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Final Report

CRACKING IN BRIDGE DECKS: CAUSES AND MITIGATION

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DEPARTMENT OF TRANSPORTATION
RESEARCH

August, 1999

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December 9, 1999

Mr. James Daves
Colorado Division of FHWA
555 Zang Street
Lakewood, CO 80228

Dear Mr. Daves:

Subject: Final Report, " Cracking in Bridge Decks: Causes and Mitigation"

Enclosed are two copies of the final report for the research study 86.71, "Investigation of Cracking in Bridge Decks"

This report summarizes the findings of a study whose primary objectives are to determine the cause of extensive transverse cracking that has been observed in some existing bridge decks, and to identify the change of material specifications and construction practice that is necessary to reduce the severity of deck cracking.

Recommendations to alleviate the bridge deck cracking problem with regards to the design, construction, and materials aspects are provided for CDOT to consider. A new mix, termed class DSL, is recommended in this report. In this new mix, Type II cement is used, the silica fume content is limited to 6% by weight of cement, the content of Type F fly ash is 20% by weight, and the total content of cementitious materials is limited to 568 lb. per cubic yard of concrete. This mix is to be used in warm weather during summer months.

Sincerely,

Richard Griffin
Research Coordination Engineer

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16. **Abstract**

This report summarizes the findings of a study whose primary objectives are to determine the cause of extensive transverse cracking that has been observed in some existing bridge decks, and to identify the change of material specifications and construction practice that is necessary to reduce the severity of deck cracking. To achieve these goals, recent studies on the cause of bridge deck cracking were reviewed, an experimental study was conducted to compare the shrinkage properties of different concrete mixes, and the current material and design specifications and construction practice adopted by the Colorado Department of Transportation (CDOT) were reviewed to identify areas that need improvement. A survey was conducted on seven newly constructed bridges to examine the extent of cracking in concrete decks that were constructed with the different mix designs and curing procedure that were currently used by CDOT. Based on the literature review, factors that influence deck cracking have been identified. Ways to improve existing concrete mixes to reduce the severity of deck cracking have been proposed. Further studies are recommended to develop and evaluate improved concrete mixes that can reduce deck cracking. A new mix, termed class DSL, is recommended in this report. It is suggested that the performance of selected bridge decks be systematically monitored over a duration of one year or more to assess the severity of the deck cracking problem with the concrete mixes currently being used by CDOT and to evaluate the effectiveness of new mix designs that are to be developed and tested, including class DSL.

Implementation

Recommendations to alleviate the bridge deck cracking problem on the design, construction, and materials aspects are provided for CDOT to consider. The design factors should be taken into consideration whenever possible. The desired construction practice recommended in Section 5.3 should be implemented to the fullest extent possible. A new mix, termed class DSL, is recommended in this report. In this new mix, Type II cement is used, the silica fume content is limited to 6% by weight of cement, the content of Type F fly ash is 20% by weight, and the total content of cementitious materials is limited to 568 lb. per cubic yard of concrete. This mix is to be used in warm weather during summer months.

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by

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Appendix E of this report was written by Brad Kline, a former undergraduate research assistant at the University of Colorado, who conducted the shrinkage study.

EXECUTIVE SUMMARY

This report summarizes the findings of a study whose primary objectives are to determine the cause of extensive transverse cracking that has been observed in some existing bridge decks, and to identify the change of material specifications and construction practice that is necessary to reduce the severity of deck cracking.

To achieve these goals, recent studies on the cause of bridge deck cracking were reviewed, an experimental study was conducted to compare the shrinkage properties of different concrete mixes, and the current material and design specifications and construction practice adopted by the Colorado Department of Transportation (CDOT) were reviewed to identify areas that need improvement. A survey was conducted on seven newly constructed bridges to examine the extent of cracking in concrete decks that were constructed with the different mix designs and curing procedure currently used by CDOT.

Based on the literature review, factors that influence deck cracking have been identified. Ways to improve existing concrete mixes to reduce the severity of deck cracking have been proposed. This involves the use of Type II cement, reducing the cement content in concrete, and the use of Type F fly ash to reduce the heat of hydration and the early strength of silica fume concrete that is frequently used in bridge decks for the purpose of reducing chloride permeability. It has been found that the deck curing procedures currently adopted by the Colorado Department of Transportation are a step forward and effective for the control of deck cracking. The deck survey indicates that a small quantity of silica fume does not jeopardize the performance of bridge decks provided a proper curing procedure is used. However, the current database is limited and further information on the long-term performance of some recently constructed bridge decks needs to be gathered.

Further studies are recommended to develop and evaluate improved concrete mixes that can reduce deck cracking. A new mix, termed class DSL, is recommended in this report. In this new mix, Type II cement is used, the silica fume content is limited to 6% by weight of cement, the content of Type F fly ash is 20% by weight, and the total content of cementitious materials is limited to 568 lb. per cubic yard of concrete. This mix is to be used in warm weather during summer months. It is recommended that the mix design be thoroughly studied in laboratory and tried in new decks. The performance of selected bridge decks should be systematically monitored over a duration of one year or more to assess the severity of the deck cracking problem with the concrete mixes currently used by CDOT and to evaluate the performance of new mix designs that are to be developed and tested, including class DSL.

Implementation Statement

Recommendations to alleviate the bridge deck cracking problem on the design, construction, and materials aspects are provided in Section 5 for CDOT to consider. The design factors should be taken into consideration whenever possible. The desired construction practice recommended in Section 5.3 should be implemented to the fullest extent possible. A new mix, termed class DSL, is recommended in this report. In this new mix, Type II cement is used, the silica fume content is limited to 6% by weight of cement, the content of Type F fly ash is 20% by weight, and the total

total content of cementitious materials is limited to 568 lb. per cubic yard of concrete. This mix is to be used in warm weather during summer months.

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1.0 INTRODUCTION

This report summarizes the findings of a study whose primary objectives are to:

1. Determine the cause of extensive transverse cracking in some existing bridge decks; and
2. Identify the change of material specifications and construction practice that is necessary to reduce the severity of deck cracking.

To achieve these goals, the following tasks were carried out in the study:

1. Review of recent studies on the cause of bridge deck cracking and identification of material and design specifications, and construction practice that can help to reduce the severity of deck cracking.
2. Performance of an experimental study to compare the shrinkage properties of different concrete mixes that had been used by the Colorado Department of Transportation (CDOT) since 1971 and to examine the influence of cement content and fly ash on the drying shrinkage of concrete.
3. Review of current CDOT material and design specifications, and construction practice; and identification of areas that need improvement.
4. Survey of seven newly constructed bridges to examine the extent of deck cracking.
5. Identification of important factors that influence deck cracking and development of recommendations that can be adopted by CDOT to reduce deck cracking.
6. Identification of improved concrete mixes to reduce the severity of deck cracking.

The findings from the above tasks are summarized in the following sections.

2.0 LITERATURE REVIEW

Recent studies on the cause of cracking in concrete bridge decks were reviewed. Main factors that contribute to deck cracking, the significance of their influence, and remedial considerations are summarized in this section. The main sources of information provided here are the following technical reports and papers:

1. Kraus, P.D. and Rogalla, E.A. (1996). "Transverse Cracking in Newly Constructed Bridge Decks." *NCHRP Report 380*, Transportation Research Board, National Research Council, Washington, D.C.
2. Schmitt, T.R. and Darwin, D. (1995). "Cracking in Concrete Bridge Decks." *Report No. K-Tran: KU-94-1*, Kansas Department of Transportation, Topeka, Kansas.
3. Whiting, D. and Detwiler, R. (1998). "Silica Fume Concrete for Bridge Decks." *NCHRP Report 410*, Transportation Research Board, National Research Council, Washington, D.C.
4. Babaei, K. and Fouladgar, A.M. (1997). "Solutions to Concrete Bridge Deck Cracking." *Concrete International*, July, 34-37.
5. McDonald, D.B., Krauss, P.D., and Rogalla, E.A. (1995). "Early-Age Transverse Deck Cracking." *Concrete International*, May.
6. Rogalla, E.A., Krauss, P.D., and McDonald, D.B. (1995). "Reducing Transverse Cracking in New Concrete Bridge Decks." *Concrete Construction*, September, 735-737.
7. Burrows, R.W. (1998). "The Visible and Invisible Cracking of Concrete." *Monograph No. 11*, ACI, Farmington Hills, Michigan.
8. French, C.E., Eppers, L.J., Le, Q.T., and Hajjar, J.F. (1999). "Transverse Cracking in Bridge Decks: Summary Report" *Report No. MN/RC-1999-05*, Minnesota Department of Transportation, St. Paul, Minnesota.
9. ACI Committee 305 (1991). "Hot Weather Concreting." *Report No. ACI 305R-91*, ACI, Farmington Hills, Michigan.
10. Lerch, W. (1957). "Plastic Shrinkage." *ACI Journal*, Vol. 53, No. 8, February, 797-802.
11. ACI Committee 234 (1996). "Guide for the Use of Silica Fume in Concrete." ACI, *Report No. ACI 234R-96*, ACI, Farmington Hills, Michigan.

In addition to detailed reviews of previous studies on deck cracking, some of the above articles also provide new information gathered from analytical modeling, field inspections, and laboratory testing. According to these studies, factors that may influence the severity of deck cracking can be classified into three main categories: (a) materials factor, (b) design factor, and (c) construction practice. Their influence, significance, and remedial considerations are summarized in table form in Sections 2.1 through 2.3.

2.1 Materials Factors

Transverse cracks in concrete decks are mainly caused by the shrinkage and temperature effects. The severity of deck cracking depends on the properties of concrete, such as the early age modulus of elasticity, creep, amount of plastic and drying shrinkage, and heat of hydration. The influence of the properties of concrete on deck cracking is summarized in Section 2.1.1, while the impact of different ingredients of concrete mixes on these properties and thereby deck cracking is presented in Section 2.1.2.

2.1.1 Influence of Material Properties

Properties	**Influence on Cracking**	**Level of Influence**	**Remedial Considerations**
Plastic Shrinkage	Caused by the loss of moisture from concrete surface while it is still in a plastic state. Plastic shrinkage cracks are usually no more than 2 or 3 ft. (600 or 900 mm) long and are typically shallow - 2 to 3 in. (50 to 75 mm) deep. Their size may grow due to applied loads or drying shrinkage.	High	Use of proper curing procedure and favorable weather conditions to prevent moisture loss at early age.
Drying Shrinkage	Caused by moisture losses from hardened concrete. It is one of the main causes of deck cracking. The ultimate drying shrinkage strain is normally around 700 microstrain and not less than 500 microstrain for most concrete. Curing conditions may change the rate of drying shrinkage but will only have a small influence on the ultimate shrinkage strain. A Minnesota study indicates that the rate of shrinkage has a more significant impact on deck cracking than the ultimate shrinkage strain. For a concrete prism fully restrained at both ends, cracks may develop at a shrinkage strain of around 200~250 microstrain not accounting for creep. This may occur at an age of 10 days under normal room temperature and	High	Shrinkage can be reduced by reducing paste volume and water content, and by using Type II cement. However, there is no conclusive evidence that drying shrinkage can be significantly reduced by reducing paste volume and water content.

	50% humidity based on the data presented in Section 3.		
Creep	Creep reduces tensile stresses introduced by restrained drying shrinkage and thermal effects, and thereby, reduces deck cracking. Concrete with a higher creep has also a lower compressive strength. However, the variation of the compressive strength of concrete has a larger impact on creep than on the tensile strength and the modulus of elasticity.	High	Use concrete that exhibits a high creep at early age (within first month after casting). Such concrete normally has low early strength. High early creep can be achieved by slowing down the heat of hydration rates and using pozzolan admixtures. Since high creep is often associated with low compressive strength, it is advisable to specify the 90-day compressive strength rather than the 28-day compressive strength in design.
Modulus of Elasticity	A low modulus of elasticity reduces shrinkage and thermal stresses and therefore, reduces cracking. Concrete with a lower modulus of elasticity will also have a lower compressive strength and a lower tensile strength. According to the ACI formulas, both the modulus of elasticity and tensile strength are	High	Use aggregates with a low modulus of elasticity. Use concrete with low early modulus of elasticity.

	proportional to the square root of the compressive strength. Hence, the main advantage of using a low modulus concrete seems to derive from the fact that such concrete also exhibits a higher creep. However, there is no conclusive evidence on the effectiveness of low modulus of elasticity in reducing concrete cracking.		
Heat of Hydration	Heat of hydration can create thermal stresses. Higher heat of hydration also leads to higher early strength and modulus of elasticity. Modern high strength concrete has this kind of drawback.	High	Limit concrete temperature at placement to 80°F (27°C). Use retarding agents to limit temperature rise, use Portland cements that have a low heat of hydration, and use low-permeability fly ash-blast furnace slag-Portland cement mixtures.
Coefficient of Thermal Expansion	Thermal stresses introduced by diurnal temperature changes are a lot more significant than those introduced by seasonal temperature changes. The latter introduces a more uniform temperature change throughout the deck and girders. A low coefficient of thermal expansion is desirable to minimize the thermal stresses caused by diurnal temperature changes. The coefficient of thermal expansion of the hardened cement paste is normally 2-3 times the coefficient of thermal expansion of aggregate. The coefficient of thermal expansion of concrete is	Moderate	Increase the aggregate content. Use aggregates with lower coefficients of thermal expansion.

	in the range of 4 to 7 micostrain/°F (7 to 12 microstrain/°C), while that for steel is 7 microstrain/°F (12 microstrain/°C).		
Slump	Most studies indicate no conclusive relation between the slump and cracking for slumps within the normal range. Kansas study shows increased cracking in monolithic decks with increased slump, but not in bridge deck overlays. This can be due to settlement cracking in monolithic decks.	Minor	Avoid excessive slumps.

2.1.2 Influence of Concrete Mix Ingredients

Ingredients	**Influence on Cracking**	**Level of Influence**	**Recommend-ations**
Aggregate Type and Size	Aggregate type and size influence the strength, elastic modulus, shrinkage, and creep. Concrete with limestone aggregate is more resistant to cracking than that with other types. Reasons for this are not clear, but it could be partly due to the lower water absorption property of limestone. Some studies indicate that concrete with larger-size aggregate is more resistant to cracking. Larger aggregate permits lower cement paste and less water content to arrive at a desired slump. Smaller aggregate with rough texture may require more water to arrive at a desired slump. However, there is no conclusive evidence to support this. Softer aggregate may be less effective in restraining drying shrinkage, but it results in a lower modulus of elasticity, which reduces shrinkage and thermal stresses.	High	Use low-shrinkage aggregates. User larger-size aggregates as possible.

Cement Type	Modern cement (since 1970's) has a higher early strength than older cement. This increases the risk of cracking. Concrete with Type II cement has a lower risk of cracking than that with Type I because Type II cement has a lower heat of hydration. Type III cement gains strength rapidly and may increase the risk of cracking. Cement with coarse particles and low tricalcium silicate content has lower early strength and heat of hydration. Cement with low alkali content tends to have lower modulus of elasticity and higher creep, and can, therefore, extend more before cracks develop.	High	Use Type II cement. Avoid finely ground cement and Type III cement.
Cement Content	Reducing cement content reduces the heat of hydration and shrinkage and therefore, the risk of cracking. However, there is no conclusive evidence to support this. Cracking tendency tests indicate a weak correlation between time-to-cracking and cement content. In general, concrete with high cement content and low water-to-cement ratio is more susceptible to cracking than that with low cement content (470 lb/yd^3) and high-water-to-cement ratio (0.40 to 0.50) because the latter creeps more.	High	Limit cement content to a maximum of 470 lb/yd^3. Kansas study suggests that a cement paste volume less than 27.5% significantly reduces cracking.
Water-to-Cement Ratio	Increasing water-to-cement ratio increases shrinkage and therefore, the risk of cracking. On the other hand, it increases creep that may decrease the risk of cracking. Low water-to-cement ratio can lead to less creep, more autogenous shrinkage, and more plastic shrinkage cracks. In most studies, little correlation has been observed between the water-to-cement ratio and cracking	Moderate	Water-to-cement ratio in the range of 0.40 to 0.50 is adequate.

	tendency. However, concrete with high cement content and low water-to-cement ratio is more susceptible to cracking than that with low cement content (470 lb/yd^3) and high water-to-cement ratio (0.40 to 0.50) because the latter creeps more.		
Air Content	Some studies indicate that increasing air content reduces cracking, while other studies do not show a clear correlation between the two.	Minor	Use air-entrained concrete. Kansas study suggests an air content of 6% by volume or more.
Shrinkage-Compensating Cement	The ultimate shrinkage strain of shrinkage-compensated concrete is normally between 400 and 600 microstrain. Results of laboratory and field studies on the effectiveness of shrinkage-compensating cement are mixed. It is promising but requires further studies.	Moderate	Worthwhile to try but it needs further studies.
Fly Ash	Fly ash, especially Class F, reduces the rate of strength gain and early concrete temperatures, and may therefore, reduce cracking. In Germany, it is a common practice to use 100 lb. of fly ash in one cubic yard of concrete for bridge decks, and they have no deck cracking problems. However, restrained concrete ring tests with 28% of the Portland cement replaced by fly ash are somewhat inconclusive. Further field studies are needed as restrained ring tests may not properly reflect the thermal effect in large decks.	Negligible to Moderate	The use of fly ash needs further studies. However, in dry climate, fly ash should be used with care and proper curing procedures.
Silica Fume	Silica fume concrete normally has higher heat of hydration, which introduces higher thermal stresses, and bleeds less and is	High	Reduce or avoid silica fume. Use fog sprays or misting right

	therefore more prone to plastic shrinkage cracks. Some studies indicate that silica fume concrete undergoes intense autogenous shrinkage. It also has higher elastic modulus and lower creep. All these factors increase cracking. In a recent study (NCHRP Report 410), it has been found that silica fume influences early age cracking only in concrete with improper curing. Silica fume concrete should be continuously moist cured for 7 days. Furthermore, silica fume has little effect on the ultimate shrinkage of concrete, but may lead to higher early shrinkage. Concrete with silica fume is also more sensitive to w/c than that without. Even though silica fume can result in dramatic reduction of chloride permeability and increase in strength, the increase of silica fume beyond 6% has a diminishing return on the reduction of diffusivity.		after concrete placement. Recommend 7-day continuous moist curing to reduce early age cracking. To reduce chloride diffusivity, the silica fume content does not have to exceed 6% by weight of cement.
Retarders	Increase plastic shrinkage cracking, but lower the heat of hydration and therefore reduce thermal stresses. May increase cracking. No conclusive evidence on its influence.	Negligible	Evaporation retarder films and fogging may reduce plastic shrinkage cracks when retarders are used in hot or cold weather.
Accelerators	Can increase shrinkage, early temperature rise, and early modulus of elasticity. It can also increase early strength and reduce plastic shrinkage cracking. No conclusive evidence on its influence.	Negligible	
Fiber Reinforcement	May reduce plastic shrinkage and settlement cracking. May reduce	Not clear	Need further studies.

	crack widths. Its influence on drying shrinkage crack is not known. May lead to more diffuse and finer cracks.		

