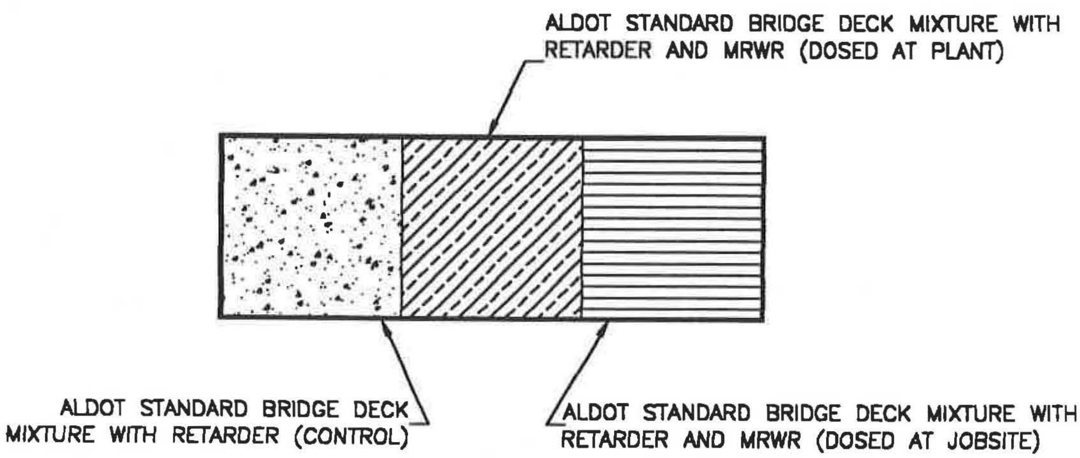

Fig. 1.1. Three Span Test Bridge Deck - Summer 2001 Placement

5. Prepare, with assistance from ALDOT, test specimens on site and bring these to Auburn for testing for:

    - Drying shrinkage
    - Rapid chloride ion penetration
    - Freeze-thaw/durability

6. Have follow-up meetings with concrete ready-mix suppliers and construction contractors to discuss the concrete mixtures, any production difficulties, and their construction friendliness.

7. Identify an improved bridge deck concrete mixture employing a MRWR (with assistance from ALDOT and Master Builders, Inc.) and perform laboratory testing to evaluate its performance. It is expected that the improved mixture will have

    - Less Cement – 385 lb/yd^3
    - Lower *w/c* and less water, *w/c*= 0.42
    - Class "C" Fly Ash (30%)
    - MRWR (6-8%)
    - SR admixture (1 ½ - 2%)
    - Retarder

8. Gather the results from Nos. 3-7 above, analyze, draw appropriate conclusions and recommendations, and prepare a final report.

1.4 Scope

The field investigation originally planned was to be limited to summer concreting work and minimal changes in mixture components. However, it should provide an dedication of the construction friendliness and sensitivity of concrete mixtures employing MRWR sufficient to judge the advisability of using such mixtures in future bridge deck placements. Testing of the improved concrete mixture was to be limited to the laboratory, and if the results of this investigation were positive, trial testing via application to a bridge deck would be employed later for field evaluation.

2. BACKGROUND AND LITERATURE REVIEW

2.1 Background

The three major innovations in the concrete industry during this century have probably been: 1) the water cement ratio (*w/c*) rule discovered by Duff Abrams; 2) the use of properly entrained air to provide resistance to freezing and thawing; and 3) the invention of the high-range water-reducing (HRWR) admixture that allows for great water reduction and/or significant slump increase. This latter innovation allows bridge deck owners to have low water content and the associated good strength and good durability concrete, while simultaneously allowing the construction contractor to have good flowable concrete that provides good workability and low placement, consolidating and finishing costs. Thus it resolves the age-old conflict between owners wanting little water in their concrete (for improved hardened properties), and contractors wanting a lot of water (for improved fresh properties).

First generation (around 1980) superplasticizers were widely used in the U.S. in the precast concrete industry; however, this was not the case for ready-mixed concrete because of problems with relatively rapid slump losses. Current, or third generation, superplasticizers are reported to retain their superplasticizing actions over a much longer period of time (as much as 2 hours). During recent years, it has been discovered that the workability of superplasticized concrete can be improved by the use of pozzolans in the mixture. However, as indicated in Chapter 1, ALDOT has recently experimented with the use of superplasticizers in their bridge deck concrete and found it to be quite sensitive to the concrete producer and construction contractor proficiencies in working with this concrete. For this reason, they have backed away fromSuper- P in concrete at this time and want to experiment with mid-range water-reducing (MRWR) admixtures in their bridge deck concrete

There appears to be a consensus of opinion of ALDOT engineers that concrete drying shrinkage is the primary cause of their bridge deck cracking, and in turn, deck cracking is the primary cause of premature deck deterioration [21]. Shrinkage of concrete, in particular drying shrinkage, is inevitable; and because of restraint, cracking can occur. To minimize drying shrinkage, the total water content of the concrete mixture must be kept as low as possible for the intended application. This can be achieved by using high content of hard rigid aggregates that are free of clay coating, and by using MRWR or HRWR admixtures. In addition to reducing drying shrinkage, HRWR and MRWR can increase flowability of concrete as indicated in Fig. 2.1. This is important to ALDOT in order that contractors can achieve quality in-place concrete decks. As previously indicated, ALDOT would like to experiment with a MRWR concrete mixture and this will be the focus of this research

2.2 Literature Review

In 1962, ASTM C 494 "Standard Specification for Chemical Admixtures" was introduced to define parameters that have to be met for classification as normal water reducing or set controlling admixtures [1]. Originally specifying classifications for three types of admixtures, ASTM C 494 has since been revised to recognize five categories of

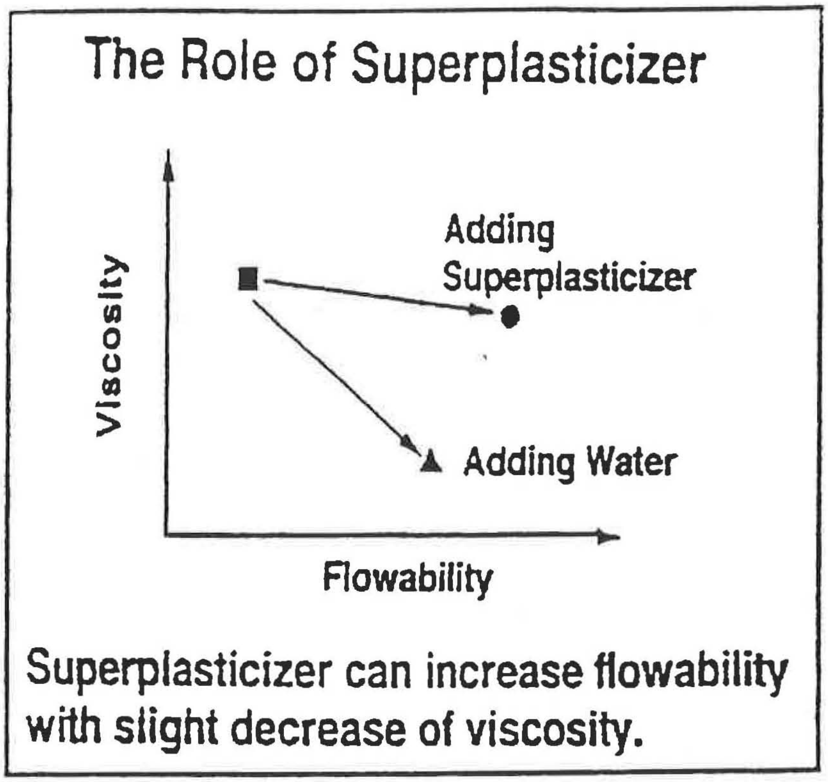

Figure 2.1 Effect of Superplasticizers [13]

Table 2.1 Properties of Conventional, Mid-Range and High-Range Water Reducers [24]

Water Reducer	Typical Water Reduction	Typical Dosage Rate	Strength Enhancement	Finishability
Conventional (ASTM C494, Type A)	5%-10%	3-5 oz/cwt.	10%	Average
Mid-Range	8%-18%	5-10 oz/cwt.	15%	Excellent
High-Range (ASTM C 494, Types F &G)	12%-25%	12-16 oz/cwt.	20%+	Average

water-reducing admixtures. These are, conventional water reducers (Type A), water-reducing and retarding (Type D), water-reducing and accelerating (Type E),with high-range water-reducing (Type F) and high-range water-reducing and retarding (Type G) being the two classes added in the 1980 revision.

For several years, beginning in 1983, the problem of the durability of concrete structures was a major topic of interest in Japan [18]. Sufficient compaction by skilled workers is required in order to realize durable concrete structures. However, a gradual reduction in the number of skilled workers in Japan's construction industry led to similar reduction in the quality of construction work. Japanese engineers realized that the development of self-compacting concrete would be necessary to guarantee durable concrete structures in the future. While adding water leads to improved flowability of the cement paste, it also leads to decreased viscosity. For the achievement of self-compatibility, therefore, a superplasticizer is indispensable [18]. With a superplasticizer, the paste can be made more flowable with little accompanying decrease in viscosity as indicated in Fig. 2.1.

In the U.S. the workability or consistency of concrete is usually measured by the slump test. It is reported [10] that this test gives satisfactory results when slumps are below 6", but beyond this the slump test is a questionable indicator of workability. Slumps for superplasticized concrete will typically be above 6". In Germany a flow table (see Fig. 2.2), specified in German Standard DIN 1048 (1972), is employed to measure the consistency of flowing concrete [10]. A fixed amount of concrete is cast in a mold placed on a smooth surface and the mold is then jolted in a standard manner. After the

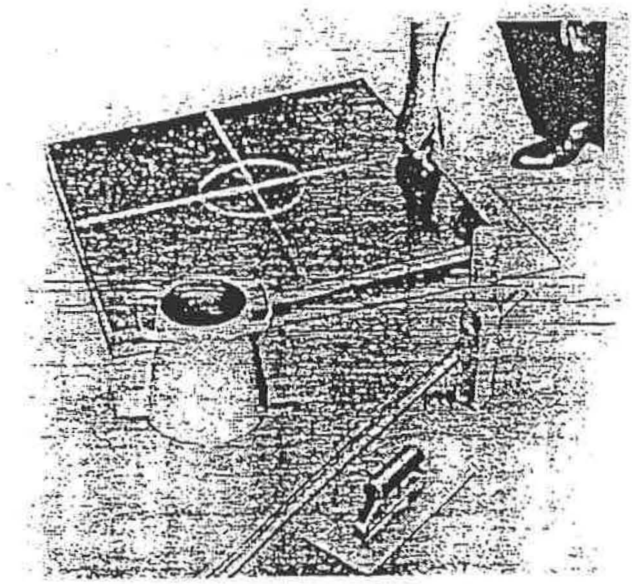

Figure 2.2 Flow test apparatus [10]

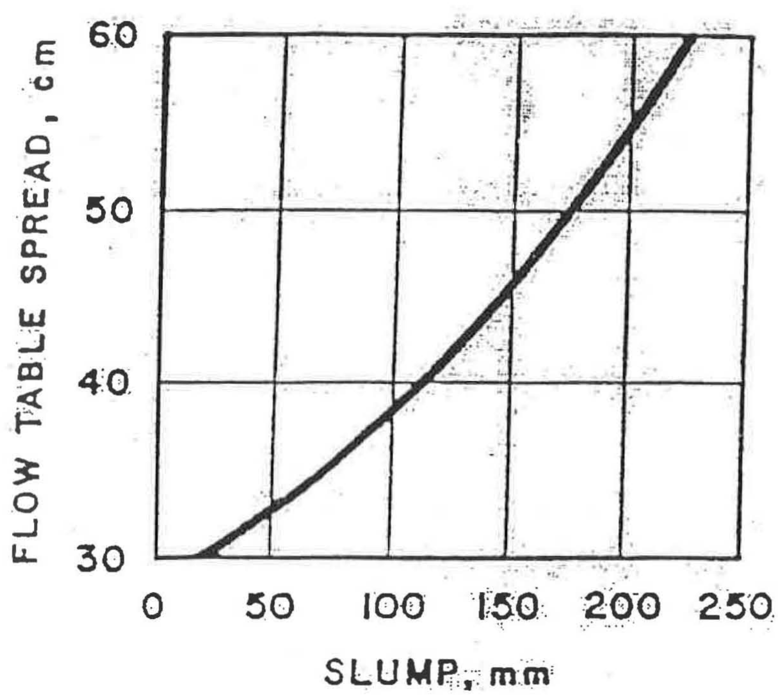

Figure 2.3 Relationship between flowable spread and slump [10]

jolting, the radial spread of the concrete is measured. A relationship between the results of slump and flowable test is indicated in Fig 2.3.

Results of a recent survey [2] indicated that restrained shrinkage of concrete is the leading cause of bridge deck cracking. The restraint may take the form of internal reinforcing steel, external deck/girder shear connectors, and girder/abutment connections. In Alabama, shrinkage cracking is probably the leading cause of bridge deck deterioration and reduced service life.

Plastic, drying, and thermal shrinkage of concrete are dependent on many parameters. However, the dominant ones appear to be:

- The ingredients and mixture proportions of the concrete
- The curing provided at time of placement
- The weather exposure conditions

According to Lerch [9], plastic shrinkage is the shrinkage that occurs in the surface of fresh concrete within the first few hours after placement while the concrete is still plastic and before it has attained any significant strength. It is well known that plastic shrinkage cracking is dependent on the surface evaporation rate and the concrete bleed rate. The surface evaporation rate is a function of the weather exposure conditions, and the bleed rate is primarily a function of the concrete mixture design and the amount of water in the mixture and its bleed characteristics.

Drying shrinkage is primarily a paste issue and it, too, is strongly dependent on the amount of water in the mixture. Drying shrinkage and its effects are graphically illustrated in Fig. 2.4. Raina [20] defines drying shrinkage as the reduction in volume of concrete caused by the chemical and physical loss of water from the concrete during the

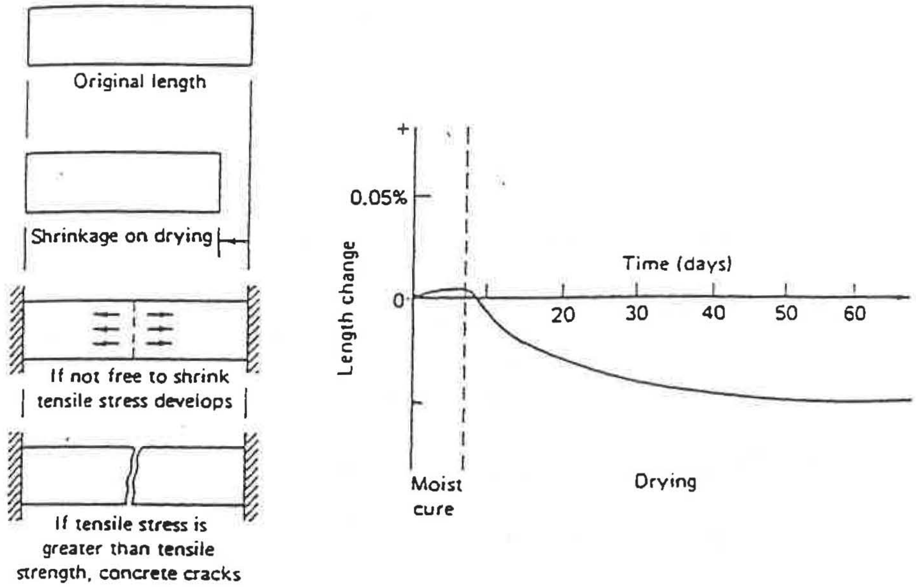

Figure 2.4 Drying Shrinkage of Concrete [21]

hardening process and exposure to unsaturated air. Drying shrinkage cracks occur only when the concrete is in a restrained condition due to tensile stresses which develop from the drying shrinkage. Raina states that loss of water by evaporation is the primary cause of the drying shrinkage.

Tests indicate that the drying shrinkage of small, plain concrete specimens (without reinforcement) ranges from about 400 to 800 μ strain when exposed to air at 50% humidity [8]. Drying shrinkage values decrease as relative humidities increase. It can be noted that concrete with a drying shrinkage of 550 μ strain shortens about the same amount as the thermal contractions caused by a decrease in temperature of 100 degrees F. The shrinkage of large concrete components is less than that of small test specimens because of movement restraints offered by other components of the structure and by the concrete reinforcing steel. In reinforced concrete structures with normal amounts of reinforcement, drying shrinkage is commonly assumed to be 200 to 300 μ strain. This is approximately the same strain level as for 50 degrees F change in temperature.

The most important controllable factor affecting the drying shrinkage of normal portland cement concrete is the amount of water per unit volume of concrete. The results of tests illustrating the water content-shrinkage relationship are shown in Figure 2.5. This figure indicates that shrinkage is a direct function of the unit water content of fresh content. The close grouping of these curves shows that drying shrinkage is governed mainly by unit water content (note the narrowness of the band of water content on shrinkage regardless of cement content or water-cement ratio).

The curves of Figure 2.5 along with results from other mixtures testing can be banded as shown in Figure 2.6 and illustrate the dramatic increases in drying shrinkage with increasing water content. Thus, shrinkage can be minimized by keeping the water content of concrete as low as possible (and still achieve the required workability). This is achieved by keeping the total coarse aggregate concrete of the concrete as high as possible. Use of low slumps and placing methods that minimize water requirements and use of water reducers are thus major factors in controlling concrete shrinkage [8].

Concrete mixtures may be classified based on drying shrinkage as follows:

No shrinkage: <0.004% shrinkage

Low shrinkage: 0.004% - 0.04% shrinkage

Moderate shrinkage: 0.04% - 0.08% shrinkage

High shrinkage: >0.08% shrinkage

There appears to be a consensus of opinion of ALDOT engineers that concrete shrinkage is the primary cause of bridge deck cracking, and, in turn, deck cracking is the

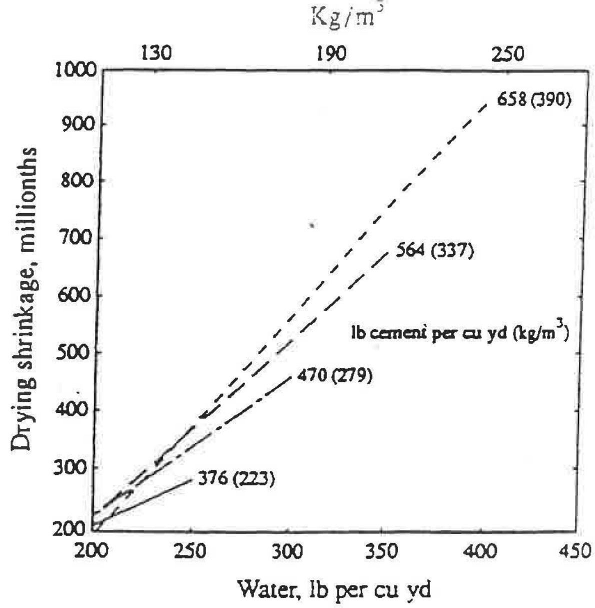

Figure 2.5. Interrelation of Shrinkage, Cement Content, and Water Content [Unknown Source].

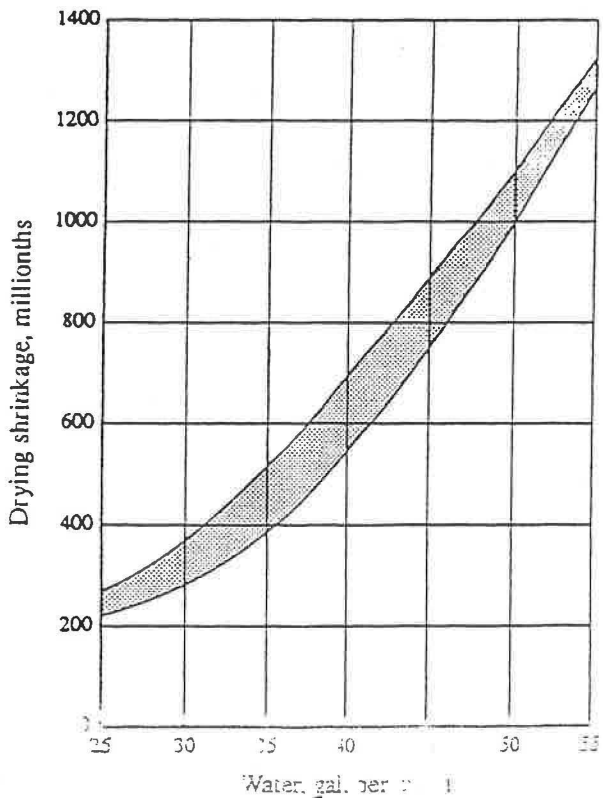

Figure 2.6. Water Content vs. Drying Shrinkage [8].

primary cause of premature deterioration and reduced durability of bridge decks in Alabama. The primary causes of the shrinkage cracking are felt to be the concrete mixture and poor quality concrete curing.

There are two sets of criteria that must be considered when developing a concrete mixture:

1. Long-term requirements of the hardened concrete such as strength, durability, and volume stability.
2. Short-term requirements while the concrete is still in the plastic state, which are generally lumped together under the term "workability."

Unfortunately, these two sets of requirements are not complementary, and a compromise is needed between them. However, the more recent development of superplasticizers as a concrete admixture show great promise in overcoming the heretofore conflicting mixture requirements to attain good workability during placement and good strength and durability in the hardened concrete. Indeed, as mentioned earlier, high-range water reducing (HRWR) admixtures, or superplasticizers, appear to be the single biggest innovation in the concrete industry over the past couple of decades. They are known to allow reductions in water content and the accompanying reductions in permeability and drying shrinkage, while at the same time increasing the workability and in-place quality and durability of concrete.

Thermal expansion and contraction (shrinkage) of concrete varies with factors such as aggregate type, cement type and content, water cement ratio, temperature range, concrete age, and relative humidity. Of these, aggregate type probably has the greatest influence. Some aggregate types along with their effect on thermal coefficient of expansion of concrete are listed in Table 2.2. An average value for the coefficient of thermal expansion of unreinforced and reinforced concrete is 5.5 and 6.0 millionths of an inch per inch per degree Fahrenheit, respectively.

According to Raina [20], early thermal contraction strains far exceed drying shrinkage strains and are primarily responsible for early cracking in retaining walls and reinforced concrete bridge deck structures. The reaction of cement with water, known as hydration, is a chemical reaction, which produces heat. If insulated and large enough, the rate of heat gain in a concrete element is likely to exceed the rate of heat loss to the atmosphere, causing a rise in temperature. After the first day, the rate of heat gain falls below the rate of heat loss, and the concrete member begins to cool, resulting in contraction. Cracking can result if the concrete is restrained internally or externally and adequate strength has not developed to resist tensile stresses caused by the contraction. Internal restraint occurs due to rebar mats and differential cooling of the member, e.g., the surface of the member cools faster than the core. External restraint refers to restraint provided by external supports. Raina indicates that the core of concrete cools to ambient

Table 2.2. Effect of Aggregate on Thermal Coefficient of Expansion of Concrete [8].

Aggregate type (from one source)	Coefficient of Expansion millionths in/in per °F
Quartz	6.6
Sandstone	6.5
Gravel	6
Granite	5.3
Basalt	4.8
Limestone	3.8

temperature in 7 to 14 days. Hence, thermal movement cracks are more likely to occur during this period. One of the most important factors which assists in differentiating between thermal movement cracks and long-term drying shrinkage cracks is knowledge of when the crack forms. A crack which develops in the first few weeks is unlikely to be a drying shrinkage crack unless the deck is subjected to extreme drying conditions.

In summary, shrinkage of concrete, in particular drying shrinkage, is inevitable, and because of internal and external restraints, can lead to cracking. To minimize drying shrinkage, the total water content of the concrete mix must be kept as low as possible for the intended application. This can be achieved by using a high content of hard, rigid aggregates, and by using mid-range water reducing (MRWR) or high-range water reducing (HRWR) admixtures. High-range water reducing (HRWR) admixtures, or superplasticizers, appear to be the single biggest innovation in the concrete industry over the past couple of decades. They are known to allow reductions in water content and the accompanying reductions in permeability and drying shrinkage, while at the same time increasing the workability and in-place quality and durability of concrete. Thus, they can help in resolving the age-old conflict between owners wanting little water in their concrete (for improved hardened properties) and contractors wanting a lot of water (for improved fresh properties).

Water reducing admixtures are classified based on the amount of water reduction achieved with a standard concrete mixture under laboratory conditions [4]. A minimum of 5% water reduction is required to be considered a water-reducing admixture. Table 2.1 shows the approximate ranges of water reduction for various admixtures. It should be noted that under the guides of ASTM C 494 there is not a provision for mid-range water-reducers. MRWR tend to be classified as a Type A or Type F or both. However, the mid-range water-reducing admixture, occupies a vital position in the spectrum of water reducing capabilities [7].

As reported by Collepardi [5], the three different uses (or a combination of these) for water reducing admixtures are as follows:

1. To increase the workability without changing the mix composition in order to enhance the placing characteristics, (Fig. 2.7A).
2. To reduce the amount of mixing water required and the water cement ratio (*w/c*) in order to increase the strength and improve durability of the concrete, (Fig 2.7B).
3. To reduce both water and cement requirements without changing the water to cement ratio, in order to save cement and reduce creep, shrinkage and thermal strains caused by heat of cement hydration, (Fig. 2.7C).

Water reducing admixtures are classified by ASTM C494 based on water reducing capabilities, however they are more often categorized by their composition. The three standard groups of water reducing admixture compositions are 1) salts and derivatives of lignnosulfates, 2) salts and derivatives of hydroxycarboxylic acids and, 3) polymeric materials. HRWR and MRWR are commonly composed of groups 1 and 3. The commonality for all of these groups of water reducing admixtures is that these compounds are absorbed primarily at the solid-water interface of cement particles, and this is the basis of water reduction [14]. Residual charges are found on the surface of cement particles, which may be positive, negative, or both. These opposing charges tend to attract one another, causing flocculation to occur (Fig. 2.8A). Flocculation in turn

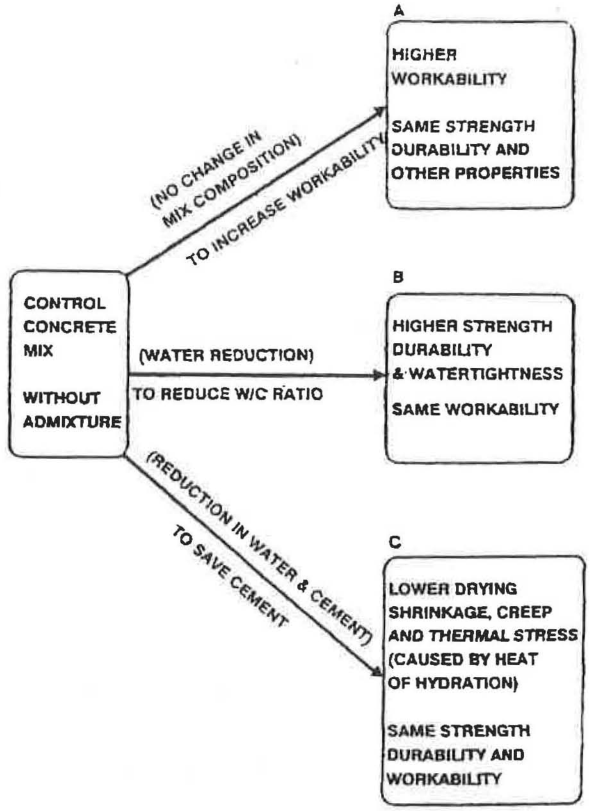

Figure 2.7. The Effect of Plasticizers and Super Plasticizers on the Properties of Concrete [5]

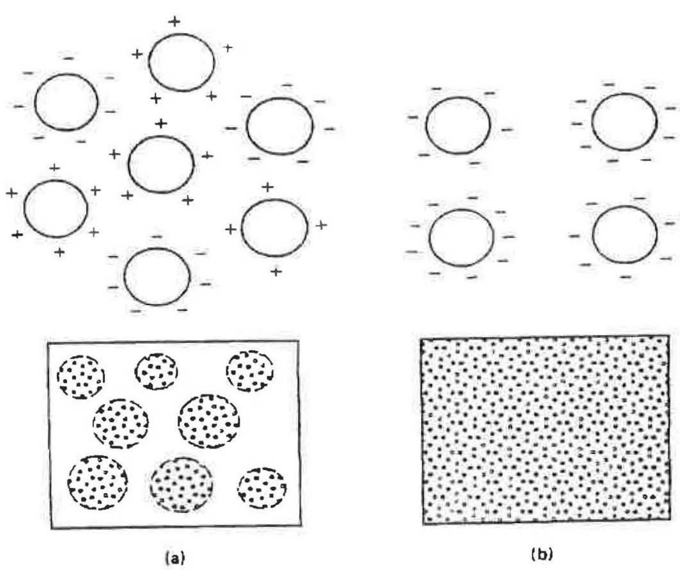

Figure 2.8. Dispersing action of water reducing admixtures (schematic representation): (a) flocculated paste; (b) dispersed paste [14].

reduces the amount of water available to increase the viscosity in the concrete mix. The water-reducing admixture interacts with these charged cement particles to neutralize their surface charges. The result is concrete particles which all have the same or neutral charge. The particles then tend to repel one another and remain fully dispersed in the concrete paste, which creates a less viscous or more flowable mixture (Fig. 2.5B) [14]. The behavior of flocculation is found to occur with fine cement particles and to some extent the fine aggregate, but there is a tendency for it to occur with all finely divided solids.

Water reducing admixtures have been found to affect other properties of concrete, in both the plastic and hardened state [14]. In fresh concrete, workability is commonly measured by the slump achieved of the concrete and translated into the effectiveness of a water-reducing admixture. However, water-reducing admixtures affect other fresh properties of concrete that are not quantified by a slump test. When high dosages of water reducing admixture are used to produce high slumps, there is a possibility of segregation to occur. This occurs due to the reduced viscosity of the mix obtained with large dosages of admixture. Water reducers have also been found to affect the air entrainment of concrete mixtures. Lignosulfate based water reducers have a tendency to entrain air when added to a concrete mix. Other water reducers have been found to decrease the air entrainment due to the reduced viscosity of the mixture. Therefore, additional air entrainment is required when using water reducers. Water reducers have also been found to increase the loss of workability in concrete by increasing the rate of slump loss in the concrete mix. This problem seems to be more pronounced in superplasticizer than in conventional water reducers. It has been attributed to the rule that the higher the initial slump of concrete, the greater the rate of slump loss [13]. Development in third generation water reducers has helped to decrease the susceptibility to this problem. Hardened properties of concrete with water reducers are enhanced in several ways with the use of water reducing admixtures. Most notably is the increase in compressive strength, which may be increased by 25% or greater than what would be expected from the decrease in *w/c* ratio. Decreasing the water/cement ratio also produces fewer voids that are filled with water, essentially increasing the density of the mix. This results in concrete that is more durable and has greater impermeability.

Schaefer [24] reported on the advantages of using MRWR to enhance the performance of concrete during placement. In comparison to Type A, conventional water reducers, Schaefer found MRWR to have a neutral influence on set times over a wide range of dosages. Whereas conventional water reducers can result in increased set times with additional dosages (see Figure 2.9). Thus, with MRWR a more consistent set time is achieved when varying the dosage of the admixture. Additionally, MRWR were found to have consistent effects on concrete properties in cold weather, as well as in milder climates. Schaefer also found MRWR to improve workability of the concrete due to an additive in the water reducer, which causes the concrete particles to slide over and around one another more freely (see Figure 2.10). Schaefer concluded that MRWR are most beneficial on slabs-on-grade, elevated slabs and other types of flatwork where finishing is crucial.

Nmai, Schlagbaum, and Violetta [15] conducted studies of several different types of MRWR admixtures to determine their effectiveness in certain concrete mixtures. Chloride-bearing MRWR were developed and produced in the late 1980's

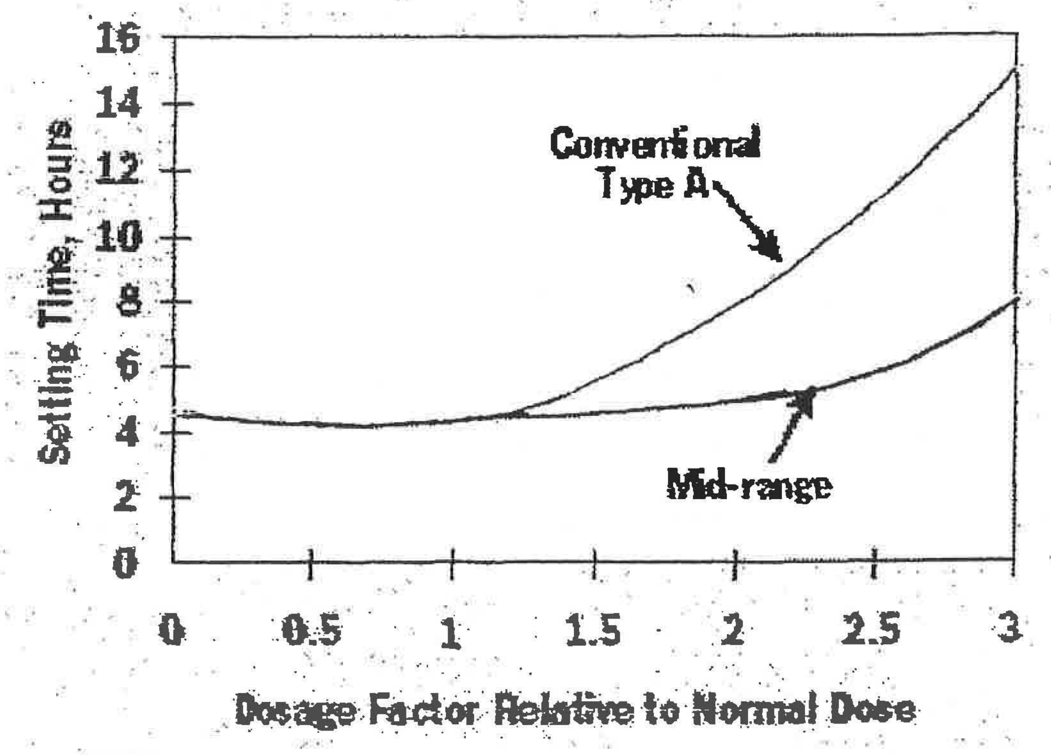

Figure 2.9. Typical Effects of Various Dosages on Setting Time for Standard and Mid Range Water Reducers [24]

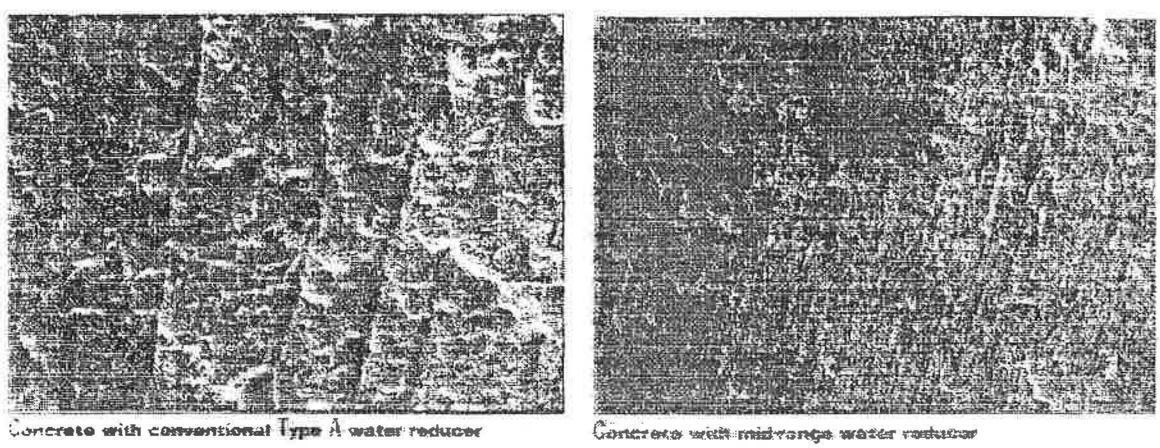

Figure 2.10. Microscope Photos of Finished Concrete Surfaces for Concrete with Water Reducers [24].

primarily to improve setting times in concrete containing blast furnace slag or fly ash. As indicated in Table 2.3, the chloride-bearing MRWR significantly decreased the set time required vs. the non-chloride-bearing admixture. In addition, the results also show an increase in compressive strength for both concrete mixes with the MRWR additive compared to the plain reference concrete.

The second of the studies performed by Nmai, Schlagbaum, and Violetta [15] was conducted using proprietary polycarboxlate technology (MRWR-PC), by GLENIUM™. The MRWR-PC contains non-chloride based set-enhancing ingredients, which provides accelerated settings for concrete containing fly ash or blast furnace slag. The test was conducted for concrete mixes with Class F fly ash replacement levels of 15, 25 and 35%. Dosages of 8, 16 and 24 fluid ounces per one hundred pounds of concrete (fl oz/cwt.) of MRWR-PC were added to all three concrete mixtures. These mixes were referenced against plain concrete with the addition of fly ash and without. For all of the mix combinations there was a decrease in set times between the concrete mixes with MRWR-PC and the fly ash reference. The compressive strength results varied with the test samples. In regard to the 15 and 25% fly ash replacement concrete with MRWR admixture, the compressive strengths were generally found to be higher than the plain concrete and the fly ash reference (See Tables 2.4 and 2.5). As for the 35% fly ash replacement with MRWR admixture, the compressive strengths were typically lower than the plain reference concrete, but higher than the fly ash reference concrete (See Table 2.6). A similar test was performed for concrete using a 25% Class C fly ash replacement with 15 fl oz/cwt. of MRWR (See Table 2.7). Results of this test showed a significant improvement in set time compared to the fly ash reference, and increased compressive

Table 2.3. Performance Data for MRWR Admixtures [15]

Parameter	Plain	Non-Chloride MRWR			Chloride-Bearing MRWR		
MRWR Dose, Fl oz/ cwt.	-	5	10	15	5	10	15
Type I Cement lb/yd^3	508	505	500	499	501	500	499
Water Content lb/yd^3	315	286	265	258	284	276	269
Water Reduction, %	-	9.2	15.9	18.1	9.8	12.4	14.6
Slump, in.	7.0	6.5	6.5	7.0	6.5	6.25	6.75
Air Content, %	1.2	2.4	3.3	4.3	2.5	3.2	3.4
Initial Set h : min	4:46	4:40	5:12	6:15	4:34	4:56	5:28
Difference h: min	-	-0:06	+0:26	+1:29	-0:12	+0:10	+0:42
7-Day Strength psi	3390	4040	4710	4820	4110	4290	4770
Difference, %	-	+19	+39	+42	+21	+26	+41
28-Day Strength, psi	4230	5260	5890	5790	4950	5510	5920
Difference, %	-	+24	+39	+41	+17	+30	+40

Non-air entrained concrete; concrete and ambient temperature = 70°F(21°C);
1 fl oz/cwt. = 65.2mL/100kg ; 1lb/yd^3 = 0.5933 kg/m^3 ; 1in = 25.4 mm; 145 psi = 1MPa

Table 2.4. Performance Data for MRWR-PC with 15% Class F Fly Ash [15].

Parameter	Plain Reference	Fly ash Reference	MRWR-PC		
Type I Cement lb/yd^3	500	425	425	425	425
Class F fly ash lb/yd^3	-	75	75	75	75
Fine Aggregate lb/yd^3	1325	1315	1350	1365	1375
3/8 in. course aggregate, lb/yd^3	595	600	600	600	600
3/4 in. course aggregate, lb/yd^3	1390	1400	1400	1400	1400
Water Content lb/yd^3	272	262	253	246	244
MRWR-PC fl oz/cwt.	-	-	8	16	24
w/cm	0.54	0.52	0.51	0.49	0.49
Slump, in.	4.25	4.5	4.5	5.0	4.5
Unit weight, lb/ft3	153.97	153.97	153.16	153.56	153.16
Initial Set h : min	4:15	4:25	3:40	3:25	3:10
Difference vs. plain reference, h : min	-	+0:10	-0:35	-1:00	-1:15
Difference vs. fly ash reference, h : min	-0:10	-	-0:45	-1:00	-1:15
Compressive strength, psi					
3-day	3180	2720	3380	3730	3730
7-day	4260	3680	4240	4650	4460
28-day	5790	5390	5830	5940	5810
56-day	6650	5390	6660	6730	6680

Non-air entrained concrete; concrete and ambient temperature = 70°F(21°C);
1 fl oz/cwt. = 65.2mL/100kg ; 1lb/yd^3 = 0.5933 kg/m^3 ; 1in = 25.4 mm; 145 psi = 1Mpa

Table 2.5. Performance Data for MRWR-PC with 25% Class F Fly Ash [15].

Parameter	**Plain Reference**	**Fly ash Reference**	**MRWR-PC**		
Type I Cement lb/yd^3	500	375	375	375	375
Class F fly ash lb/yd^3	-	125	125	125	125
Fine Aggregate lb/yd^3	1325	1300	1330	1345	1355
3/8 in. course aggregate, lb/yd^3	595	600	600	600	600
3/4 in. course aggregate, lb/yd^3	1390	1400	1400	1400	1400
Water Content lb/yd^3	272	260	241	233	221
MRWR-PC fl oz/cwt.	-	-	8	16	24
w/cm	0.54	0.52	0.48	0.47	0.44
Slump, in.	4.25	5.0	5.0	5.0	5.0
Unit weight, lb/ft3	153.97	153.97	153.36	153.16	153.16
Initial Set h : min	4:15	4:50	4:15	4:00	3:40
Difference vs. plain reference, h : min	-	+0:35	0:00	-0:15	-0:35
Difference vs. fly ash reference, h : min	-0:35	-	-0:35	-0:50	-1:10
Compressive strength, psi					
3-day	3180	2230	2910	3210	3520
7-day	4260	2870	3580	3800	4120
28-day	5790	4290	5000	5220	5480
56-day	6650	5220	5890	6070	6570
Non-air entrained concrete; concrete and ambient temperature = 70°F(21°C); 1 fl oz/cwt. = 65.2mL/100kg ; 1lb/yd^3 = 0.5933 kg/m^3 ; 1in = 25.4 mm; 145 psi = 1Mpa					

Table 2.6. Performance Data for MRWR-PC with 35% Class F Fly Ash [15].

Parameter	Plain Reference	Fly ash Reference	MRWR-PC		
Type I Cement lb/yd^3	500	325	325	325	325
Class F fly ash lb/yd^3	-	175	175	175	175
Fine Aggregate lb/yd^3	1325	1310	1335	1350	1360
3/8 in. course aggregate, lb/yd^3	595	592	592	592	592
3/4 in. course aggregate, lb/yd^3	1390	1383	1383	1383	1383
Water Content lb/yd^3	272	245	244	224	216
MRWR-PC fl oz/cwt.	-	-	8	16	24
w/cm	0.54	0.49	0.49	0.45	0.43
Slump, in.	4.25	4.75	4.75	4.0	4.75
Unit weight, lb/ft3	153.97	152.76	153.56	152.76	152.76
Initial Set h : min	4:15	4:55	4:40	4:20	4:05
Difference vs. plain reference, h : min	-	+0:40	+0:25	+0:05	-0:10
Difference vs. fly ash reference, h : min	-0:40	-	-0:15	-0:35	-0:50
Compressive strength, psi					
3-day	3180	2020	2250	2900	3150
7-day	4260	2480	2840	3290	3670
28-day	5790	3990	4140	4430	4760
56-day	6650	4830	4980	5370	5540
Non-air entrained concrete; concrete and ambient temperature = 70°F(21°C); 1 fl oz/cwt. = 65.2mL/100kg ; 1lb/yd^3 = 0.5933 kg/m^3 ; 1in = 25.4 mm; 145 psi = 1Mpa					

Table 2.7. Performance Data for MRWR-PC with 25% Class C Fly Ash [15].

Parameter	Plain Reference	Fly ash Reference	MRWR-PC
Type I Cement lb/yd^3	517	388	388
Class C fly ash lb/yd^3	-	131	131
Air-entraining admixture, fl oz/cwt.	1.0	1.1	0.7
MRWR-PC fl oz/cwt.	-	-	15
Initial Set h : min	5:21	9:13	6:07
Difference vs. plain reference, h : min	-	+3:52	+0:46
Difference vs. fly ash reference, h : min	-3:52	-	-3:06
Compressive strength, psi			
3-day	2440	2060	2580
7-day	2910	2930	3560
28-day	3920	4740	5000
Non-air entrained concrete; concrete and ambient temperature = 70°F(21°C); 1 fl oz/cwt. = 65.2mL/100kg ; $1lb/yd^3$ = 0.5933 kg/m^3 ; 1in = 25.4 mm; 145 psi = 1Mpa			

strength compared to both reference mixes. The research found an increase in finishability with the MRWR admixture due to the increase length of time the concrete bled and the decrease in bleed water volume (see Figure 2.11). The rate of stiffening to initial set was found to be somewhat slower than untreated concrete and this creates a larger finishing time window (see Figure 2.12) [15].

Nmai recommended MRWR be used for applications in flatwork, pumping, formed surfaces and precast and low slump machine placement. All of these take advantage of the enhanced workability, pumpability and finishability of MRWR admixture [15].

Hoover [7] conducted research on water-reducing admixtures effectiveness in increasing the durability of concrete. Hoover states the key to improving durability is to decrease the void spaces in the cement grains and/or block the connectivity of the pores so that gases and liquids cannot permeate the paste. The spacing of cement grains has been found to be a function of the water/cement ratio as indicated in Figure 2.13. Also, a decrease in water/cement ratio is known to have a positive effect on both compressive strength and permeability as indicated in Fig. 2.14. Therefore, a water-reducing admixture effectively increases the durability of concrete by enabling a decrease in water content required at a given slump as indicated in Fig.2.15. However, the effectiveness of any particular water reducer is dependent on dosage used, temperature, cement chemistry, and other mixture characteristics [7].

Brooks [4], conducted an investigation on the influence of plasticizers and superplasticizers on creep and drying shrinkage deformation of concrete. Brooks proposed a method to allow for changes in mix proportions when admixtures were used,

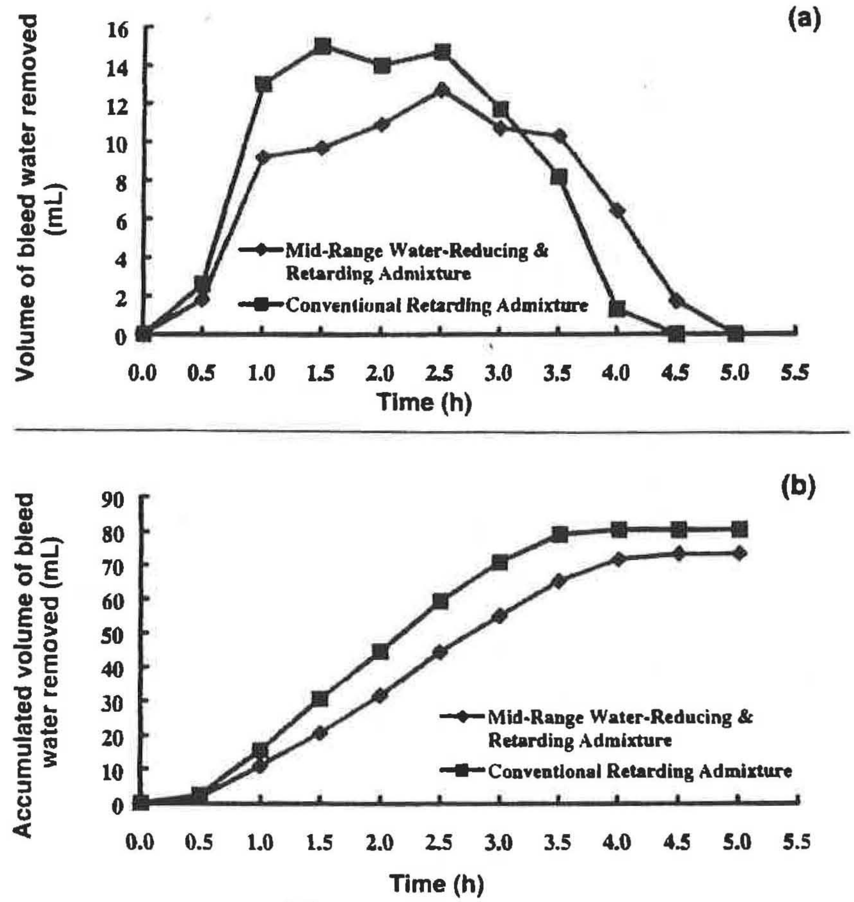

Figure 2.11. Effect of MRWR and Retarding Admixture on Bleeding at 90°F [15].

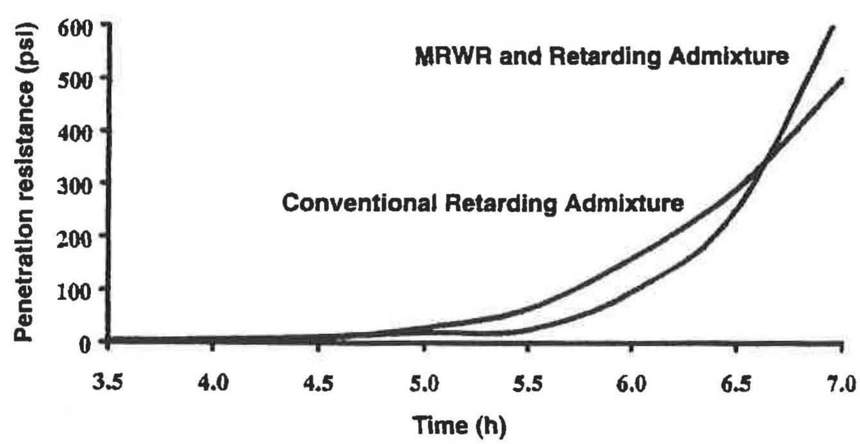

Figure 2.12. Effect of MRWR on Rate of Stiffening at 70° F [15].

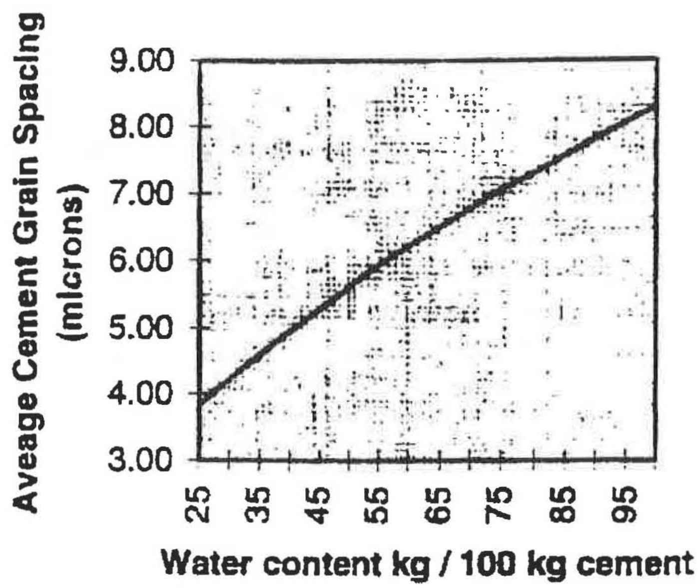

Figure 2.13. Clear spacing between cement grains as a function of water content per 100-kg cement, assuming a cubic lattice arrangement of cement grains [7].

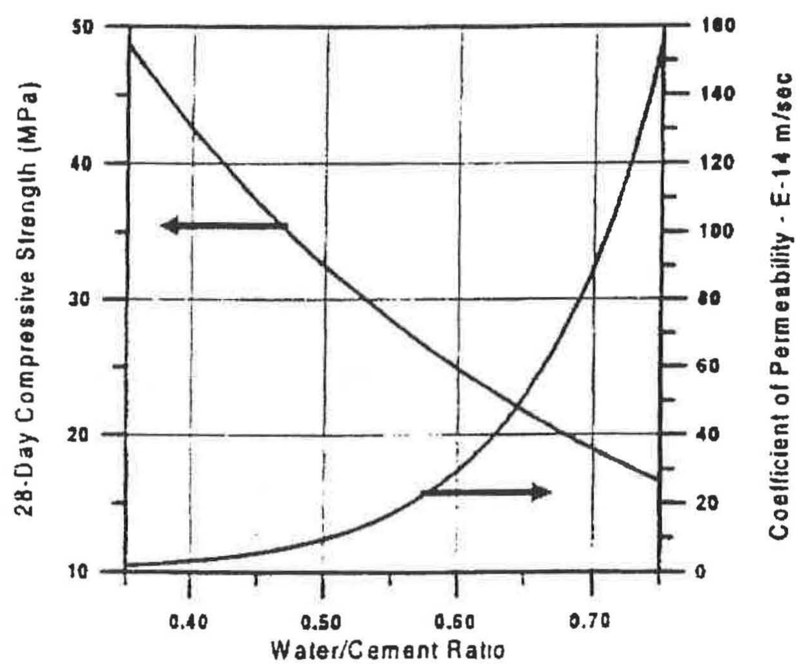

Figure 2.14. Effect of water/cement ratio on compressive strength and permeability [7].

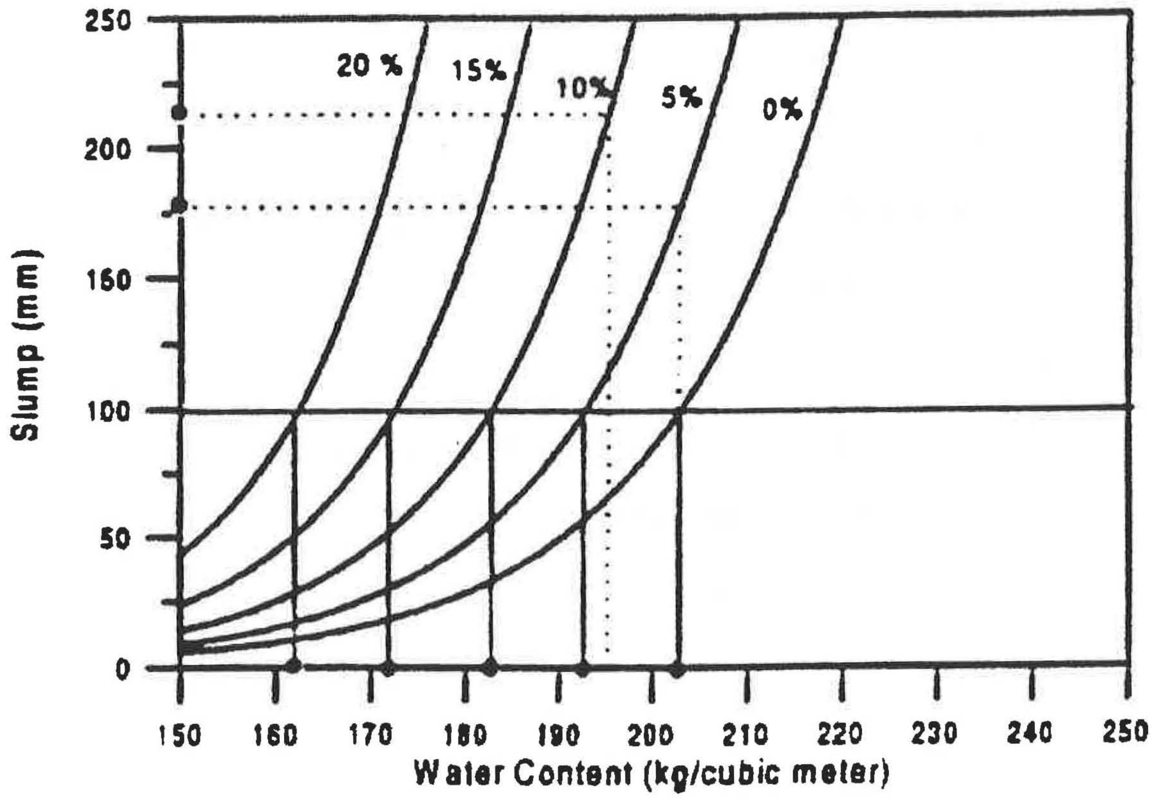

Figure 2.15. Relationship between water content and slump for a mixture incorporating 20 mm course aggregate with various levels of water reducing admixture effectiveness [7].

so the influence of the deformations is attributed to the admixture, not by water/cement ratio or cement paste content.

Brooks found an overall increase in deformation, from 3% to 132%, for all admixtures tested. It was also suggested from the research performed, that some admixtures did not effect shrinkage in some cases, or creep in other cases. In a general overview of all admixtures tested the increase in long term deformation was found to be approximately 20%.

The aforementioned studies and tests of water reducing admixtures have demonstrated several advantages to its use as a concrete admixture. The increased fresh properties, such as increased workability, regulation of slump for adverse weather conditions, improved finishability and pumpability and the enhanced hardened properties of concrete such as, increased compressive strength, enhanced permeability, durability and lower drying shrinkage are various effects of concrete due to the addition of MRWR admixtures. Due to these previous findings it is prudent to determine the effects of using a MRWR in addition to the standard ALDOT concrete mix, as well as an enhanced concrete design for bridge decks, and evaluate the properties thereof.

3. LABORATORY TESTING PROGRAM

3.1 General

The primary objective of this research was to assess the effects of a mid-range water reducer (MRWR) in improving concrete mixtures for bridge decks. Reduced drying shrinkage, improved durability, improved strength and increased workability were four of the improvements that were of interest in this research. Testing of the effects of adding a MRWR was conducted in two phases as described in the introduction of this report. The first phase was the laboratory testing of an improved concrete mixture. ALDOT and representatives of Master Builders, Inc. recommended an experimental concrete mixture with the addition of MRWR for this research. This hopefully improved mixture design, along with ALDOT's standard mixture for reference/control, were used in performing laboratory testing to evaluate fresh and hardened properties of the mixtures. The second phase of the research was to conduct field evaluations via the use of MRWR in ALDOT's standard bridge deck concrete in a deck placement in the field to assess its construction friendliness and its effect on the fresh and hardened properties of the concrete.

3.2 Laboratory Testing of "Improved" MRWR Mixture

Concrete Mixtures Tested. The improved concrete mixture design used in this research was created to produce a highly workable concrete that would have improved durability and reduced drying shrinkage properties for bridge decks in Alabama. The two mixtures used in the laboratory testing were as follows:

1) Improved Mixture (IMP) with Type-1 Portland Cement and Type C fly ash. This concrete was developed by ALDOT and representatives from Master Builders, Inc. for potential use in bridge decks in Alabama.
2) ALDOT Standard Bridge Deck Mixture. This mixture was used as a reference and control sample. It is the standard mixture currently use by ALDOT for bridge decks.

Mixture proportions for each of these mixtures is shown in Table 3.1

Raw Materials Used. The concrete mixtures were composed of Type-1 Portland Cement, type C fly-ash a Mid range water-reducing admixture, an air-entrainment admixture, a shrinkage reducing admixture, and a set retarding admixture. A description of each ingredient follows:

- Type-1 Portland Cement - The Type-1 Cement was produced by Leigh Cement Company based in Birmingham, Alabama and was manufactured to meet all requirements of ASTM C 150. The cement was obtained from the Twin Cities Concrete Company in Auburn, Alabama.
- Type C Fly Ash – The Type C fly ash used for this research was produced by Holnam in Birmingham, Alabama. The fly ash was used in the "improved" mixture to reduce the amount of cement needed for the concrete. The fly ash was also obtained from the Twin Cities Concrete Company in Auburn, Alabama.

Table 3.1 Laboratory Concrete Test Mixture Proportions

Mix Component	Concrete Mixtures	
	IML	SML (Control)
Cement (lb/yd^3) Type I	385	620
C-Ash (lb/yd^3)	165	N/A
Course Aggregate (#57 Limestone) (lb/yd^3)	1910	2021
Fine Aggregate (lb/yd^3)	1362	1084
MRWR[1] (ml/yd^3)	1630	N/A
AEA[2] (ml/yd^3)	488	N/A
SRA[3] (ml/yd^3)	1789	N/A
Retarder[4] (ml/yd^3)	325	N/A
Water (lb/yd^3)	220	275
W/C Ratio	0.40	0.44

1. Polyheed 997 manufactured by Master Builders Technologies
2. MB AE-90 manufactured by Master Builders Technologies
3. Polygaurd AS20 manufactured by Master Builders Technologies
4. Pozzolith 100-XR manufactured by Master Builders Technologies

- MRWR Admixture – The mid-range water reducer used in this research was Polyheed 997 which was manufactured by Master Builders Technologies and meets the requirements of ASTM C494, Type A and F. Polyheed 997 was incorporated into the improved mix design to achieve the mixture design specifications for slump with the designated water-cement ratio and also to enhance the workability of concrete mixture.
- Shrinkage Reducing Admixture – The shrinkage-reducing admixture used in this research was Polyguard AS20, which was also manufactured by Master Builders Technologies.
- Air-Entraining Admixture – The air-entraining admixture used in this research was MB AE-90, which was manufactured by Master Builders Technologies and meets the requirements of ASTM C260. MB AE-90 was used in the improved concrete mixture to achieve the mixture design's specifications for air content.
- Set Retarding Admixture – The set-retarding admixture used in this research was Pozzolith 100-XR, which was also manufactured by Master Builders. The Pozzolith 100-XR was applied to the improved concrete mixture to simulate typical admixtures used in a concrete mixture used during hot weather construction.
- Aggregates – The course and fine aggregates used in this research were #57 limestone and river sand respectively. The course aggregate was from Martin Marietta in Auburn, Alabama. The river sand was also from Martin Marietta in Shorter, Alabama. Both aggregates were obtained from Twin Cities Concrete Company in Auburn, Alabama.

Concrete Mixing Procedure. The concrete mixing procedure used in this research was performed per ACI 223, Method B. There are two methods described in ACI 223, Method A and Method B. The difference between the two is that Method B allows water to be added to the mix after the rest period. This method more closely replicates field conditions, when taking into consideration contractors tend to add water to concrete mix when permitted. The procedure is described in the following steps:

1) Add batch ingredients into mixer.
2) Start mixer and mix for 3 minutes.
3) Stop mixer for 3 minutes.
4) Start the mixer and mix for additional 2 minutes.
5) Stop mixer and run fresh property tests.

Fresh Concrete Property Testing. The fresh concrete property testing was conducted to assess the workability and constructability of the concrete mixtures. The tests consisted of determining slump, unit weight, air content and heat of hydration concrete temperature for both mixtures. The testing/property evaluations were as shown in Table 3.2. A brief description, purpose, and identification of the testing equipment utilized for each of the tests is presented below.

- Slump Test – The slump test was conducted on each concrete mixture in accordance with ASTM C143. The purpose of this test is to determine the workability of the concrete specimen. Equipment used for the test was a slump cone, $^5/_8''$ tamping rod, scoop, and measuring tape. The improved mixture was designed to attain a slump of

7-8" while the ALDOT control mixture has a requirement of 4-5″. Figure 3.1 shows the typical equipment used to perform a standard slump test.

- Unit Weight – Unit weight tests were conducted in accordance with ASTM C138, on each concrete mixture to determine the weight per cubic foot of concrete. The equipment used was a scale, tamping rod, rubber mallet, scoop, flat strike rod, and container used for air content measurement. Figure 3.2 shows equipment used in the unit weight test.
- Air Content – Air content test was conducted on each concrete mixture to determine to determine the amount of entrained air in the fresh concrete. The tests were conducted in accordance with ASTM C231. The equipment used was a tamping rod, rubber mallet, flat strike rod and Type B air meter. Figure 3.3 shows the equipment used in the air content test.
- Concrete Temperature – Concrete temperature was conducted following ASTM 1064, on both concrete mixes. The digital thermometer was placed in the concrete and the recording the concrete's temperature after mixing had been completed.

Preparation of concrete mixes and the testing of fresh concrete properties the improved mixture and ALDOT control mixture were conducted at the laboratory facilities in the Harbert Engineering Center at Auburn University.

Table 3.2 Laboratory Fresh Concrete Property Testing

	Concrete Mixtures	
	IML	**SML (Control)**
Slump Test (ASTM C231)	X	X
Unit Weight (ASTM C138)	X	X
Air Content (ASTM C231)	X	X
Concrete Temperature (ASTM C1064)	X	X

Table 3.3 Laboratory Hardened Concrete Property Testing

Concrete Property/ Parameter	**Concrete Mixtures**	
	IML	**SML (Control)**
Compressive Strength (ASTM C39)		
7-Day	X	X
14-Day	X	X
28-Day	X	X
56-Day	X	X
Drying Shrinkage (ASTM C157)	X	X
Freeze-Thaw Durability (ASTM C666)	X	X
Rapid Chloride Ion Penetration Test (ASTM C1202) 56-Day	X	X

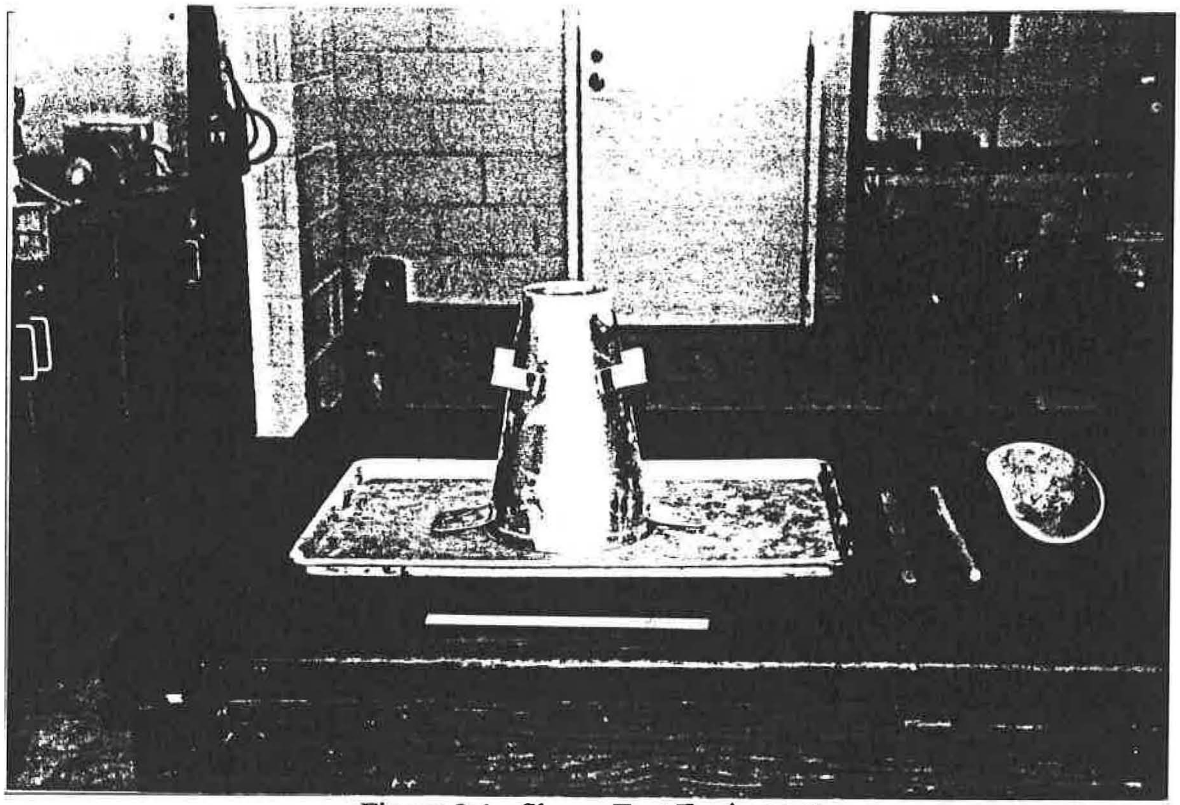

Figure 3.1. Slump Test Equipment

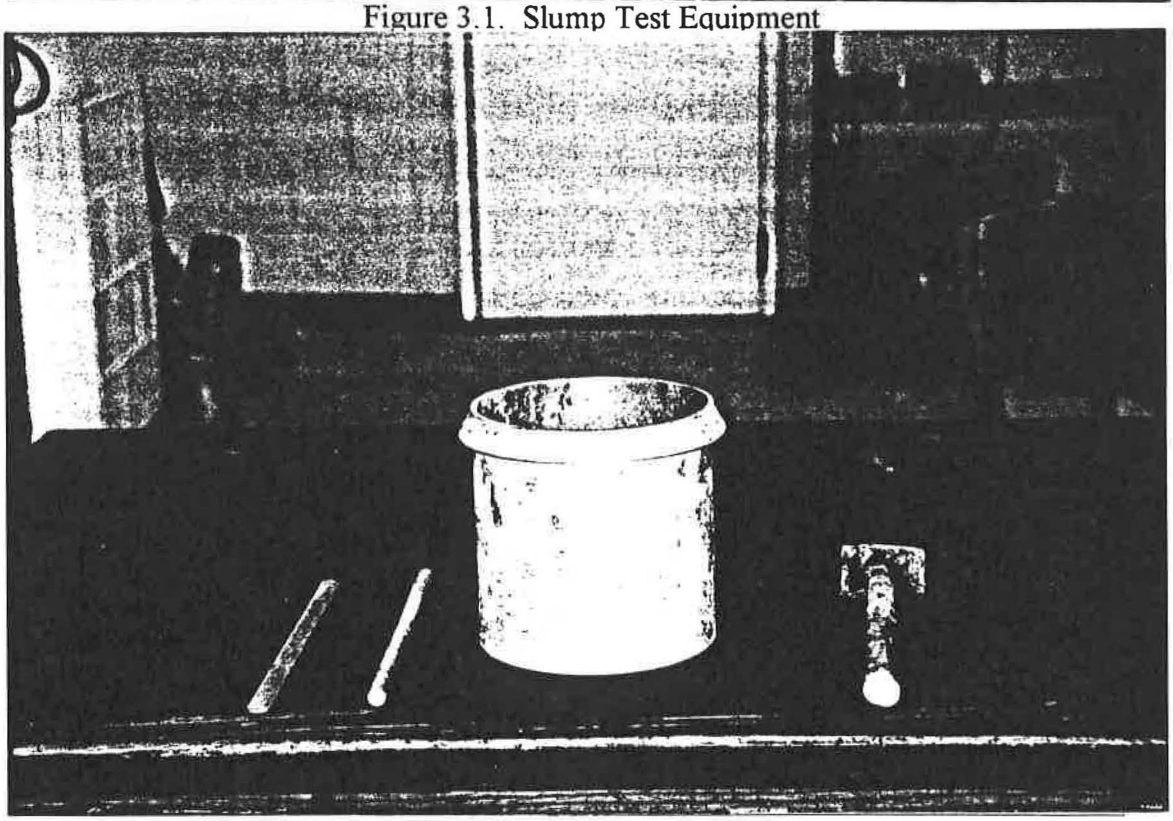

Figure 3.2. Unit Weight Test Equipment

Hardened Concrete Property Testing. The following tests were conducted on each concrete mixture to determine specific hardened properties of the concrete pertinent to this research. The testing evaluations conducted are as shown in Table 3.3. A brief description and photograph of each set of testing equipment utilized are described in the following.