2.2 Design Factors

The severity of deck cracking depends, to a certain extent, on the structural aspects of bridge decks.

Design Factors	**Influence on Cracking**	**Level of Influence**	**Recommend-ations**
Continuous/Simple Span	Continuous span bridges are more susceptible to cracking than simple-span bridges.	Moderate	
Girder Type	Cracking is more severe with steel girders than with concrete girders.	Moderate	
Girder End Conditions	Restrained ends induce more cracks	Moderate to High	Reduce longitudinal restraints.
Deck Thickness	Thinner decks are more susceptible to cracking. However, there is no conclusive evidence to support this.	Moderate	Deck thickness should not be less than 8.5 in. (215 mm).
Concrete Cover	A thicker concrete cover may reduce settlement cracks.	Minor	Use concrete cover not less than 2 in.
Girder Size and Spacing	Decks with larger girders at closer spacing are more susceptible to cracking than those with smaller girders at farther spacing.	Moderate	
Transverse Reinforcing Bars	Most transverse cracks are right above the top transverse bars. A Minnesota study indicates that decks with No. 6 bars have more severe cracks than those with No. 5 bars. They recommend using No. 5 bars at 5.5" spacing or No. 6 bars at 6.5-7.0" spacing.	Moderate	Avoid the alignment of top and bottom transverse bars within the same vertical plane. Place top longitudinal steel above transverse steel. Use smaller bars at closer

			spacing.
Creep of Prestressed Concrete Girders	Creep of prestressed concrete girders may induce stresses in decks.	Not clear	Avoid tension in prestressed concrete girders.

2.3 Construction Practice

Construction practice is another important factor on deck cracking besides concrete mix design. Studies have shown that a proper curing procedure is especially important for silica fume concrete that is more susceptible to cracking.

	Influence on Cracking	**Level of Influence**	**Recommend-ations**
Weather Conditions	High wind velocity, low humidity, high air temperature, and high evaporation rates during casting have adverse effects on cracking. Casting at either high temperatures or low temperatures increases cracking. Evaporation rate depends on the air temperature, concrete temperature, relative humidity, and wind speed.	High	Do not cast decks when air temperature is less than 45°F (7°C) or over 80°F (27°C). Avoid casting during high winds. Evaporation rate should be measured at the job site. For normal concrete, avoid concrete placement at an evaporation rate above 0.20 lb./ft.^{2}/hr. (0.98 kg/m^2/hr). Avoid pouring concrete on days when there is a large temperature range (greater than 50 °F (10 °C)).
Time of Casting	Late morning or early afternoon casting may increase concrete	High	Cast concrete decks in early

	temperature during hydration. This should be avoided in hot weather.		or mid-evening during hot weather.
Curing Period and Methods	Concrete with high cement content and low water-to-cement ratio is more affected by curing than that with low cement content and high water-to-cement ratio.	Moderate	Use chemical evaporation retarder films and fogging when evaporation rate is high. Apply fogging and moist curing as early as possible.
Finishing Procedures	Delayed finishing causes more severe cracking.	Moderate	Avoid delayed finishing.

3.0 SUMMARY OF SHRINKAGE STUDY

Since drying shrinkage is a major contributor to deck cracking, six concrete mixes were studied for their shrinkage properties. One was based on a concrete mix used by the CDOT in 1971. Two are based on the 1986 CDOT specifications. The fourth is based on the 1986 specifications but with 20% of the cement replaced by fly ash. The last two are trial mix designs, which had the cement content reduced by about 15% compared to the 1986 specifications. One of these had additional 15% of the cement replaced by fly ash. The details of the testing procedure, material properties, and shrinkage test results are provided in Appendix E. The main conclusions from this study are summarized here.

Nine prism specimens were prepared for each mix to measure shrinkage at 7, 14, 28, 35, 42, 56, 84, and 140 days after casting. Half of these were cured at 68°F and 50% humidity, and the rest in lime saturated water for the first 28 days and under the aforementioned controlled environment afterwards. The weight changes in these specimens were also measured. In addition, specimens were prepared for each concrete mix to measure the compressive strength, modulus of elasticity, and modulus of rupture at 7, 28, and 90 days after casting.

For the specimens cured at 68°F and 50% humidity, the maximum shrinkage strains measured range from 630 to 830 microstrain. The trial mix with fly ash exhibited the largest shrinkage while the 1986 mix with fly ash had the lowest shrinkage. All the rest had more or less the same amount of shrinkage, which reached 700 microstrain at 140 days. The trial mix which had a lower cement content than the 1986 mix showed slightly less shrinkage. In general, specimens cured in lime saturated water for 28 days had a lower amount of shrinkage, which ranges from 500 to 720 microstrain at 140 days. Most of them had a shrinkage lower than 600 microstrain at 140 days.

In general, the compressive strength, modulus of elasticity and modulus of rupture of the concrete with fly ash are much lower than those without fly ash. This is especially the case for the 1986 mix.

The following major conclusions can be obtained from the shrinkage studies:

1. The shrinkage properties of the 1971, 1986, and trial mixes are very similar.
2. There is no clear evidence that fly ash will influence the shrinkage properties of concrete.
3. For all the mixes considered here, shrinkage induced cracking seems inevitable. For a concrete prism with full restraints at both ends, we can expect shrinkage cracks to develop at about 10 days after casting if we ignore the creep effect.
4. Fly ash did lower the compressive strength and modulus of elasticity of concrete even at the age of 90 days.

Prior studies indicate that fly ash can reduce transverse cracking in bridge decks by lowering the early strength gain and, thereby, the early modulus of elasticity, and also by lowering the early concrete temperature. However, the cracking tendency tests using restrained concrete rings (NCHRP Report 380) indicate that replacing 28% of the Portland cement by fly ash did not have a significant influence on the cracking of restrained concrete rings. This could be due to the fact that the restrained ring tests might not properly reproduce the heat of hydration effect in a full-size concrete deck (based on communications with Mike McMullen, CDOT bridge engineer).

The use of fly ash has found great success in Germany in the control of deck cracking. Their typical concrete mixture for bridge decks contains 472 lb. of cement and 100 lb of fly ash per cubic yard of concrete (Burrows 1999). The above cement content is consistent with the recommendation from NCHRP Report 380 (see Section 2).

Based on the results of the shrinkage study, one can conclude that while shrinkage is the primary contributor to transverse deck cracking, more extensive cracking observed in newer bridges is probably not caused by the change of the shrinkage property of concrete, but by other factors such as the high early strength, low creep, and high heat of hydration of modern concrete. Under normal circumstances, shrinkage cracks are almost inevitable. However, results of recent studies indicate that it is possible to reduce deck cracking and crack widths to a tolerable level by reducing the plastic shrinkage, heat of hydration, and the early strength and modulus of elasticity of concrete through the adoption of improved concrete mixes and curing procedures.

4.0 PRELIMINARY SURVEY ON NEWLY CONSTRUCTED BRIDGE DECKS

Seven bridge decks built recently with different concrete mixes were inspected for cracking. Some of the bridge decks inspected were not yet open to traffic. For the older decks, only the shoulders were inspected. Detailed observations are presented in Appendix C.

It is recognized that additional rounds of crack survey are needed to draw definitive conclusions on the long-term performance of these decks. A more comprehensive bridge deck survey program is proposed in Sec. 6.1. We have noticed in this survey that new cracks might develop and existing hairline cracks (shrinkage cracks) might open after a bridge is open to traffic. Therefore, future investigations should examine cracks that develop under traffic loads. This can be accomplished by performing crack mapping before and after a bridge deck is open to traffic.

4.1 List of Inspected Bridge Decks

Material specifications, construction practice, and crack survey information have been collected for the following seven new bridge decks built with different representative concrete mixes:

1. 38th and Fox Avenue Bridge. The deck was placed in April of 1998 with class DGFA/10% concrete mix. The crack survey was performed at the west half of the bridge deck, between piers 5 and 6, before it was open to traffic.

2. Founders/Meadows Bridge. The deck was placed in October of 1998 with class DFA/10 concrete mix. The crack survey was performed at the southern half of the bridge deck, before it was open to traffic.

3. Wolfensenburger Road Structure over I-25, Westbound. The deck was built in 1995 with silica fume, fly ash, and calcium nitrite added to class D concrete mix. The crack survey was performed at the median shoulder only.

4. Wolfensenburger Road Structure over Plum Creek, Westbound. The deck was built in 1995 with class DFA/10 concrete mix. The crack survey was performed at the median shoulder only.

5. I-225 Structure over Colfax Avenue, Southbound. The overlay was placed in November of 1997 using class DT/IP concrete with Type F fly ash. The crack survey was performed at the outside shoulder only.

6. I-225 Structure over Tollgate Creek, Southbound. The overlay was placed in March of 1998 using class SF concrete with Type F fly ash. The crack survey was performed at the outside shoulder only.

7. I-70 Structure over Box Elder Creek, Westbound. The overlay was placed in September of 1998 with class DT concrete mix. The crack survey was performed at the median traffic lane, before it was permanently open to traffic (the lane had carried some traffic).

4.2 Crack Survey Procedure

From the durability standpoint, the acceptable crack width is between 0.1 mm and 0.2 mm according to an NCHRP study (NCHRP Report 380). Hence, our crack survey concentrated on cracks wider than 0.2 mm. The locations of both fine cracks and cracks wider than 0.2 mm on deck surfaces were determined. The widths of cracks wider than 0.2 mm were measured. Cracks were located by wetting the subject area. After the water had evaporated from the surface, the cracks were plainly visible. Each end of a crack was marked. For each end, the longitudinal and transverse distances from two reference locations were determined. Crack widths were visually determined using a crack comparator card. It should be noted that the reported crack widths are widths measured at the surface of the concrete deck, and that no measurements were taken to determine the crack depths or subsurface crack widths.

4.3 Findings

Transverse cracking was relatively minor in the first six bridge decks listed in the previous section. In all these six decks, there was 10% fly ash in the concrete mixes. One of the decks had cement Type IP in a class DT mix. Furthermore, in these bridges, deck placement took place either in the evenings or in winter months with mild weather conditions and the air temperature between 40 and 80°F. In two of the decks, it has been shown that light doses of silica fume will not increase cracking if suitable construction practices are implemented.

The seventh deck has a class DT concrete mix with no fly ash for the overlay. Cracks in the overlay deck were wider than those in the first six decks. This could be partly attributed to the inadequate finishing operation. Inadequate finishing operations can lead to considerable number of randomly oriented cracks limited to the surface of the bridge deck.

Furthermore, results of this survey indicate that the growth of cracks, especially longitudinal cracks, could be caused by a combination of several factors, such as the traffic load, the flexibility of the girders, and a smaller deck thickness.

Readers are referred to Appendix C for more details.

5.0 RECOMMENDATIONS

Based on the literature review presented in Section 2, we can conclude that mix design and construction practices are probably the most important factors influencing deck cracking. They can be readily improved for adoption by transportation departments. Structural design factors also contribute to deck cracking. These factors should be taken into consideration whenever possible.

Concrete mix designs currently adopted by CDOT for bridge decks are shown in Appendix A. It can be seen that the typical cement contents used by CDOT are 615~660 lb./cu. yd. for class D and 700 lb./cu. yd. for class DT, which are much higher than what is recommended in the literature reviewed in this study for the control of deck cracking. Furthermore, fly ash, when it is used in Colorado bridge decks, is only 10% by weight of cement. In spite of the good performance of a number of such decks as shown in the aforementioned survey, this quantity may not be sufficient to lower the heat of hydration and early concrete strength to desirable levels, especially when silica fume is used. In Minnesota and Germany, fly ash is allowed up to 20% by weight.

Some of the deck curing procedures recommended in the previous studies have already been adopted by CDOT. Such procedures have been proven to be successful in the control of deck cracking. However, the current database is limited and further information on the long-term performance of newly constructed bridge decks needs to be gathered.

After reviewing CDOT's "Standard Specifications for Road and Bridge Constructions" and the recent updates of this document, the following recommendations are provided for CDOT to consider:

5.1 Materials Aspect

1. Use Type II cement, and avoid finely ground cement and Type III cement in warm weather conditions. (*Both Type I and Type II are used by CDOT.*)
2. Limit cement content to a maximum of 470 lb./yd^3 or lower if possible. However, cement content may have to be higher for thin overlays for a good workability and the ease of surface finishing. (*CDOT uses 615~660 lb/yd^3 for class D and 700 lb/yd^3 for class DT.*)
3. As long as the chloride diffusivity property permits, use a water-to-cement ratio not lower than 0.40; studies show that concrete with a low cement content and high w/c ratio has less cracking. A low w/c ratio can lead to less creep, more autogenous shrinkage, and more plastic shrinkage cracks. Silica fume and fly ash have a lower density than Portland cement. Hence, the replacement of cement by silica fume and fly ash will increase the volume of cementitious materials. One may need to increase the w/c accordingly to account for this increase. However, an optimal w/c ratio has yet to be determined in future studies. (*Maximum permitted by CDOT is 0.44 for Class D and 0.35 for Class SF, silica fume concrete.*)

4. Based on the experience in Germany, it is recommended to use Type F fly ash with a quantity that is 20% by weight of cement. In Colorado, one may consider using such an amount of fly ash in summer months; and in winter months, the use of fly ash can be optional depending on the air temperature. The amount of fly ash may be adjusted according to weather conditions. This, however, requires further studies. Furthermore, fly ash should be used with care in the dry weather conditions in Colorado and a good curing procedure is important for such concrete. (*CDOT uses 10% FA by weight of cement in class DGFA.*)

5. Limit silica fume to 6% by weight of cement. (*CDOT uses 7.5% SF by weight of cement.*)

6. Fast strength gain in deck concrete should be avoided. In Germany, deck concrete is not allowed to exceed 870 psi within the first 12 hours. This is achieved by using coarser cement and fly ash. In the U.S., such a limit might not be feasible because of the properties of the cements that are available. In spite of this, it is desirable to compare the early strengths and the rates of strength gain of concrete mixes made with different brands of Type II cement and fly ash that are available. If there is a noticeable variation in early strengths, then a reasonable upper limit should be established on the early strength. Furthermore, based on the results of the above study, reasonable bounds on the 7-day and 28-day strengths should be established, while allowing 56 days to arrive at the specified concrete strength. (*Currently, CDOT uses the 28-day strength only. Rate of strength gain is not controlled.*)

7. Use the largest aggregate size possible and well-graded aggregate to minimize the cement paste volume. However, the maximum aggregate size should not exceed 1/3 of the deck thickness or 3/4 of the minimum clear bar spacing.

5.2 Design Factors

The design of bridge decks is often governed by the load carrying capacities. However, one should always consider the impact of design factors on the temperature and shrinkage cracks whenever possible. Some of the following recommendations are based on the literature survey, while others are based on the input from CDOT's Staff Bridge:

1. In regions over the bridge piers, the bottom of overhangs in bridge decks should have the same quantity of longitudinal reinforcement as the top to avoid severe shrinkage cracks that may develop.

2. For decks with side-by-side girders, one may consider post-tensioning the slab in the transverse direction with unbonded tendons to reduce longitudinal skrinkage cracks in the slab and enhance the shear transfer between the girders.

3. Use AASHTO/LRFD specifications to minimize the transverse reinforcement in decks; use smaller transverse bars at closer spacing as possible.

4. Use smaller girders with wider spacing as possible.

5. Reduce longitudinal restraint on bridge decks whenever possible.

5.3 Construction Practice

1. For all concrete decks, do not cast decks when air temperature is less than 40°F (7°C) or over 80°F (27°C). Avoid large temperature variation (greater than 50°F (10°C)) on the day of concrete placement. This should be applied to all concrete decks. Cast concrete decks in early or mid-evening if the forecast temperature is 80°F or above. Decks can be placed at night as long as they can be fogged for at least five hours before the air temperature goes beyond 80°. *(For silica fume concrete overlay placement, CDOT requires that concrete deck surface temperature shall not fall below 40°F. The maximum allowable air temperature is 80°F for all concrete placements.)*

2. Concrete mix temperature must be maintained above 50°F (10°C) for the first 72 hrs. and above 40°F (4°C) for the remaining curing period. Limit the maximum concrete temperature at placement to 80°F (27°C). *(CDOT currently specifies that concrete mix temperature must be maintained above 50°F for the first 72 hrs. when the ambient temperature is below 35°F and above 40°F for the remaining curing period. Current CDOT's limit on the maximum concrete temperature at placement is 90°F.)*

3. Measure or estimate evaporation rate at the job site. For all decks, avoid concrete placement when the evaporation rate is above 0.20 $lb./ft.^2/hr.$ (1.0 $kg/m^2/hr$) for normal concrete and 0.10 $lb./ft.^2/hr.$ (0.50 $kg/m^2/hr$) for concrete with low water-to-cement ratio. The evaporation rate can be calculated using the chart in Appendix D based on the measured wind velocity, concrete temperature, air temperature, and relative humidity. *(This is required by CDOT for silica fume concrete only.)*

4. Apply fogging to all concrete decks without delay until the surface has been covered by the final cure. *(Required by CDOT for silica fume concrete only.)*

5. For concrete with silica fume and/or fly ash, adopt a 7-day continuous moist curing to reduce early age cracking. Results of NCHRP Project 18-3 (NCHRP Report 410) indicate that silica fume has little influence on cracking provided that the concrete is properly cured for at least 7 days. Apply fogging and moist curing as early as possible. *(CDOT has a minimum of 5 days curing requirement for deck concrete.)*

6. Surface finishing and texturing should be completed as soon as possible to allow the final cure of the deck. Hand finishing should not be allowed except at the edge of the pavement unless it is approved by the engineer.

7. Seal all the cracks that develop in the first year after casting. Before crack sealing proceeds, conduct a crack survey and map the cracks in a manner presented in the preliminary crack survey in Appendix C. These tasks can be conducted by the contractors.

6.0 RECOMMENDED ACTIONS FOR CDOT

6.1 Bridge Deck Surveys

To assess the severity of the deck-cracking problem with the mix designs and construction practice currently adopted by the CDOT, selected newly constructed bridge decks should be surveyed and monitored for a period of one year or more. The survey should document the mix design used, concrete properties, the curing procedure, and the environmental conditions during deck casting. Sample survey forms are provided in Appendix B. It is recommended that nine bridge decks be surveyed: 3 with class D (with fly ash), 3 with class DT concrete, and 3 with class SF concrete.

Map the cracks on top and bottom of concrete decks. Deck surveys can be conducted in a detailed manner using evaluation criteria or indices similar to those used in Minnesota and Kansas, or, alternatively, it can be conducted in a quick and simple manner, depending on the resources available. From the corrosion and durability standpoint, an acceptable crack width is between 0.1 (0.004 in.) and 0.2 mm (0.008 in.) according to an NCHRP study (NCHRP Report 380). Hence, in the simple approach, it is suggested that the severity of deck cracking be quantified in terms of the number of transverse cracks with widths of 0.1 mm or above for every 20-ft. of deck length. The surveys can be conducted at approximately the following times:

- at the end of curing but within two weeks after deck casting
- just before open to traffic but within 60 days after casting
- 15 to 30 days after open to traffic
- one year after casting

Such surveys should also be conducted in the future on bridge decks constructed with new mix designs and changed construction practice to monitor the effectiveness of these measures.

6.2 Full Implementation of Desired Construction Practice

The desired construction practice recommended in Section 5.3 should be implemented to the fullest extent possible.

6.3 Development of New Mix Designs

Further studies should be pursued to develop and evaluate new concrete mixes that are more resistant to cracking. It is recommended that the cement content in concrete mixes be limited to about 470 lb./cu. yd. or lower and only Type II cement be used for deck concrete. To avoid excessive heat of hydration and high early strength that can be introduced by silica fume and to improve the workability of concrete mix, it is recommended to use 20% Type F fly ash by weight of cement for summer months. Prior studies (ACI 234R-96, "Guide for the Use of Silica Fume in Concrete") have indicated that the mixing of silica fume with fly ash does not impair the late-stage strength of concrete and can lead to a reduction in the volume of large pores. However, fly ash should be used with a good curing procedure in dry weather conditions. Silica fume content need not exceed 6% by weight of cement.

The mix design presented in Table 6.1 is recommended for consideration and further studies. This new mix is referred to as class DLS (class D with low shrinkage).

Table 6.1 – New Mix Design- Class DLS

Required 56-day Compressive Strength (psi)	4,500
Maximum Aggregate Size	0.75~1.00 in.
Cement Type	II
Cement Content	451 lb./cu.yd.
Silica Fume	27 lb./cu. yd.
Fly Ash-Class F	90 lb./cu. yd.
Maximum Water-to-Cement Ratio (based on the total cementitious materials)	0.38-0.47
Air Content (% by Volume)	7
Range of Slump (in.)	3.0~5.0

The contents of cement, fly ash, and silica fume recommended above for one cubic yard of concrete mix result in a total volume of cementitious materials that is equivalent to 610 lb. of Portlant cement. This takes the lower densities of fly ash (75% of cement) and silica fume (70% of cement) into consideration. Similarly, the range of w/c from 0.38 to 0.47 recommended in the above table is volumetrically equivalent to the range of 0.35 to 0.44 for concrete with Portland cement only. Too low a ratio may lead to more cracking, and too high a ratio may increase chloride permeability. Hence, an optimal w/c still needs to be determined in future studies to optimize the workability of the concrete mix, and the chloride diffusivity and cracking properties of hardened concrete.

The above mix design should be evaluated in terms of its workability, shrinkage and creep properties, the modulus of elasticity at different ages, the tendency to form cracks (restrained ring tests), and the chloride permeability. A parametric study should be conducted to fine tune the mix design and establish necessary guidelines for construction practice. In particular, the following issues need to be addressed:

- The proportions of silica fume and fly ash should be fine tuned to achieve the desired crack resistance and chloride permeability.
- The influence of the quantity of fly ash and temperature conditions on the concrete set time should be examined.
- Different brands of Type II cement and fly ash should be compared with respect to their influence on the early strength and heat of hydration so that a limit on the early strength can be established if necessary.
- A desired w/c in the range of 0.38 to 0.47 needs to be established to achieve a good workability, chloride permeability property, and crack resistance.

After the basic evaluation study, the new concrete mix can be tried in actual bridge decks for long-term field evaluations. Restrained ring tests can be used for quality control in the field.

In the future, the possibility of using new cement types, such as Type IP and those with low alkali and tricalcium silicate contents and with coarser particles, should also be explored and studied.

APPENDIX A

APPENDIX A. DECK CONCRETE MIXES ADOPTED BY CDOT

Class D

Period: 1986-1998	
Required 28-day Compressive Strength (psi)	4,500
Maximum Aggregate Size	0.75~1.00 in.
Cement Type	I or II or I/II LA or III for high early strength
Cement Content (lbs./cu. yard)	615-660
Maximum Water-to-Cement Ratio	0.44
Percentage of Paste Volume	-
Air Content (% by Volume)	5~8
Retarder Content	Mix design specific
Accelerator Content	Mix design specific
Type and Quantity of Fiber Reinforcement	Mix design specific
Range of Slump (in.)	1~3

Class DGFA/10%

Period: Current	
Required 28-day Compressive Strength (psi)	4,500
Maximum Aggregate Size	0.75~1.00 in.
Cement Type	I or II or I/II LA or III for high early strength
Cement Content including Fly Ash (lbs./cu. Yard)	615-660
Maximum Water-to-Cement Ratio	0.44
Percentage of Paste Volume	-
Air Content (% by Volume)	5~8
Fly Ash Content	Up to 10% by weight of cement
Retarder Content	Mix design specific
Accelerator Content	Mix design specific
Type and Quantity of Fiber Reinforcement	Mix design specific
Range of Slump (in.)	Mix design specific plus 1.5 inch max

Class SF

Period: Current	
Required 28-day compressive strength (psi)	5,800
Maximum Aggregate Size	0.75~1.00 in.
Cement Type	I or II or I/II LA or III for high early strength
Minimum Cement Content including Silica Fume and fly ash (lbs./cu. yard)	660
Maximum Water-to-Cement Ratio	0.35
Percentage of Paste Volume	-
Air Content (% by Volume)	4~8
Silica Fume Content	7.5% by weight of cement
Retarder Content	Mix design specific
Accelerator Content	Mix design specific
Type and Quantity of Fiber Reinforcement	Mix design specific ~ 1.5 lbs. per cubic yard
Range of slump (in.)	Mix design specific plus 1.5 inch max

Class DT

Period: Current	
Required 28-day Compressive Strength (psi)	4,500
Maximum Aggregate Size	0.50~0.75 in.
Cement Type	I or II or I/II LA or III for high early strength
Cement Content including Fly Ash (lbs./cu. Yard)	700
Maximum Water-to-Cement Ratio	0.44
Percentage of Paste Volume	-
Air Content (% by Volume)	5~8
Fly Ash Content	Up to 10% by weight of cement
Retarder Content	Mix design specific
Accelerator Content	Mix design specific
Type and Quantity of Fiber Reinforcement	Mix design specific
Range of Slump (in.)	Mix design specific plus 1.5 inch max

APPENDIX B

APPENDIX B. BRIDGE DECK SURVEY FORMS

Identify the bridge structure, location, year of construction, and the season in which the deck was cast. Indicate the severity of deck cracking if such information is available.

Bridge ID:
CDOT Project No.:
Deck Type:
Location:
Deck Placement:

1. General Information

Describe the concrete Placement technique.	
Describe the ease of Placement or any difficulties encountered.	
Describe changes in the batched and delivered concrete. Explain why the changes are needed and what their effects are.	
Report concrete behavior at time of placement.	
Costs of labor and materials	
Was there a standard or special provision used to construct the deck topping?	
If a new cement material (such as Type IP) or a modified concrete mix (including Class SF) is used, what are the physical properties (such as workability) compared to Class D and Class DT?	

2. Mix Design

Class:

Design Strength:

Aggregate Type (Granite, Limestone, etc.) and Maximum Size	
Cement Type (I, II, III, Shrinkage-Compensating, etc.)	
Cement Content	
Water-to-Cement Ratio	
Percentage of Paste Volume	
Air Content (% by Volume)	
Fly Ash Type and Content	
Silica Fume Content	
Retarder Content	
Accelerator Content	
Type and Quantity of Fiber Reinforcement	
Slump (in.)	

3. Bridge Design

Span: Continuous or Simple? End Conditions	
Deck Thickness/Concrete Cover Thickness	
Placement of Top Transverse Reinforcement Bars (Alignment of top and bottom transverse bars, size and spacing of transverse bars, above or below longitudinal bars, etc.)	
Girder Type, Size, and Spacing (Steel, Concrete, Prestressed, etc.)	
For prestressed concrete girders, any tension at the top?	

4. Construction Practice

Weather Conditions during Deck Placement: • Wind velocity • Humidity • Air Temperature • Evaporation Rates	
Time of Deck Casting (e.g., late morning, early evening, etc.)	
Curing Period and Methods Used	
Finishing Process (Applied early or delayed?)	

5. Deck Concrete Compressive Strength

Age	Compressive Strength (psi)

6. Degree of Deck Cracking

Include a crack mapping if available.

Date of Inspection	Describe severity of deck cracking.

7. General Comments

APPENDIX C

APPENDIX C. RESULTS OF PRELIMINARY DECK SURVEY

List of Bridges Inspected

1. 38th and Fox Avenue Bridge. The deck was placed in April of 1998 with class DGFA/10% concrete mix. The crack survey was performed at the west half of the bridge deck, between piers 5 and 6, before it was open to traffic.

2. Founders/Meadows Bridge. The deck was placed in October of 1998 with class DFA/10 concrete mix. The crack survey was performed at the southern half of the bridge deck, before it was open to traffic.

3. Wolfensenburger Road Structure over I-25, Westbound. The deck was built in 1995 with silica fume, fly ash, and calcium nitrite added to class D concrete mix. The crack survey was performed at the median shoulder only.

4. Wolfensenburger Road Structure over Plum Creek, Westbound. The deck was built in 1995 with class DFA/10 concrete mix. The crack survey was performed at the median shoulder only.

5. I-225 Structure over Colfax Avenue, Southbound. The overlay was placed in November of 1997 using class DT/IP concrete with Type F fly ash. The crack survey was performed at the outside shoulder only.

6. I-225 Structure over Tollgate Creek, Southbound. The overlay was placed in March of 1998 using class SF concrete with Type F fly ash. The crack survey was performed at the outside shoulder only.

7. I-70 Structure over Box Elder Creek, Westbound. The overlay was placed in September of 1998 with class DT concrete mix. The crack survey was performed at the median traffic lane, before it was permanently open to traffic (the lane had carried some traffic).

1. 38TH & FOX Avenue Bridge

Bridge ID: E-16-ON
CDOT Project No.: NHD 0252-274 (10605)
Deck Type: New deck
Location: 38th & Fox Avenue, Denver
Decking Placement: April – June 1998

The concrete mix used for this deck is identified as CDOT mix design #95093, and is shown in the table below. This is a class DGFA/10% mix with 10% class C fly ash. Note that the achieved compressive strength on the trial mix in the laboratory after 28 days is 6500 psi, while the required laboratory design strength is 5438 psi.

The entire bridge deck was built in several phases at different dates with the air temperature ranging from 40 to 80 °F:

Unit A: Cured with a membrane compound followed by the placement of insulated blankets.

Pour No. 1: 4/23/98, 6:30 a.m-3:30 p.m.
Pour No. 2: 4/29/98, 7:00 p.m-2:30 a.m.

Unit B: Cured with a membrane compound followed by the placement of wet burlap.

Pour No. 1: 6/06/98, 7:00 p.m-5:00 a.m.
Pour No. 2: 6/08/98, 7:00 p.m-3:00 a.m.

It was reported that no cracks were observed in the first 10 days after pouring. The deck was previously inspected on September 8, 1998. It was observed that cracking was very minor. Unit A-Pour No. 1 had slightly more severe cracking than the other pours. The main difference is that Unit A-Pour No. 1 took place in the morning and afternoon, while the other pours took place at night. The good performance could also be attributed to a good curing procedure. The first pour might have also been affected by the differences in the amount of post-tensioning in the girders and the maturity of the concrete compared to the other pours.

The span between pier #5 and pier #6 (Unit A-Pour No. 2) was inspected again for cracking on November 17, 1998, just before the bridge was open to traffic. The bridge deck spanning pier #5 and pier #6 was poured on April 29, 1998. The pour began at 7:00 p.m. and ended at 2:30 a.m. The air temperature on that day ranged from 40 to 80°F. The inspection was performed at the west half of the bridge deck, which is 22 ft. wide including a 10-ft. shoulder and a 12-feet traffic lane over the entire 172 ft. span. At the time of inspection, the weather was cool and cloudy and the temperature ranged from 40 to 50°F. The crack mapping is summarized in Fig. 1. The locations of the individual cracks were determined by measuring the longitudinal distance from the expansion joint at pier #6 to the crack, and the transverse distance from the west edge of the deck to the crack. A set of transverse cracks with relatively even spacing was noticed along the shoulder close to pier #5. To avoid the development of such cracks in future similar conditions, the design engineer recommended the following: " When adding longitudinal steel to the top of a deck over piers, one should also add longitudinal steel to the bottom of the overhanging slab." However, these transverse cracks were relatively fine with a maximum width of 0.4 mm.