- Compressive Strength Test – The compressive strength test was conducted in accordance with ASTM C39. Two 4″x8″ cylinders for each trial mixture were constructed in accordance with ASTM C192, for each curing condition. Each cylinder was cured in a 100% moisture environment for the required amount of time prior to testing. Testing for each cylinder was conducted using a Forney Model QC-400-02 with 400,000-pound capacity. Figure 3.4 shows a cylinder undergoing a compressive strength test.
- Unrestrained Drying Shrinkage – The unrestrained drying shrinkage test was conducted to determine the length change in the concrete. The test was conducted in accordance with ASTM C157. The test was conducted on two specimens of each mixture. After mixing the concrete, the mold was filled in two equal layers and rodded 30 times with a 3/8″ rod for each layer. After the second layer had been applied the mold was smoothed with a flat strike bar. The tops of the molds were then covered with plastic and allowed to cure. ASTM C157 states that the specimen remains in the mold for 12 hours prior to the initial measurement. However, due to the C-ash added in the improved mixture, specimens were allowed to cure for an additional 6 hours before the initial reading. For this reason, the ALDOT mixture was also cured for 18 hours prior to its initial reading. The measurements of the

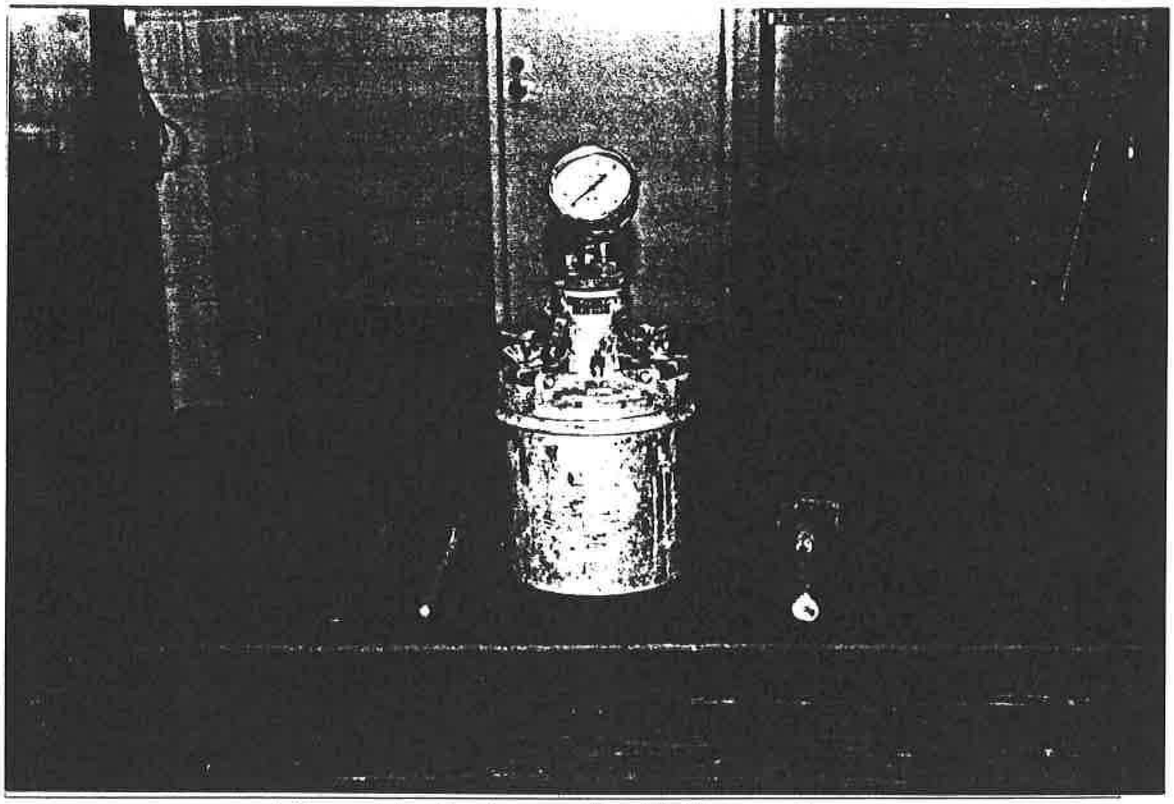

Figure 3.3. Equipment for Air Content Test

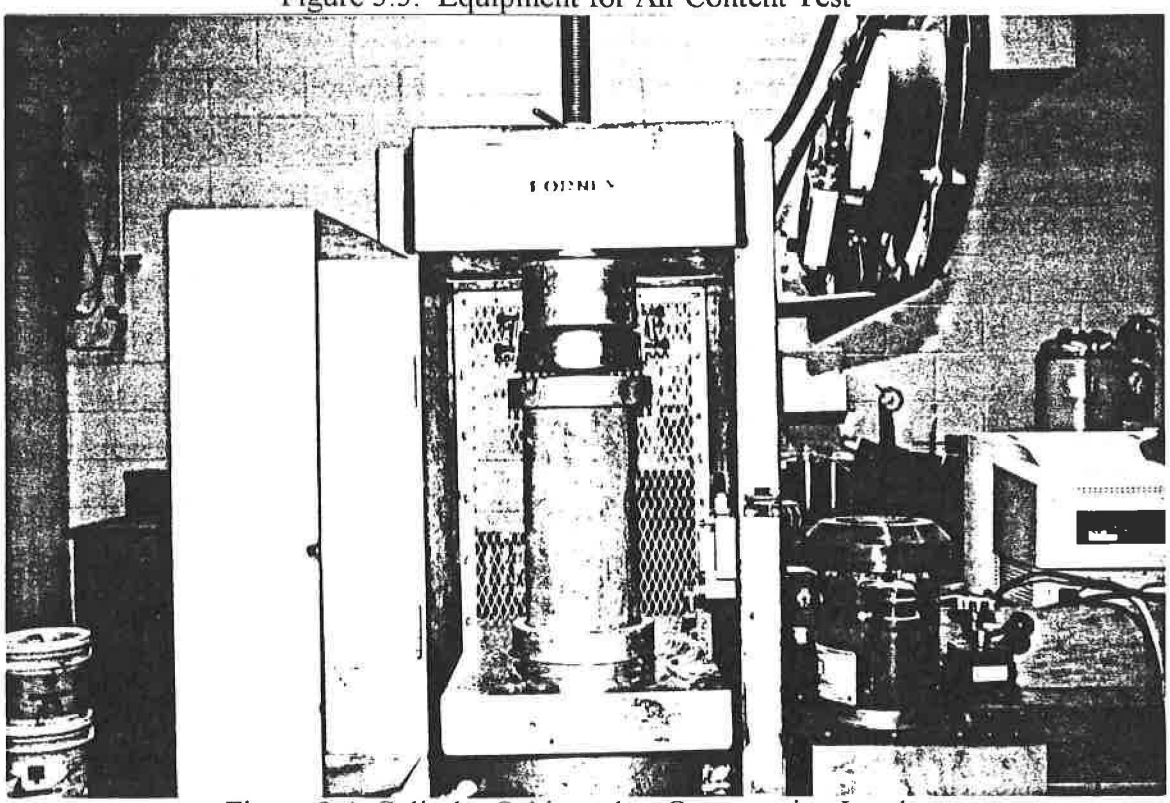

Figure 3.4. Cylinder Subjected to Compressive Load

specimens were conducted using a H3250 length comparator by Humbolt Manufacturing Company.The molds were cured at laboratory conditions and measured every day. Figure 3.5 and Figure 3.6 are photographs of the molds and the length comparator used respectively.

- Freeze-Thaw Durability – The Freeze-Thaw Durability test was conducted in accordance with ASTM C666. Specimens were created using a 3″x 4″x 16″ steel mold and cured according to ASTM C31. After initial curing of 24 hours, the specimens were stripped from the molds and placed in a moist cure environment chamber. The specimens were cured under these conditions for 14 days. At 14days, the initial fundamental frequency was recorded using a C-2010 sonometer by Geotest Instrument Corporation. The specimens were then placed in the freeze-thaw cabinet for repeated freezing and thawing cycles. ASTM C-666, Procedure A requires the specimens to be immersed in 1/8″ of water throughout the freeze thaw cycle. The freeze-thaw cycle involves lowering the temperature from 40° F to 0° F and then raising it from 0° F to 40°. Each cycle is approximately 3-4 hours in duration. The test was performed for 300 cycles, stopping approximately every 30 cycles to record the fundamental frequency. Figure 3.7 and Figure3.8 are photographs of the freeze-thaw cabinet and Sonometer.

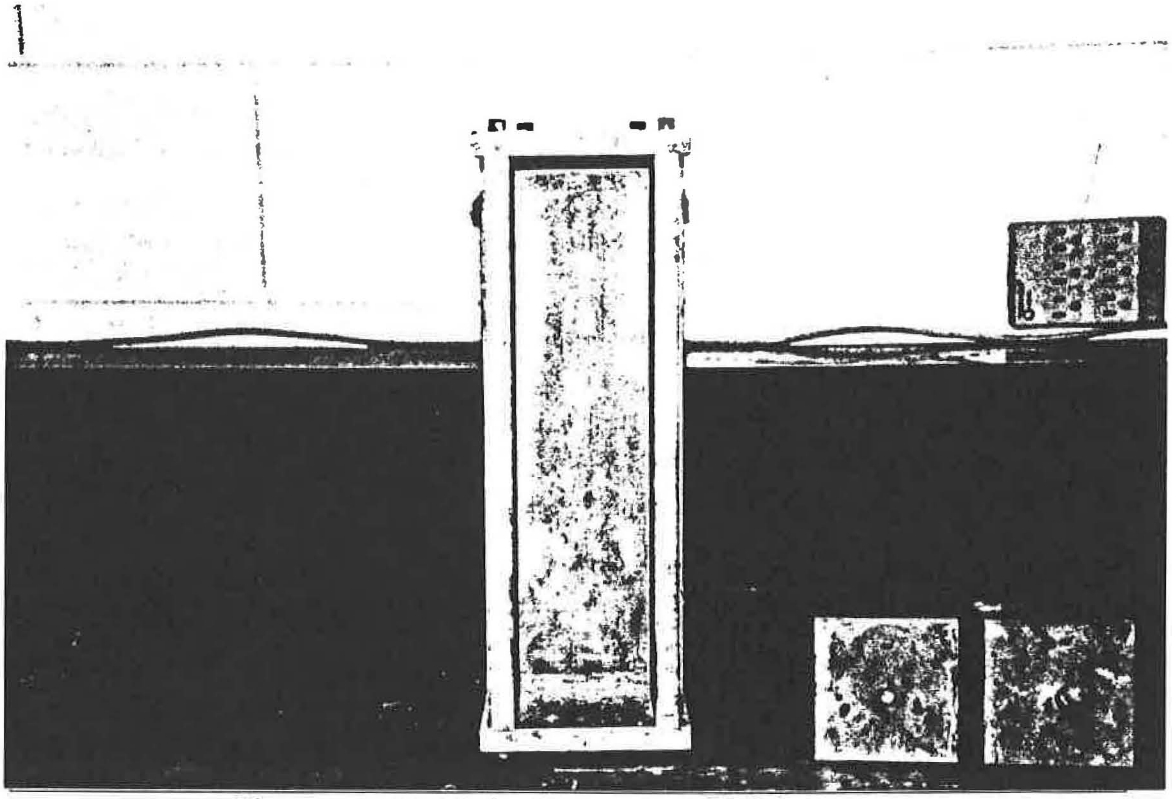

Figure 3.5. Molds for Unrestrained Shrinkage Bars

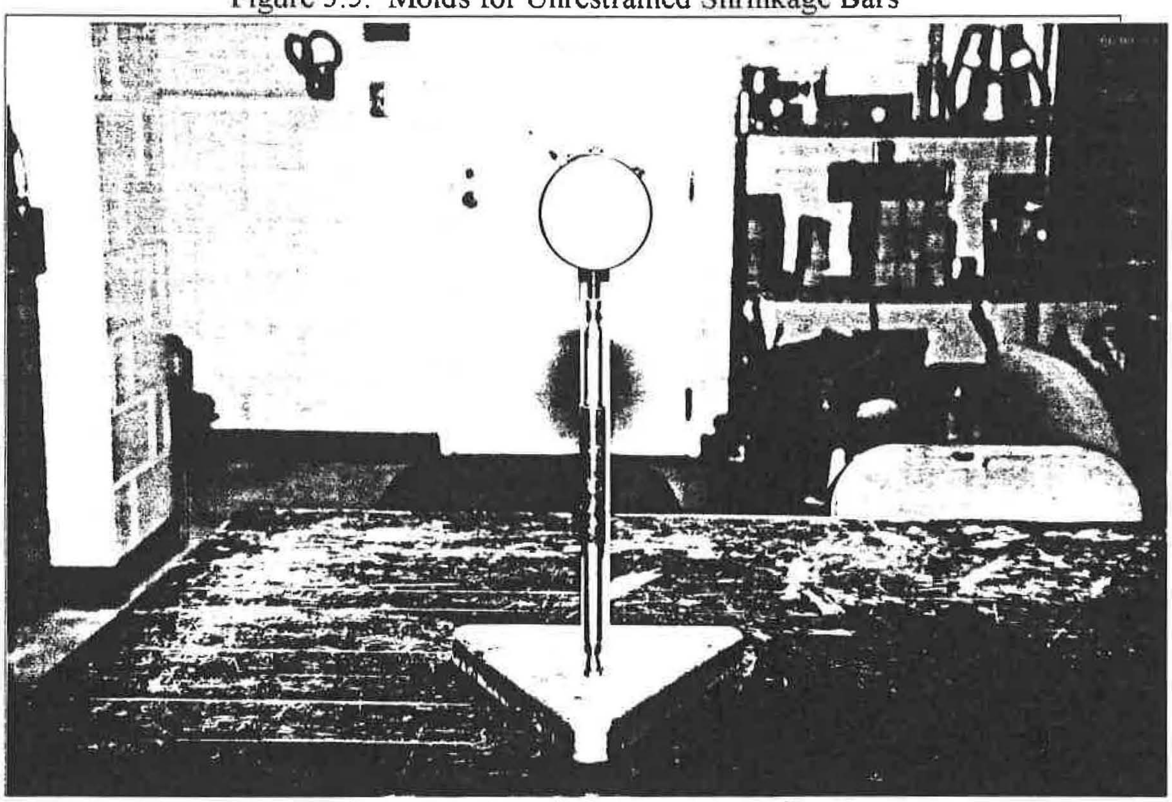

Figure 3.6. Length Comparator Unit

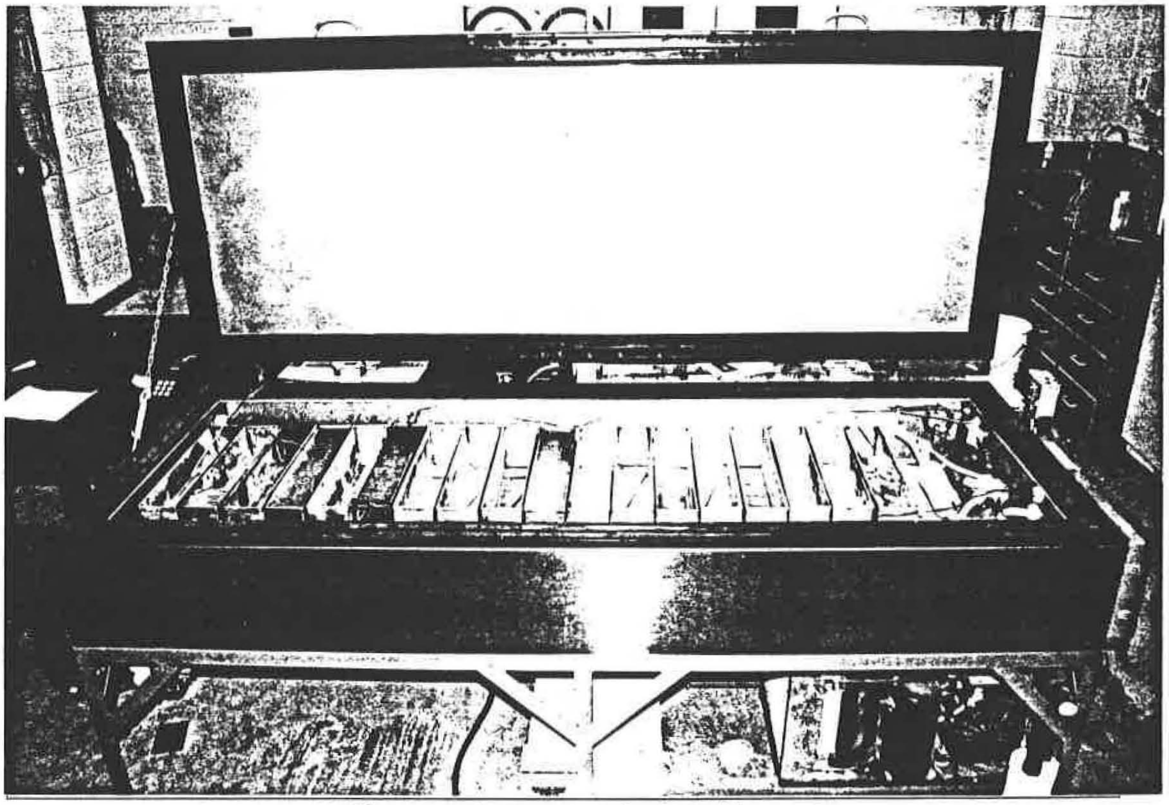

Figure 3.7. Freeze Thaw Cabinet

Figure 3.8. Sonometer

- Rapid Chloride Ion Penetration – The Rapid Chloride Penetration test was conducted in accordance with ASTM C1202. Specimens for the chloride ion test were constructed in accordance with ASTM C31. For each concrete specimen, two 4 x 8 in. cylinders were cast and moist cured for 56 days. At the conclusion of the 56-day curing cycle the permeability of the concrete was conducted. The apparatus used to perform the testing is shown in Figures 3.9 and 3.10. The rapid chloride Ion Penetration test measures the amount of electrical current or charges in coulombs that pass through a 2 in thick disk cut from a 4″ x 8″ in. cylinder during a 6-hour period. A capsule is placed on both ends of the specimen, with a sodium chloride solution in one and sodium hydroxide solutions in the other. A 60-volt current is then maintained across the ends of the specimen. The amount of coulombs passed through the sample during the 6-hour duration of the test is then related to the total resistance of the specimen to chloride ion penetration. A classification of chloride ion permeability in concrete as it relates to charge passed is as follows:

Charge Passed (Coulombs)	Chloride Ion Permeability Classification
> 4000	High
2000-4000	Moderate
1000-2000	Low
100-1000	Very Low
< 100	Negligible

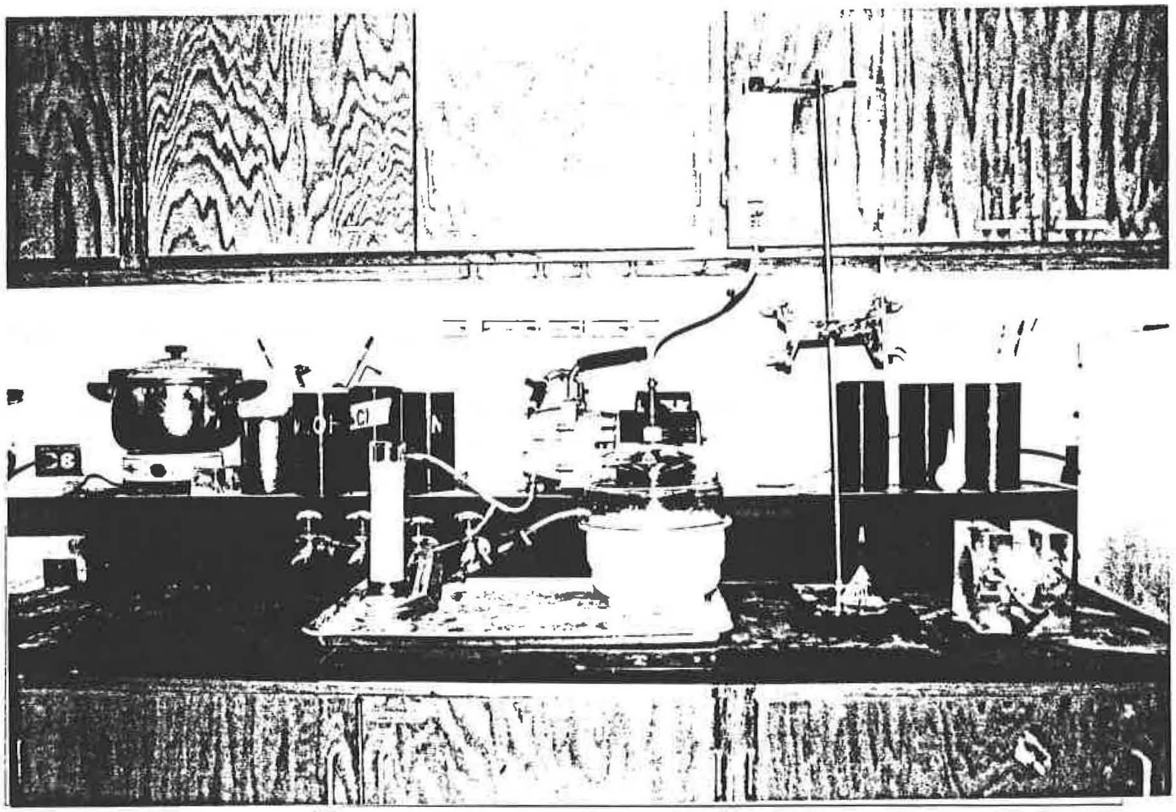

Figure 3.9. Vacuum Saturation Process

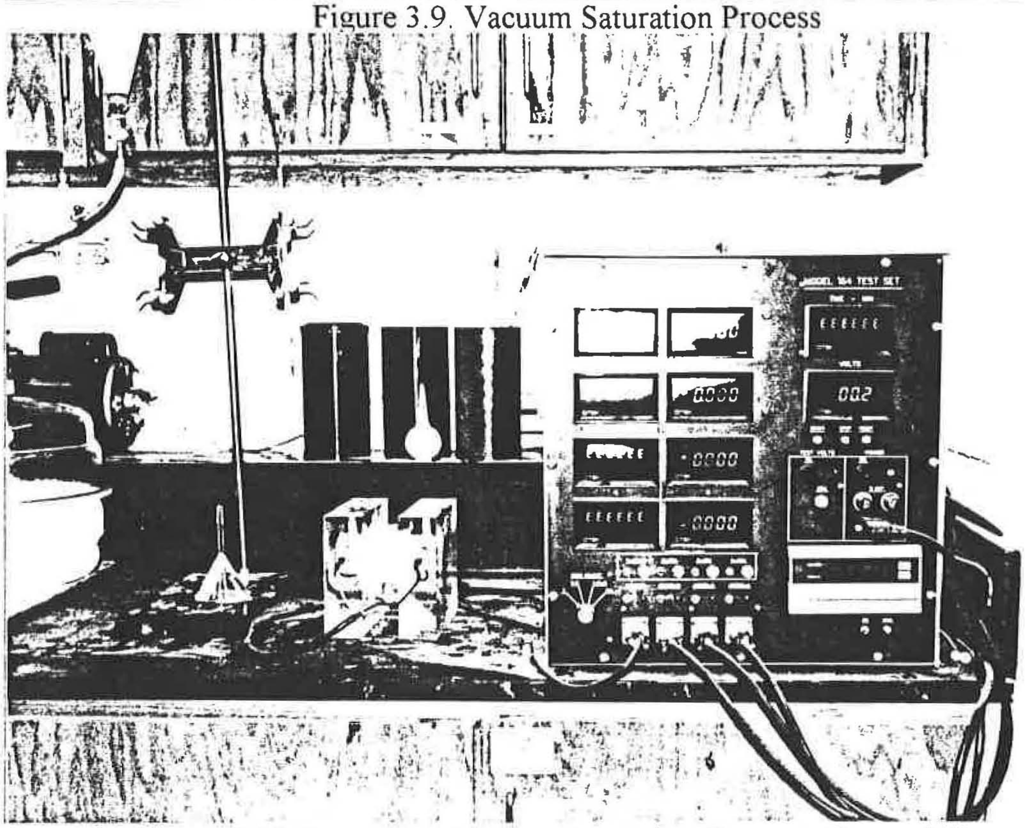

Figure 3.10. Instrument Used to Determine Concrete Permeability

3.3 Other Laboratory Mixtures Tested

When the ALDOT standard bridge concrete mixture was first prepared in the laboratory, the AEA (air entrainment admixture) was left out. The fresh concrete properties were evaluated for the mixture and test specimens for the hardened properties were prepared before this error was caught. Since the specimens were already made, it was decided to use them to evaluate the hardened properties to document the importance of entrained air on the fresh and hardened properties of the ALDOT standard bridge concrete mixture. This mixture is designated as ALDOT/NA-L in this report and its proportions were identical to those shown in Table 3.1 for the ALDOT-L mixture except that it contained no AEA. Raw materials, mixing procedure, fresh property testing, and hardened property testing were identical to those shown in Section 3-2 for the IM-L and ALDOT-L mixtures.

4. MODIFIED FIELD TESTING PROGRAM

4.1 General

ALDOT's standard bridge deck concrete with a MRWR was to be tested in the field on a three-span test bridge deck as indicated in Fig. 1.1 in Chapter 1. The testing was originally planned for Summer 2000, but was shifted to Summer 2001 when the scheduling and details could not be arranged. Unfortunately, the ALDOT was also not able to arrange the use of the mixture with a contractor in Summer 2001, and a modified testing plan needed to be devised. This plan consisted of placing 1 cubic yard of three different concrete mixtures in 4' x 8' x 5 ½" simulated deck forms adjacent to the Harbert Engineering Center as indicated in Figs. 4.1-4.3. The mixtures were batched and delivered by a local ready-mix company and placed on three consecutive mornings (between 9:00 - 10:00 am) in August 2001. The mixtures tested, mixing procedure, and fresh and hardened properties tested are described in the sections below.

4.2 Modified Field Concrete Mixture Testing

Concrete Mixtures Tested. Three mixtures were tested in the field testing program, and were as follows:

1. ALDOT Standard Bridge Deck Mixture (ALDOT-F). This mixture was used as a reference and control sample. It is the standard mixture currently used by ALDOT for bridge decks.

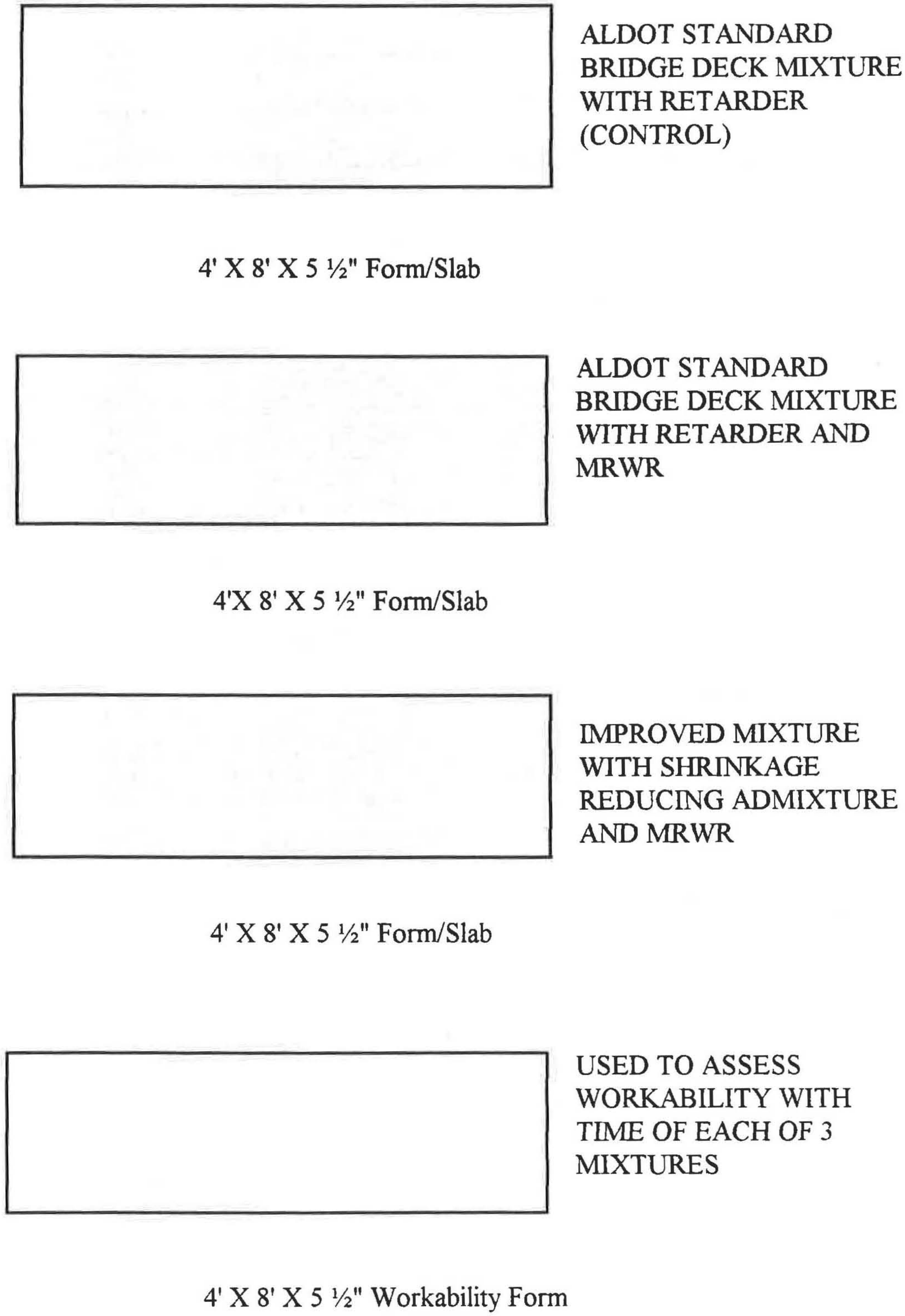

Fig. 4.1. Simulated Bridge Deck Slabs

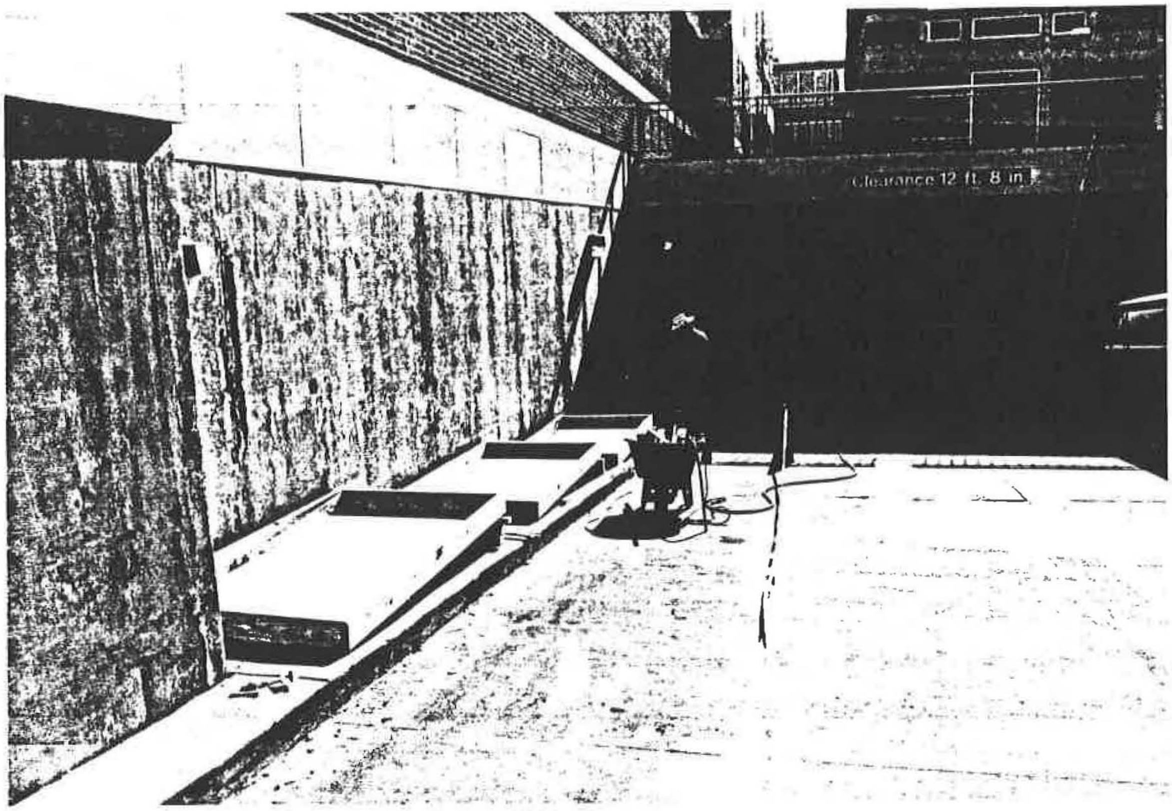

Fig. 4.2. Simulated Deck Slab Forms Ready for Concrete

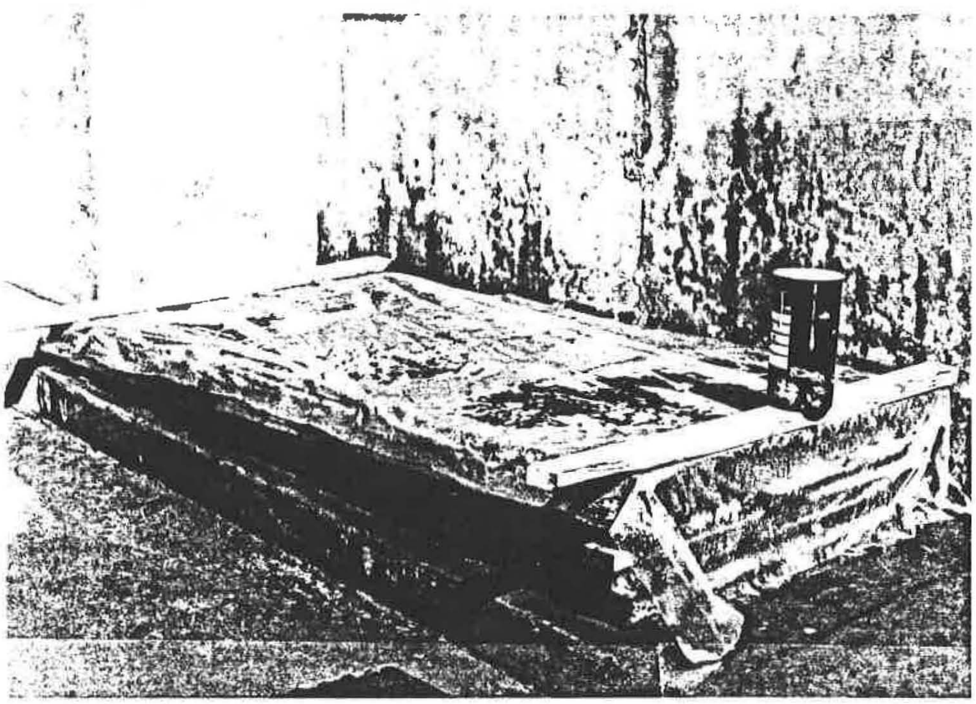

Fig. 4.3. ALDOT-F Mixture Panel Curing 1-Day After Placement

2. ALDOT Standard Bridge Deck Concrete with a MRWR (ALDOT/WR-F). This mixtures was used to assess how the addition of a MRWR would effect the fresh and hardened properties of ALDOT's standard bridge deck concrete.