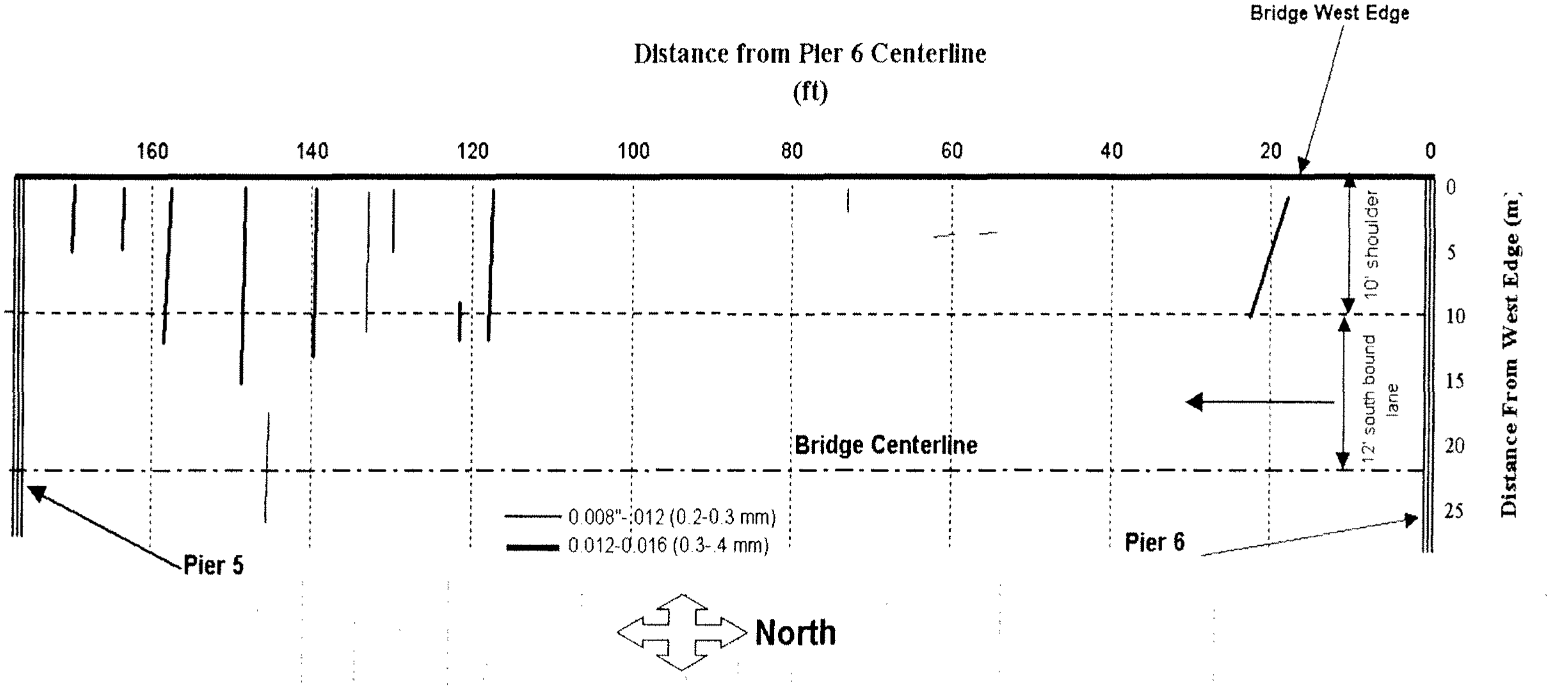
Class DGFA/10%

Aggregate Type (Granite, Limestone, etc.) and Maximum Size	RMCC Bromley Lake
Cement Type (I, II, III, Shrinkage-Compensating, etc.)	I/IILA
Cement Content	600 lb./cu. yd.
Water-to-Cement Ratio	0.38
Percentage of Paste Volume	
Air Content (% by Volume)	7.2%
Fly Ash Type and Content	Class C; 60 lb./cu. yd.
Silica Fume Content	None
Retarder Content	None
Accelerator Content	None
Type and Quantity of Fiber Reinforcement	None
Slump (in.)	3.0

Span: Continuous or simple?	continuous
Placement of Top Transverse Reinforcement Bars (Alignment of top and bottom transverse bars, size and spacing of bars, above or below longitudinal bars, etc.)	top transverse bars on top of longitudinal bars (#6@6")
Girder Type (Steel, Concrete, Prestressed, etc.)	post-tensioned single-box concrete girders

Crack No.	1		2		3		4		5		6		7		8		9		10		11		12		13		14	
	From	To	From	To	From	To	From	To	From	To	From	To	From	To	From	To	From	To	From	To	From	To	From	To	From	To	From	To
Distance form CL Pier 6 (ft)	18	22.5	54.45	56.75	59.65	62.45	73.1	73.1	117.45	117.9	121.5	121.5	129.75	129.75	133	133.15	139.5	139.75	145.33	145.6	148.25	148.7	157.6	158.4	163.5	163.6	169.6	169.9
Distance from West Edge (ft)	0.9	10.16	3.65	3.75	3.75	3.93	0.25	2.15	0.33	11.9	9	11.9	0.25	5.1	0.45	11.5	0.2	13.25	17.5	26	0.2	15.25	0.2	12.1	0.15	4.9	0	5.1
Crack Width (in)	0.016		0.007		0.007		0.005		0.013		0.013		0.009		0.007		0.013		0.007		0.016		0.013		0.01		0.016	
Crack Length (ft)	10.3		2.3		2.8		1.9		11.6		2.9		4.9		11.1		13.1		8.5		15.1		11.9		4.8		5.1	

Fig.1: Results of Crack Survey for Portion of 38th/Fox Bridge Over I-25



2. Founders/Meadows Bridge

Bridge ID: G-17-AH
CDOT Project No.: STU 0252-294
Deck Type: New deck
Location: Meadow/Founder exit to Castle Rock, over I-25
Decking Placement: October 22, 1998

The deck pour for this structure occurred on October 22, 1998. The concrete mix used for this deck is identified as CDOT mix design #96074, and is shown in the table below. This is a class DFA concrete mix that includes 10% class C fly ash. Note that the achieved compressive strength on the trial mix in the laboratory after 28 days is 6110 psi, while the required laboratory design strength is 5440 psi. The pour began at 10:00 p.m. and ended at 4:00 a.m. The measured concrete temperature ranged from 59 to 70°F. The wind speed ranged from 5 to 8 mile/hour. The relative humidity was approximately 35%. The air temperature ranged from 39 to 54°F. The bridge was cured with a membrane curing compound followed by the placement of insulated blankets. The construction operation was smooth.

The south half of the bridge deck, which is 57 ft. wide and 228 ft. long from abutment 1 to abutment 3, was inspected for cracking. The crack survey was performed on December 15, 1998 in the afternoon (52 days after deck placement). The air temperature was approximately 45°F. Cracking was very minor. We found only three fine, longitudinal cracks, 0.13-0.25 mm in width and less than 7.9 in. in length, around pier 2 (at mid-distance between abutment 1 and abutment 3).

After the bridge deck was sand blasted and sealed, it was easier to see a few additional transverse cracks near the abutments. Soon after the traffic had been on the bridge, more longitudinal cracking was evident. On March 25, 1999, the project engineers observed quite noticeable cracking occurring parallel to the girders in a location where two girders butt up against each other. The differential deflections of the flexible girders under traffic load caused this type of cracking. The motion of the bridge deck could be witnessed when a large truck was driven over. The shallow girders also flexed with the weight of one person in the center of the span. In addition, it was noticed that the girders lacked camber. This required minimizing the dead load by reducing the bridge deck thickness. A thinner deck is more vulnerable to cracking and the penetration of moisture. The project engineers recommended sealing the bridge deck on a regular basis. In the second phase of the construction, the deck thickness will be increased over the pier cap while avoiding loading up the mid span.

The above discussion suggests that the growth of cracks, especially longitudinal cracks, could result from the combination of several factors, such as the traffic load, the flexibility of the girders, and a smaller deck thickness. All these factors led to longitudinal shear cracks between adjacent girders in the inspected deck.

In order to avoid the problems mentioned above, the design engineer suggested to strengthen the joints between girders and to add a small amount of transverse unbonded post-tensioned steel in the deck.

Class DFA 10

Aggregate Type (Granite, Limestone, etc.) and Maximum Size	RMCC Bromley Lake
Cement Type (I, II, III, Shrinkage-Compensating, etc.)	I/II/V
Cement Content	607 lb./cu. yd.
Water-to-Cement Ratio	0.40
Percentage of Paste Volume	
Air Content (% by Volume)	6.8%
Fly Ash Type and Content	Class C; 67 lb./cu. yd.
Silica Fume Content	None
Retarder Content	None
Accelerator Content	None
Type and Quantity of Fiber Reinforcement	None
Slump (in.)	3.0

3. Wolfensenburger Road Structure Over I-25 (West Bound)

Bridge ID: F-17-DF
CDOT Project No.: IM 0252-272
Deck Type: New deck
Location: Wolfensenburger Road over I-25
Deck Placement: October 17, 1995

The deck pour for this structure occurred on October 17, 1995. The concrete mix used for this deck is identified as CDOT mix design #95064, and is shown in the following table. This is a special class D mix that included 10% fly ash, 21 lb. of silica fume and 24 lb. of calcium nitrite. Note that the achieved compressive strength on the trial mix in the laboratory after 28 days is 7670 psi, while the required laboratory design strength is 5625 psi. The pour began at 11:00 p.m. and ended at 4:00 a.m. The weather for that day was clear and calm with a temperature range of 35-75°F. The temperature during the pour was between 35 and 60°F.

The deck was cured with a membrane forming curing compound in accordance with Section 601.16 of CDOT's "Standard Specifications for Road and Bridge Construction" (1991). The membrane was applied as a single coat immediately after the concrete was textured. The curing compound was applied at an application rate that slightly exceeded the requirements of Section 601.16 of the specifications.

The bridge deck was inspected for cracking on March 10, 1999. The crack survey was performed across the median shoulder of the west bound lanes for an area 13 ft. wide and 49 ft. long. The results are summarized in Fig. 2. The surface of the deck was roughly finished. There were many places where small grooves were formed when the wet concrete was placed and not smoothed completely in the finishing operation. Many of these grooves appeared to be cracks but were not. Most of the cracks occurred due to inadequate finishing. They were randomly oriented, curved, very fine, and had a very shallow depth. There were some places where a crack was straight and either parallel or perpendicular to the traffic lanes. These cracks were fine and most likely deeper than the random cracks.

From this survey, it is appropriate to conclude that 1) randomly oriented surface cracking was caused by the finishing operation; 2) the few straight cracks that were short and very fine (less than 0.2 mm) were due to other factors, including shrinkage; 3) the cracking of the deck was acceptable, implying that light doses of silica fume was not detrimental; and 4) the intensity of cracking in the traffic lanes was higher that that in the shoulder.

Class D/Spec

Aggregate Type (Granite, Limestone, etc.) and Maximum Size	Coarse aggregate and sand: Cooley/Sedalia Intermediate aggregate: RMCC Bromley Lake
Cement Type (I, II, III, Shrinkage-Compensating, etc.)	I/IILA
Cement Content	600 lb./cu. yd.
Water-to-Cement Ratio	0.425
Percentage of Paste Volume	
Air Content (% by Volume)	6.7%
Fly Ash Type and Content	Class C; 60 lb./cu. Yd.
Microsilica	21 lb./cu. yd.
Retarder Content	None
Accelerator Content	None
Type and Quantity of Fiber Reinforcement	None
Slump (in.)	6.0

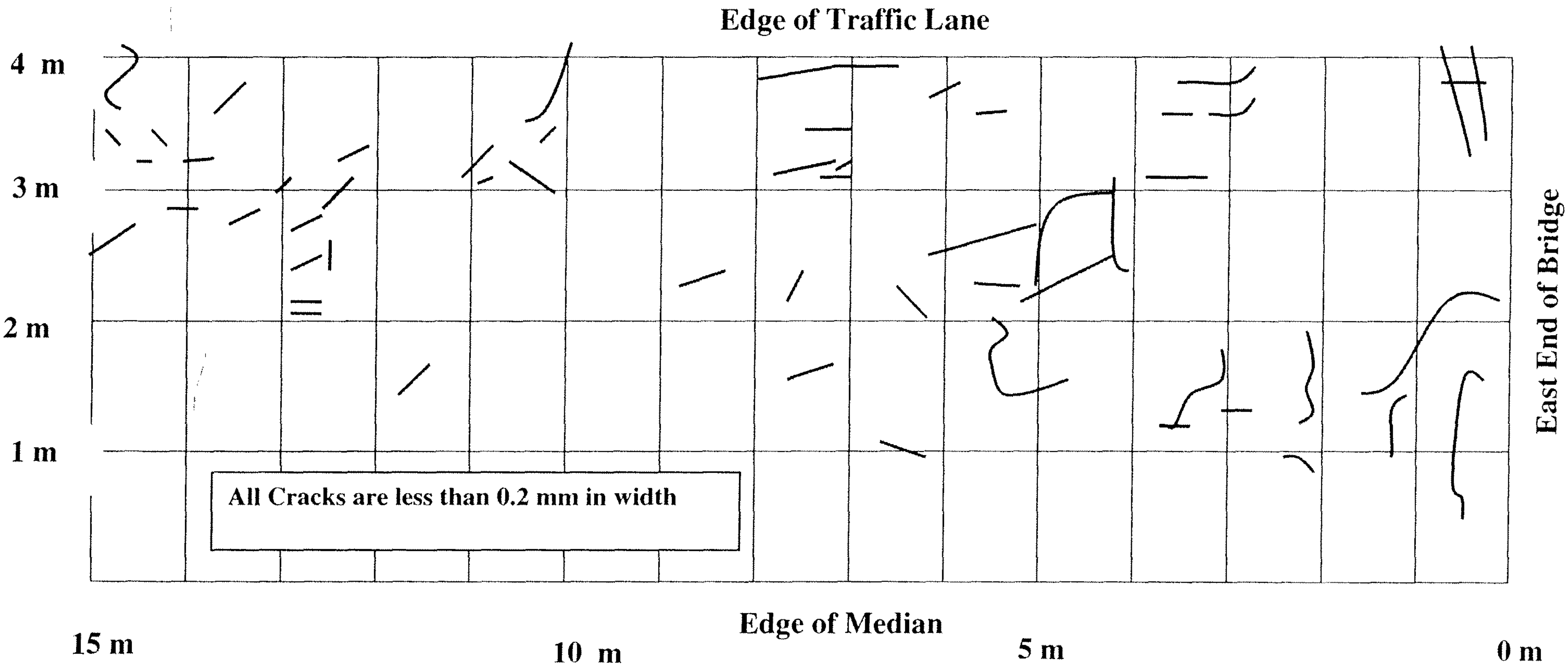


Fig. 2: Wolfensenburger Structure over I-25 (West Bound), Median Shoulder

4. Wolfensenburger Road Structure Over Plum Creek (West Bound)

Bridge ID: F-17-DE
CDOT Project No.: IM 0252-272
Deck Type: New deck
Location: Wolfensenburger Road over Plum Creek
Deck Placement: September 28, 1995

The deck pour for this structure occurred on September 28, 1995. The concrete mix used for this deck is identified as CDOT mix design #95111, and is shown in the table below. This is a class DFA with 10% class C fly ash. Note that the achieved compressive strength on the trial mix in the laboratory after 28 days is 6570 psi, while the required laboratory design strength is 5625 psi. The pour began at 8 p.m. and ended at 1:00 a.m. The weather for that day was cloudy and calm with a temperature range of 40-80°F. The temperature during the pour was between 45 and 70°F.

The deck was cured with a membrane forming curing compound in a procedure identical to that used for the deck described in the previous section.

The deck was inspected for cracking on March 10, 1999. The observations and conclusions are essentially the same as those for the deck in the previous section. The crack pattern is shown in Fig. 3.

Class DFA 10

Aggregate Type (Granite, Limestone, etc.) and Maximum Size	Coarse aggregate and sand: Cooley/Sedalia Intermediate aggregate: RMCC Bromley Lake
Cement Type (I, II, III, Shrinkage-Compensating, etc.)	I/IILA
Cement Content	600 lb./cu. yd.
Water-to-Cement Ratio	0.38
Percentage of Paste Volume	
Air Content (% by Volume)	7.0%
Fly Ash Type and Content	Class C; 60 lb./cu. yd.
Silica Fume Content	None
Retarder Content	None
Accelerator Content	None
Type and Quantity of Fiber Reinforcement	None
Slump (in.)	3.0

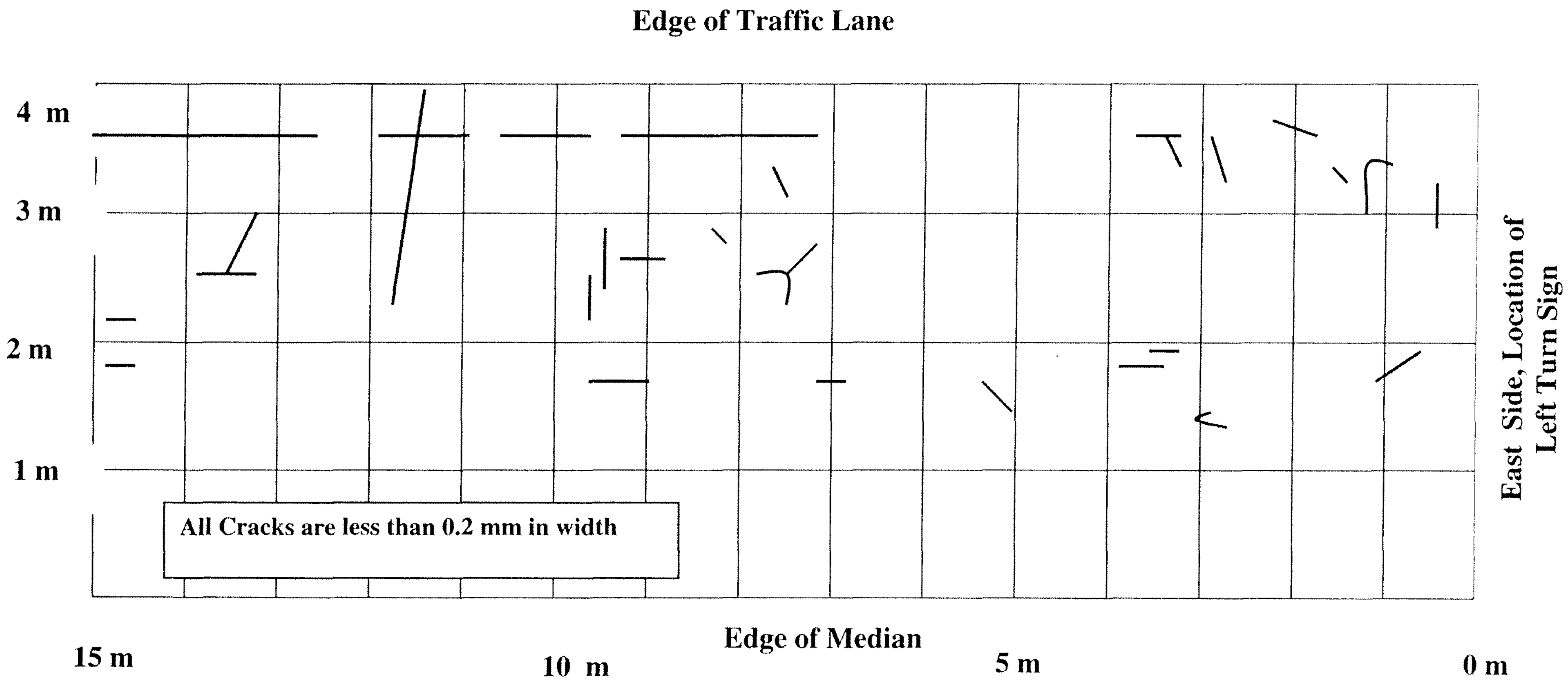


Fig. 3: Wolfensenburger Structure over Plum Creek (West Bound), Median Shoulder

5. I-225 Structure over Colfax Avenue (South Bound)

Bridge ID: F-17-JK
CDOT Project No.: HB 2254-053 (10604)
Deck Type: Overlay
Location: I-225 over Colfax Avenue
Deck Placement: November 25, 1997

Overlaying the deck on this structure occurred on November 25, 1997 and began at 8:00 a.m. The concrete mix used for this deck is identified as CDOT mix design #97145, and is shown in the table below. This is a class DT mix, with cement Type IP and 10% class F fly ash. The 28-day compressive strength obtained in the laboratory is 8120 psi. The weather for that day was partly cloudy and warm, and the temperature during the pour was between 45 and 70°F.

In 1997, a new type of blended cement, Type IP cement, appeared in the market. It is a Type I/II Portland cement interground with calcined clay. This type of cement seems to be a promising alternative to silica fume concrete.

The outside shoulder of the deck was inspected for cracking on December 23, 1998. The area checked was 49 ft. long beginning at the north end of the structure and extending from the barrier 13 ft. toward the traffic lanes. Crack locations were determined by the longitudinal distance from the north expansion joint to the crack, and the transverse distance from the outside edge of the shoulder to the crack. There is a longitudinal joint 10 ft. from the outside edge of the shoulder. The crack survey results are summarized in Fig. 4.

The shoulder deck looked very good with short and very fine cracks less than 0.15 mm in width . There were considerable branched fine cracks in an area between the shoulder joint and the traffic lane on the bridge deck over the Colfax Avenue, but very little cracking of any kind or size outside that zone. The cracks over the Colfax Avenue were short and tend to be longitudinal.

Class DT/IP

Aggregate Type (Granite, Limestone, etc.) and Maximum Size	
Cement Type (I, II, III, Shrinkage-Compensating, etc.)	IP
Cement Content	722 lb./cu. Yd.
Water-to-Cement Ratio	0.32
Percentage of Paste Volume	
Air Content (% by Volume)	5.8%
Fly Ash Type and Content	Class F; 80 lb./cu. yd.
Silica Fume Content	None
Retarder Content	None
Accelerator Content	None
Type and Quantity of Fiber Reinforcement	Fibermesh/ploy fiber; 2 lb./cu. yd.
Slump (in.)	6.5

	I-225 over Colfax Avenue									
Crack No.	1		2		3		4		5	
	From	To	From	To	From	To	From	To	From	To
Distance form North Expansion Joint (m)	1	0.4	0.9	1.8	1	1.8	3	4	3.4	4
Distance from the Edge of West Shoulder	3.6	4	2.8	4	3.8	4	3.5	4	3.4	3.9
Crack Width (mm)	0.15		0.15		0.15		0.15		0.15	
Crack Length (m)	0.7		1.5		0.8		1.1		0.8	

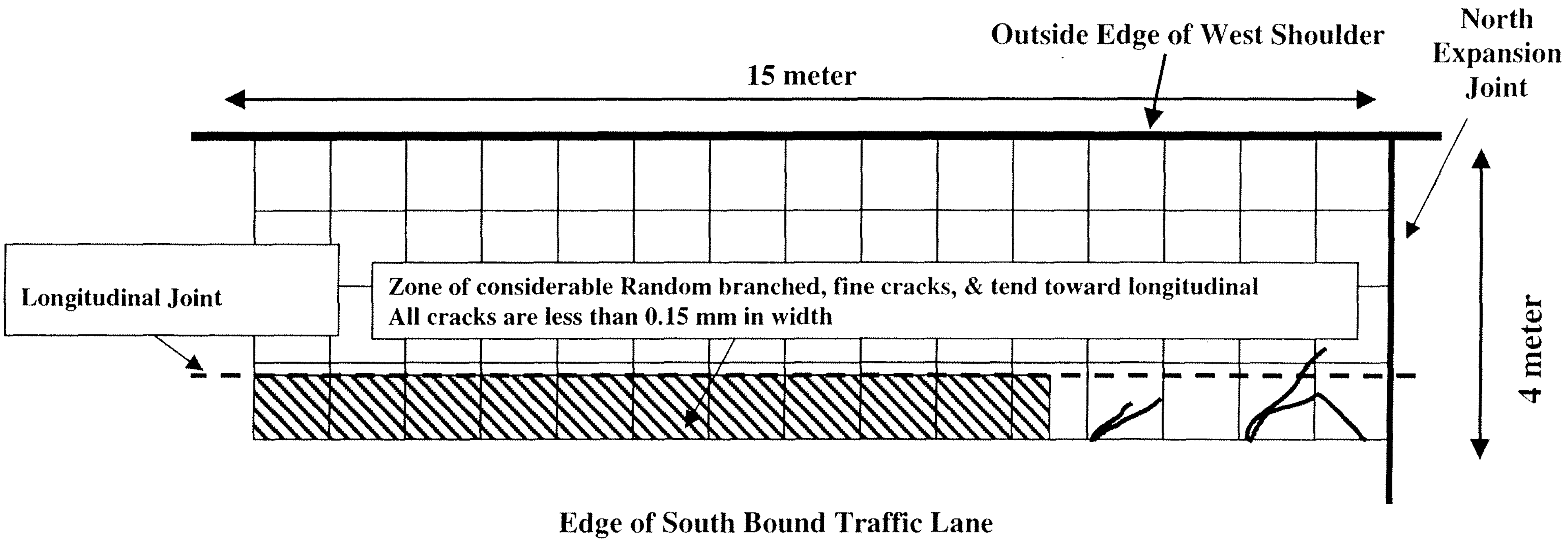


Fig. 4: I-225 Structure Over Colfax Avenue, South Bound, Outside Shoulder

6. I-225 Structure over Tollgate Creek (South Bound)

Bridge ID: F-17-GG
CDOT Project No.: HB 2254-053 (10604)
Deck Type: Overlay
Location: I-225 over Tollgate Creek
Deck Placement: March 12, 1998

Overlaying the deck on this structure occurred on March 12, 1998 and began at 9:00 a.m. The concrete mix used for this deck is identified as CDOT mix design #97034, and is shown in the table below. This is a silica fume overlay concrete mix with 10% class F fly ash. The required strength is 6000 psi at 28 days. The weather for that day was partly cloudy and warm, and the temperature during the pour was between 28 and 55°F.

The outside shoulder of the decks was inspected for cracking on December 23, 1998. The area checked was 49 ft. long beginning at the north end of the structure and extending from the barrier 13 ft. toward the traffic lanes. Crack locations were determined by the longitudinal distance from the north expansion joint to the crack, and the transverse distance from the outside edge of the shoulder to the crack. There is a longitudinal joint 10 ft. from the outside edge of the shoulder. The crack survey results are summarized in Fig. 5.

The crack condition of this deck was very similar that of the deck over the Coflax Avenue described in the previous section. However, the cracks over the Colfax Avenue were short and tended to be longitudinal, but the Tollgate bridge deck had longer transverse cracks that extended into the traffic lanes.

Class SF

Aggregate Type (Granite, Limestone, etc.) and Maximum Size	
Cement Type (I, II, III, Shrinkage-Compensating, etc.)	I/II/V
Cement Content	683 lb./cu. yd.
Water-to-Cement Ratio	0.35
Percentage of Paste Volume	
Air Content (% by Volume)	4-8%
Fly Ash Type and Content	Class F; 76 lb./cu. yd.
Micro Silica Fume	57 lb./cu. Yd.
Retarder Content	None
Accelerator Content	None
Type and Quantity of Fiber Reinforcement	fibermesh; 2 lb./cu.yd.
Slump (in.)	5-8

	I-225 over Tollgate Creek									
Crack No.	1		2		3		4		5	
	From	To	From	To	From	To	From	To	From	To
Distance form North Expansion Joint (m)	1.3	1.5	6.1	6.1	5.4	5	9.9	9.8	14.9	15.2
Distance from the Edge of West Shoulder	2.8	3.5	2.8	3.1	1.5	2.4	3	4	1.3	4
Crack Width (mm)	0.15		0.15		0.15		0.15		0.2	
Crack Length (m)	0.7		0.3		1.0		1.0		2.7	

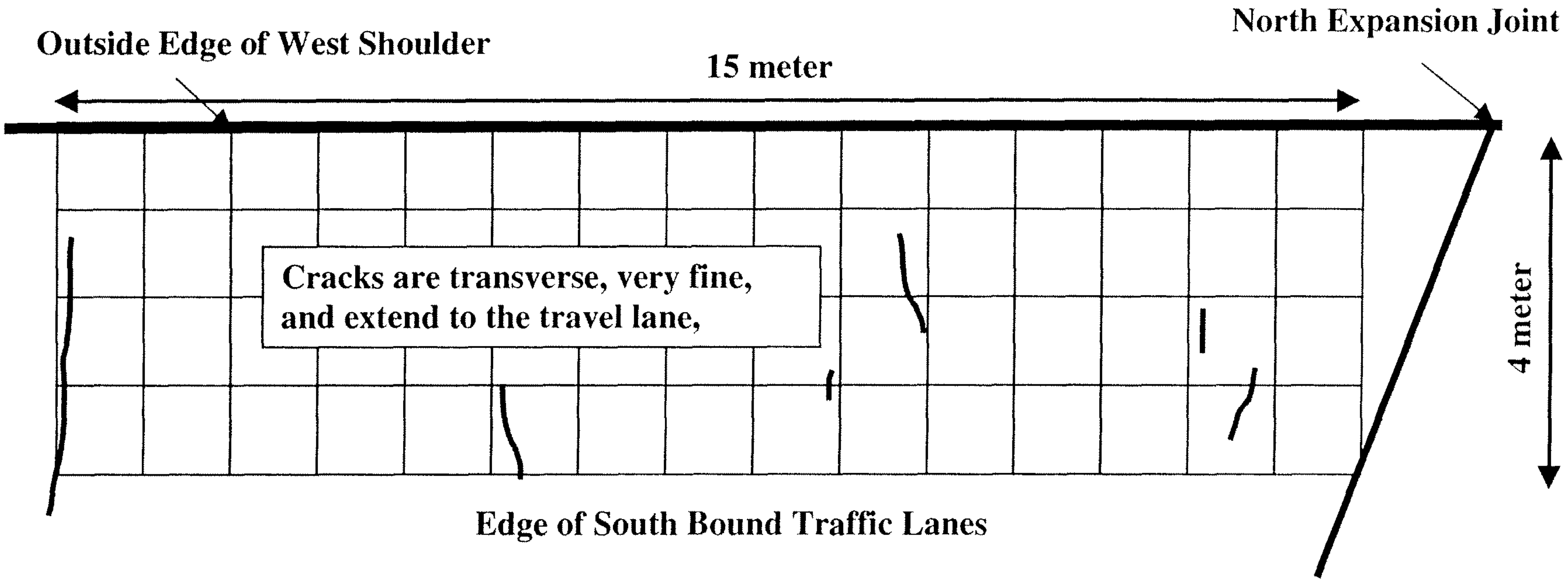


Fig. 5: I-225 Structure Over Tollgate Structure, South Bound, Outside Shoulder

7. I-70 Structure Over Box Elder Creek (West Bound)

Bridge ID: F-18-F
CDOT Project No.: IR (CX) 070-4 (143)
Deck Type: Overlay
Location: I-70 over Box Elder Creek
Deck Placement: September 4, 1998

Overlaying the bridge deck of this structure occurred on September 4, 1998. The concrete mix used for this overlay is identified as CDOT mix design #98025, and is shown in the table below. This is a class DT mix with no fly ash. The weather for that day was cloudy and warm, with an air temperature was in the range of 40-80°F. The laboratory design strength is 5625 psi, while the 28-day compressive strength obtained in the laboratory is 6380 psi. Prior to the pour, the existing bridge deck was checked for delamination by "Chain Drag." No delamination was detected. Before the pour, the deck surface was roughened, sand blasted, and blown clean. The surface was then wetted with cement slurry just ahead of the paver to aid in bonding.

The existing bridge decks of several structures along I-70 near the town of Watkins were overlaid with this DT concrete mix. They include the structures over Box Elder Creek, Quail Creek and Manila Creek. Extensive transverse cracking was noticed along the eastbound lanes overlaid during the spring of 1998, especially along the Quail Creek structure. Less transverse cracking was noticed along the westbound lanes overlaid in late 1998. Possible causes for the extensive transverse cracking (most likely due to shrinkage) could be the thinner overlay (2"), the placement of concrete during hot weather, inadequate curing, and deviation from the approved concrete mix. Other possibilities would be the dry surface of the existing pavement surface that sucked out the water from the fresh concrete. The existing pavement should be "saturated surface dry," requiring wetting the night before.

The structure over Box Elder Creek was inspected for cracking on November 20, 1998. The air temperature on that date was around 45°F. Considerable random branched fine and coarse cracks were noticed everywhere. This made it very difficult to conduct accurate and comprehensive crack mapping. In such and similar cases, we believe that the use of a camera to photograph the actual cracks may assist the documentation of the crack locations in future surveys. The crack survey was performed only on a portion of the median lane due to limited duration of the lane closure. The survey was concentrated on the coarse cracks (0.5-0.75 mm in width). The survey started at the west expansion joint of the structure and extended 32 feet east. The locations of individual cracks were determined by measuring the longitudinal distance from the edge of the expansion joint to the crack, and the transverse distance from the edge of the median concrete curb to the crack. Please refer to Fig. 6 for the orientation and reference points and for a summary of the crack survey results.

As before, the considerable number of randomly oriented and branched fine cracks developed are most likely due to the inadequate finishing operation (e.g., screeding very fast). The coarse cracks can be described as longitudinal, short, and relatively wide (0.5 to 0.75 mm). The cracks seemed to be distributed non-evenly along the entire bridge deck. Groups of cracks appeared 25 to 35 feet east of the expansion joint reflecting local problems in that area. Conditions in this area might be different from those in the other areas in terms of the concrete mix, the construction practice (shortage in the applications of the curing compound in this area), and the conditions of the existing bridge deck before the concrete pour.

We recommend extracting cores from the Quail and Box Elder structures to evaluate the observed cracking pattern. We also suggest lab examination of the shrinkage potential of DT mix used in this project.

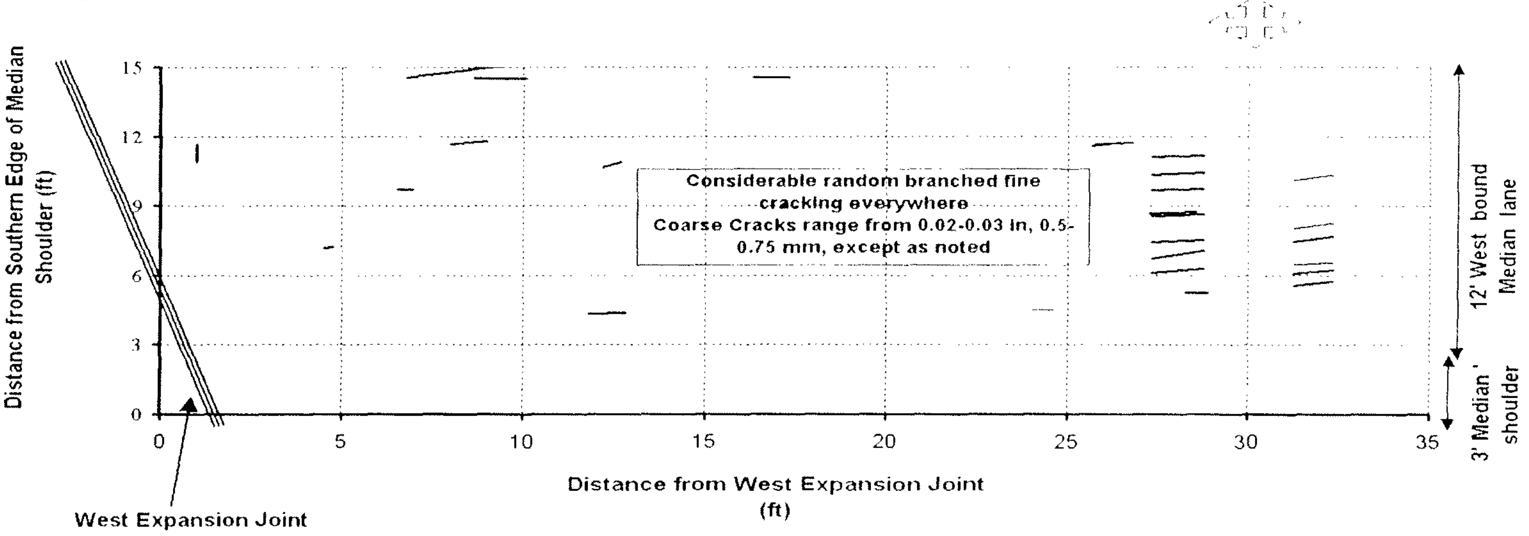
Class DT

Aggregate Type (Granite, Limestone, etc.) and Maximum Size	
Cement Type (I, II, III, Shrinkage-Compensating, etc.)	I/II/V
Cement Content	705 lb./cu. Yd.
Water-to-Cement Ratio	0.38
Percentage of Paste Volume	
Air Content (% by Volume)	5.0%
Fly Ash Type and Content	None
Silica Fume Content	None
Retarder Content	None
Accelerator Content	None
Type and Quantity of Fiber Reinforcement	None
Slump (in.)	2.5