3. Improved Mixture (IM-F). This mixture was used to assess the fresh and hardened properties of a mixture designed to be an improved concrete mixture for bridge decks. It is the same mixture used in the laboratory testing program, i.e., the IM-L mixture.

The planned proportions for the three mixtures are shown in Table 4.1. Note that one of the mixtures is the "improved" mixture tested in the laboratory, i.e., IM-L. The originally planned field testing did not allow the placement of this mixture since it was not a tested and ALDOT approved mixture. However, with the modified simulated deck panel testing, this mixture could be and was included.

Unfortunately, the concrete ready-mix supplier made significant errors in batching the mixtures as indicated in Table 4.2 which shows the specified and the delivered concrete proportions. The batching error in the ALDOT standard mixture was that of not knowing the amount of water used in the mixture; but, based on the slump of the concrete, it was felt that the water used was probably satisfactory. For the ALDOT standard with MRWR, the mixture was over-sanded by approximately 300 pounds or 25%. In the "improved" MRWR mixture, the shrinkage reducing admixture (SRA) was left out. All three mixtures had a heavy dosage of retarder that grossly prolonged the set-time.

Table 4.1. Planned Modified Field Testing Concrete Test Mixture Proportions

Mix Component	Concrete Mixtures		
	ALDOT-F[5]	**ALDOT/WR-F[6]**	**IM-F**
Cement (lb/yd3) Type I	620	620	385
C-Ash (lb/yd^3)	N/A	N/A	165
Course Aggregate (#57 Limestone) (lb/yd^3)	2021	2021	1910
Fine Aggregate (lb/yd^3)	1084	1084	1362
MRWR[1] (ml/yd^3)	N/A	1656	1630
AEA[2] (ml/yd^3)	≈488	≈488	≈488
SRA3 (ml/yd3)	N/A	N/A	1789
Retarder[4] (ml/yd^3)	As Needed	As Needed	325
Water (lb/yd^3)	275	242	220
W/C Ratio	0.44	0.39	0.40

1. Polyheed 997 manufactured by Master Builders Technologies
2. MB AE-90 manufactured by Master Builders Technologies to acheive 4-6% air content
3. Polygaurd AS20 manufactured by Master Builders Technologies
4. Pozzolith 100-XR manufactured by Master Builders Technologies
5. 3.5" Maximum slump
6. 5-6" slump

Table 4.2. Specified and Delivered Modified Field Testing Concrete Test Mixture Proportions

Mix Component	Concrete Mixtures					
	ALDOT-F		ALDOT/WR-F		IM-F	
	Specified[5]	Delivered	Specified[6]	Delivered	Specified	Delivered
Cement (lb/yd3) Type I	620	620	620	625	385	385
C-Ash (lb/yd^3)	N/A	0	N/A	0	165	165
Course Aggregate (#57 Limestone) (lb/yd^3)	2021	2021	2021	2000	1910	1910
Fine Aggregate (lb/yd^3)	1084	1084	1084	1420	1362	1362
MRWR[1] (ml/yd^3)	N/A	0	1656	1656	1630	1626
AEA[2] (ml/yd^3)	≈488	118	≈488	118	≈488	118
SRA3 (ml/yd3)	N/A	0	N/A	0	1789	0
Retarder[4] (ml/yd^3)	As Needed	532	As Needed	532	325	532
Water (lb/yd^3)	275	?	242	245	220	227
W/C Ratio	0.44	?	0.39	0.39	0.40	0.41

1. Polyheed 997 manufactured by Master Builders Technologies
2. MB AE-90 manufactured by Master Builders Technologies to achieve 4-6% air content
3. Polygaurd AS20 manufactured by Master Builders Technologies
4. Pozzolith 100-XR manufactured by Master Builders Technologies
5. 3.5" Maximum slump
6. 5-6" slump

Concrete Batching/Mixing Procedure. All three mixtures were batched (one cubic yard of each), mixed, and delivered to the field test location behind the Harbert Engineering Center by Blue Circle Materials Company in Auburn. This procedure was used to more realistically simulate a deck field placement situation. Unfortunately, it resulted in significant errors in the mixture proportions indicated in Table 4.2.

4.3 Fresh Concrete Property Testing

The fresh concrete property testing conducted on the field mixtures was as follows:

- Slump vs. Time Testing
- Air Content vs. Time Testing
- Unit Weight vs. Time Testing
- Concrete Temperature vs. Time Testing
- Workability vs. Time Testing

Individual slump, air content, unit weight, and concrete temperature tests were conducted according to ASTM standards as indicated in Table 3.2, and these were repeated periodically with time. The concrete used for testing air content was discarded after each test. The workability vs. time testing was conducted in the extra 4' x 8' x 5 ½" workability form (see Figs. 4.1 and 4.4) to assess the ease or difficulty in working the mixture with time.

4.4 Hardened Concrete Property Testing

The hardened concrete property testing was the same as that for the laboratory testing of the "Improved" MRWR testing described earlier, i.e.,

- Compressive Strength at 7, 14, 28, 56-days

- Drying Shrinkage
- Freeze-Thaw Durability
- Rapid Chloride Ion Penetration

Each of these tests were conducted according to ASTM standards as indicated in Table 3.3.

For each of the field mixture panels shown in Fig. 4.1, ambient and internal concrete temperatures were monitored for the first two days. Also, the total shrinkage of the 4' x 8' panels were periodically measured for the first two months. Figures 4.5 and 4.6 show a thermocouple lead coming from the center of a panel, and the drying shrinkage of a concrete panel away from its form respectively.

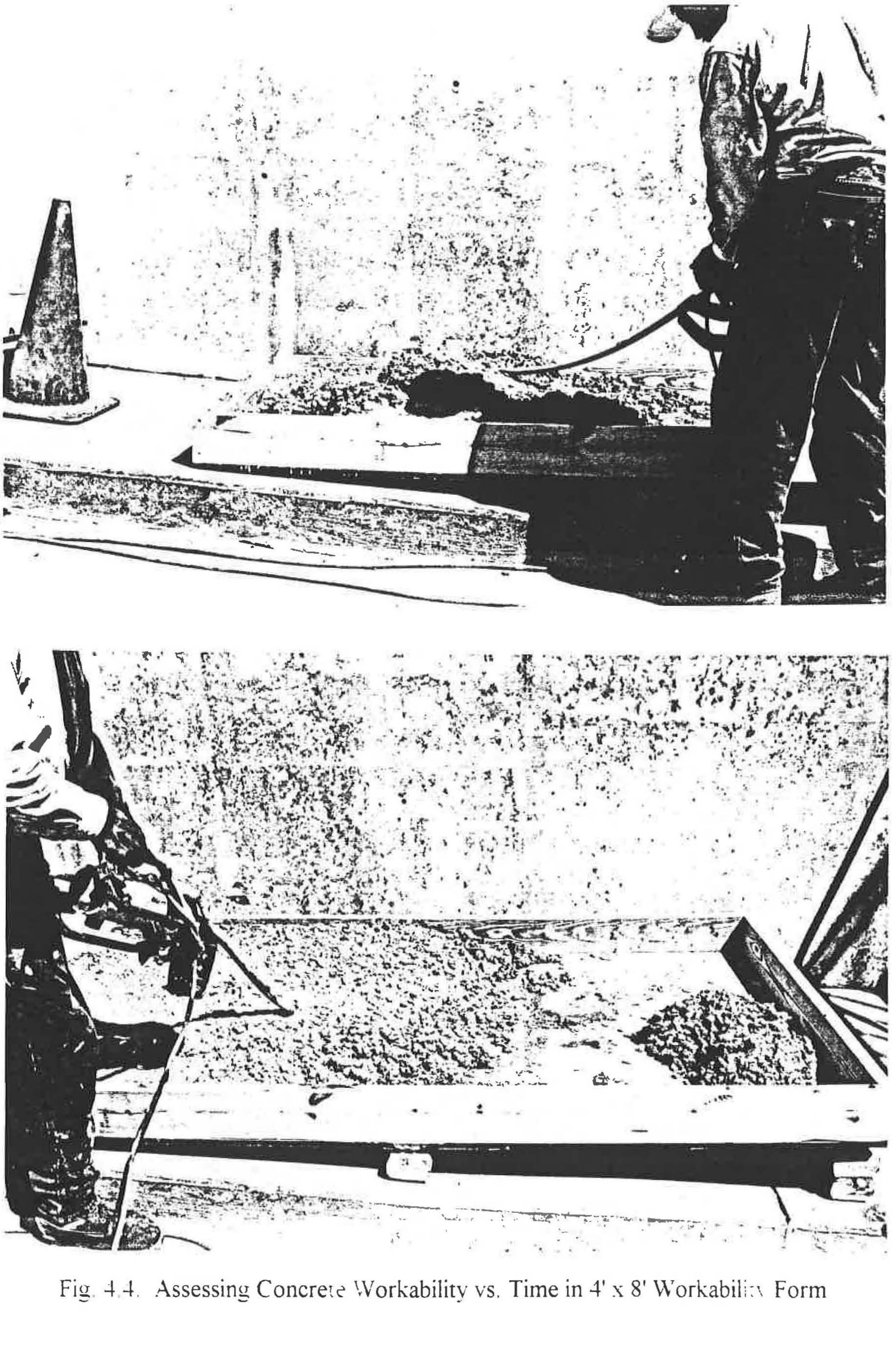

Fig. 4.4. Assessing Concrete Workability vs. Time in 4' x 8' Workability Form

5. PRESENTATION OF LABORATORY RESULTS

5.1 General

As mentioned in Chapter 3, laboratory testing was conducted on the following three mix designs:

- IM-L – "Improved" concrete mixture containing mid-range water reducer.
- ALDOT-L (Control) – ALDOT standard bridge deck mixture
- ALDOT/NA-L – ALDOT standard bridge deck mixture without air entrainment.

The principal objective of the laboratory testing program was to asses the effects of mid-range water reducers (MRWR) in improving concrete mixtures for bridge decks. The evaluations of the concrete mixtures are discussed in the following results of the fresh and hardened properties tested.

5.2 Fresh Concrete Property Results

The fresh concrete property testing was conducted to assess the workability and constructability of the concrete mixtures. The tests consisted of determining slump, unit weight, air content and concrete temperature for all mixtures. The results shown are an average of two replica tests for each concrete mixture. Results of these tests are discussed below.

Slump Test – Slump tests were performed immediately after completion of mixing for each concrete mixture. Results of the slump tests are shown in Table 5.1 and in Figure 5.1. Figure 5.1 shows the slump of the mixtures on the same plot to facilitate comparison. As expected the IM-L mixture has a much higher slump compared to the control mixture. This demonstrates the effectiveness of the adding the MRWR in the IM-L mixture, to increase slump of concrete while holding the *w/c* ratio down. The ALDOT-L (Control) mixture demonstrates a higher slump than ALDOT/NA-L, which had no air entrainment. The air content in the concrete mixture had a considerable effect on the slump which is as one would expect.

Unit Weight- Unit weight was measured at the completion of mixing of the concrete and the results are shown in Table 5.1 and in Figure 5.2. Figure 5.2 shows the unit weight of each mixture on the same plot to facilitate comparison. The high unit weight of the IM-L mixture is probably due to its reduced water content (see Table 3.1).

Air Content – Air content was conducted on each mixture at the completion of mixing of the concrete. The results for the air content are shown in Table 5.1 and Figure 5.3. The plot of Figure 5.3 is used to facilitate comparison of air content for each mixture. The air entrainment admixture (AEA) dosage was the same for both the IM-L and ALDOT-L (Control) and produced approximately the same percent air content. The ALDOT/NA-L was mixed without the addition of the air entrainment admixture. The air content in this mixture is a measure of the "natural" air content that results when preparing and mixing a concrete mixture.

Concrete Temperature – The temperature of the concrete was observed at the completion of the mixing of the concrete and the results are shown in Table 5.1. There

5.1 Fresh Concrete Property Testing Results

Concrete Property/Parameter	Concrete Mixture		
	IM-L	**ALDOT-L (Control)**	**ALDOT/NA-L**
Slump ASTM C143 (inches)	7.25	5.5	3.5
Unit Weight ASTM C138 (lbs/cf)	149.7	150.3	151.2
Air Content ASTM C231 (%)	5.5	5.7	2.5
Concrete Temperature ASTM C1064 (°F)	76	78	76

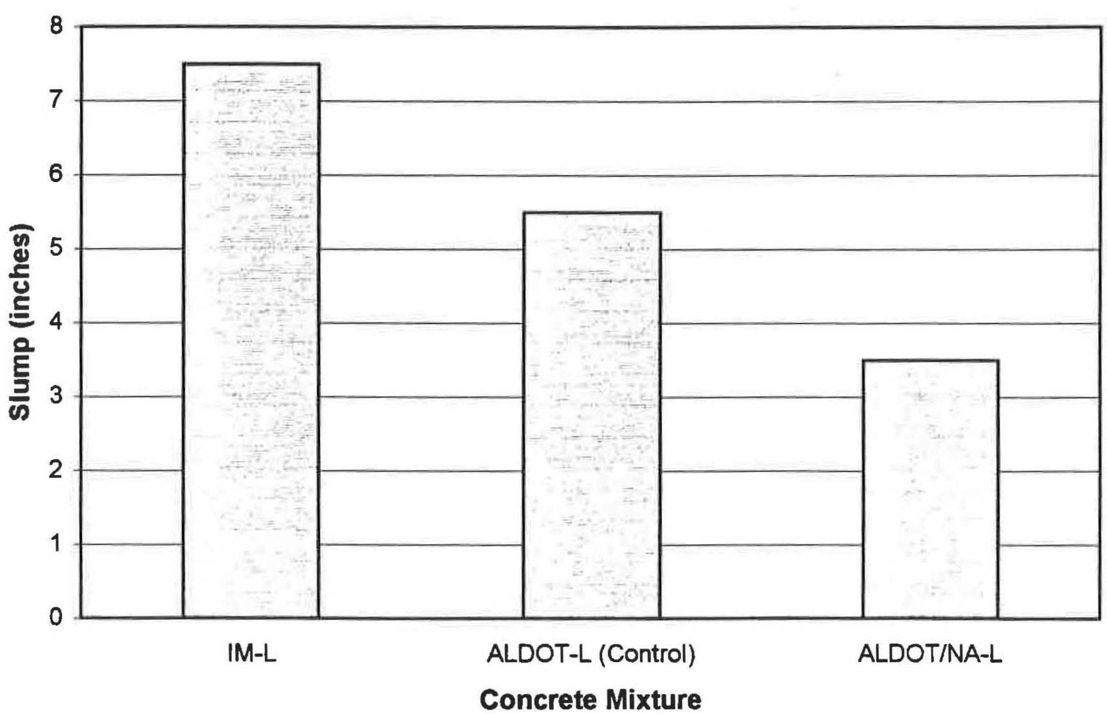

Figure 5.1 Slump for Concrete Mixtures

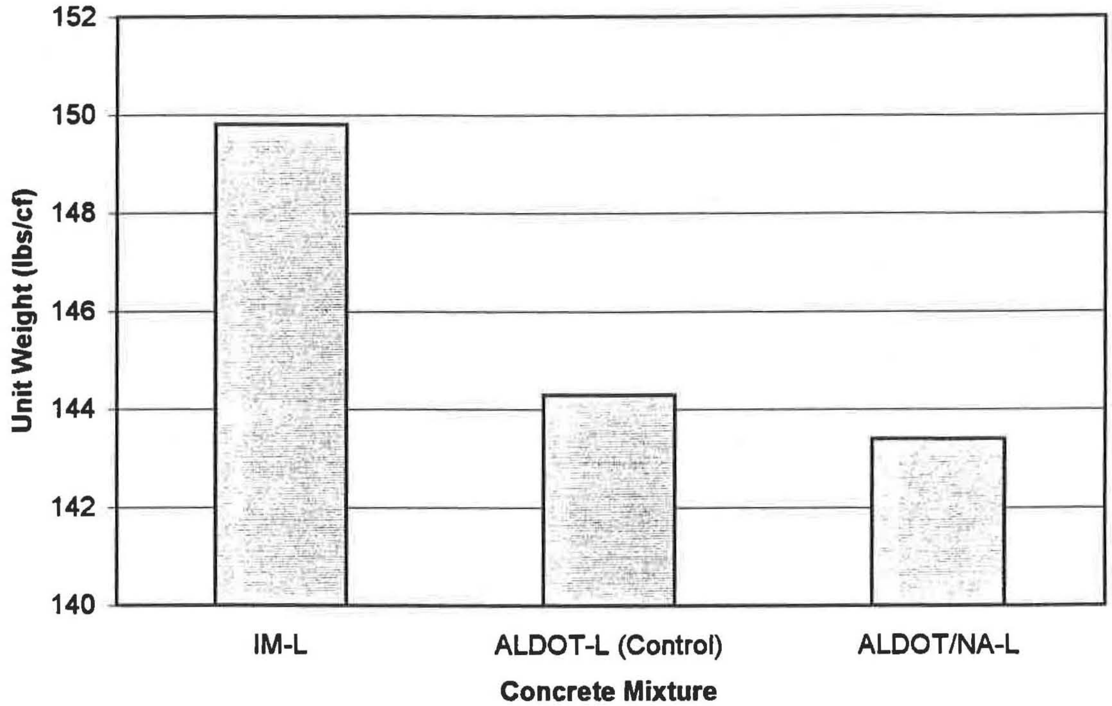

Figure 5.2 Unit Weight for Concrete Mixtures

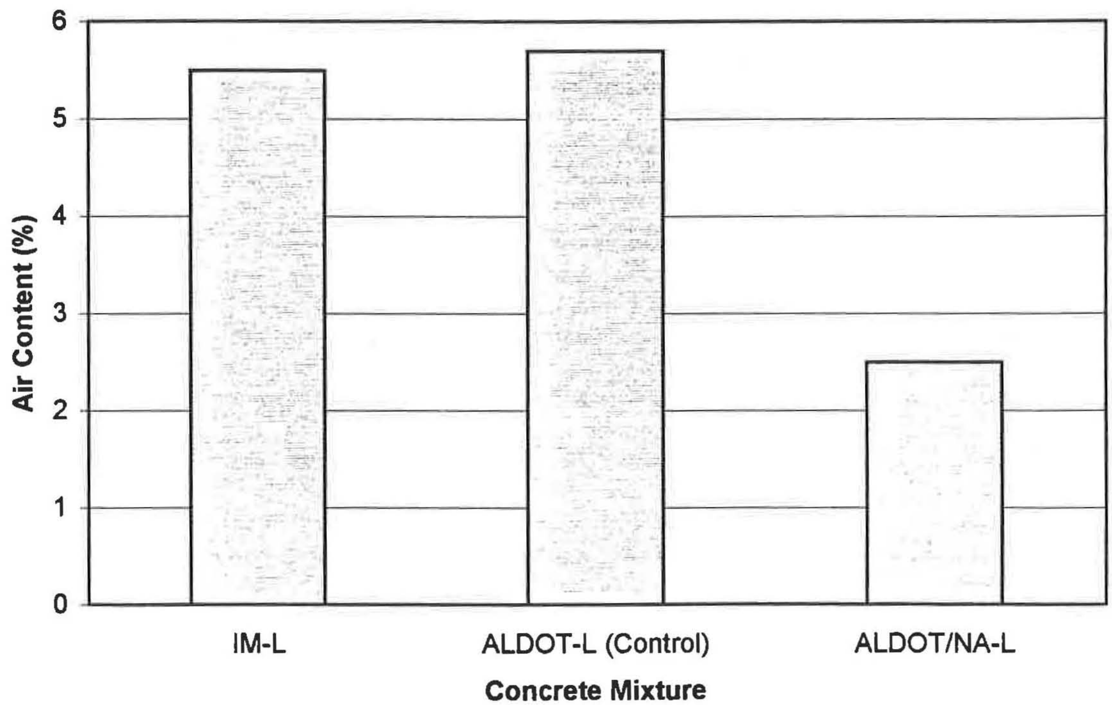

Figure 5.3 Air Content for Concrete Mixtures

was no significant difference between the temperatures of the concrete mixtures, which were approximately 2-3°F above the ambient temperature at the time of mixing

5.3 Hardened Concrete Property Results

The following hardened concrete property tests were conducted to examine certain characteristics of the concrete mixtures: compressive strength, unrestrained bar shrinkage, freeze-thaw durability and rapid chloride ion penetration. All results are an average of two replica tests. Results from each test are discussed below.

Compressive Strength - Compressive strength of each concrete mixture was conducted at 7, 14, 28 and 56 days using 4″x8″ specimens. The results of the compressive strength for all mixtures are presented in Table 5.2 and Figure 5.4. Figure 5.4 shows the three different mixtures on the same plot to facilitate comparing the results.

The ALDOT/NA-L mixture displayed the highest and fastest gaining strength of the three mixtures. This was not totally unexpected considering the lack of air entrainment in this mixture. However, one might expect that the lower *w/c* ratio of the IM-L mixture would result in it having the higher strength. The IM-L mixture attained very good final compressive strength, exceeding the compressive strength requirements of the ALDOT-L (Control) mixture used for bridge decks, even though it contained 11% less cementious material (see Table 3.1). Also the IM-L mixture rate of strength gain was about the same as the other two mixtures even though it contained 30% cement replacement with C-ash (see Table 3.1). The ALDOT-L (Control) had the lowest concrete strength of the three mixtures, which is probably as should be expected.

Unrestrained Bar Shrinkage – The unrestrained drying shrinkage tests were observed daily over a 60-day period. All of the samples tested were cured under relatively constant laboratory temperature and humidity. The results are presented in Table 5.3, Figure 5.5 and Appendix A. The Table 5.3 shows only the results after 60-days, and Figure 5.5 is a plot of the shrinkage data from days 1-60 shown in Appendix A.

The results for the unrestrained bar shrinkage were very similar for all three mixtures, with the IM-L mixture producing the best results. This is as expected due to the use of a shrinkage reducing admixture and a reduced *w/c* ratio in the IM-L mixture. However, how much of the reduced shrinkage was due to each (shrinkage reducing admixture and reduced w/c ratio) is not known. The reason for the significantly larger shrinkage of the ALDOT/NA-L mixture relative to that of the ALDOT-L mixture is also not known.

Freeze-Thaw Durability – The freeze-thaw durability results were observed approximately every 30 cycles for 350 cycles. The results of the freeze-thaw durability are shown in Table 5.4 and Figures5.6 – 5.7. Figure 5.6 displays the results for the IM-L and ALDOT-L (Control) mixtures for comparison. Figure 5.7 displays the results of the ALDOT/NA-L. The trends for the ALDOT-L (Control) and the IM-L mixtures were significantly different. The ALDOT-L mixture displayed a relatively large decrease in durability over the initial 30-90 cycles, after which its durability factor leveled out. The IM-L mixture also displayed a relatively large decrease in durability over the first 30 cycles. However, the IM-L mixture regained durability from 30-150 cycles after which its durability factor dramatically dropped by about 6% from 150-250 cycles before leveling out to its final durability. The sudden increase in durability (from 30-150 cycles) of the IM-L mixture may be attributed to the use of C-ash in the mixture, which causes slower strength gain. The final results of the ALDOT-L and IM-L mixtures were relatively close in overall durability, with the ALDOT-L mixture showing a slightly better durability factor. The IM-L mixture also exhibited a greater occurrence of scaling on the surface of the samples. Figure 5.8 and 5.9 show the extent of scaling on both the IM-L and ALDOT-L mixtures at the completion of the testing.

The freeze-thaw durability results for the ALDOT/NA-L mixture was observed approximately every 30 cycles for 150 cycles. Figure 5.7 displays the results for the ALDOT/NA-L mixture. The result of not having proper air entrainment in the concrete mixture during the freeze-thaw cycle is evident by the rapid and unacceptable decline in durability in Figure 5.7. The ALDOT/NA-L mixture specimens at the end of 150 cycles had cracked and scaled to the extent that no significant reading could be obtained.

Rapid Chloride Ion Penetration – The rapid chloride ion penetration test was conducted on two samples of each concrete mixture after a curing period of 56 days. The results of these tests are displayed in Table 5.5 and Figure 5.10. Figure 5.10 shows plots of the results of all three mixtures for convenience in comparison. As can be seen in Table 5.5 and Figure 5.10, the results of the rapid chloride ion test were quite similar for all these mixtures. All of the mixtures are classified as "moderate" pertaining to the permeability classification of the ASTM rating. The ALDOT-L (Control) mixture performed slightly better than the IM-L mixture.

Table 5.2 Compressive Strength Results for Concrete Mixtures

Concrete Property/Parameter		Concrete Mixture		
		IM-L	ALDOT-L (Control)	ALDOT/NA-L
Compressive Strength ASTM C39 (psi)	7-day	3482	2588	4198
	14-day	4059	2967	5929
	28-day	5054	3801	6765
	56-day	5730	4188	8153

Table 5.3 Unrestrained Bar Shrinkage Results for Concrete Mixtures[1]

Concrete Mixture	% of Length Change @ 60 Days	Shrinkage Classification
IM-L	-0.039	Low Shrinkage
ALDOT-L (Control)	-0.045	Moderate Shrinkage
ALDOT/NA-L	-0.068	Moderate Shrinkage

1. Complete Shrinkage bar results are shown in Appendix A.

Table 5.4 Freeze-Thaw Durability Results for Concrete Mixtures

Concrete Mixture	Initial Frequency (Hz)	Final Frequency[1] (Hz)	Durability Factor (%)
IM-L	1913	1774	92.7
ALDOT-L (Control)	1735	1644	94.7
ALDOT/NA-L	1954	0	0

1. After 300 freeze-thaw cycles.

Table 5.5 Rapid Chloride Ion Penetration Results for Concrete Mixtures

Concrete Mixture	Charged Passed (Coulombs)	ASTM C1202 Rating
IM-L	2950	Moderate
ALDOT-L (Control)	2534	Moderate
ALDOT/NA-L	2551	Moderate

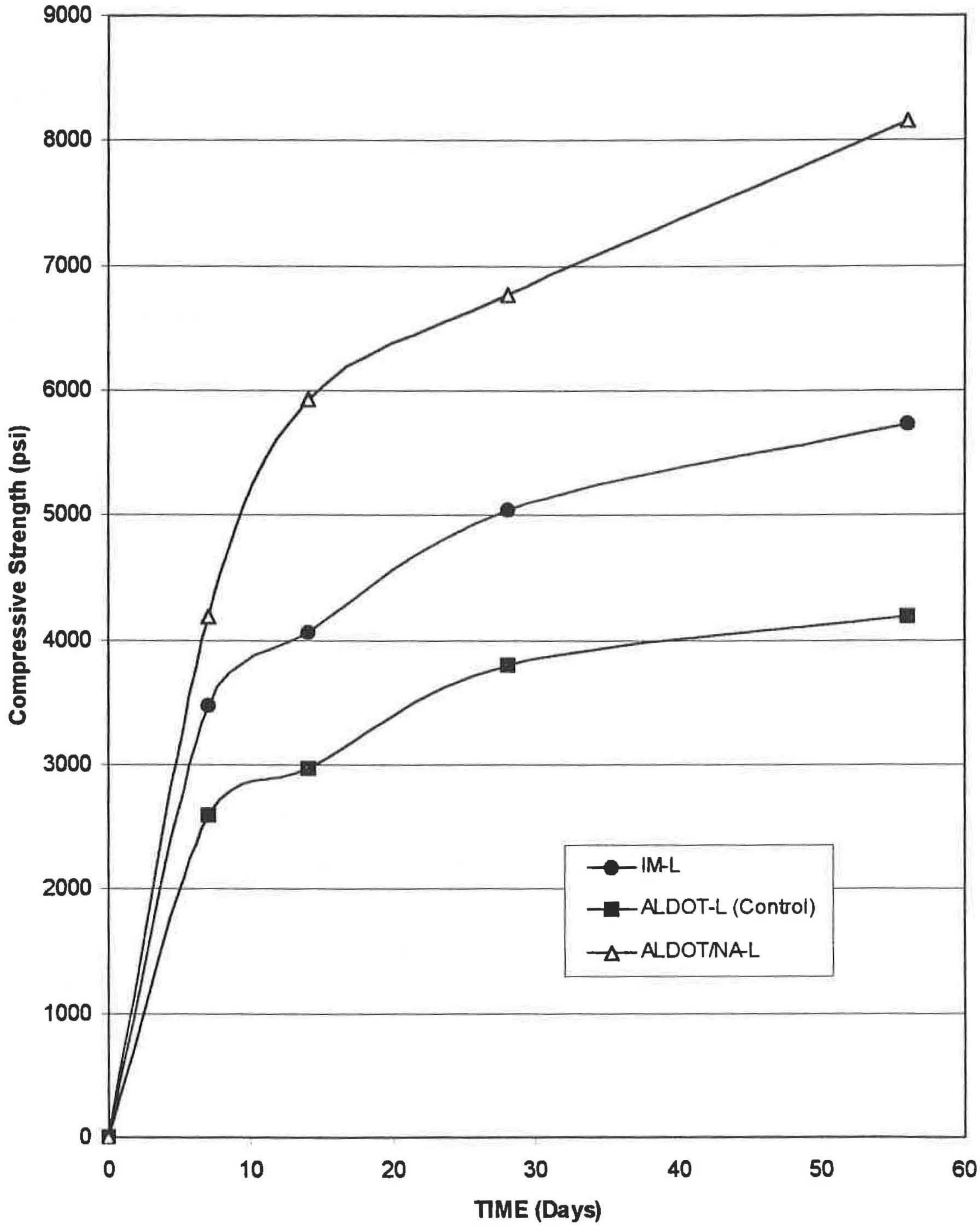

Figure 5.4 Compressive Strength for Concrete Mixtures

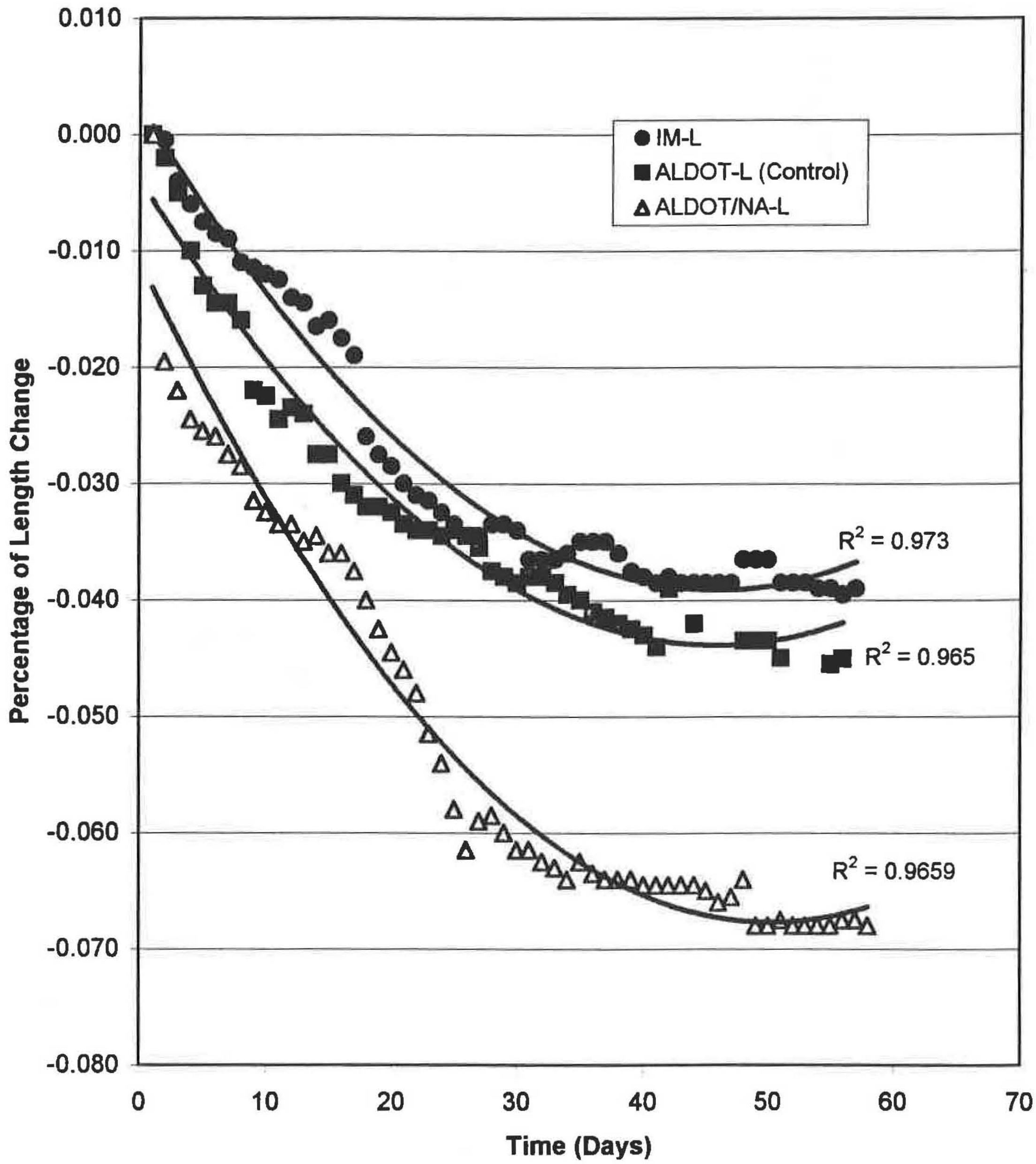

Figure 5.5 Unrestrained Bar Shrinkage for Concrete Mixtures

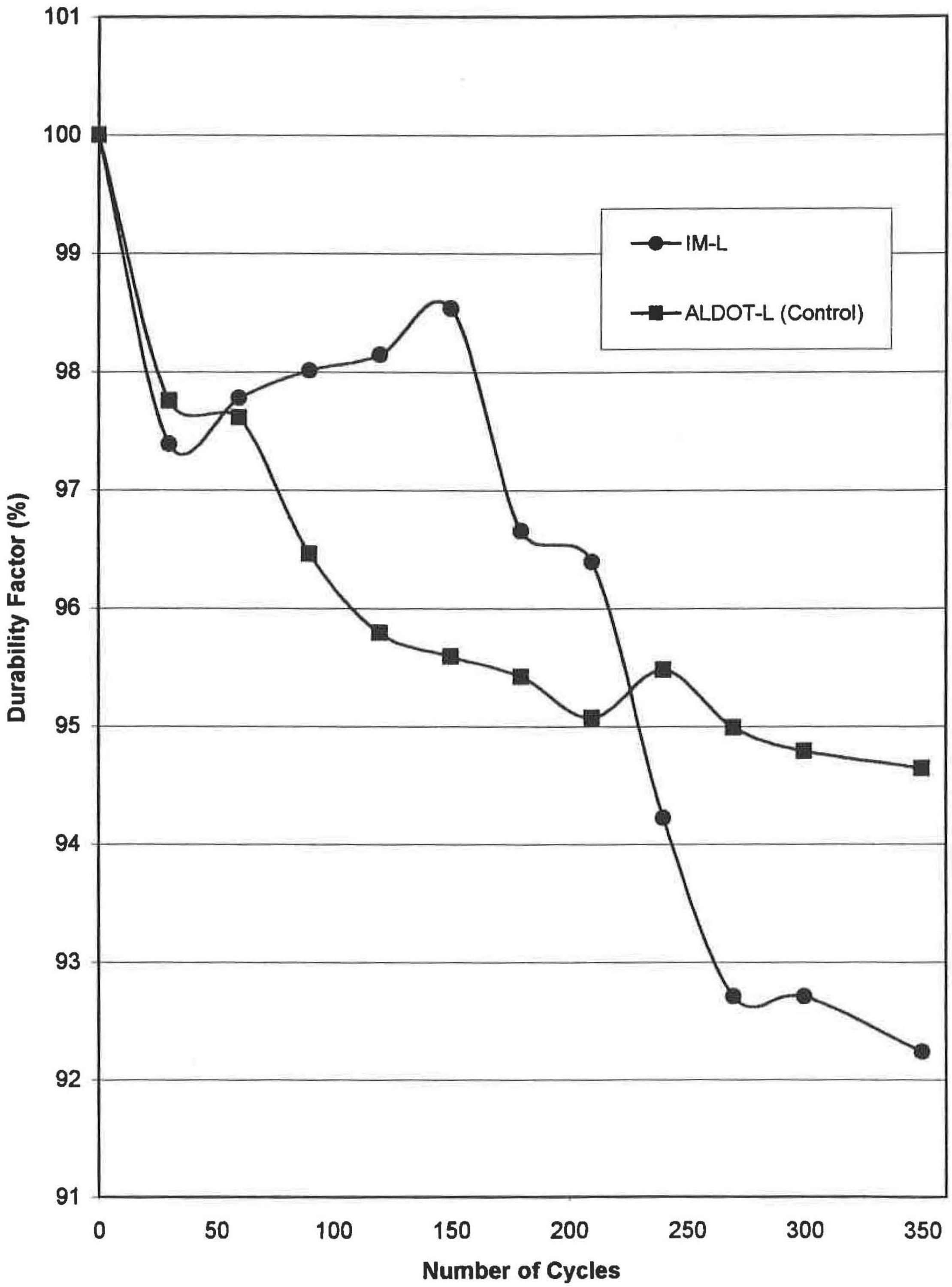

Figure 5.6 Freeze-Thaw Durability Results for Concrete Mixtures

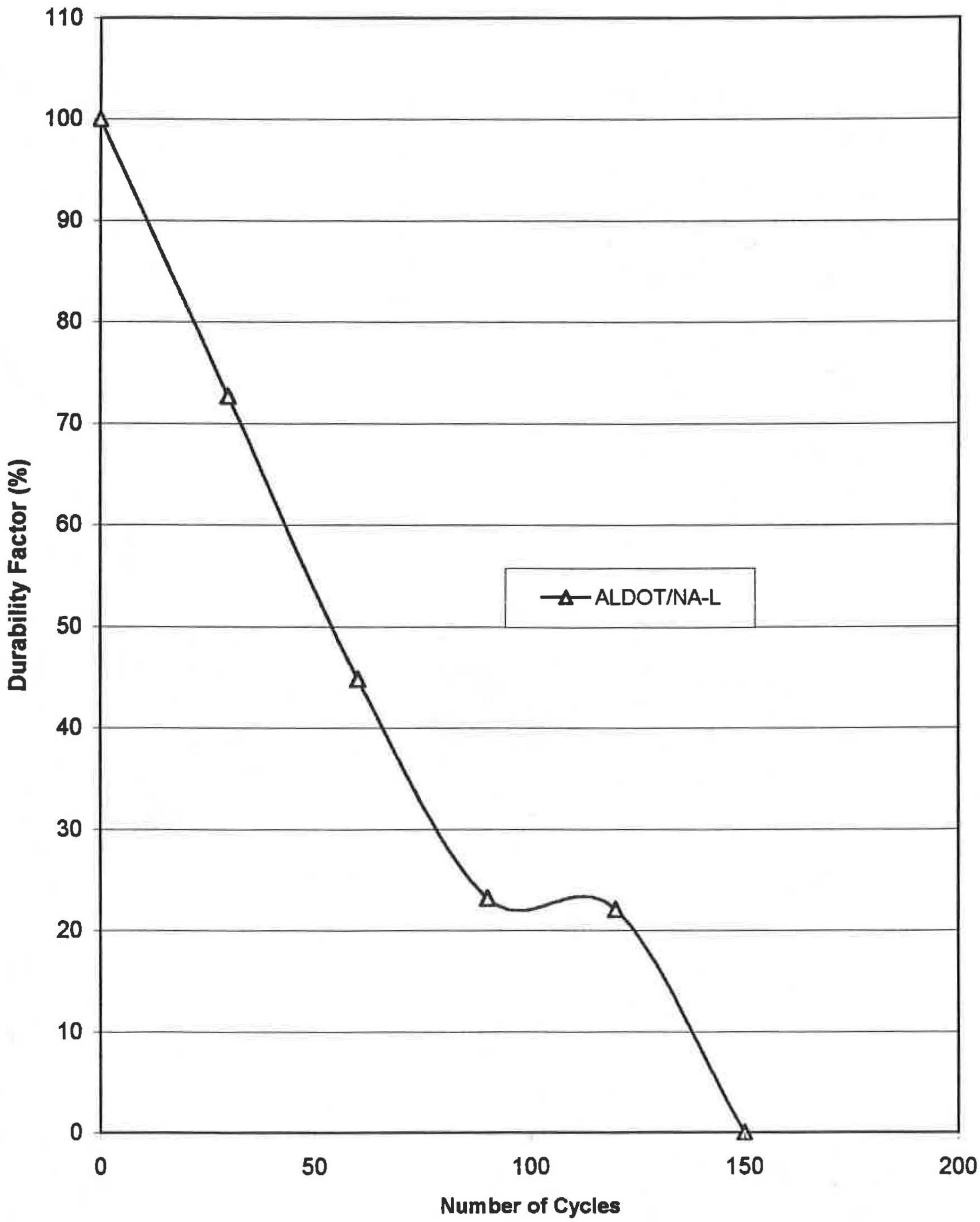

Figure 5.7 Freeze-Thaw Durability Results for ALDOT/NA-L Concrete Mixture

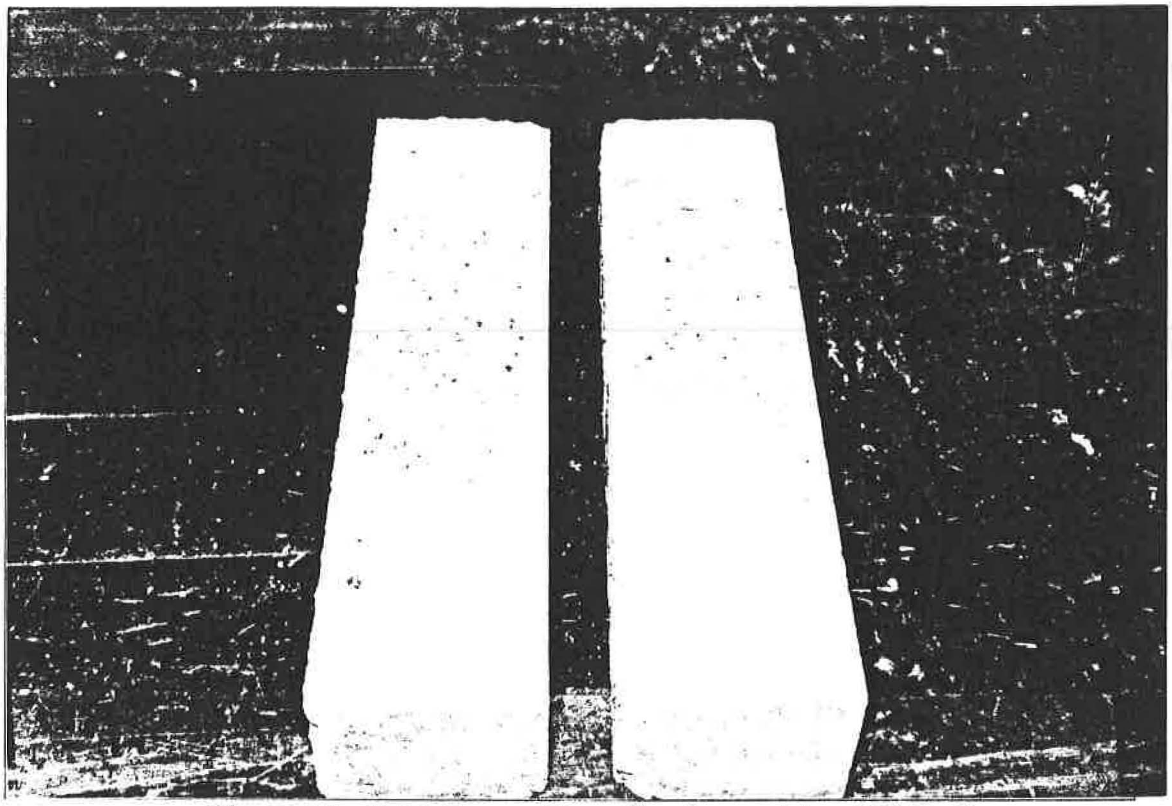

Figure 5.8. IM-L Freeze-Thaw Specimens After 300-Cycles

Figure 5.9. ALDOT-L (Control) Freeze-Thaw Specimens

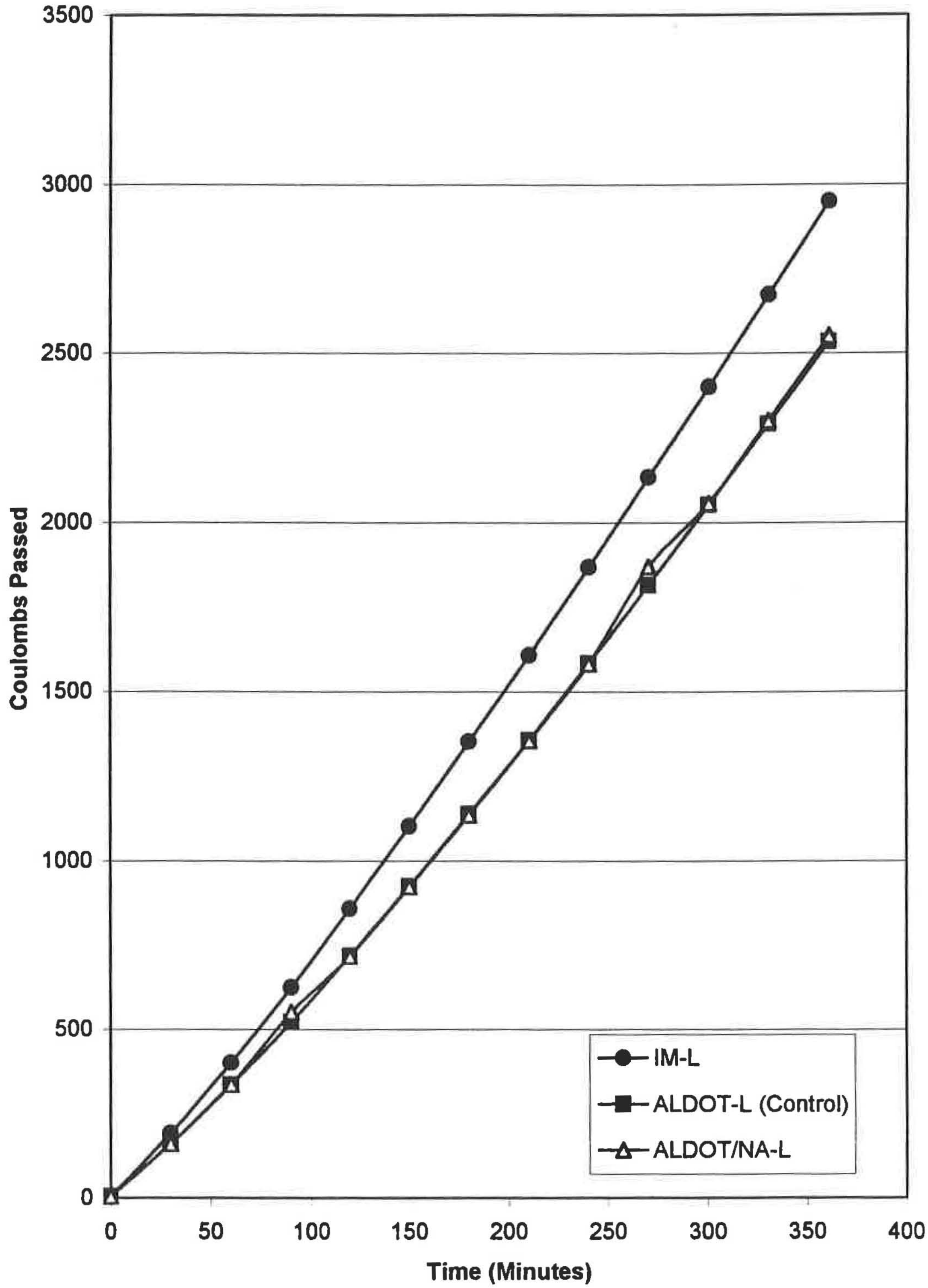

Figure 5.10 Rapid Chloride Ion Penetration Results for Concrete Mixtures

6. PRESENTATION OF MODIFIED FIELD RESULTS

6.1 General

As mentioned in Chapter 4, laboratory and modified field testing were conducted on the following three mix designs:

- IM-F – "Improved" concrete mixture containing mid-range water reducer.
- ALDOT-F (Control) – ALDOT standard bridge deck mixture
- ALDOT/WR-F – ALDOT standard bridge deck mixture with water reducer.

The "F" designation on the above mixtures indicates that they are one of the modified field mixtures tested. It was planned that the IM-F and IM-L (see Chapter 3) be the same mixture and the same for the ALDOT-F and ALDOT-L mixture. However, the concrete ready-mix supplier made substantial deviations from the designed mixtures and thus they were not the same

The principal objectives of the modified field-testing program were to assess the effects of mid-range water reducers (MRWR) in improving concrete mixtures for bridge decks, and to determine if the improved mixture (IM mixture) was indeed an improvement over the ALDOT standard. The evaluations of the concrete mixtures are discussed in the following sections of results of the fresh and hardened properties tested.

6.2 Fresh Concrete Property Results

The fresh concrete property testing was conducted to assess the workability and constructability of the concrete mixtures. The tests consisted of determining slump, unit weight, air content, concrete temperature, set-time and large-scale workability testing for all mixtures. All results are an average of two replica tests with the exception of the large-scale workability testing which included only one test per mixture. Results of these tests are discussed below.

Slump Test – Slump tests were performed at approximately 30-minute intervals after completion of mixing of the concrete. Results of the slump tests are shown in Table 6.1 and in Figure 6.1. Figure 6.1 shows the slump of the mixtures on the same plot to facilitate comparison. The ALDOT-F mixture had the largest initial slump as well as the lowest loss of slump rate. This is expected, considering the ALDOT-F mixture had the highest specified *w/c* ratio. The IM-F and ALDOT/WR-F, which had approximately the same *w/c* ratio mixtures, had initial slumps that were below the expected value. The Figure 6.1 also revels that the two mixtures with MRWR had the fastest loss of slump over time. The loss of slump in both mixtures may be attributed to the loss of effectiveness of the MRWR in the mixtures.

Unit Weight - Unit weight was measured at the completion of mixing of the concrete and the results are shown in Table 6.1 and in Figure 6.2. Figure 6.2 shows the unit weight of each mixture on the same plot to facilitate comparison. The high unit weight of the IM-F and ALDOT/WR-F mixtures is probably due to its reduced water content (see Table 4.2).

Air Content – The air content was observed at approximatly15-minute intervals following the completion of mixing of the concrete. The results for the air content are shown in Table 6.1 and Figure 6.3. The plot of Figure 6.3 is used to facilitate comparison of air content for each mixture. The objective of the air entrainment was to achieve between a 4 and 6 percent air content for adequate freeze-thaw characteristics. All mixtures received the same dosage of air entrainment admixture (AEA) during the mixing process. However, the IM-F and ALDOT/WR-F mixture had initial air contents of approximately 7.0 %, which is approximately 2% higher than the ALDOT-F (Control) mixture. The high air content in the mixtures with MRWR may reduce the permeability. During the 90-minute evaluation period, the air contents of all three mixtures leveled out to a range between 4% and 5%.

Set-Time – The set-time was observed at the completion of mixing of the concrete. The results for the set-time are shown in Table 6.1 and Figure 6.4. Figure 6.4 show set-time for each concrete mixture to facilitate comparison. The initial set-time is reached when the penetration resistance reaches 500psi and the final set-time is when the penetration resistance reaches 4000 psi. The penetration resistance is the mortars resistance to a 1inch needle penetrating the concrete's surface 1 inch. All three mixtures set-time were longer than expected. Each of the three mixtures had the same amount of set retarder applied. The IM-F mixture had the shortest set time followed by the ALDOT/WR-F and ALDOT-F respectfully. The long set-times may be attributed to the excessive amounts of retarder applied during mixing at the batching plant.

Heat of Hydration – The concrete temperature and ambient temperature were recorded after the placement of the concrete. The results for concrete temperature are shown in Table 6.1 and Figures 6.5-6.7. Figures 6.5-6.7 show the effect of the ambient temperature on the internal concrete temperature for each mixture. As expected, the ALDOT-F mixture produced the most heat due to the hydration of water in the concrete. The IM-F produced the lowest peak temperature of the three mixtures. The peak temperature for the ALDOT-F and IM-F mixture were reached in approximately 30 hours, while the peak temperature of the ALDOT/WR-F was reached in 7 hours. The delay of the peak heat of hydration for the ALDOT-F and IM-F mixture may have been due to the application of the excessive retarder.

Large Scale Workability – The consistency/ workability of each mixture was assessed by working with approximately 0.4yd^3 of concrete in a 4′ x 8′ by 5 ½ ″ form via hoe, shovel, and vibrator as discussed in Chapter 4 and shown in Figure 4.4. The assessment was repeated in 20-30 minute intervals until the mixture became very stiff and unworkable. Obviously this procedure is subjective but did provide us a good measure of the constructability and workability of each of the mixtures. Results from this testing are given in Table 6.2 and shown graphically in Figure 6.8. Photographs of the concrete corresponding to the consistencies and workabilities described in Table 6.2 are given in Appendix B.

Table 6.1 Fresh Concrete Property Testing Results

Concrete Property/Parameter		Concrete Mixture: IM-F	ALDOT-(Control)	ALDOT/WR-F
Slump ASTM C143 (inches)	1-min.	2.5	4.75	3
	15-min.	1.25	4.75	2.25
	30-min.	1.0	4.5	1.25
	45-min.	0.5	4.5	1.00
Unit Weight ASTM C138 (lbs/cf)		145.2	143.2	146.2
Air Content ASTM C231 (%)	1-min.	7.7	4.8	7.0
	30-min.	4.9	4.5	5.5
	60-min.	4.1	4.2	5.3
	90-min.	4.0	4.2	5.1
Set-Time ASTM (C403)	Initial (500psi)	6 hrs. 21 min	18 hrs. 42 min	13 hrs. 40 min
	Final (4000psi)	7 hrs. 36 min.	19 hrs. 23 min.	14 hrs. 25 min.
Concrete Temperature ASTM C1064 (°F)		84.1	86.5	85.2
Large-Scale Workability/ Consistency		See Table 6.2		

Table 6.2 Concrete Consistency/Workability vs. Time Based on Working Concrete in Simulated Deck Panel Form.

Mixture	Time After Placement (min.)	Consistency /Workability	
		Narrative Description	Visual/Photo
ALDOT-F	0*	Medium consistency, flows easy and easy to work	Fig. B.1
	15	Still flows and easy to work	Fig. B.2
	45	Still flowable and fairly easy to work	Fig. B.3
	65	Stiff but workable	Fig. B.4
	110	Very stiff and very difficult to work	Fig. B.5
	150	Very stiff and not workable	Fig. B.6
ALDOT/WR-F	0*	Stiff consistency but flows well with vibrator	Fig. B.7
	10	Stiff but flows with vibrator	Fig. B.8
	25	Quite stiff but still workable	Fig. B.9
	40	Quite stiff but still workable	Fig. B.10
	60	Very stiff and very difficult to work	Fig. B.11
	80	Very stiff and very difficult to work	Fig. B.12
	95	Very stiff and not workable	Fig. B.13
IM-F	0*	Stiff consistency, flows but not easily	Fig. B.14
	20	Quite stiff but still workable	Fig. B.15
	45	Very stiff and not workable	Fig. B.16

* Water first added to mixtures approximately 30 minutes prior to placement in "workability" form.