Crack No.	1		2		3		4		5		6		7		8		9		10		11		12		13		14	
	From	To	From	To	From	To	From	To	From	To	From	To	From	To	From	To	From	To	From	To	From	To	From	To	From	To	From	To
Distance form West Expansion Joint (ft)	1	1	4.5	4.75	6.55	7	6.8	12	8	9	11.8	12.8	8.65	10	12.2	13	24	24.7	25.7	26	27.3	29	28.3	29	16.3	17	27.3	29
Distance f. Southern Edge of Median Shoulder (ft)	10.9	12	7.18	7.25	9.7	9.7	14.6	16	11.66	11.8	4.33	4.4	14.5	15	10.7	11	4.5	4.5	11.6	12	8.67	9	5.26	5.3	14.6	15	6.1	6.3
Crack Width (in)	0.03		0.03		0.025		0.025		0.02		0.03		0.03		0.03		0.013		0.03		0.025		0.025		0.03		0.02	
Crack Length (ft)	0.8		0.3		0.5		4.8		1.0		1.0		1.5		0.6		0.7		0.8		1.3		0.6		1.0		1.4	

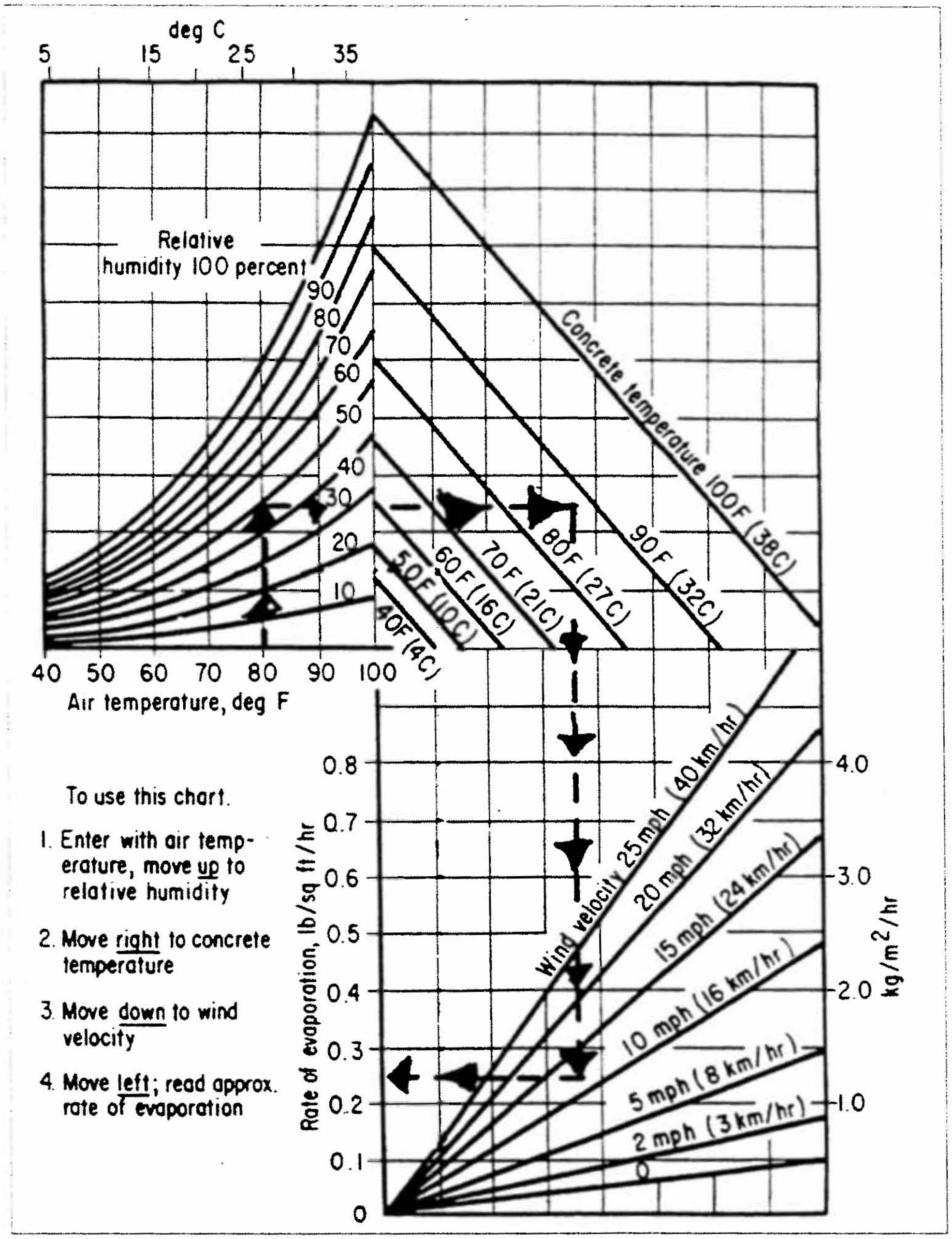
Crack No.	15		16		17		18		19		20		21		22		23		24		25		26		27		28	
	From	To	From	To	From	To	From	To	From	To	From	To	From	To	From	To	From	To	From	To	From	To	From	To	From	To	From	To
Distance form West Expansion Joint (ft)	27.33	29	27.3	28.8	27.3	28.8	27.3	29	27.33	28.8	27.3	28.8	25.8	27	31.3	32	31.3	32.3	31.3	32	31.3	32	31.3	32	31.3	32	31.3	32
Distance f. Southern Edge of Median Shoulder (ft)	6.75	7.1	7.45	7.55	8.55	8.65	9.65	9.8	10.33	10.5	11.1	11.2	11.7	12	5.55	5.8	6.08	6.25	6.45	6.6	7.45	8	8	8.3	9.55	9.8	10.1	10
Crack Width (in)	0.025		0.02		0.02		0.025		0.025		0.02		0.03		0.025		0.025		0.02		0.025		0.025		0.016		0.02	
Crack Length (ft)	1.5		1.4		1.4		1.4		1.4		1.4		1.1		1.1		1.1		1.1		1.1		1.1		1.1		1.1	

Fig. 6: Results of Crack Survey for Port of I-70 Structure Over Elder Box Creek



APPENDIX D

APPENDIX D. ACI EVAPORATION CHART



To use this chart.

1. Enter with air temperature, move up to relative humidity
2. Move right to concrete temperature
3. Move down to wind velocity
4. Move left; read approx. rate of evaporation

Chart for determining the rate of evaporation of surface moisture based on the measured concrete and air temperatures, relative humidity, and wind velocity (ACI 305R-91, originally developed by Lerch 1957)

APPENDIX E. REPORT ON SHRINKAGE TESTS

Shrinkage Study

Five mix designs were tested for their behavior in shrinkage in this study (See Table 1). Three designs were taken from CDOT concrete bridge deck specifications. These are labeled in this study as 1971 (mix specified from 1971 to 1985), 1986, and 1986-Fly Ash (mix designs specified from 1986 to present). Two experimental designs were also tested to examine the influence of replacing cement with fly ash and reducing the quantity of cement in the mix. These are labeled Trial and Trial-Fly Ash.

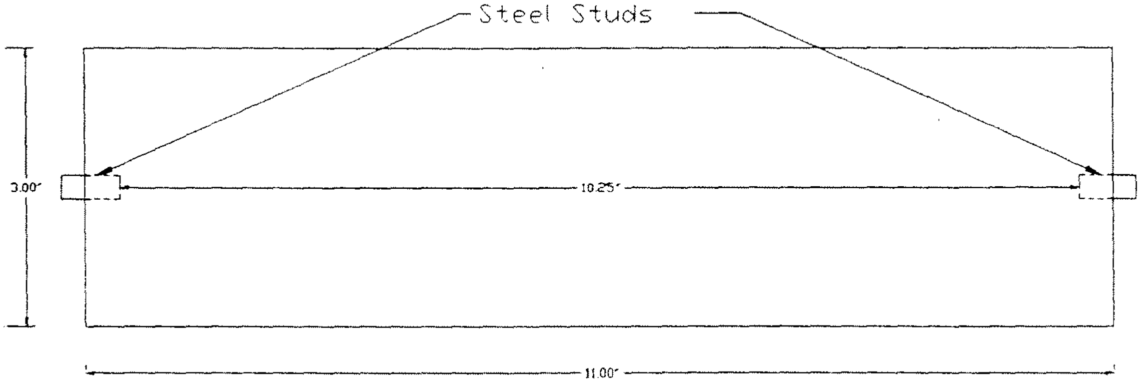
I. Preparation of Test Specimens

A. Mixing

All concrete was mixed according to the procedures outlined in *ASTM C192-90a*. Air entrainment (Daravair by Grace Concrete Products) was added to all mixes and water reducer (WRDA-82 by Grace) was added to the 1986-I, 1986-II, 1986-Fly Ash, Trial, and Trial-Fly Ash mixes. Prior to batching the test samples, a small test batch was prepared to determine the necessary quantity of air entrainment (1 to 3 fl oz. per 100 lbs of cement) needed to achieve the specified air content for each mix design. Water reducer was added at 3 fl. oz per 100 lbs of cement. Slump and air content were measured prior to casting of test specimens to verify mix characteristics.

B. Casting

For each mix design, the following specimens were cast: nine 6" x 12" cylinders were cast for strength and stiffness measurements (three cylinders each for 7, 28, and 90 day tests); nine 3" x 3" x 11" prisms were cast to measure flexural strength (three prisms each for 7, 28, and 90 day tests) ; and six to eight 3" x 3" x 11" prisms were cast as shrinkage specimens. Rounded steel studs were imbedded into the shrinkage specimens at the ends to provide a constant point at which to measure length. The distance between the near ends of the studs was taken as the gage length for shrinkage.



C. Curing

All specimens were allowed to set for 24 hours after casting. Strength specimens were then placed in a fog room. Shrinkage specimens were placed in lime saturated water. Half of the shrinkage specimens from each mix design remained in the lime saturated water for 4 days and were then removed to a room maintained at 68°F and 50% humidity. The remaining shrinkage specimens stayed in lime saturated water for 28 days before placement in the same environmentally controlled room according to *ASTM C 490-89*. The purpose of using two wet curing times was to examine the effect of different curing conditions upon the shrinkage of each mix design.

II. Shrinkage Specimens:

A. Shrinkage Measurement

A dial micrometer mounted on a length comparator was used to measure the length. The shrinkage of the specimens was measured by comparison with a stainless steel reference bar maintained at room temperature. These details are in accordance with *ASTM C 490-89*. Measurements were recorded for each of the first four days after casting. Thereafter, measurements were recorded at 7, 14, 28, 35, 42, 56, 84, and 140 days after casting. Little shrinkage was observed when the specimens were submerged in lime-saturated water. So, shrinkage plots show the shrinkage of the batches after permanent removal from lime saturated water. Hence, a 140 day measurement for specimens removed at 4 days from lime saturated water will appear as a 136 day reading on the plots. The reference point is the date on which the specimen was removed from the lime saturated water.

B. Measurement of Weight Loss

The weight loss of the shrinkage specimens was also measured. Specimen weights were recorded at the same intervals as specimen lengths. Specimens were dripped dried prior to weighing when in lime saturated water. The weight change was measured relative to the weight of the specimen 24 hours after casting. The specimens increased in weight when placed in water and gradually lost weight after removal to the environmentally controlled room due to evaporation. The results of the average weight change of each mix can be found in Figures 10 and 11.

III. Measurements of Mechanical Properties:

The flexural strength of each mix was found by the third-point bending test according to *ASTM C78-84* using 3" x 3" x 11" prisms. The specimens were supported one inch from the ends and then loaded at the third points until failure. The compressive strength and stiffness were measured according to *ASTM C469-87a*. Sulfur caps were placed on the cylinders prior to testing. Strains were obtained by the use of two LVDT's (linear variable differential transducers) mounted on opposite sides of the 6" x 12" cylinders. A data acquisition system recorded the loads (from a pressure transducer) and displacements simultaneously. The specimens were loaded just beyond the linear range. The LVDT's were removed and the specimen loaded to failure. The elastic modulus is taken from the measurements at 45% of the specimen's ultimate strength.

Conclusions:

The dominant effect upon the mixes in this study was curing conditions. On the average, specimens submerged for 28 days in lime saturated water shrank 15% less than those removed after 4 days (See Figures 1 - 5). The mix design exhibiting the greatest shrinkage under any curing conditions was the Trial - Fly Ash. This mix shrank 15% more than the average of the other mixes when immersed in lime-saturated water for 4 days, and 30% more than the average of the other mixes when immersed for 28 days. The design exhibiting the least total shrinkage was the 1986 - Fly Ash. The 1986 - Fly Ash shrank 25% less than the average of the other mixes under 4 day submersion in lime saturated water, and 30% less than the average of the other mixes under 28 day submersion (See Figures 6 and 7). The effort to measure the effect of fly ash on the shrinkage of the designs was inconclusive (See Figures 8 and 9). The effect of differences in the cement content between the studied mixes was minimal. Disregarding the Trial -Fly Ash mix, the total shrinkage of the mix designs fell within 10 to 15% of each other in both 4 and 28 day curing in lime saturated water.

Six plots (See Figures 12 - 17) show how shrinkage effects compare to the tensile strength of the concrete. Dividing the rupture strength of each mix design by its tested elastic modulus provides a theoretical failure strain of a bar of concrete restrained at both ends. Theoretical failure strains were computable at 7, 28, and 90 days for each mix. Both durations of submersion exceeded the theoretical failure strain envelope for all mixes.

Table 1 - Mix Information

Mix	w/c		Air Content (%)		Slump (in)		Fly Ash Replacement (lbs/yd^3)	Type-I Portland Cement (lbs/yd^3)	Water (lbs/yd^3)	%Agg. by Vol	
	Actual	Spec. Max.	Actual	Specified	Actual	Specified				Coarse	Fine
1971	0.48	0.51	4.5	4 - 7	3.50	2 - 4	0	611	293	43	28
1986 - I	0.42	0.44	4.0	5 - 8	2.50	2 - 3	0	660	277	32	39
1986 - II	0.42	0.44	7.0	5 - 8	2.75	2 - 3	0	660	277	32	39
1986 - FA	0.41	0.44	6.0	5 - 8	2.50	2 - 3	132	528	271	32	39
TRIAL	0.42	0.44	4.0	5 - 8	2.50	2 - 3	0	565	240	33	41
TRIAL - FA	0.41	0.44	4.5	5 - 8	2.50	2 - 3	87	493	238	34	41

Table 2 - Compressive Strength

Mix	28 Day Design Strength (ksi)	7 Day Strength (ksi)		28 Day Strength (ksi)		90 Day Strength (ksi)	
		Mean	C.O.V.	Mean	C.O.V.	Mean	C.O.V.
1971	3.0	3.55	14%	4.60	7%	5.00	5%
1986 - I	4.5	5.25	7%	4.80	18%	5.60	4%
1986 - II	4.5	4.84	2%	5.62	4%	6.60	4%
1986 - FA	4.5	3.40	8%	4.40	2%	4.40	5%
TRIAL	4.5	4.85	2%	5.46	2%	6.20	8%
TRIAL - FA	4.5	3.90	7%	4.82	4%	5.19	4%

Table 3 - Elastic Modulus

Mix	7 Day Elastic Modulus (ksi)			28 Day Elastic Modulus (ksi)			90 Day Elastic Modulus (ksi)		
	Mean	C.O.V.	ACI	Mean	C.O.V.	ACI	Mean	C.O.V.	ACI
1971	2910	8%	3396	3100	4%	3866	3512	2%	4031
1986 - I	3280	7%	4130	3820	5%	3949	3950	6%	4265
1986 - II	3090	8%	3965	3200	13%	4274	4400	7%	4631
1986 - FA	2155	31%	3324	2870	1%	3781	3347	2%	3781
TRIAL	3100	14%	3965	3557	2%	4212	4203	8%	4489
TRIAL - FA	2960	3%	3560	3577	3%	3957	4041	10%	4105

Table 4 - Modulus of Rupture

Mix	7 Day Strength (psi)			28 Day Strength (psi)			90 Day Strength (psi)		
	Mean	C.O.V.	K*	Mean	C.O.V.	K*	Mean	C.O.V.	K*
1971	619	10%	10.4	670	8%	9.9	750	4%	10.6
1986 - I	782	10%	10.8	776	10%	11.2	868	4%	11.6
1986 - II	587	2%	8.8	669	2%	8.9	702	4%	8.7
1986 - FA	520	8%	8.9	548	9%	8.3	690	6%	10.4
TRIAL	664	9%	9.5	729	4%	9.9	856	2%	10.9
TRIAL - FA	548	1%	8.8	649	11%	9.3	802	7%	11.1

* $K = (\text{Modulus of Rupture})/(f'c)^{1/2}$

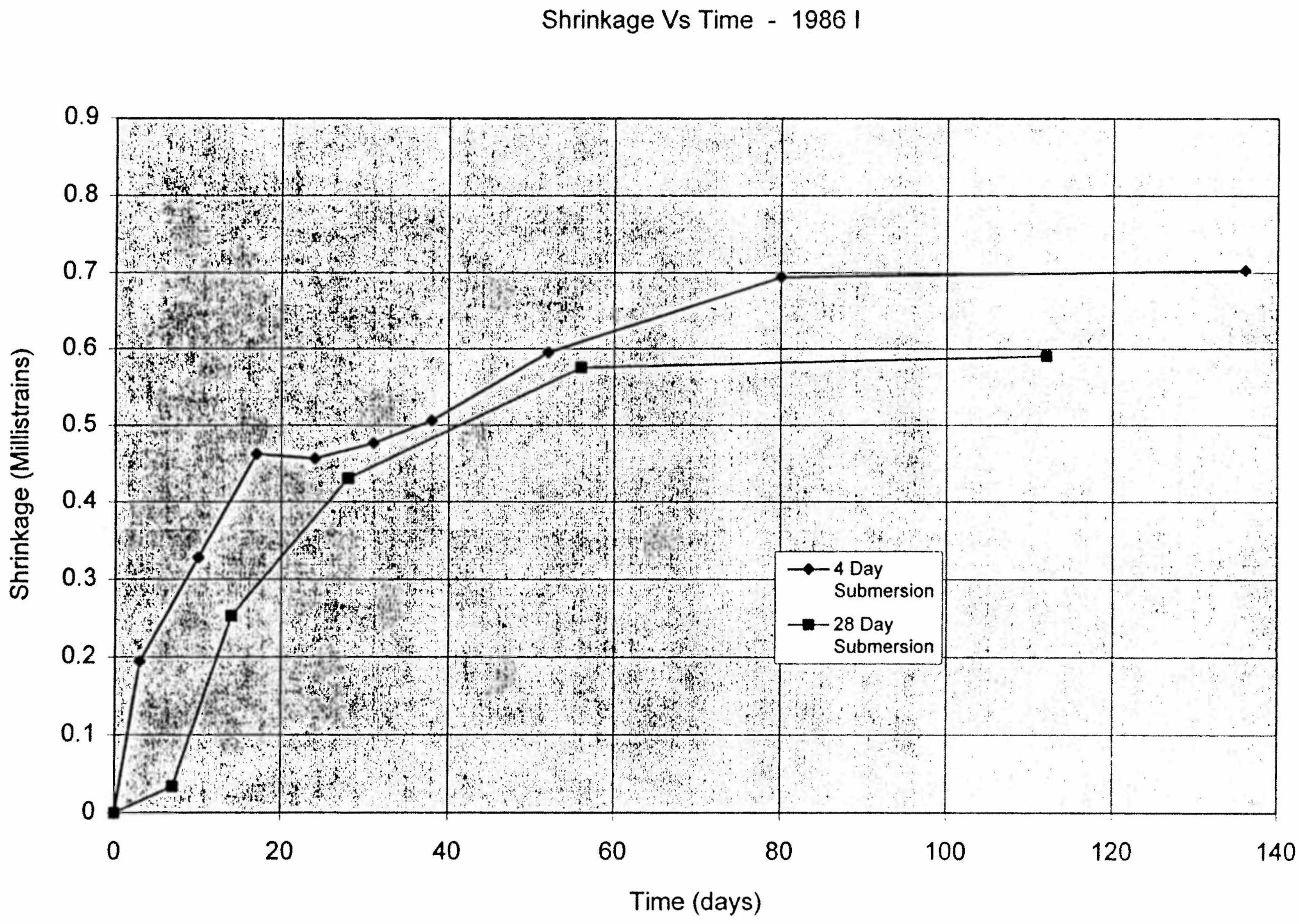

Shrinkage Vs Time - 1986 I
Shrinkage (Millistrains)
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
0
20
40
60
80
100
120
140
Time (days)
4 Day Submersion
28 Day Submersion

Figure 1

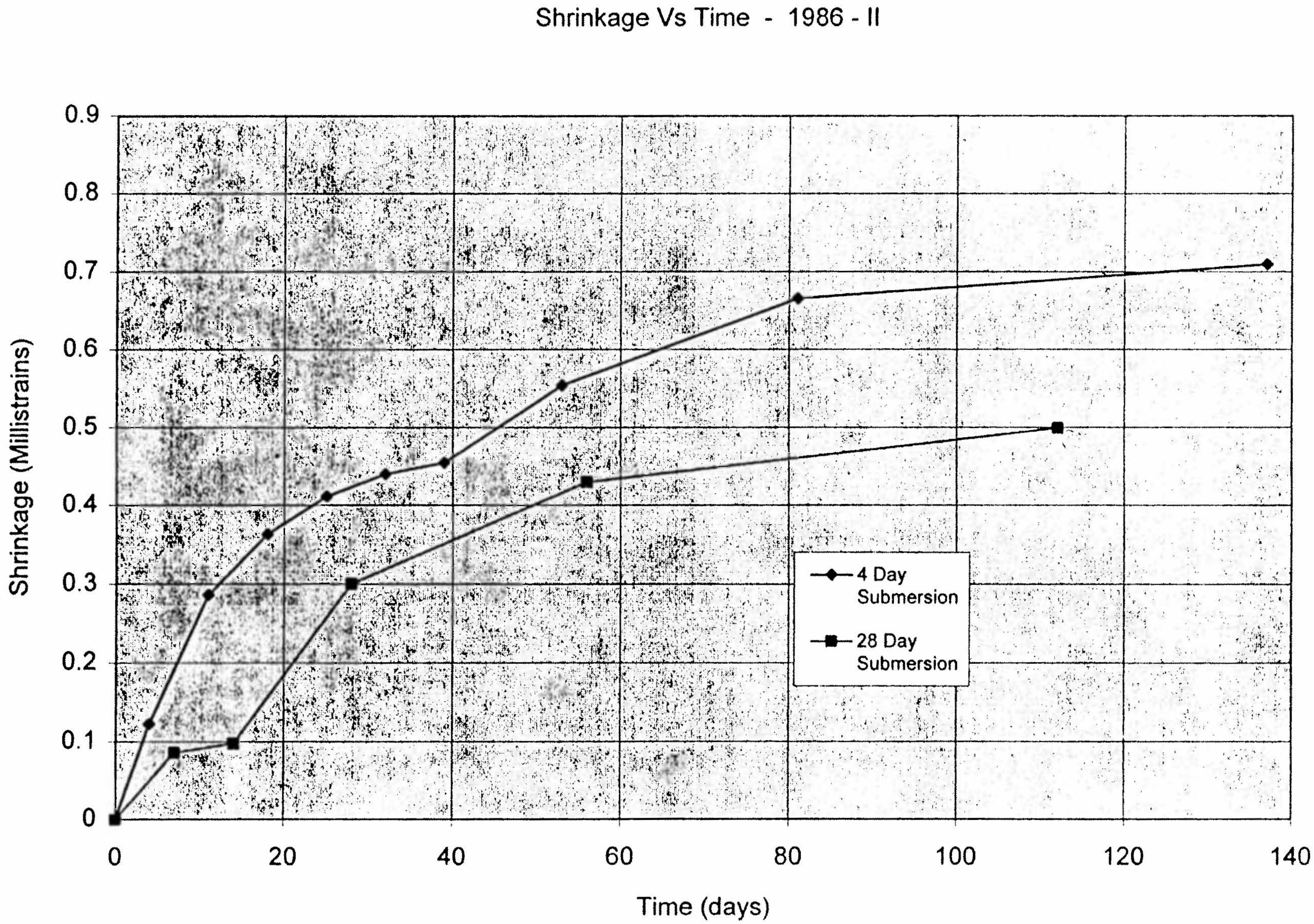

Shrinkage Vs Time - 1986 - II
Shrinkage (Millistrains)
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
0
20
40
60
80
100
120
140
Time (days)
4 Day Submersion
28 Day Submersion

Figure 1a

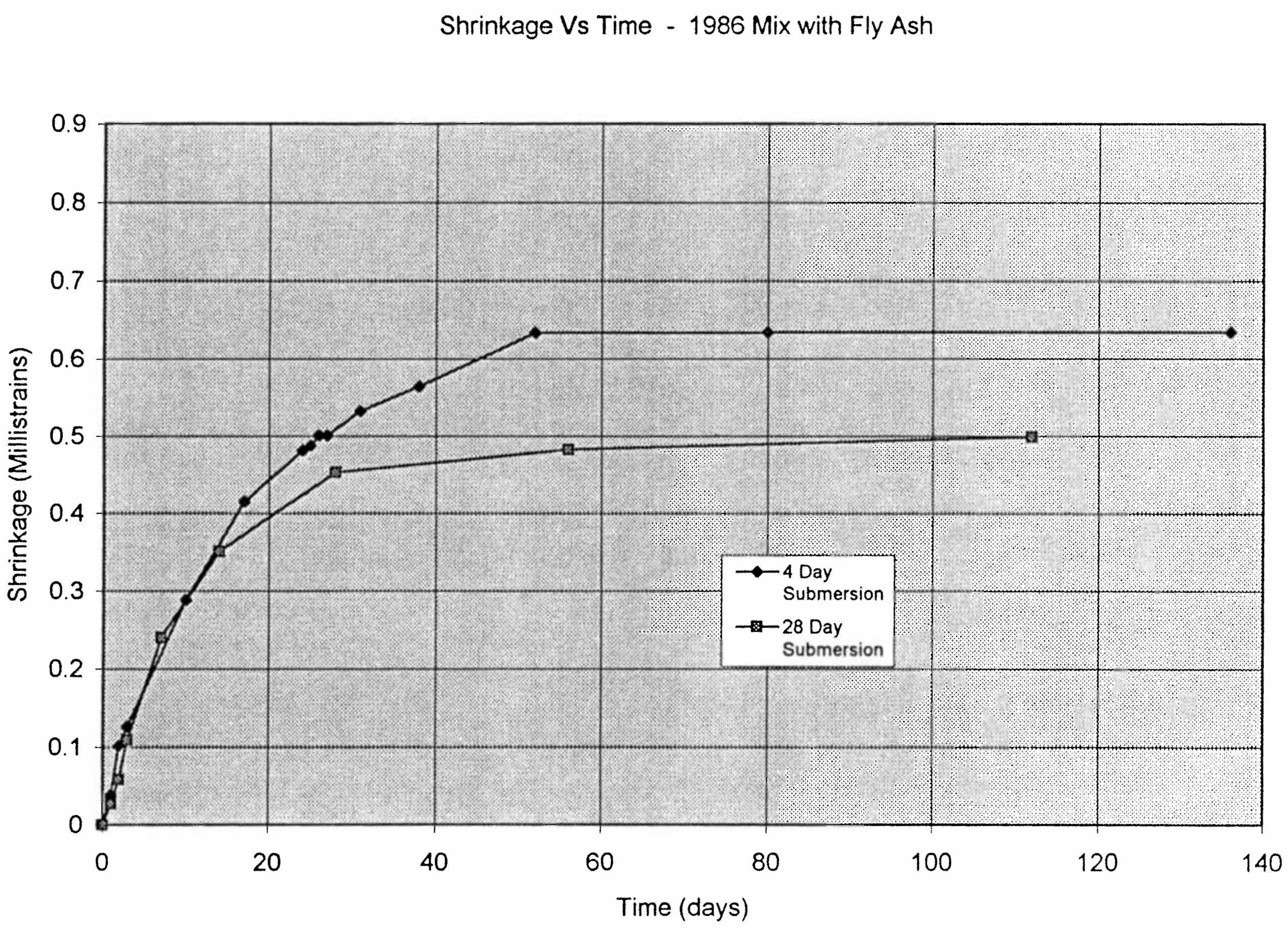

Shrinkage Vs Time - 1986 Mix with Fly Ash
Shrinkage (Millistrains)
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
0
20
40
60
80
100
120
140
Time (days)
4 Day Submersion
28 Day Submersion

Figure 2

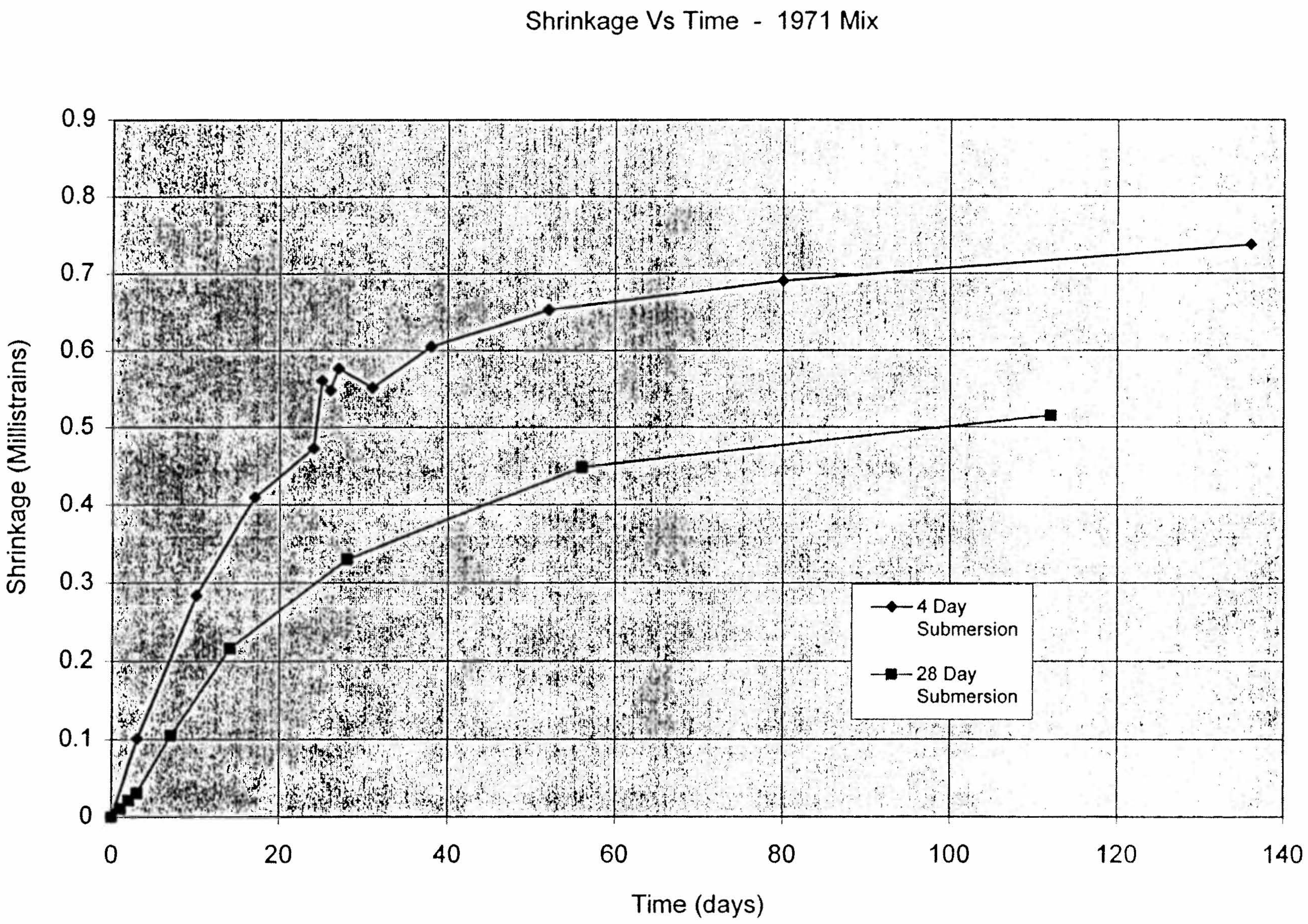

Shrinkage Vs Time - 1971 Mix
Shrinkage (Millistrains)
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
0
20
40
60
80
100
120
140
Time (days)
4 Day Submersion
28 Day Submersion

Figure 3

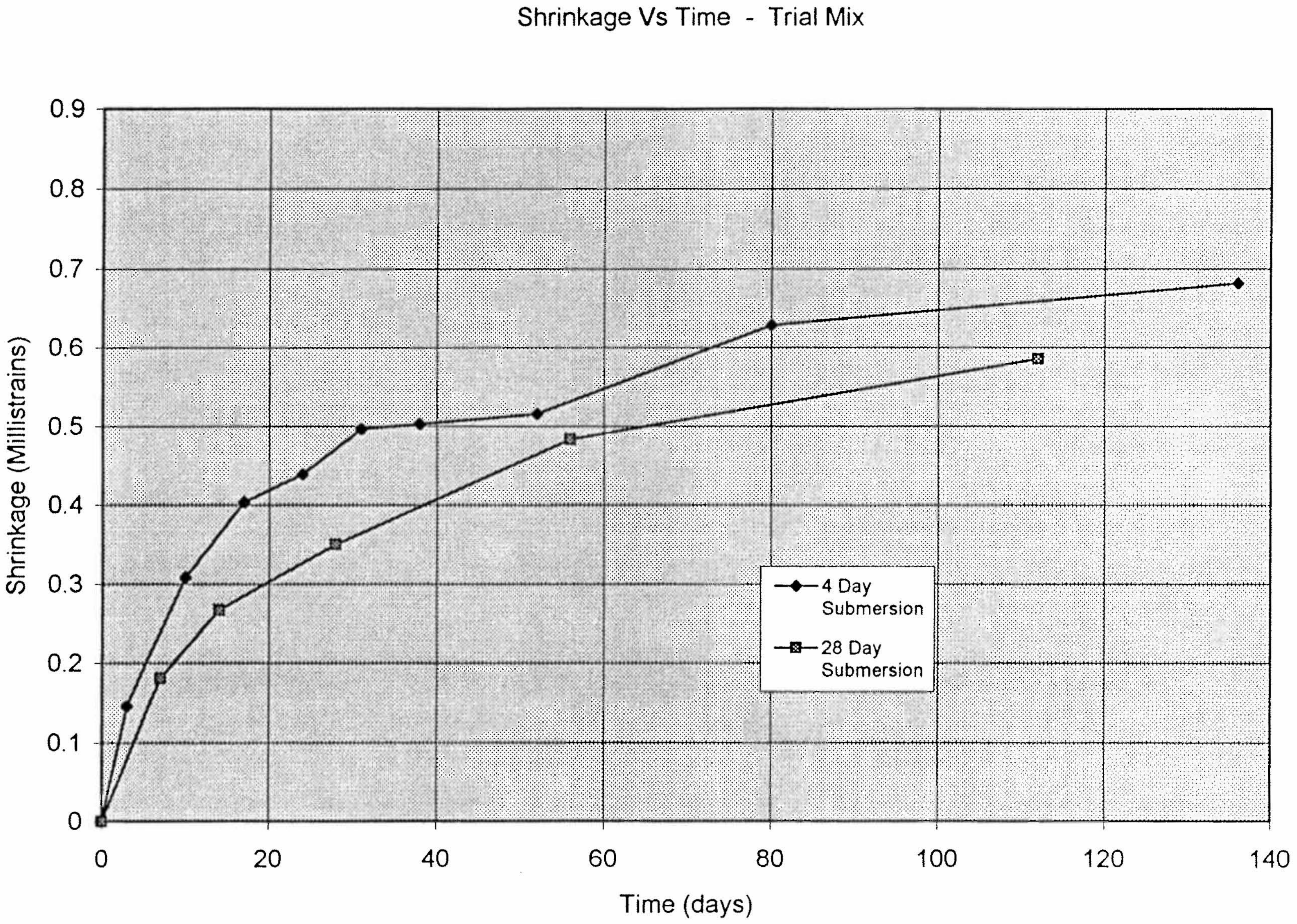

Shrinkage Vs Time - Trial Mix
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
Shrinkage (Millistrains)
0
20
40
60
80
100
120
140
Time (days)
4 Day Submersion
28 Day Submersion