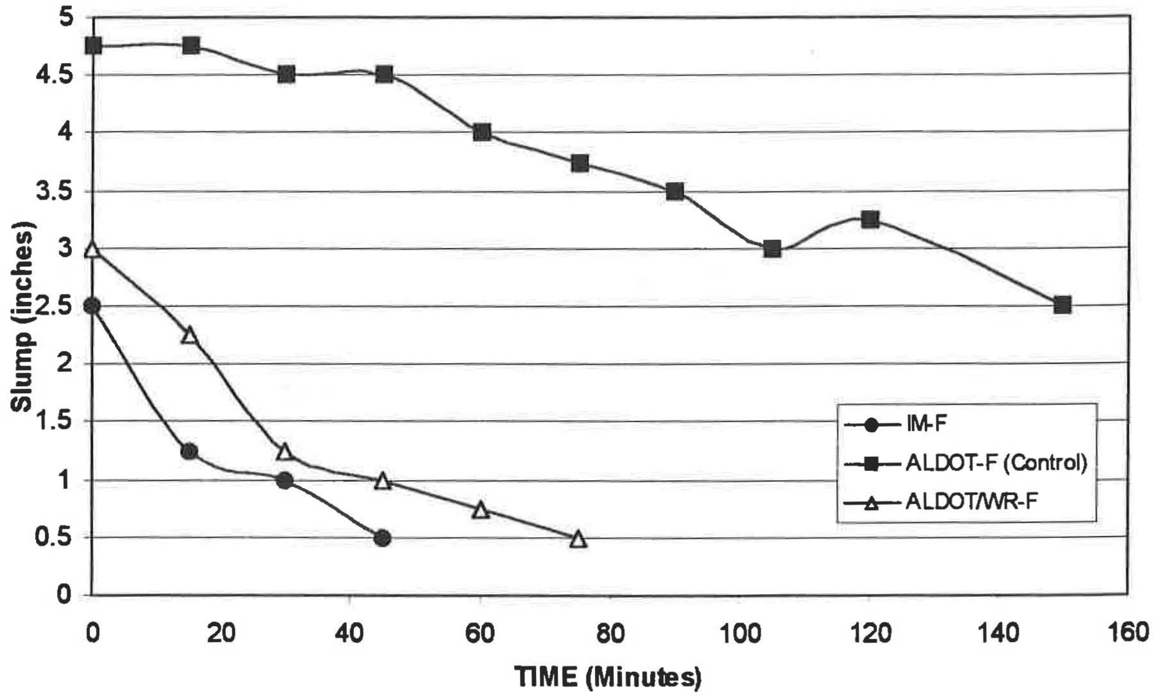

Figure 6.1 Slump for Concrete Mixtures

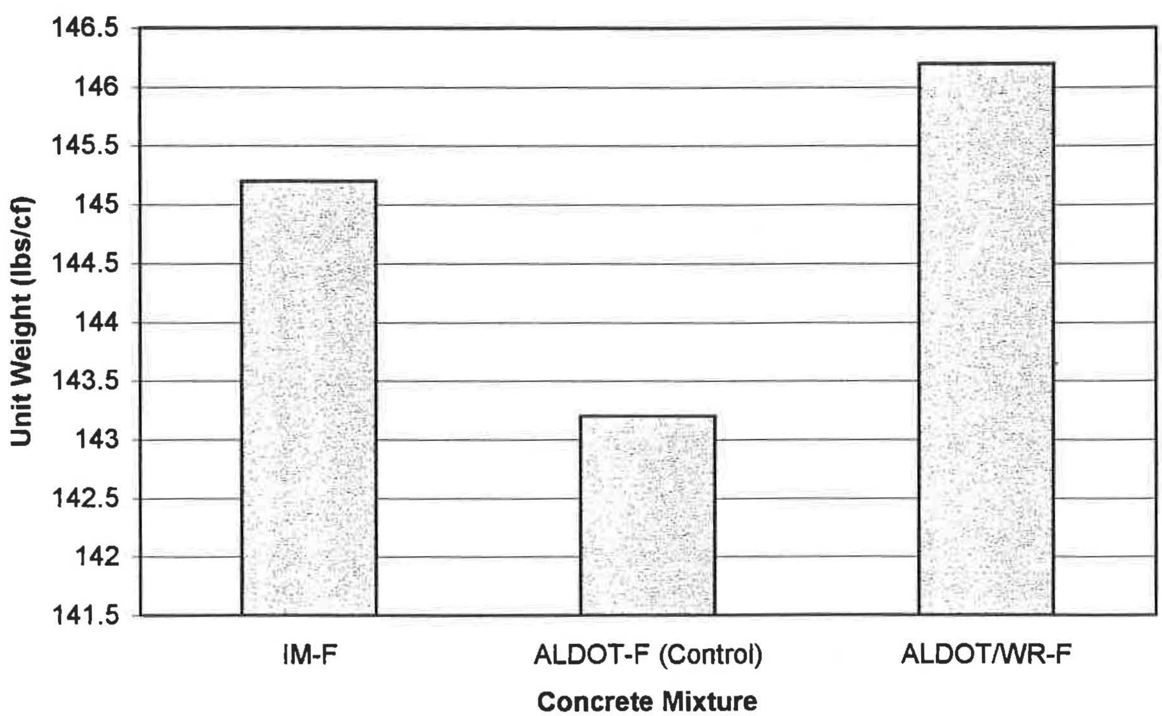

Figure 6.2 Unit Weight for Concrete Mixtures

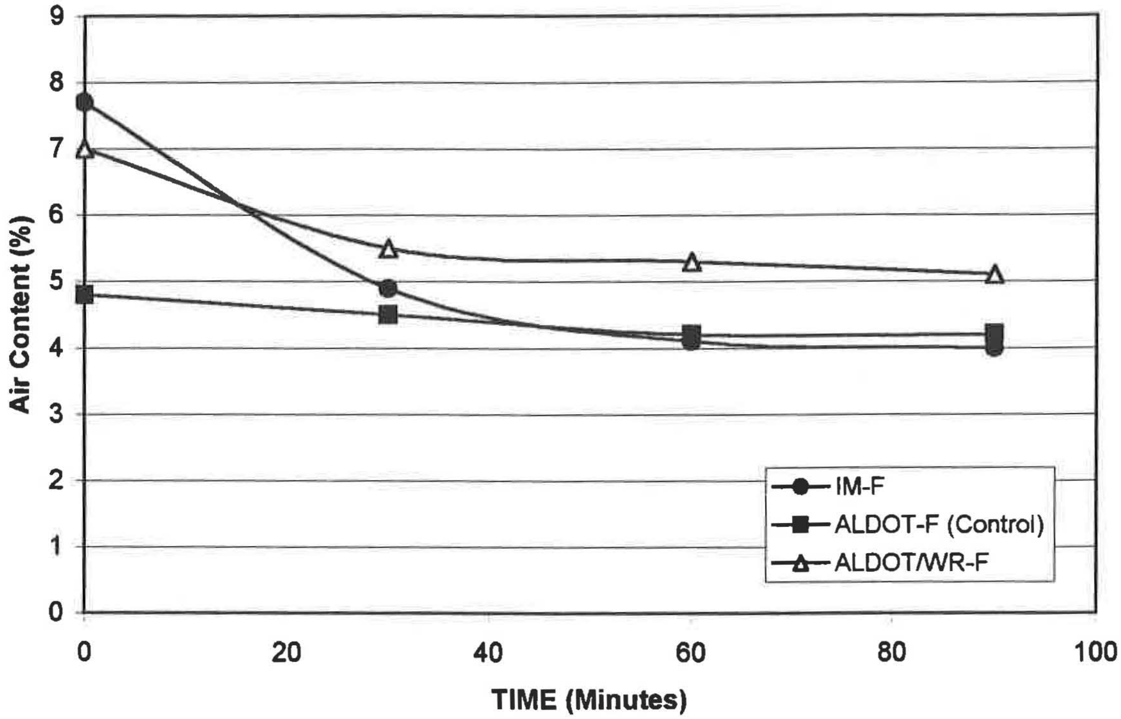

Figure 6.3 Air Content for Concrete Mixtures

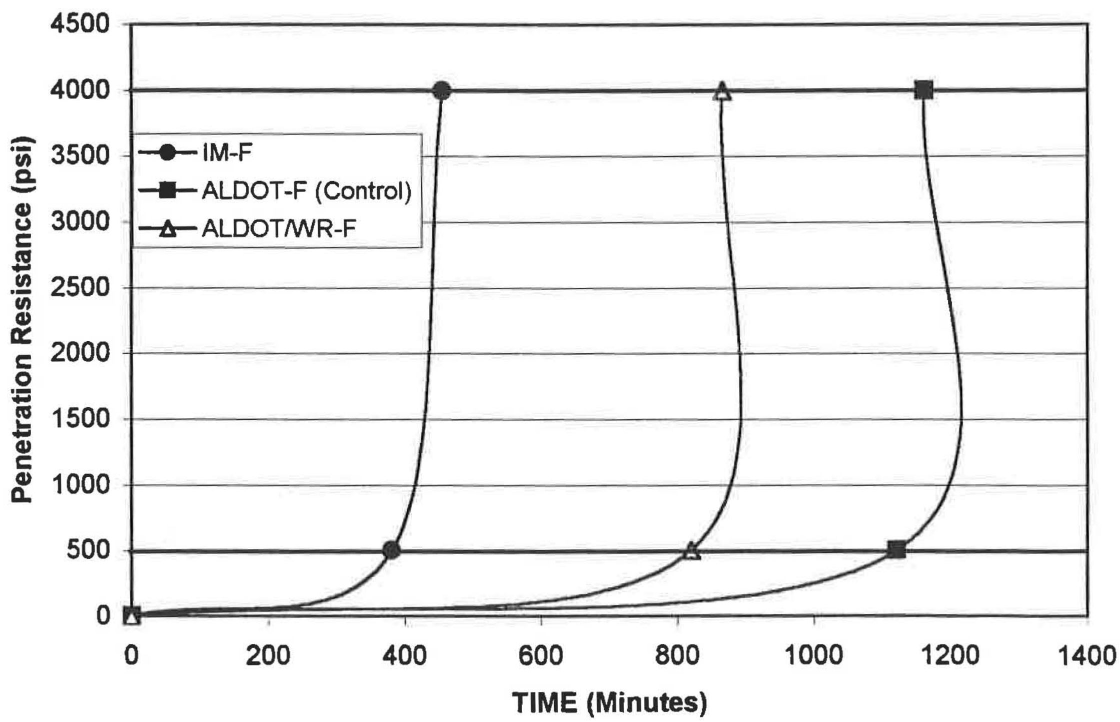

Figure 6.4 Initial and Final Set Times for Concrete Mixtures

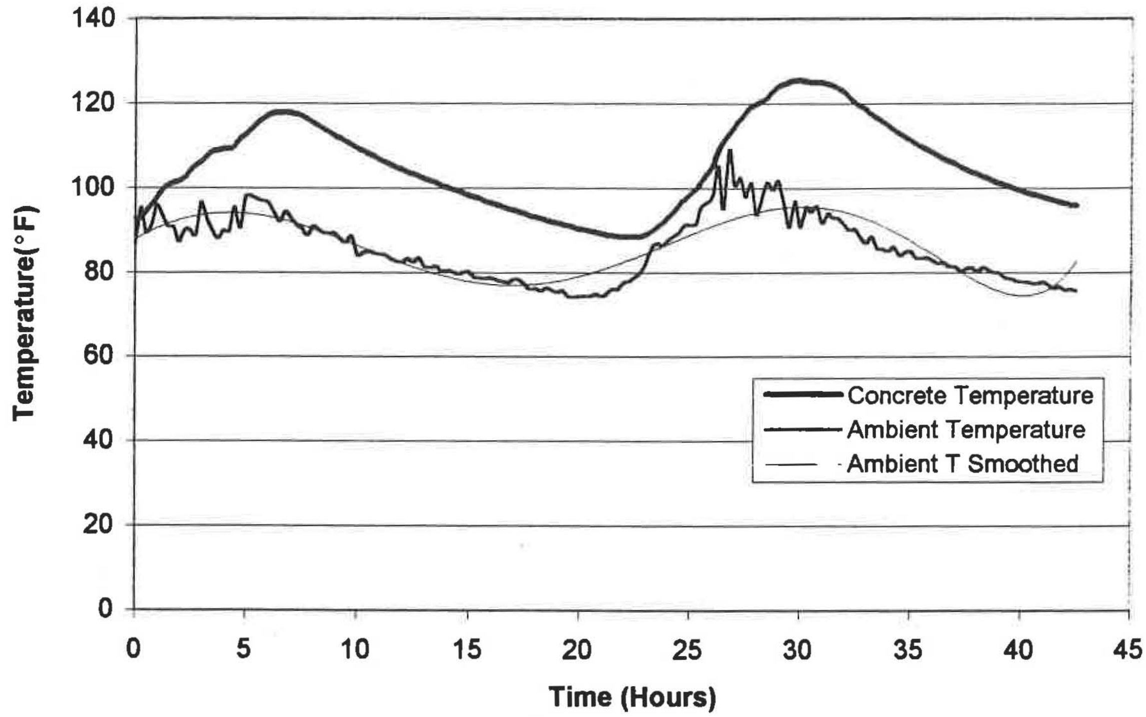

Figure 6.5 Heat of Hydration Results for IM-F Mixture

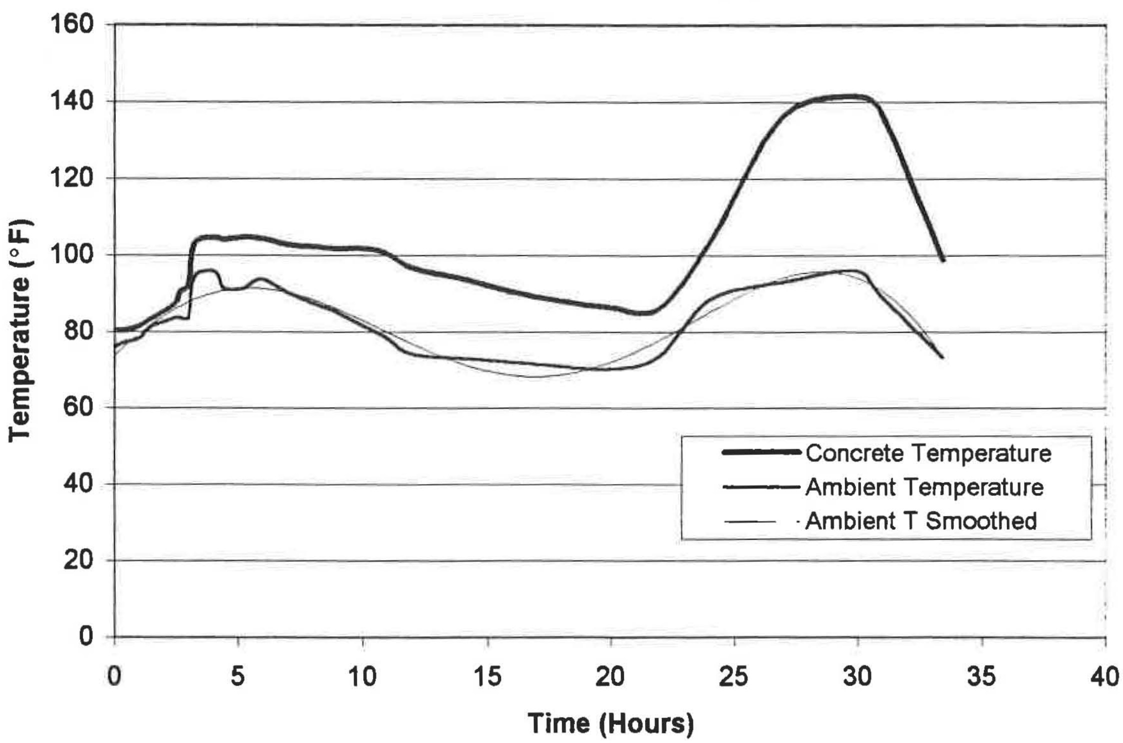

Figure 6.6 Heat of Hydration Results for ALDOT-F (Control) Mixture

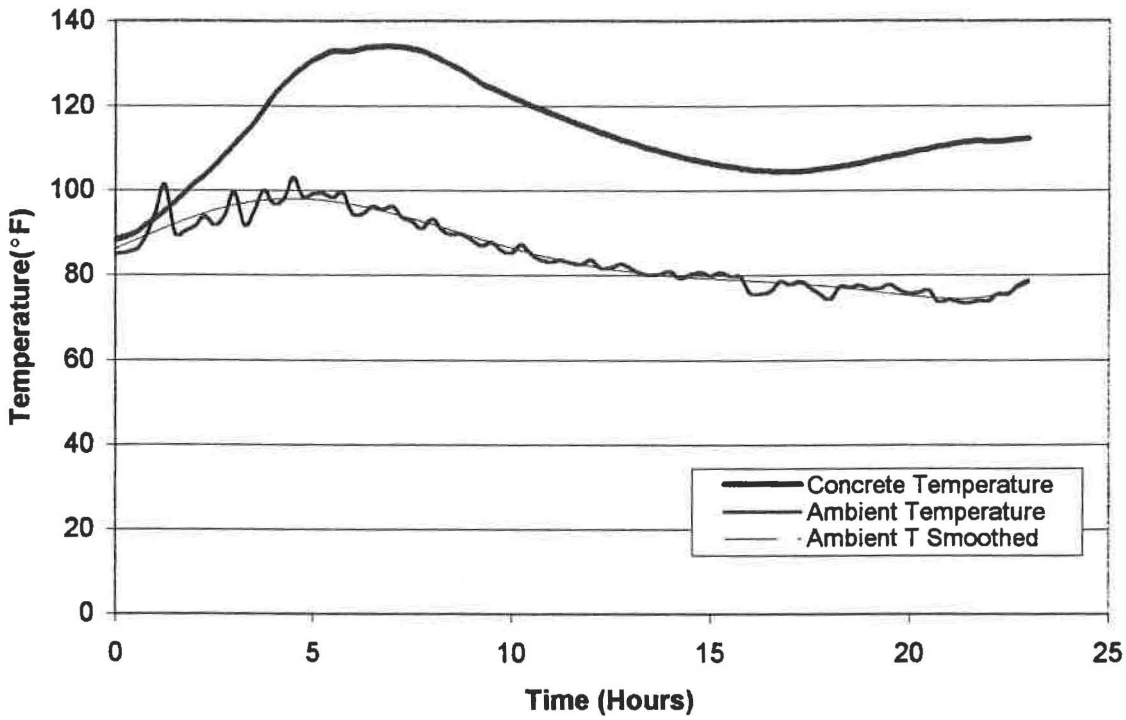

Figure 6.7 Heat of Hydration Results for ALDOT/WR-F Mixture

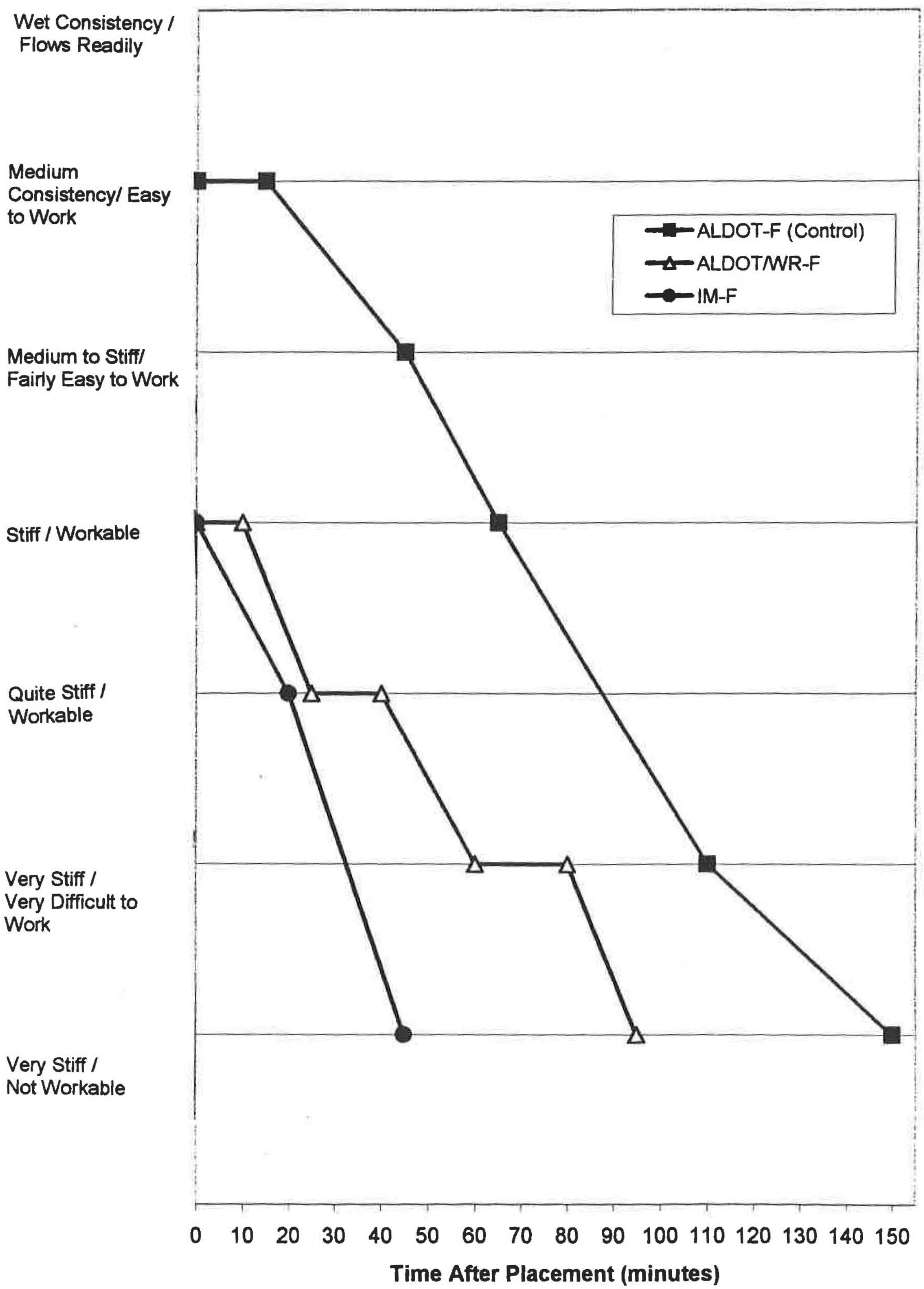

Figure 6.8 Consistency/Workability vs. Time For Field Test Mixtures

6.3 Hardened Concrete Property Results

The following hardened concrete property tests were conducted to examine certain characteristics of the concrete mixtures: compressive strength, unrestrained bar shrinkage, freeze-thaw durability and rapid chloride ion penetration. All results are an average of two replica tests. Results from each test are discussed below.

Compressive Strength - Compressive strength of each concrete mixture was conducted at 7, 14, 28 and 56 days using 4"x 8"specimens. The results of the compressive strength for all mixtures are presented in Table 6.3 and Figure 6.9. Figure 6.9 shows the three different mixtures on the same plot to facilitate comparing the results.

The ALDOT-F (Control) mixture exhibited the highest and fastest strength of the three mixtures. However, one might expect that the lower *w/c* ratio of the ALDOT/WR-F and IM-F mixture would result in them having the higher strength. The IM-F mixture attained very good final compressive strength, exceeding the compressive strength requirements of the ALDOT-F (Control) mixture used for bridge decks. The ALDOT/WR-F mixture also attained a final compressive strength exceeding the compressive strength requirements of the ALDOT-F (Control) mixture.

Unrestrained Bar Shrinkage - The unrestrained drying shrinkage tests were observed daily over a 60-day period. All of the samples tested were cured under relatively constant laboratory temperature and humidity. The results are presented in Table 6.4, Figure 6.10 and Appendix A. The Table 6.4 shows only the results after 60-days, and Figure 6.10 is a plot of the shrinkage data from days 1-60 shown in Appendix A. The ALDOT-F is an average of two replica tests. The ALDOT/WR-F and IM-F are the results of one test.

The results of the unrestrained shrinkage bars were very similar with the IM-F mixture producing the best results. This is as expected due to the low *w/c* ratio in the IM-F mixture, even though the shrinkage reducing admixture had been omitted from this mixture. However, the ALDOT/WR-F mixture with the same w/c ratio observed the highest shrinkage of the three mixtures. The ALDOT-F (Control) displayed an overall shrinkage similar to the IM-F mixture.

<u>Drying Shrinkage of 4′ x 8′ Panels</u> – Drying shrinkage of the 4′x 8′x 5 ½ ″ concrete test panels were periodically measured relative to the panel forms for the first two months as discussed in Chapter 4 and shown in Figure 4.6. Results from this drying shrinkage monitoring are shown in Table 6.5-6.6 and Figure 6.11. All three mixtures exhibited very similar drying shrinkage as can be seen in Figure 6.11. Also the correlation between the drying shrinkage of the 4′x 8′ panels and the 3″x 3″x 11″ shrinkage bars was similar in general shape/signature, however the panels had an overall drying shrinkage approximately 10 times greater than the shrinkage bars tested in the lab. The difference in drying shrinkage can be attributed partly due to the different drying conditions of the shrinkage bars and the panels. The panels, after 7-days of wet curing were left exposed to direct sunlight, and hot August temperatures, while the shrinkage bars were wet cured and then exposed to ambient laboratory temperatures.

<u>Freeze –Thaw Durability</u> - – The freeze-thaw durability results were observed approximately every 30 cycles for 300,cycles and are shown in Table 6.7 and Figure6.12. Figure 6.12 displays the results of the ALDOT-F (Control) and ALDOT/WR-F mixtures for comparison. Both the ALDOT-F and ALDOT/WR-F mixtures behaved in a very similar manner during the freeze-thaw cycles. The largest drop in durability of

approximately 4.5% was experienced in the first 60 cycles. Both mixtures leveled out at a final durability factor of approximately 92%. Scaling of the ALDOT/WR-F mixture was slightly more pronounced than the control mixture. Figures 6.13 and 6.14 show the extent of scaling on both the ALDOT-F (Control) and ALDOT/WR-F mixture at the completion of the testing.

After the wet curing process of 14 days, the initial frequency of the IM-F sample was measured to be 655 Hz. This initial frequency was approximately 30% of the initial frequencies of the other two mixtures, as can be seen in Table 6.7. The freeze-thaw durability results for the IM-F mixture were observed for 30 cycles. At the completion of the initial 30 cycles, the IM-F samples displayed a catastrophic amount of cracking. Due to the extent of cracking, a natural frequency of the specimen was unattainable. The possible cause for the extent of cracking experienced in the IM-F samples could be attributed to the amount of retarder placed in the mixture. The retarder in the IM-F mixture, in addition to the C-ash, caused extremely slow strength and stiffness gain in all of the IM-F mixture specimens. It is possible that the IM-F samples did not cure long enough prior to being placed in the freeze-thaw chamber. The excess water present in the samples may have caused the extensive cracking of the concrete. Figure 6.15 shows the extent of cracking of the IM-F mixture after 30 cycles.

Rapid Chloride Ion Penetration – The rapid chloride ion penetration test was conducted on two samples of each concrete mixture after a curing period of 56 days. The results of these tests are displayed in Table 6.8 and Figure 6.16. Figure 6.16 shows plots of the results of all three mixtures for convenience in comparison. ALDOT/WR-F produced the best results, with ALDOT-F slightly higher. Both ALDOT-F and

ALDOT/WR-F produced "moderate" permeability. The IM-F produced the highest permeability of the three mixtures.

Table 6.3 Compressive Strength Results for Concrete Mixtures

Concrete Property/Parameter		Concrete Mixture		
		IM-F	ALDOT (Control)	ALDOT/WR-F
Compressive Strength ASTM C39 (psi)	7-day	1050	4881	2983
	14-day	2402	5277	4038
	28-day	4129	5767	4793
	56-day	5052	7379	5966

Table 6.4 Unrestrained Bar Shrinkage Results for Concrete Mixtures at 60-Days[1]

Concrete Mixture	% of Length Change @ 60 Days	Shrinkage Classification
IM-F	-0.060	Moderate Shrinkage
ALDOT-F (Control)	-0.065	Moderate Shrinkage
ALDOT/WR-F	-0.076	Moderate Shrinkage

[1] Complete Shrinkage bar results are shown in Appendix A.

Table 6.5 Drying Shrinkage Data for Concrete Panels

Concrete Property/Parameter		Concrete Mixture		
		IM-F	ALDOT-F (Control)	ALDOT/WR-L
Panel Shrinkage	7-day	-0.295	-0.393	-0.296
	14-day	-0.468	-0.574	-0.534
	28-day	-0.841	-0.834	-0.771
	56-day	-0.873	-0.858	-0.845

Table 6.6 Drying Shrinkage Results for Concrete Panels at 56-Days

Concrete Mixture	% of Length Change @ 56 Days	Shrinkage Classification
IM-F	-0.873	High Shrinkage
ALDOT-F (Control)	-0.858	High Shrinkage
ALDOT/WR-F	-0.845	High Shrinkage

Table 6.7 Freeze-Thaw Durability Results for Concrete Mixtures

Concrete Mixture	Initial Frequency (Hz)	Final Frequency[1] (Hz)	Durability Factor (%)
IM-F	655	0	0
ALDOT-F (Control)	1806	1670	92.5
ALDOT/WR-F	1771	1629	92.0

[1] After 300 freeze-thaw cycles.

Table 6.8 Rapid Chloride Ion Penetration Results for Concrete Mixtures

Concrete Mixture	Charged Passed (Coulombs)	ASTM C1202 Rating
IM-F	4864	High
ALDOT-F (Control)	3496	Moderate
ALDOT/WR-F	2683	Moderate

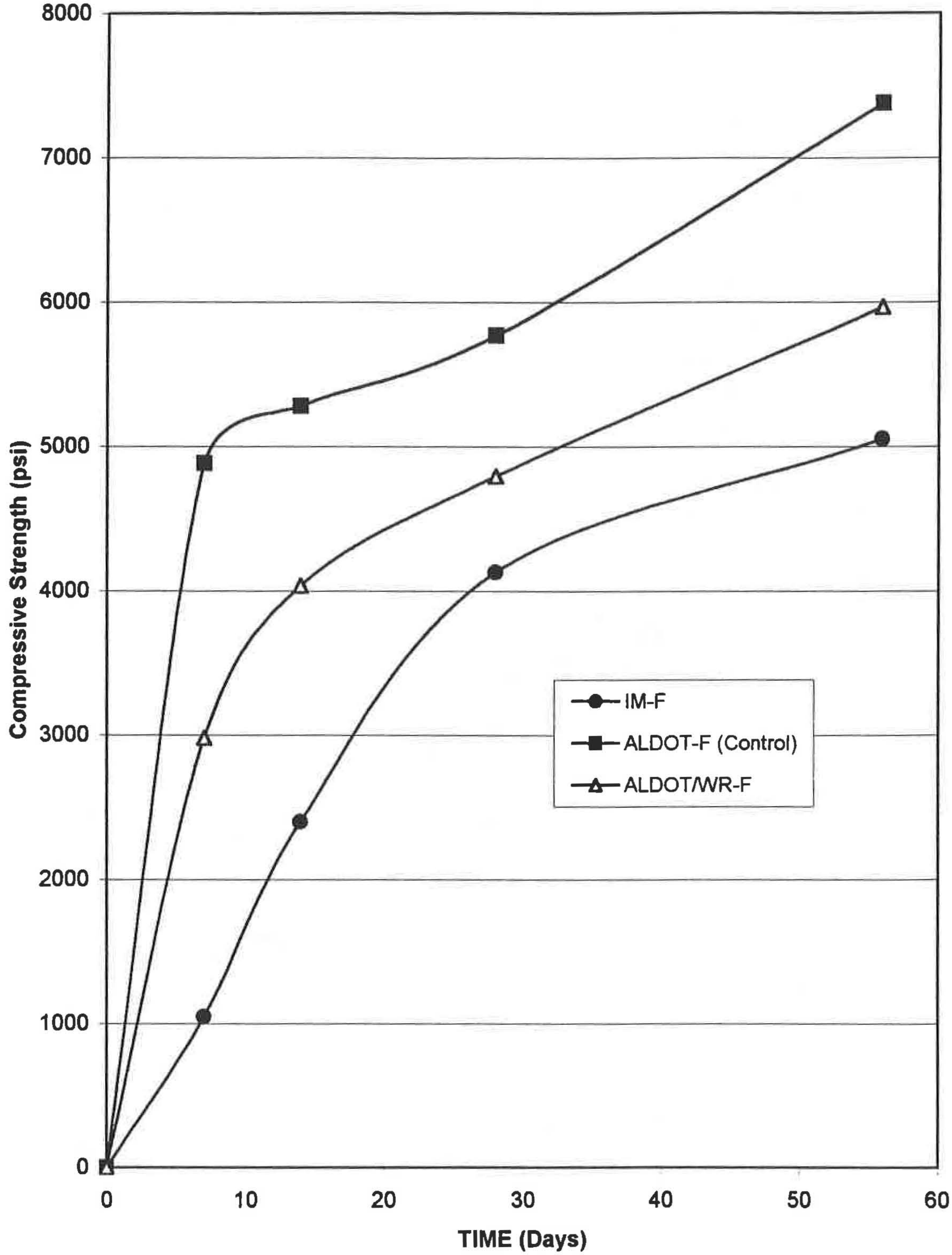

Figure 6.9 Compressive Strength for Concrete Mixtures

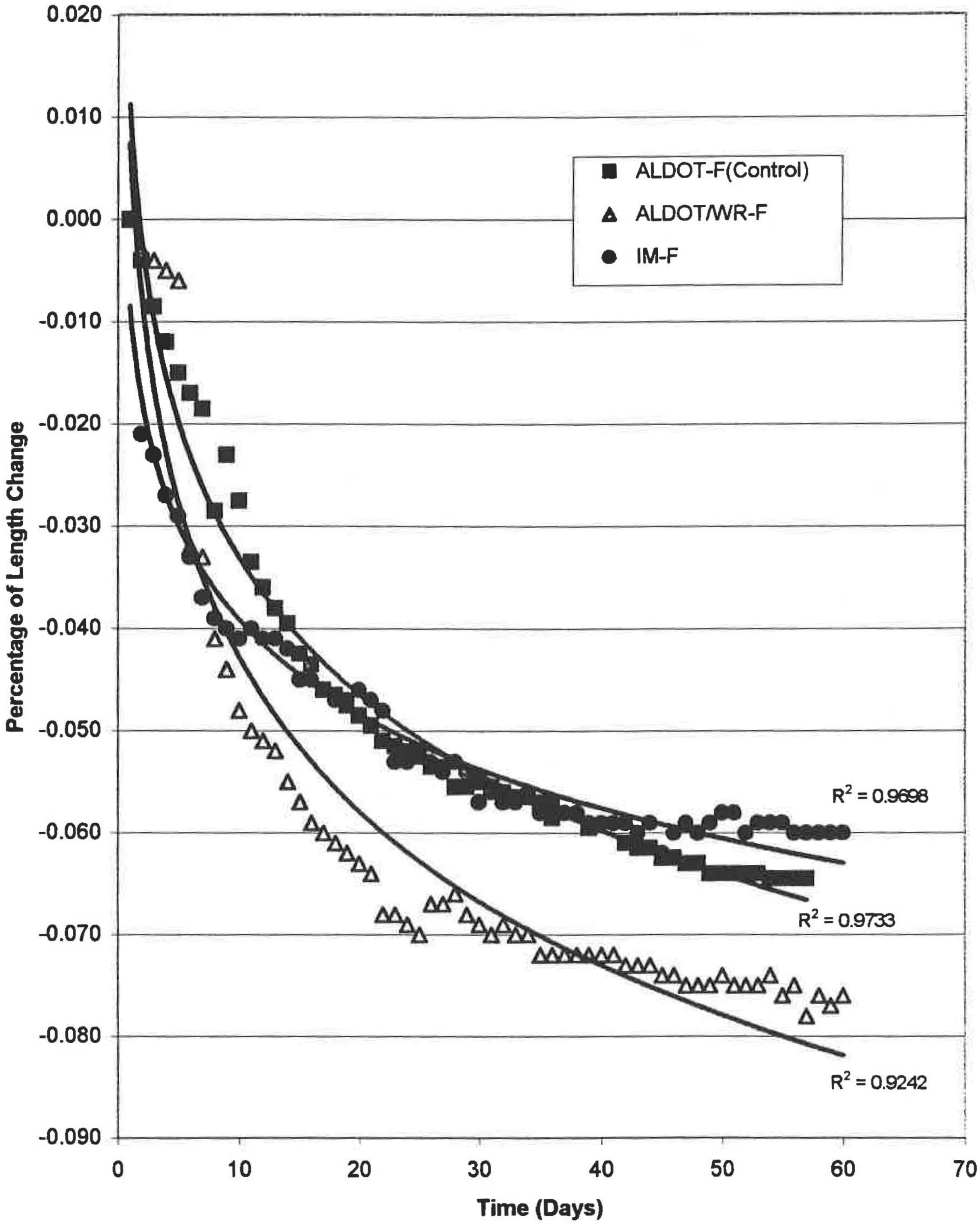

Figure 6.10 Unrestrained Bar Shrinkage for Concrete Mixture

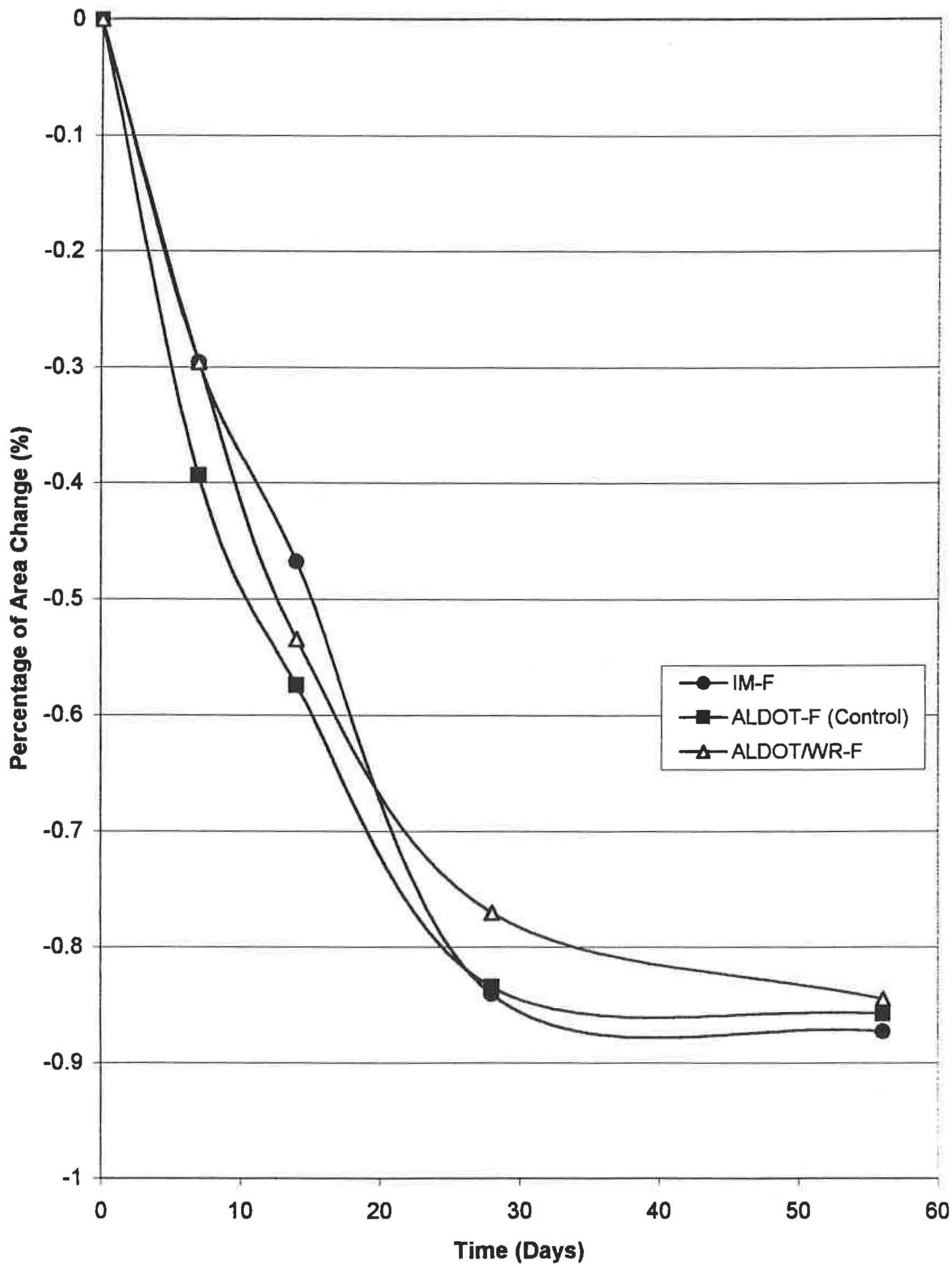

Figure 6.11 Drying Shrinkage of Concrete Panels

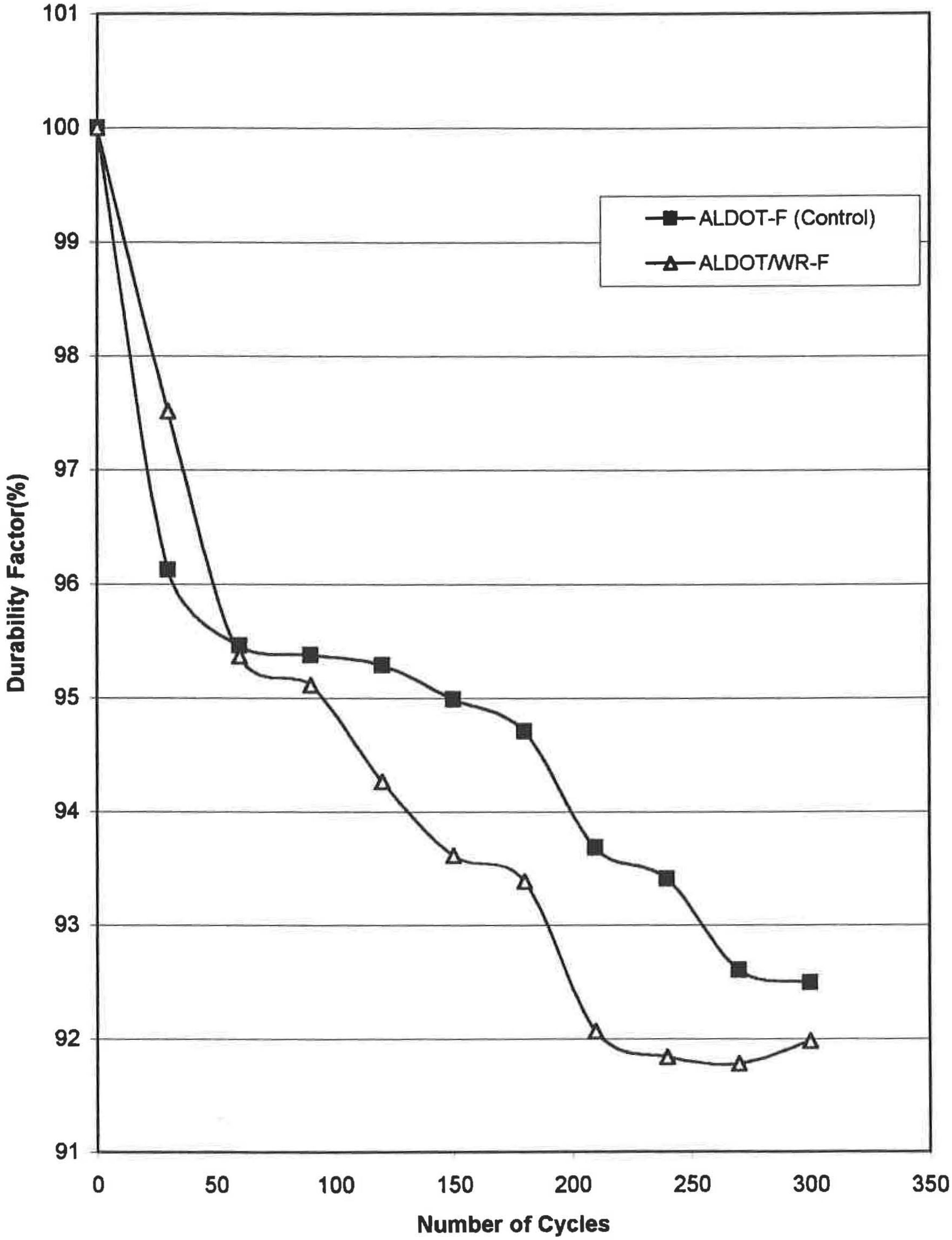

Figure 6.12 Freeze-Thaw Durability Results for Concrete Mixtures

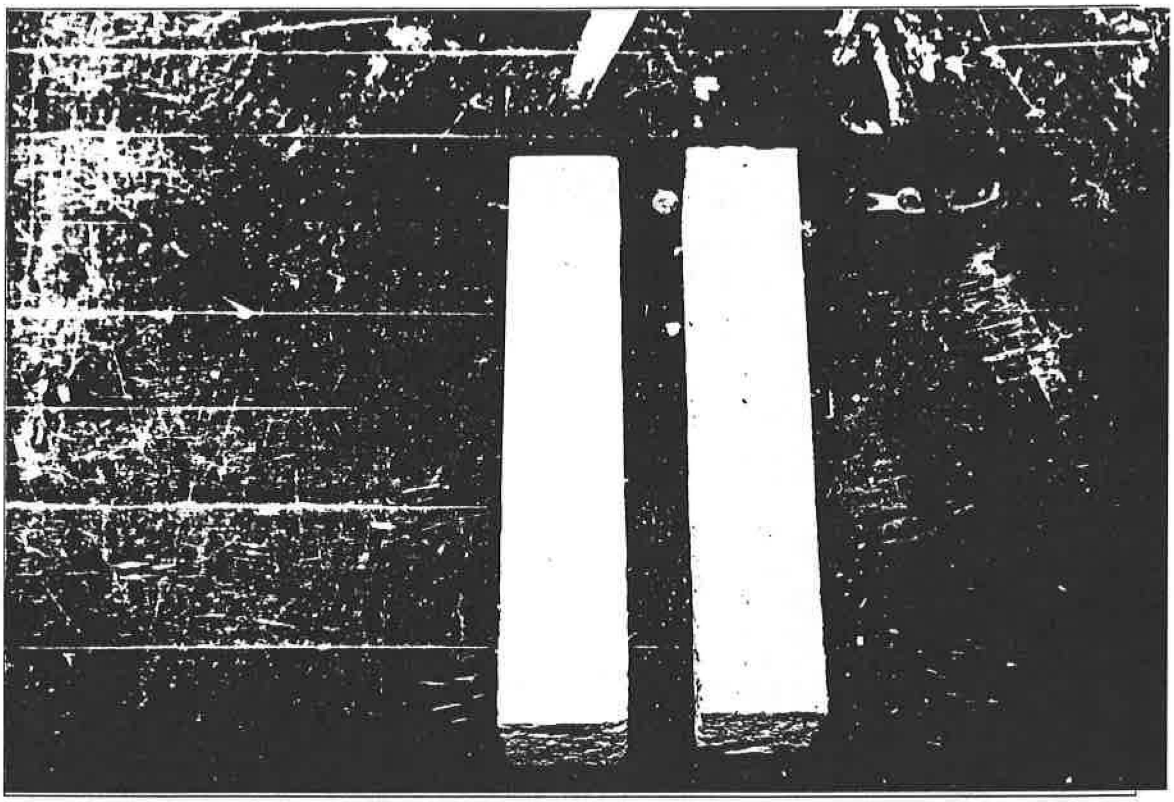

Figure 6.13. ALDOT-F (Control) Freeze-Thaw Specimens After 300-Cycles

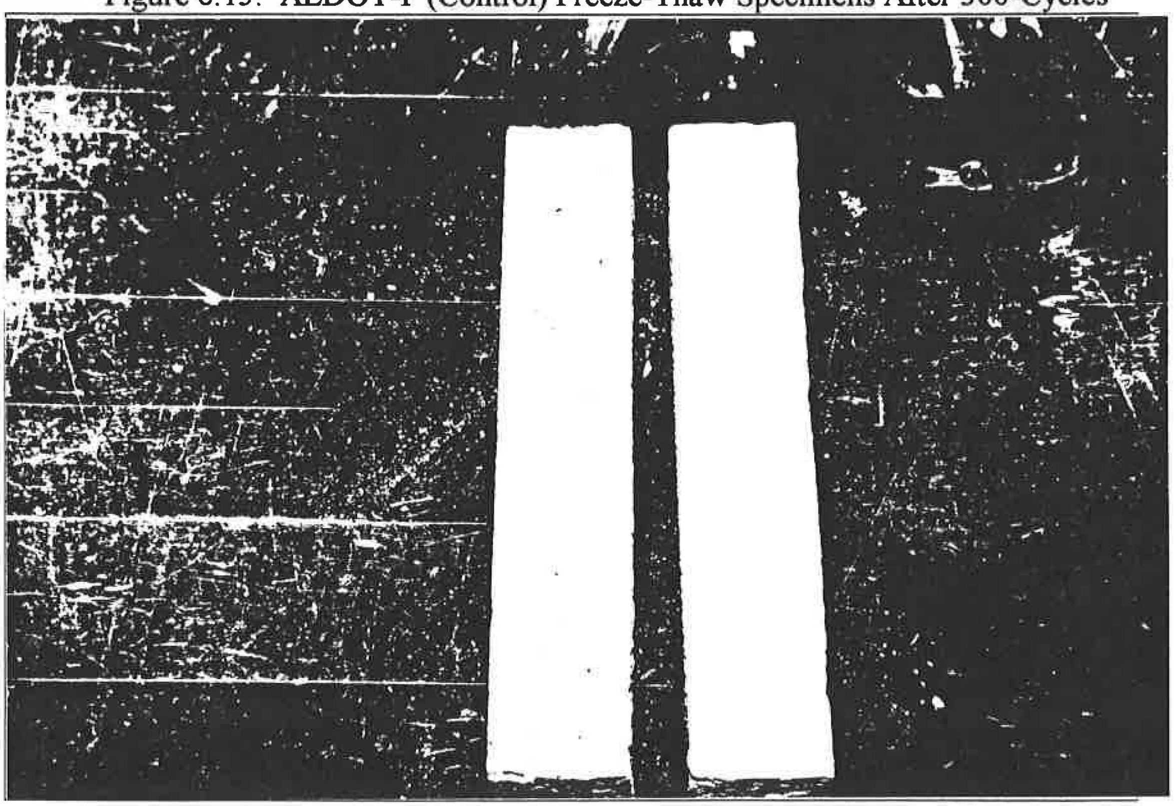

Figure 6.14. ALDOT/WR-F Freeze-Thaw Specimens After 300 Cycles

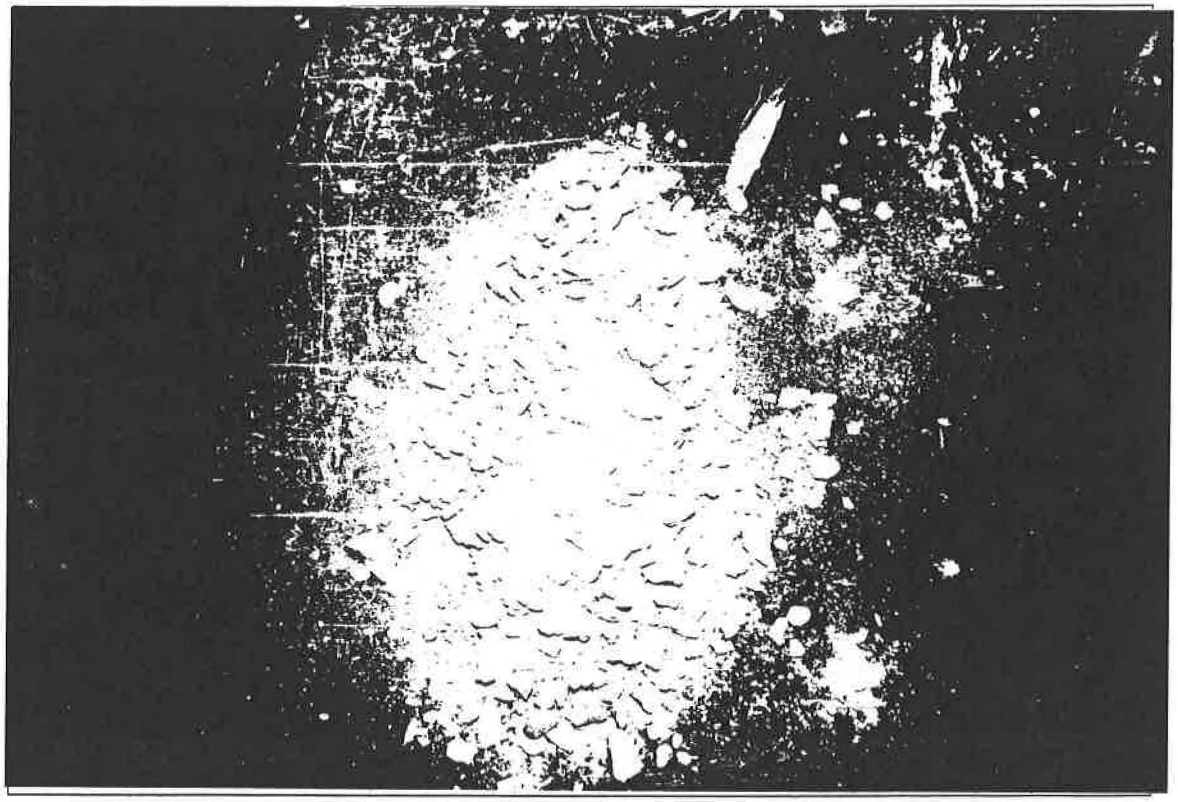

Figure 6.15. IM-F Freeze-Thaw Specimens After 30 Cycles

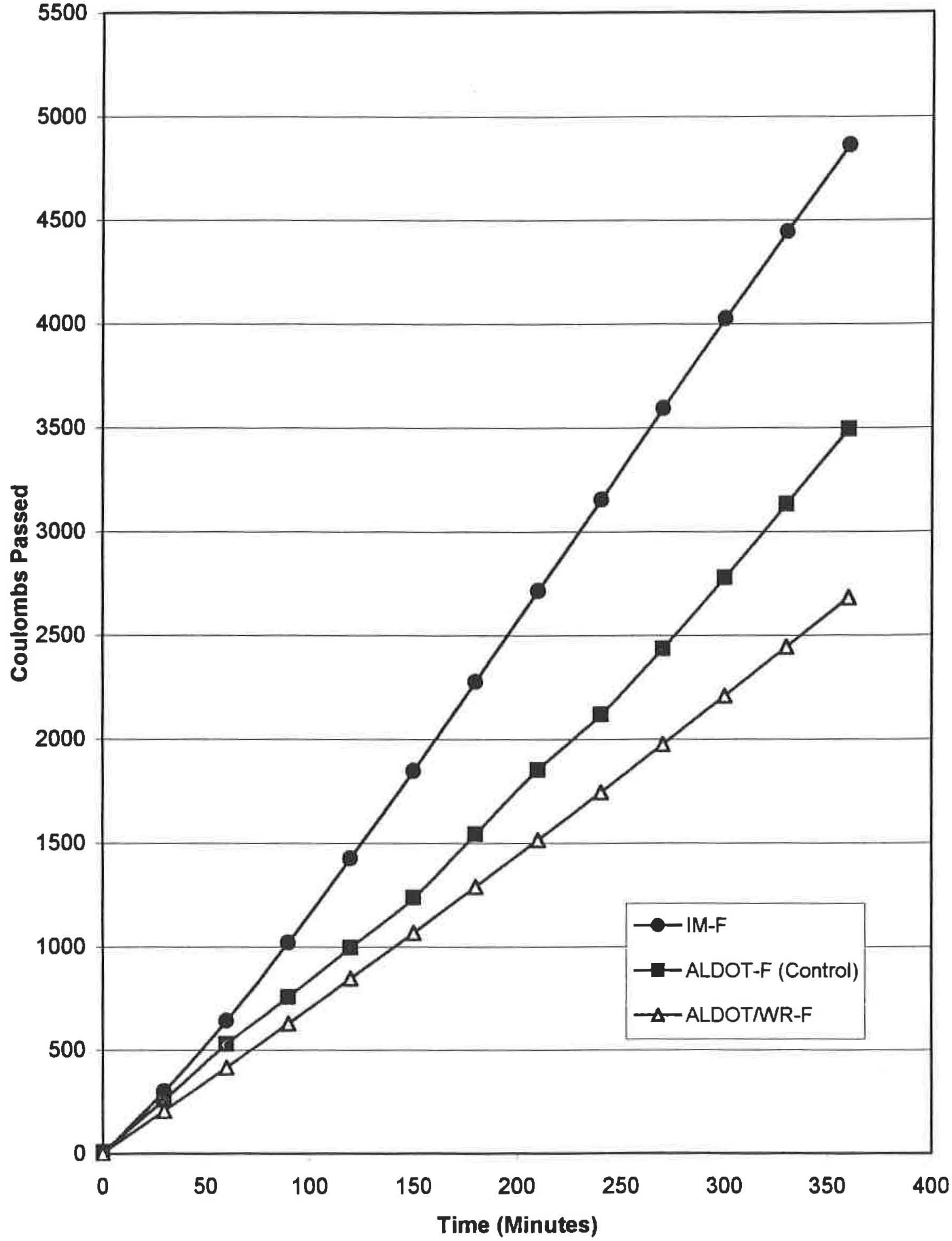

Figure 6.16 Rapid Chloride Ion Penetration Results for Concrete Mixtures

7. CONCLUSIONS AND RECCOMENDATIONS

7.1 General

There are two sets of criteria that must be considered when developing a concrete mixture:

1. Long-term requirements of the hardened concrete such as strength, durability, and volume stability, and

2. Short-term requirements, while the concrete is still in the plastic state, which are generally lumped together under the term "workability.'

Unfortunately these two sets of requirements are not complementary, and a compromise is needed between them. However, the development of water reducing admixtures and the more recent development of superplasticers show great promise in overcoming the heretofore-conflicting mixture requirements to attain good workability during placement, and good strength and durability in the hardened concrete. High-range water reducing (HRWR) and mid-range water reducing (MRWR) admixtures are known to allow reductions in water content, and the accompanying increase in strength and reductions in permeability and drying shrinkage, while at the same time increasing the workability and in-place quality and durability of concrete. The Alabama Department of Transportation (ALDOT) experimented with using HRWR concrete mixtures to improve constructability of bridge decks in Summer 1999 and unfortunately the results were not good. Therefore, an assessment of concrete mixtures using mid-range water reducers (MRWR), which are reported to be more user friendly, was viewed as the next logical step. This was the impetus and purpose of this investigation. Fresh and hardened concrete properties of

ALDOT standard bridge mixtures as well as an improved concrete mixture were evaluated and compared. The investigation was limited to testing of laboratory prepared mixtures and ready-mix prepared mixtures, evaluated under laboratory conditions.

7.2 Conclusions

Based on performing the fresh and hardened properties for the laboratory and field-testing, the following conclusions were made:

Laboratory Testing – The fresh properties of the laboratory mixtures produced comparable results, except for initial concrete slump. As expected the IM-L mixture has a much higher slump compared to the ALDOT-L (Control) mixture. This demonstrates the effectiveness of the adding the MRWR in the IM-L mixture, to increase slump of concrete while maintaining the lowest *w/c* ratio of all the mixtures. The ALDOT-L (Control) mixture demonstrates a higher slump than ALDOT/NA-L, which had no air entrainment. The air content present in the concrete mixture had a considerable effect on slump and workability, as expected. The hardened properties also showed comparable results with some variation in the compressive strength and freeze-thaw durability. The ALDOT/NA-L mixture displayed the highest and fastest gaining strength of the three mixtures. This was not totally unexpected considering the lack of air entrainment in this mixture. The IM-L attained very good final compressive strength, exceeding the compressive strength requirements of the ALDOT-L (Control) mixture, even though it contained 11% less cementious material. The ALDOT-L (Control) produced the lowest final compressive strength. The IM-L mixture results displayed the lowest unrestrained drying shrinkage. However, it is not known how much of the reduced shrinkage was attributable to the low *w/c* ratio and how much to the presence of the shrinkage-reducing admixture. The IM-L and ALDOT-L (Control) mixtures produced similar freeze-thaw durability results. However, the ALDOT-L (Control) was found to have the least tendency for scaling. The result of not having proper air entrainment in the ALDOT/NA-L concrete mixture during the freeze-thaw cycle produced rapid and unacceptable decline in durability. No significant reading could be obtained in the ALDOT/NA-L mixtures due to the extensive cracking and scaling after 150 freeze-thaw cycles.

Field Testing – As mentioned before, the concrete ready-mix supplier made substantial deviations from the designed mixtures planned for the field-testing. Our limited experience with the ready-mix supplier indicates the need to use only reputable concrete suppliers and to have in-plant and/ or field inspectors and testing procedures in place to assure that the mixture ordered is what is being supplied. Results of the slump test indicated the ALDOT-F (Control) mixture had the highest initial slump and lowest rate of loss of slump. The IM-F and ALDOT/WR, which both contain MRWR, produced lower initial slumps with much higher rates of slump loss. The low slump and high rate of slump loss also resulted in poor workability for the IM-F and ALDOT/WR mixtures, which resulted in substantial loss in available placement time compared to the ALDOT-F (Control) mixture. The set-time results for all three mixtures were longer than expected. The IM-F mixture had the shortest set-time followed by the ALDOT/WR-F and ALDOT-F respectfully. It is suspected that the long set-times may be attributable to the excessive amounts of retarder applied during mixing at the batching plant. The ALDOT-F mixture showed the highest and fastest strength gain of all three mixtures. However, both the ALDOT/WR-F and the IM-F attained a final compressive strength exceeding the compressive strength required by ALDOT. Comparable results were obtained in the unrestrained drying shrinkage test, with the IM-F mixture producing the best results. Freeze-thaw durability results were very similar for the ALDOT-F and ALDOT/WR-F mixtures. The IM-F mixture experienced severe cracking and scaling after the initial 30 freeze-thaw cycles, which prevented any additional readings possible on the specimens. The possible cause for the extent of cracking experienced in the IM-F samples could be attributed to the amount of retarder placed in the mixture, combined with the 30% C-ash replacement, which prohibited the concrete from gaining adequate strength prior to the freeze-thaw testing. The rapid chloride ion penetration results showed the ALDOT/WR-F having the lowest permeability of all three mixtures, with a "moderate" permeability rating. The ALDOT-F mixture exhibited a slightly higher but still "moderate" permeability rating. The IM-F mixture produced the poorest results and a "high" permeability rating.

7.3 Recommendations

Based on the results of this study, the following recommendations are made.

1. The IM-L mixture did not show significant improvements in the fresh and hardened properties over the current ALDOT bridge deck mixture to warrant further testing or recommendation of use.
2. Due to the high amount of error incurred during the batching of the field mixtures, the author recommends in future testing, no concrete batches of 1cubic yard or smaller be produced by ready mix plants for testing purposes.

3. Further testing of the effects of MRWR should be considered. The authors recommend laboratory testing to be performed on the fresh and hardened properties of mortar produced with the addition of MRWR. The mortar would be comprised of cement, Ottawa sand, water and MRWR. This would allow evaluation of the effects of MRWR on the fresh and hardened properties of the mortar mixtures without introducing the effects of variation in aggregates, aggregate proportions, and aggregate water content into the results.
4. Mortar specimens would also be good for assessing the effectiveness of shrinkage reducing agents and other chemical and mineral admixtures on concrete properties, and it is recommended that such testing be conducted in the initial evaluation of these admixtures.

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APPENDIX A

UNRESTRAINED SHRINKAGE BAR DATA FOR LABORATORY AND MODIFIED FIELD MIXTURES

Table A1: Unrestrained Drying Shrinkage Data for Laboratory Mixtures

	IM-L		ALDOT-L (Control)		ALDOT/NA-L	
Days	Specimen #1	Specimen #2	Specimen #1	Specimen #2	Specimen #1	Specimen #2
1	0.000	0.000	0.000	0.000	0.000	0.000
2	-0.001	0.000	-0.002	-0.002	-0.019	-0.020
3	-0.004	-0.004	-0.006	-0.004	-0.021	-0.023
4	-0.006	-0.006	-0.010	-0.010	-0.023	-0.026
5	-0.008	-0.007	-0.011	-0.015	-0.024	-0.027
6	-0.009	-0.008	-0.011	-0.018	-0.026	-0.026
7	-0.009	-0.009	-0.011	-0.018	-0.027	-0.028
8	-0.011	-0.011	-0.012	-0.020	-0.027	-0.030
9	-0.012	-0.011	-0.018	-0.026	-0.030	-0.033
10	-0.012	-0.012	-0.018	-0.027	-0.031	-0.034
11	-0.013	-0.012	-0.021	-0.028	-0.032	-0.035
12	-0.014	-0.014	-0.018	-0.029	-0.032	-0.035
13	-0.014	-0.015	-0.018	-0.030	-0.034	-0.036
14	-0.016	-0.017	-0.022	-0.033	-0.034	-0.035
15	-0.016	-0.016	-0.021	-0.034	-0.035	-0.037
16	-0.017	-0.018	-0.023	-0.037	-0.036	-0.036
17	-0.018	-0.020	-0.024	-0.038	-0.038	-0.037
18	-0.022	-0.030	-0.025	-0.039	-0.042	-0.038
19	-0.023	-0.032	-0.025	-0.039	-0.045	-0.040
20	-0.025	-0.032	-0.026	-0.039	-0.047	-0.042
21	-0.027	-0.033	-0.027	-0.040	-0.049	-0.043
22	-0.028	-0.034	-0.027	-0.041	-0.051	-0.045
23	-0.029	-0.034	-0.027	-0.041	-0.056	-0.047
24	-0.030	-0.035	-0.027	-0.042	-0.058	-0.050
25	-0.031	-0.036	-0.027	-0.041	-0.064	-0.052
26	-0.032	-0.037	-0.027	-0.042	-0.070	-0.053
27	-0.032	-0.037	-0.028	-0.043	-0.067	-0.051
28	-0.030	-0.037	-0.030	-0.045	-0.066	-0.051
29	-0.030	-0.037	-0.031	-0.045	-0.068	-0.052
30	-0.031	-0.037	-0.031	-0.046	-0.070	-0.053
31	-0.033	-0.040	-0.031	-0.045	-0.070	-0.053
32	-0.033	-0.040	-0.031	-0.045	-0.071	-0.054
33	-0.033	-0.040	-0.031	-0.046	-0.072	-0.054
34	-0.033	-0.039	-0.032	-0.047	-0.072	-0.056
35	-0.032	-0.038	-0.033	-0.047	-0.069	-0.056
36	-0.032	-0.038	-0.034	-0.048	-0.072	-0.055
37	-0.032	-0.038	-0.035	-0.048	-0.073	-0.055
38	-0.033	-0.039	-0.035	-0.049	-0.072	-0.056
39	-0.033	-0.042	-0.035	-0.050	-0.072	-0.056
40	-0.034	-0.042	-0.036	-0.050	-0.073	-0.056
41	-0.034	-0.043	-0.037	-0.051	-0.073	-0.056
42	-0.034	-0.042	-0.031	-0.047	-0.073	-0.056
43	-0.035	-0.042	-0.032	-0.048	-0.073	-0.056
44	-0.035	-0.042	-0.034	-0.050	-0.073	-0.056
45	-0.035	-0.042	-0.034	-0.050	-0.073	-0.057
46	-0.035	-0.042	-0.035	-0.050	-0.075	-0.057
47	-0.035	-0.042	-0.035	-0.050	-0.075	-0.056
48	-0.033	-0.040	-0.036	-0.051	-0.075	-0.053
49	-0.033	-0.040	-0.036	-0.051	-0.077	-0.059
50	-0.033	-0.040	-0.036	-0.051	-0.077	-0.059
51	-0.035	-0.042	-0.037	-0.053	-0.076	-0.059
52	-0.035	-0.042	-0.037	-0.053	-0.077	-0.059
53	-0.035	-0.042	-0.037	-0.053	-0.077	-0.059
54	-0.035	-0.043	-0.037	-0.053	-0.077	-0.059
55	-0.035	-0.043	-0.037	-0.054	-0.077	-0.059
56	-0.036	-0.043	-0.037	-0.053	-0.076	-0.059
57	-0.035	-0.043	-0.037	-0.053	-0.076	-0.059
58	-0.035	-0.043	-0.037	-0.053	-0.077	-0.059
59	-0.035	-0.043	-0.037	-0.053	-0.077	-0.059
60	-0.035	-0.043	-0.037	-0.053	-0.077	-0.059

Table A2: Unrestrained Drying Shrinkage Data for Modified Field Mixtures

	IM-F	ALDOT-F (Control)		ALDOT/WR-F
Days	Specimen #1	Specimen #1	Specimen #2	Specimen #1
1	0.000	0.000	0.000	0.000
2	-0.021	-0.004	-0.004	-0.003
3	-0.023	-0.008	-0.009	-0.004
4	-0.027	-0.011	-0.013	-0.005
5	-0.029	-0.013	-0.017	-0.006
6	-0.033	-0.015	-0.019	-0.032
7	-0.037	-0.017	-0.020	-0.033
8	-0.039	-0.019	-0.038	-0.041
9	-0.040	-0.020	-0.026	-0.044
10	-0.041	-0.021	-0.034	-0.048
11	-0.040	-0.029	-0.038	-0.050
12	-0.041	-0.031	-0.041	-0.051
13	-0.041	-0.032	-0.044	-0.052
14	-0.042	-0.034	-0.045	-0.055
15	-0.045	-0.036	-0.049	-0.057
16	-0.045	-0.037	-0.050	-0.059
17	-0.046	-0.040	-0.052	-0.060
18	-0.047	-0.041	-0.052	-0.061
19	-0.047	-0.042	-0.053	-0.062
20	-0.046	-0.043	-0.054	-0.063
21	-0.047	-0.044	-0.055	-0.064
22	-0.048	-0.045	-0.057	-0.068
23	-0.053	-0.046	-0.057	-0.068
24	-0.053	-0.046	-0.058	-0.069
25	-0.052	-0.047	-0.058	-0.070
26	-0.053	-0.049	-0.058	-0.067
27	-0.054	-0.047	-0.060	-0.067
28	-0.053	-0.049	-0.062	-0.066
29	-0.054	-0.049	-0.062	-0.068
30	-0.057	-0.050	-0.060	-0.069
31	-0.056	-0.051	-0.060	-0.070
32	-0.057	-0.051	-0.061	-0.069
33	-0.057	-0.052	-0.061	-0.070
34	-0.056	-0.051	-0.062	-0.070
35	-0.058	-0.052	-0.062	-0.072
36	-0.057	-0.052	-0.065	-0.072
37	-0.058	-0.052	-0.066	-0.072
38	-0.058	-0.052	-0.066	-0.072
39	-0.059	-0.052	-0.067	-0.072
40	-0.059	-0.053	-0.067	-0.072
41	-0.059	-0.053	-0.067	-0.072
42	-0.059	-0.054	-0.068	-0.073
43	-0.060	-0.055	-0.068	-0.073
44	-0.059	-0.055	-0.068	-0.073
45	-0.062	-0.055	-0.070	-0.074
46	-0.060	-0.055	-0.070	-0.074
47	-0.059	-0.055	-0.071	-0.075
48	-0.060	-0.055	-0.071	-0.075
49	-0.059	-0.056	-0.072	-0.075
50	-0.058	-0.056	-0.072	-0.074
51	-0.058	-0.056	-0.072	-0.075
52	-0.060	-0.056	-0.072	-0.075
53	-0.059	-0.056	-0.072	-0.075
54	-0.059	-0.057	-0.072	-0.074
55	-0.059	-0.057	-0.072	-0.076
56	-0.060	-0.057	-0.072	-0.075
57	-0.060	-0.057	-0.072	-0.078
58	-0.060	-0.057	-0.073	-0.076
59	-0.060	-0.057	-0.073	-0.077
60	-0.060	-0.057	-0.073	-0.076

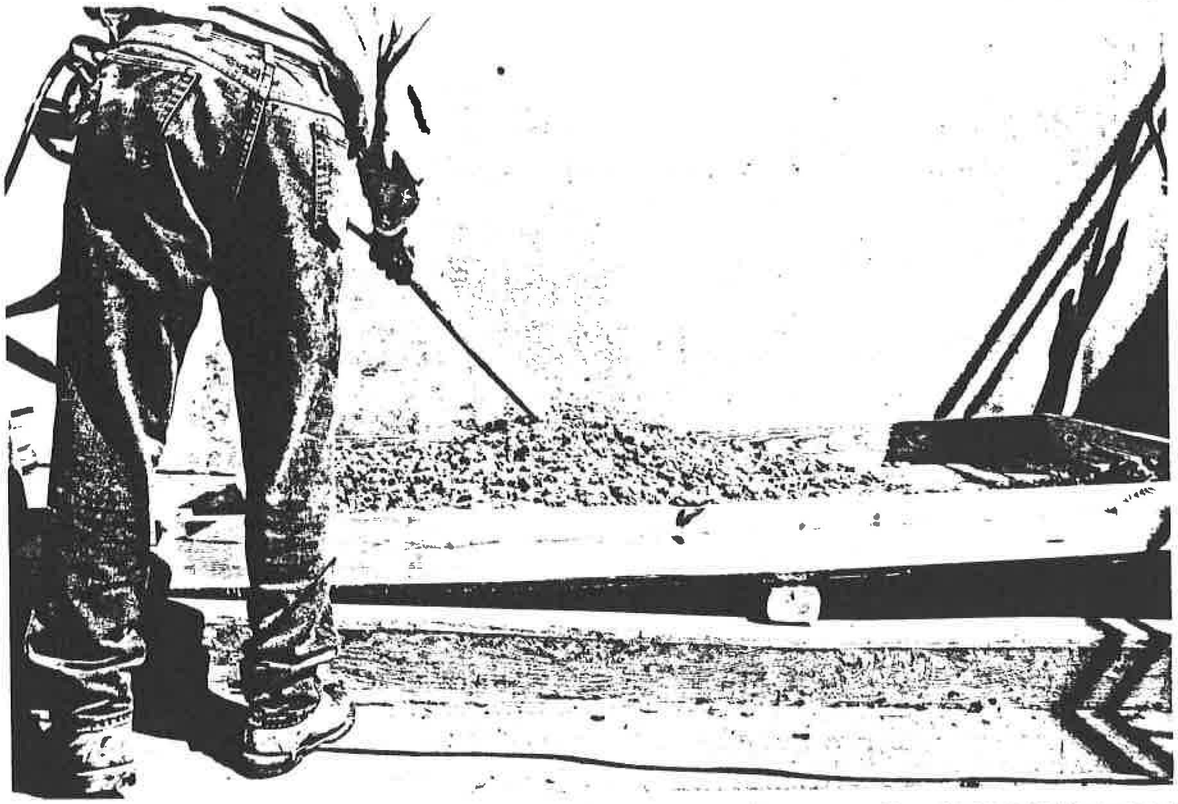
APPENDIX B

RESULTS OF LARGE-SCALE CONCRETE CONSISTENCY/WORKABLITY TESTING

Table B.1. Concrete Consistency/Workability vs. Time Based on Working Concrete in Simulated Deck Panel Form.

Mixture	Time After Placement (min.)	Consistency /Workability	
		Narrative Description	Visual/Photo
ALDOT-F	0*	Medium consistency, flows easy and easy to work	Fig. B.1
	15	Still flows and easy to work	Fig. B.2
	45	Still flowable and fairly easy to work	Fig. B.3
	65	Stiff but workable	Fig. B.4
	110	Very stiff and very difficult to work	Fig. B.5
	150	Very stiff and not workable	Fig. B.6
ALDOT/WR-F	0*	Stiff consistency but flows well with vibrator	Fig. B.7
	10	Stiff but flows with vibrator	Fig. B.8
	25	Quite stiff but still workable	Fig. B.9
	40	Quite stiff but still workable	Fig. B.10
	60	Very stiff and very difficult to work	Fig. B.11
	80	Very stiff and very difficult to work	Fig. B.12
	95	Very stiff and not workable	Fig. B.13
IM-F	0*	Stiff consistency, flows but not easily	Fig. B.14
	20	Quite stiff but still workable	Fig. B.15
	45	Very stiff and not workable	Fig. B.16

* Water first added to mixtures approximately 30 minutes prior to placement in "workability" form.



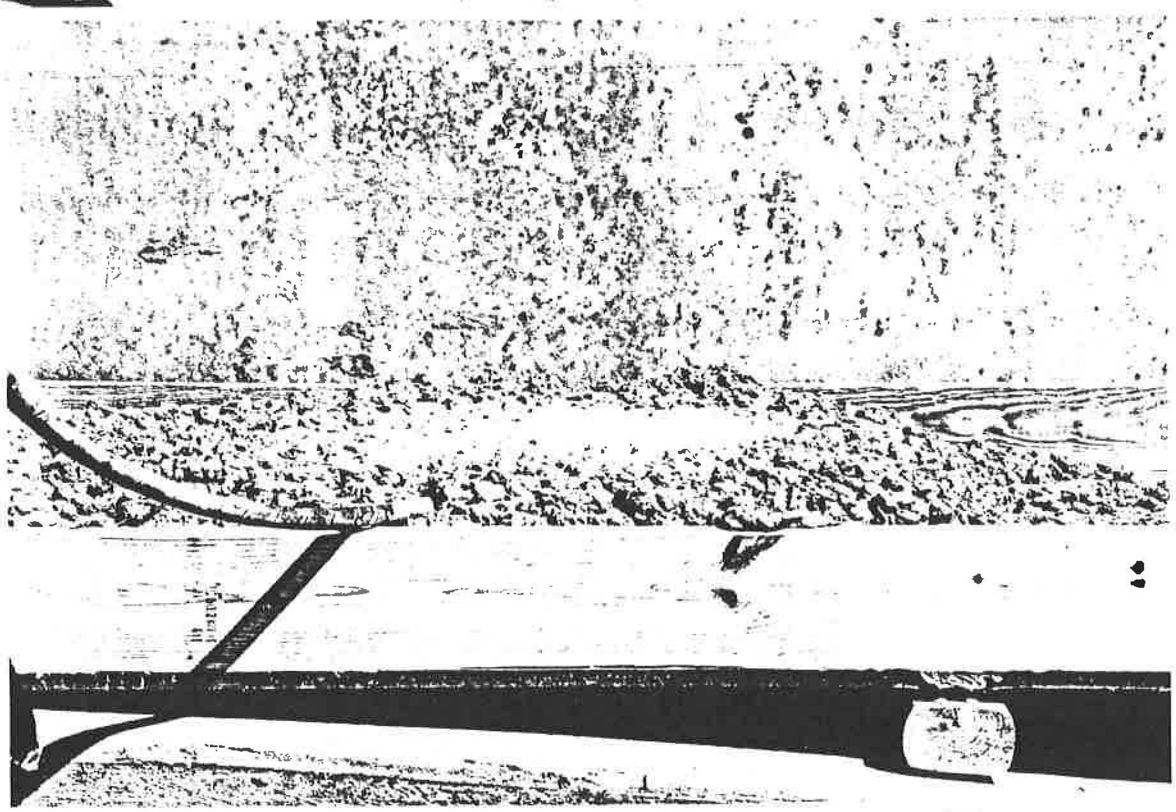


Figure B.1. ALDOT-F Mixture in Workability Form at Time of Placement – Mixture was Medium Consistency.

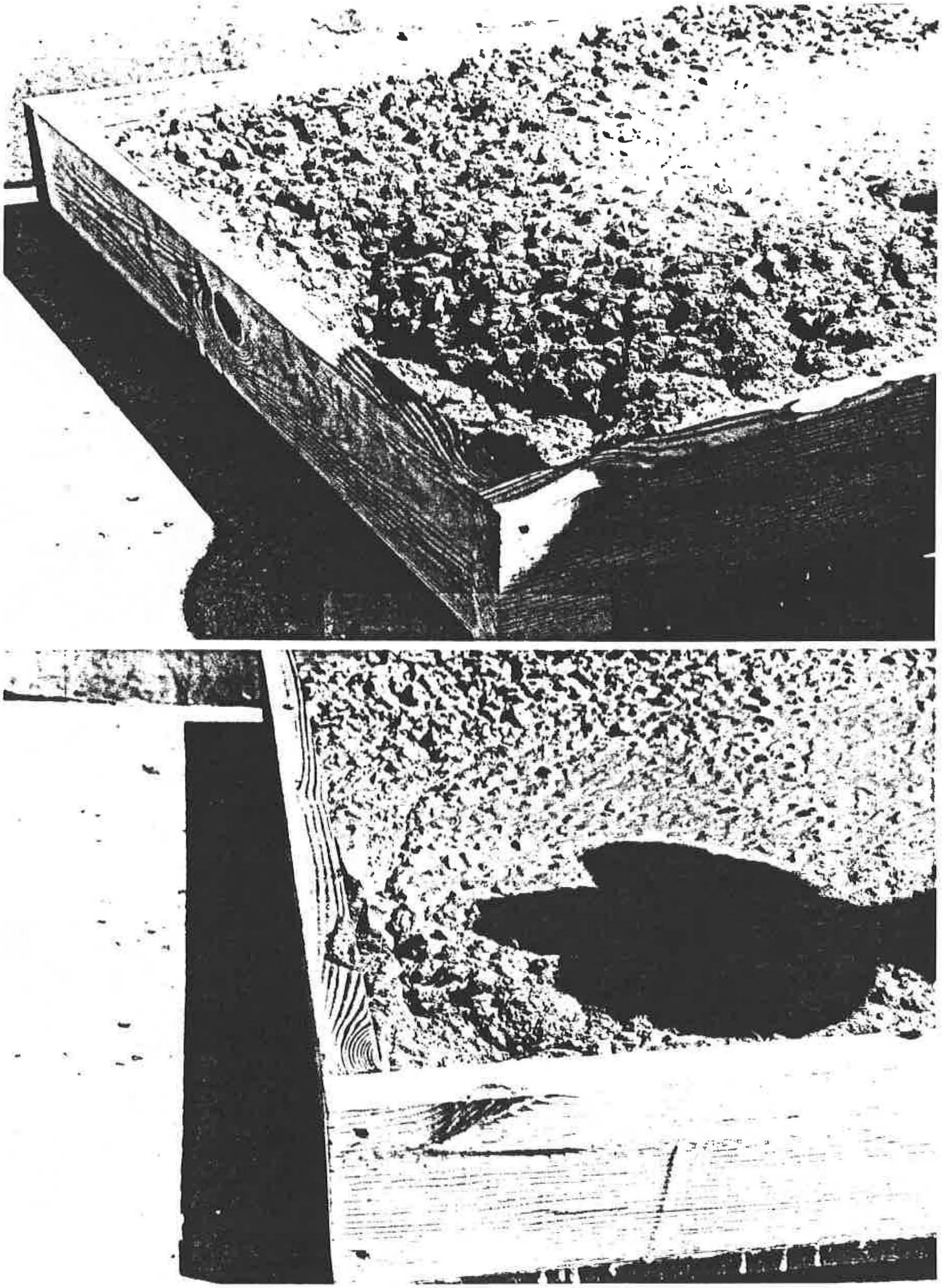


Figure B.2. ALDOT-F Mixture 15-Minutes After Placement –Mixture Flowable and Easy to Work.

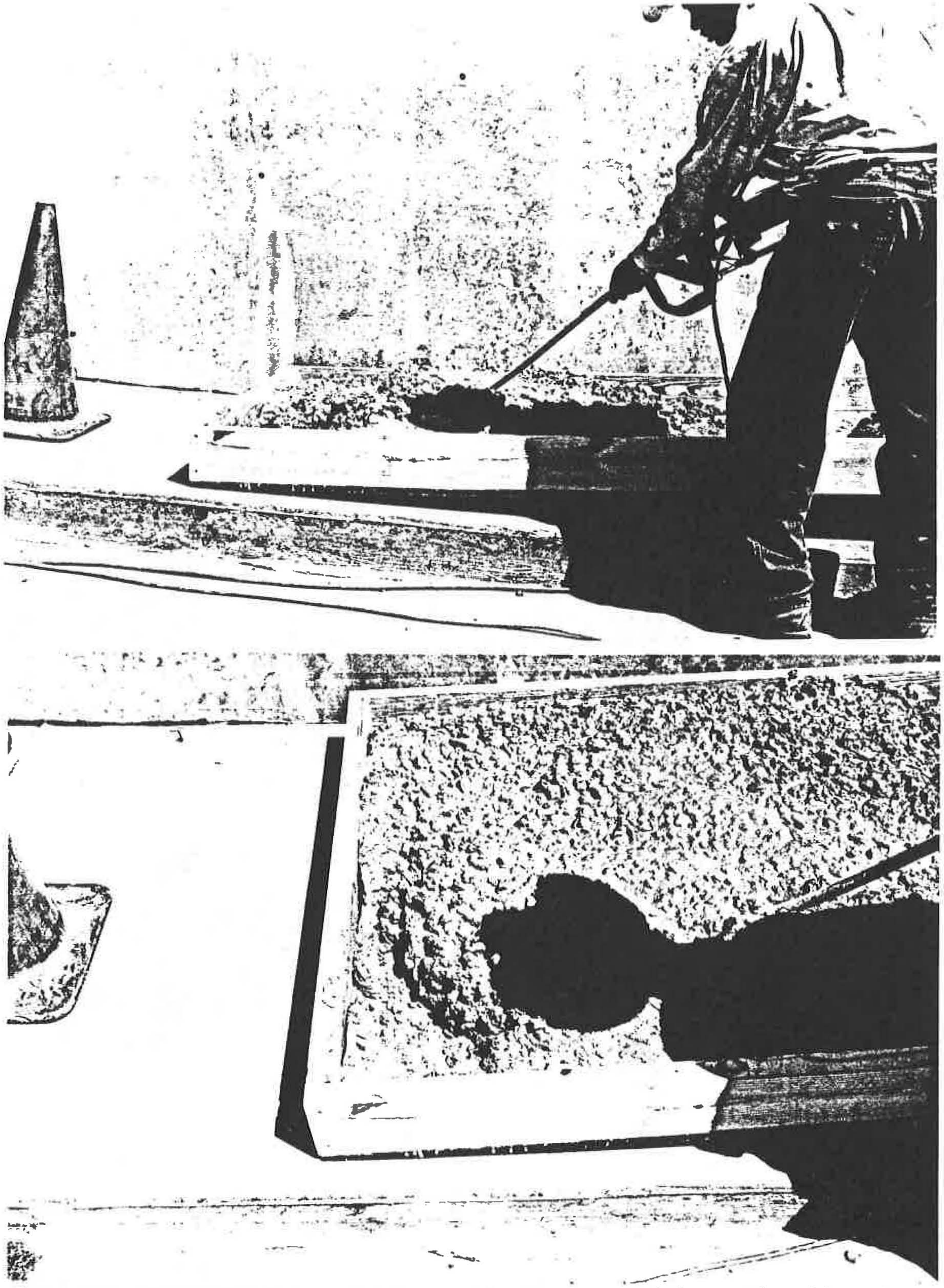


Figure B.3. ALDOT-F Mixture 45-Minutes After Placement –Mixture Flowable and Fairly Easy to Work.

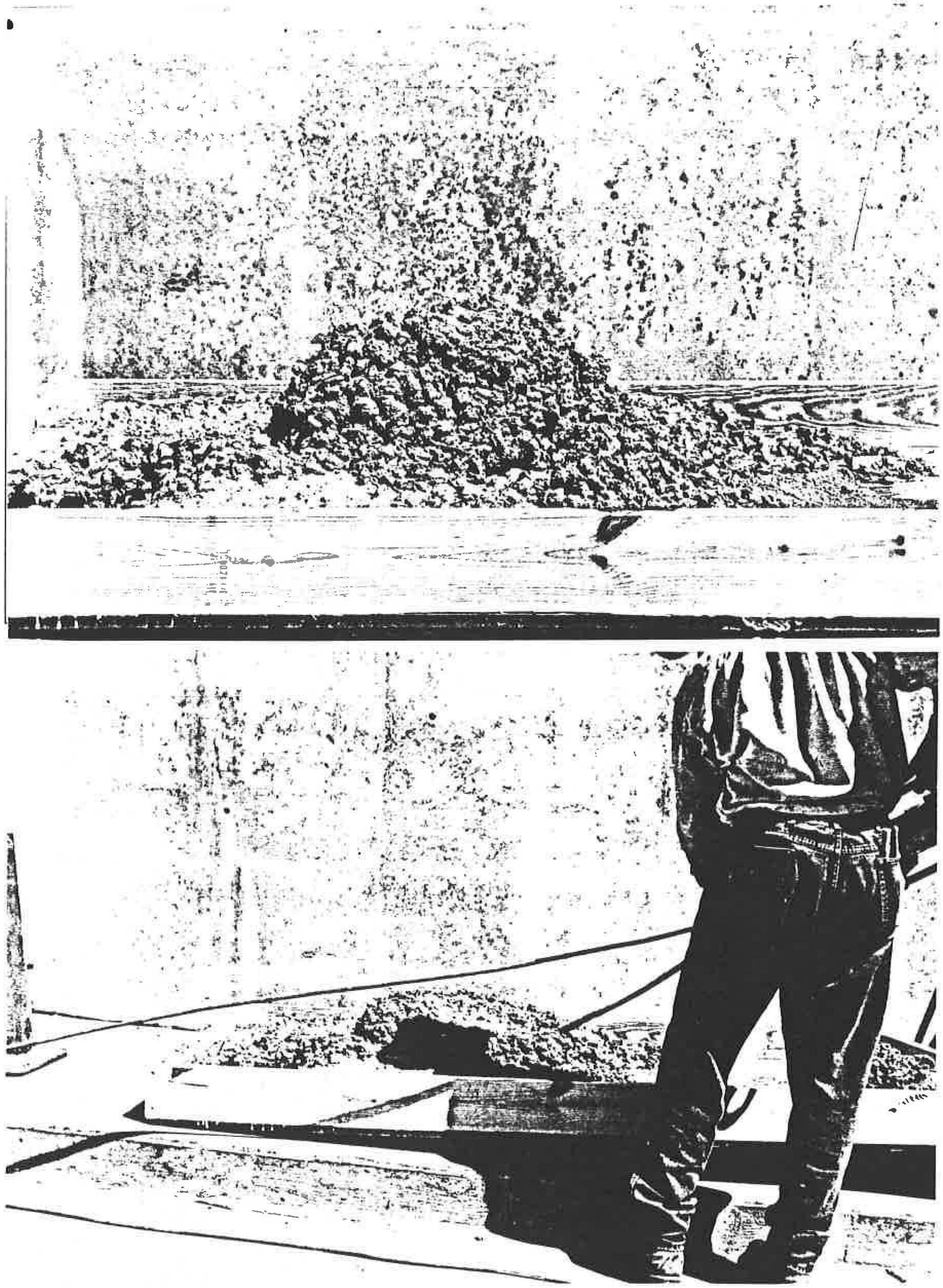


Figure B.4. ALDOT-F Mixture 65-Minutes After Placement –Mixture was Stiff but Workable.

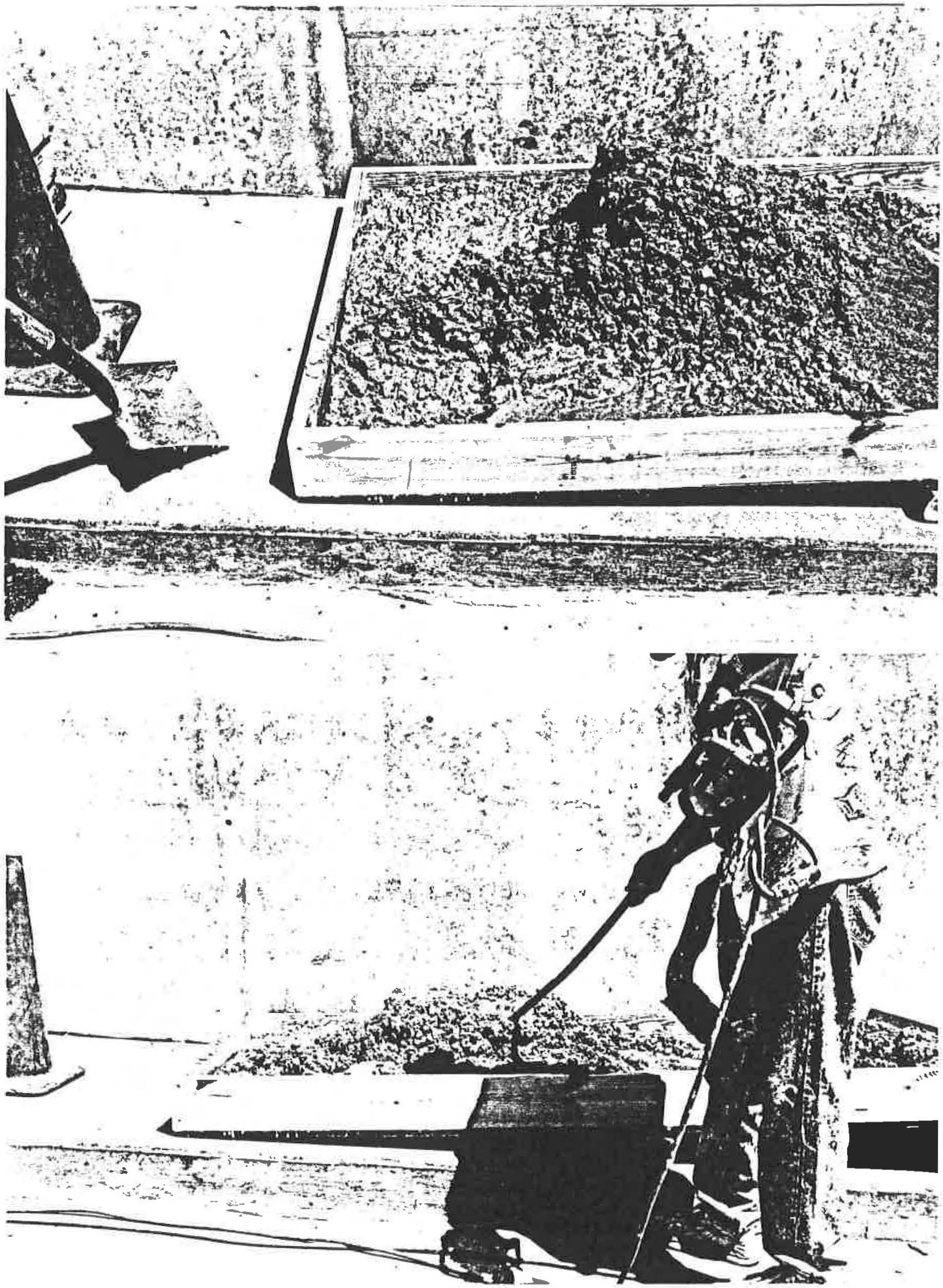


Figure B.5. ALDOT-F Mixture 110-Minutes After Placement –Mixture was Very Stiff and Very Difficult to Work.

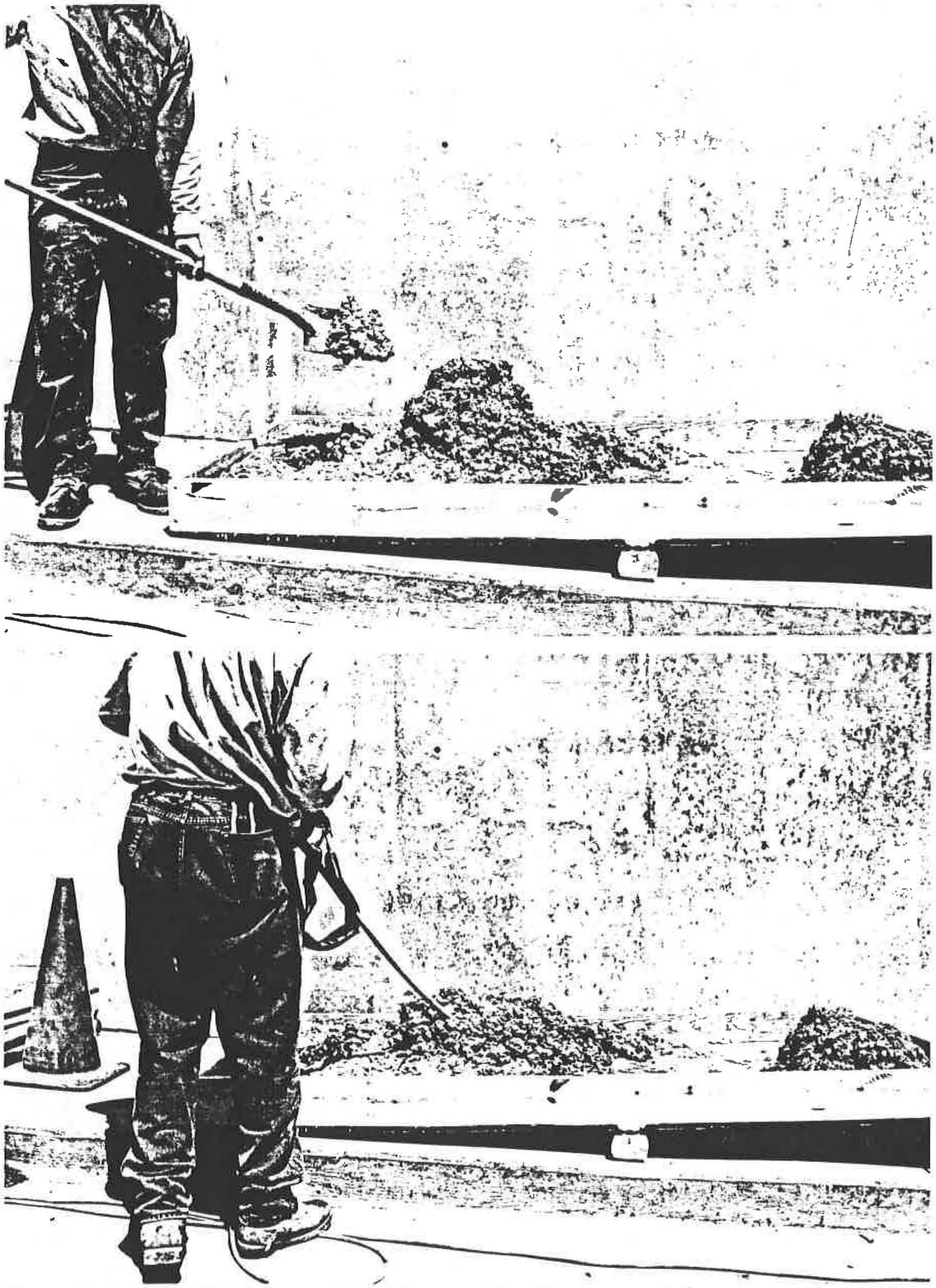


Figure B.6. ALDOT-F Mixture 150-Minutes After Placement –Mixture was Very Stiff and Not Workable.

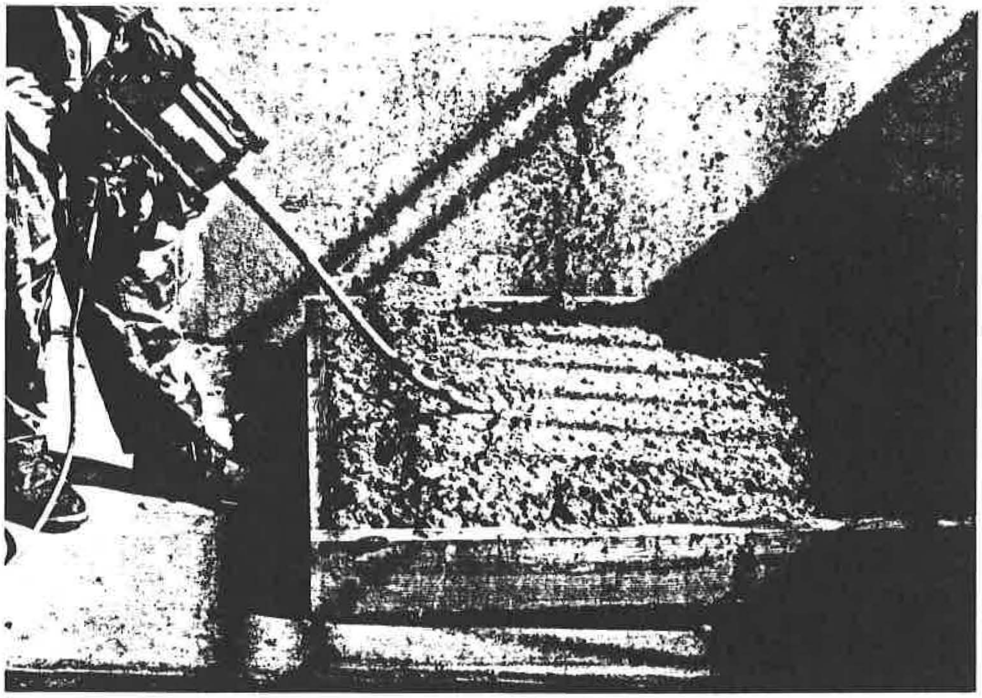


Figure B.7. ALDOT/WR-F Mixture in Workability Form at Time of Placement-Mixture was Fairly Stiff.

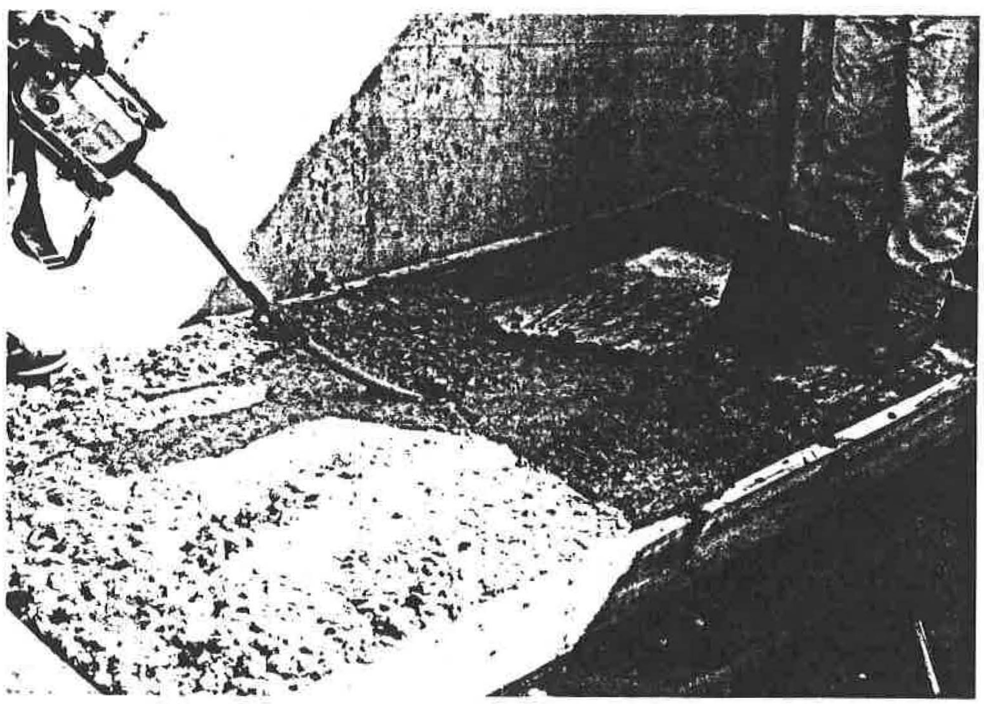


Figure B.8. ALDOT/WR-F Mixture 10-Minutes After Placement –Mixture was Stiff but Flowed Well with Vibrator.

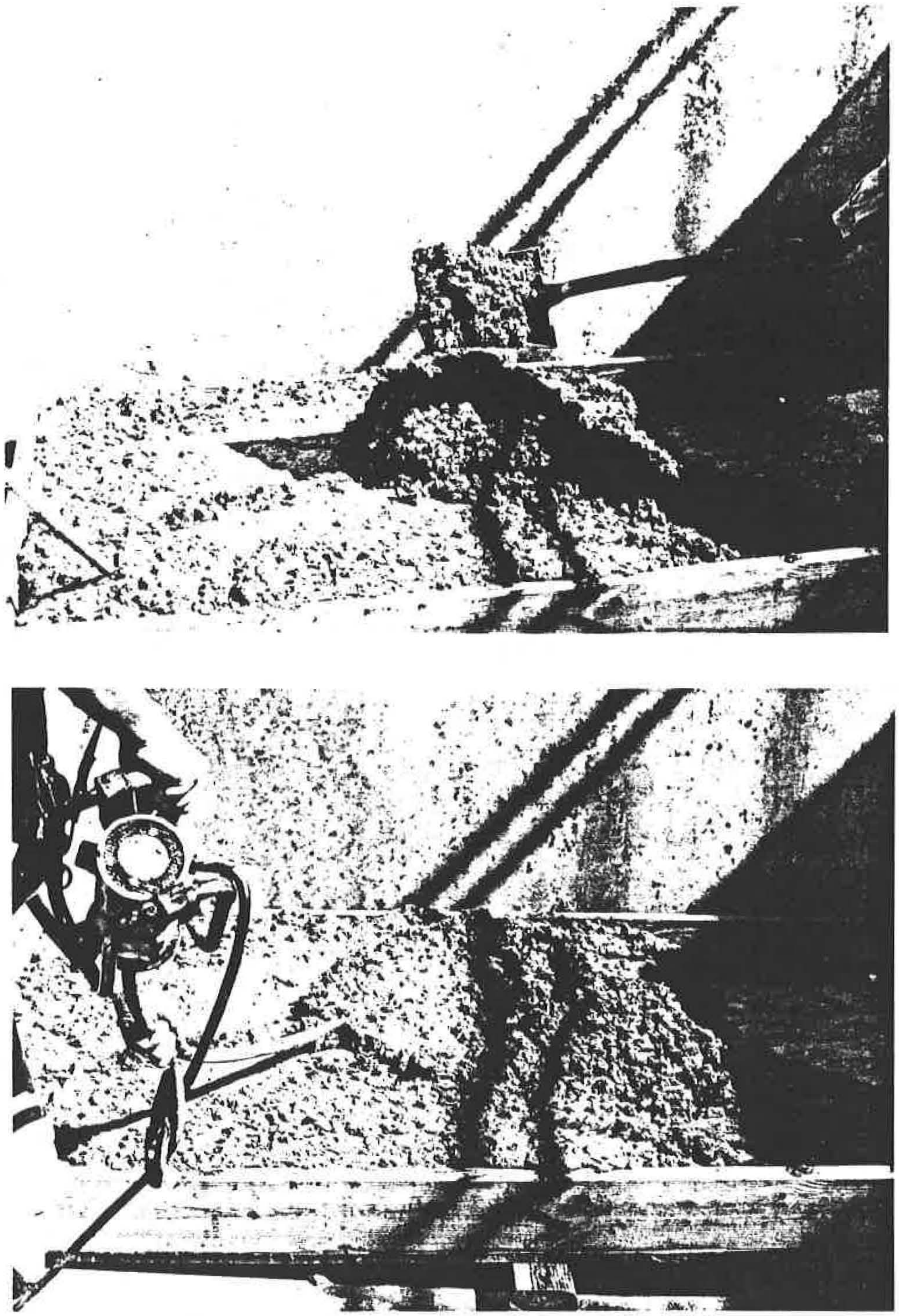


Figure B.9. ALDOT/WR-F Mixture 25 Minutes After Placement –Mixture was Quite Stiff but Still Workable.

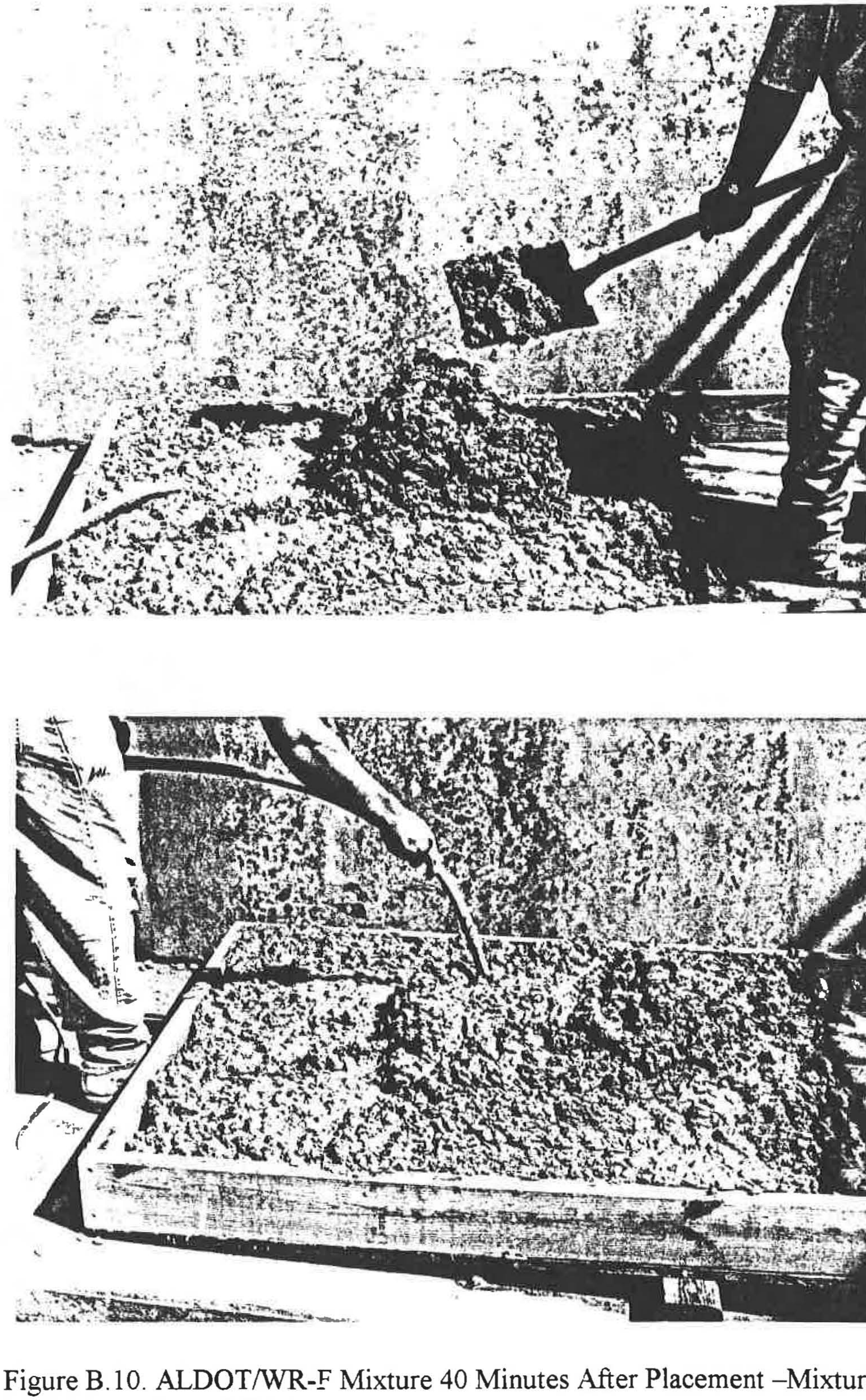


Figure B.10. ALDOT/WR-F Mixture 40 Minutes After Placement –Mixture was Quite Stiff but Still Workable.

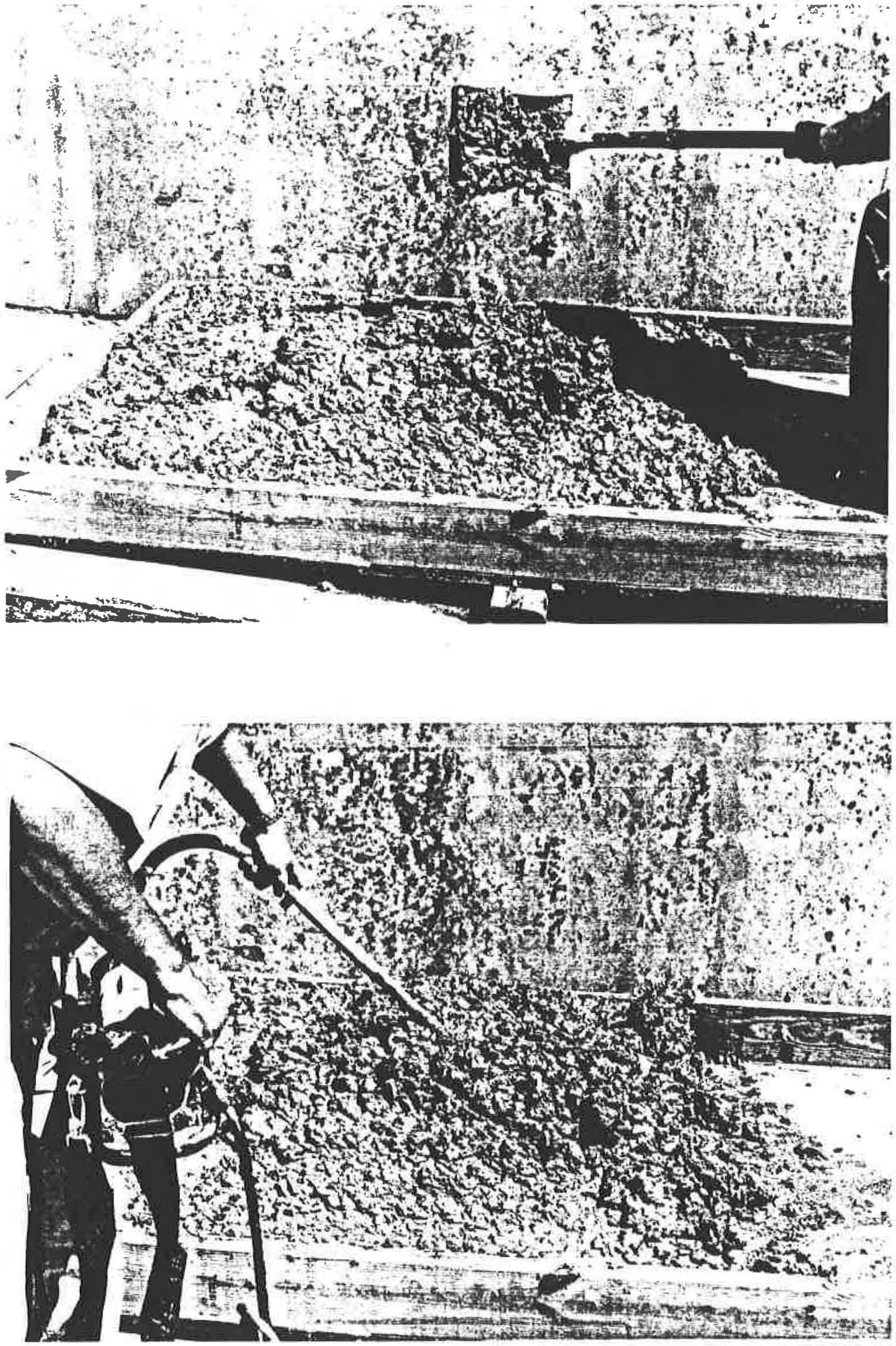


Figure B.11. ALDOT/WR-F Mixture 60 Minutes After Placement –Mixture was Very Stiff and Very Difficult to Work.