Figure 4

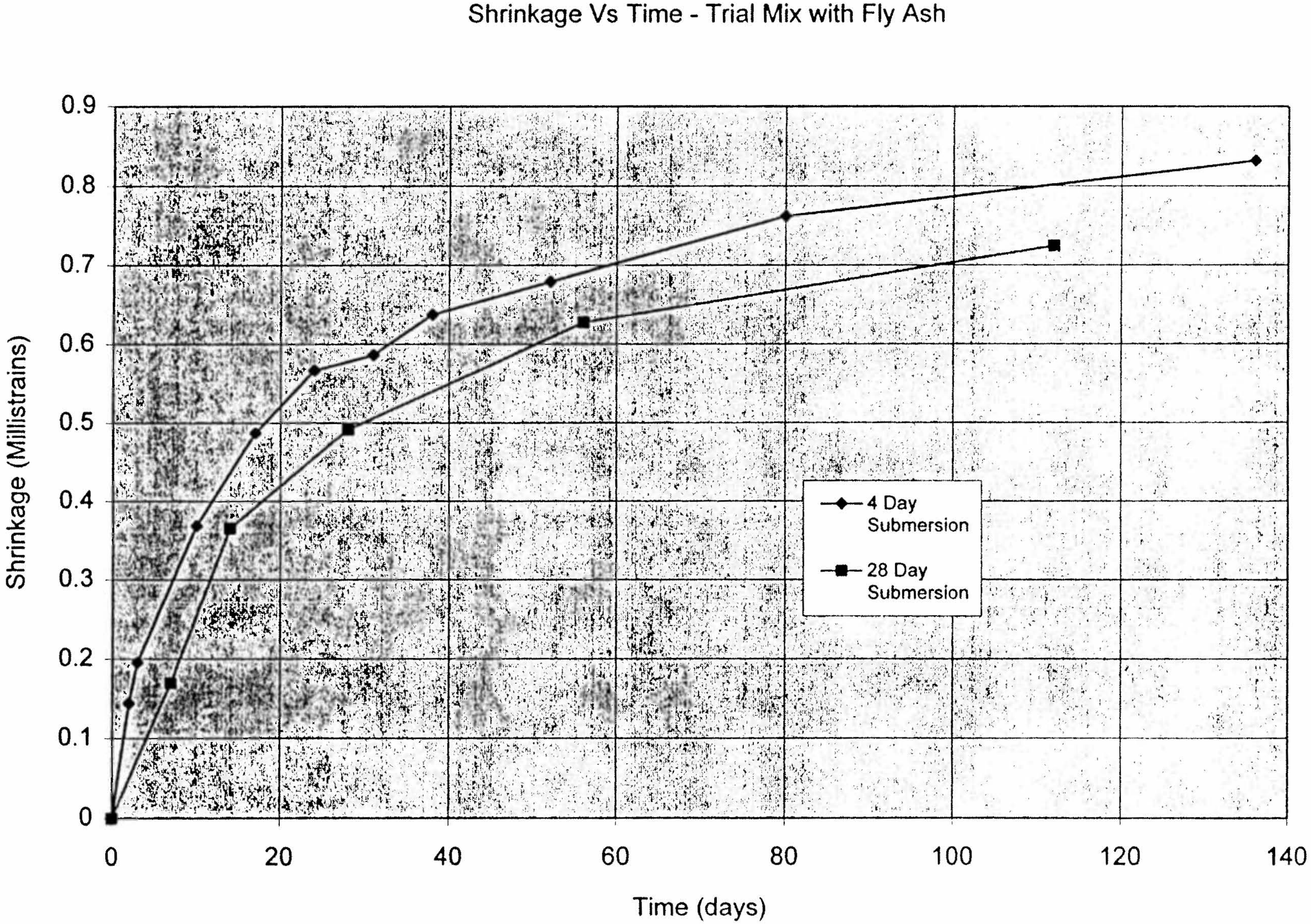

Shrinkage Vs Time - Trial Mix with Fly Ash
Shrinkage (Millistrains)
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
0
20
40
60
80
100
120
140
Time (days)
4 Day Submersion
28 Day Submersion

Figure 5

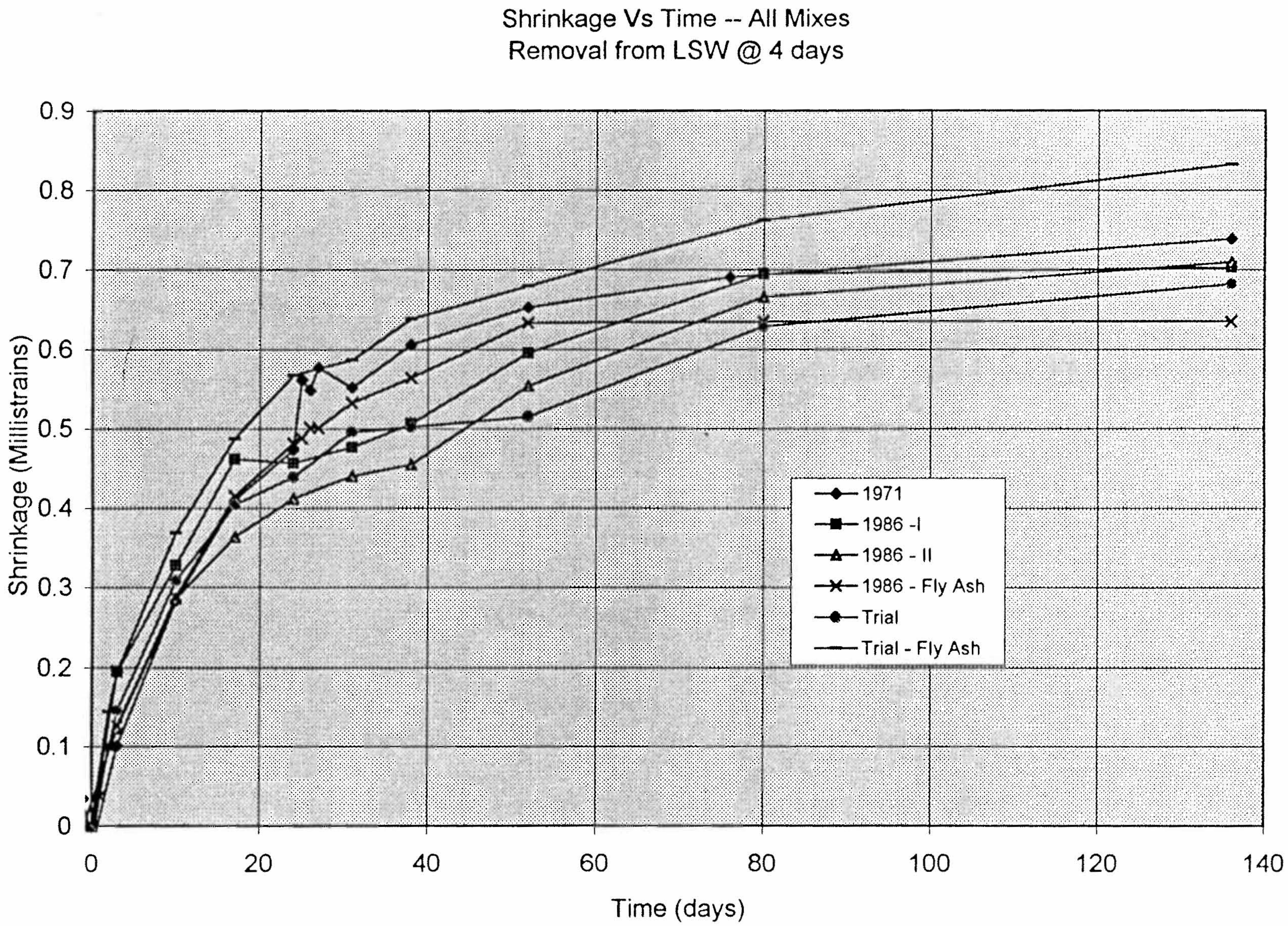

Shrinkage Vs Time -- All Mixes
Removal from LSW @ 4 days
Shrinkage (Millistrains)
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
0
20
40
60
80
100
120
140
Time (days)
1971
1986 -I
1986 - II
1986 - Fly Ash
Trial
Trial - Fly Ash

Figure 6

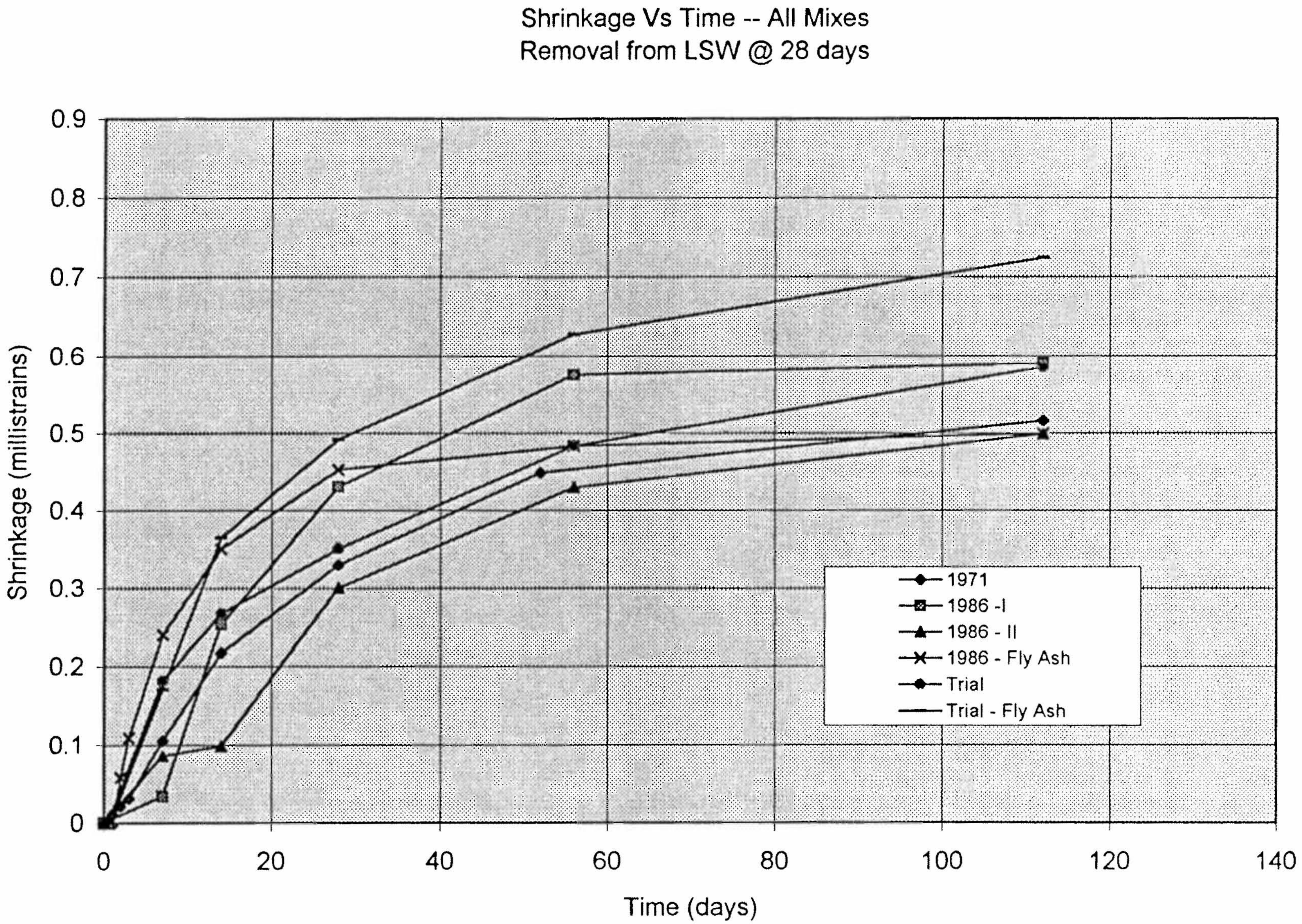

Shrinkage Vs Time -- All Mixes
Removal from LSW @ 28 days
Shrinkage (millistrains)
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
0
20
40
60
80
100
120
140
Time (days)
1971
1986 -I
1986 - II
1986 - Fly Ash
Trial
Trial - Fly Ash

Figure 7

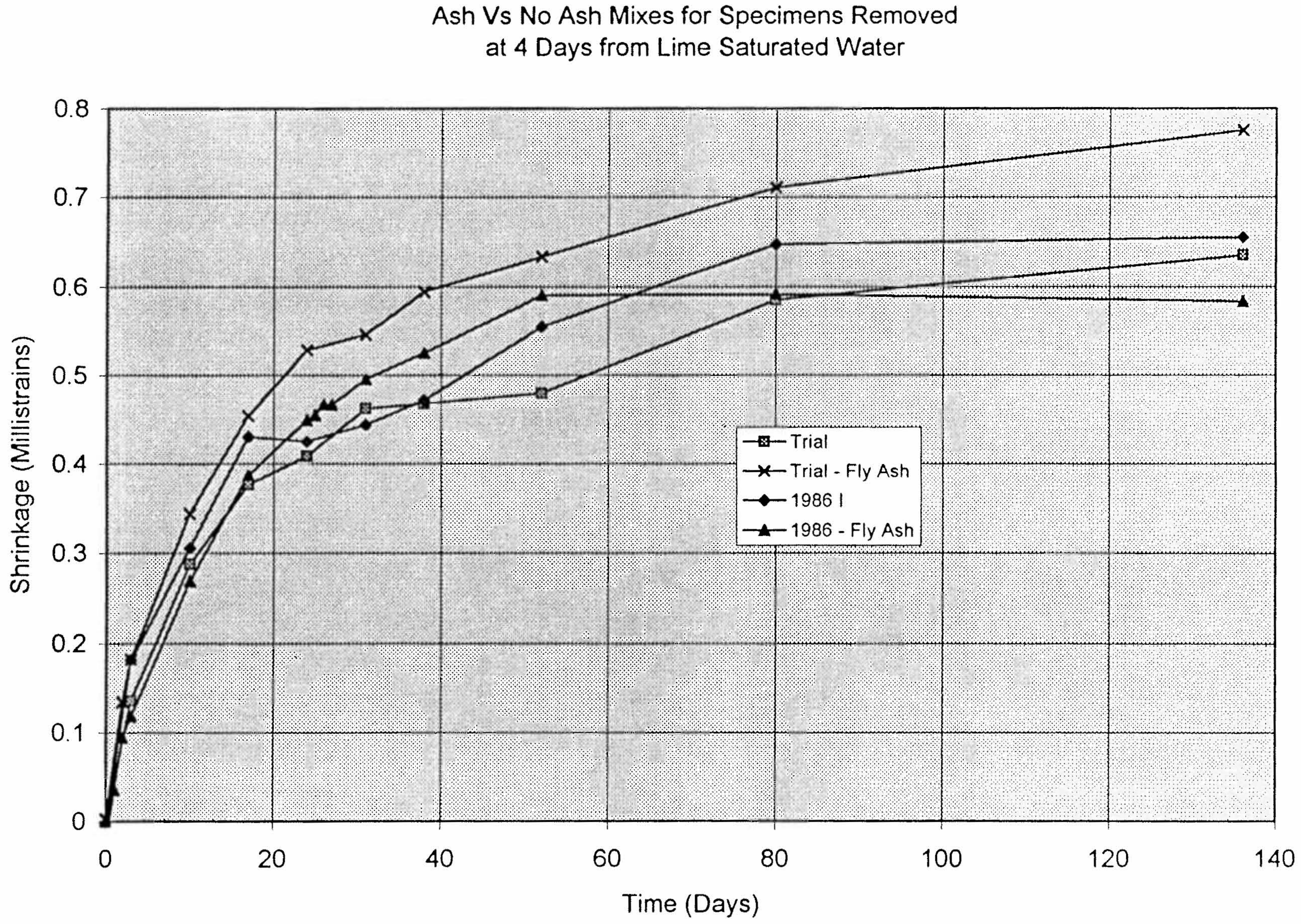

Ash Vs No Ash Mixes for Specimens Removed
at 4 Days from Lime Saturated Water

Figure 8

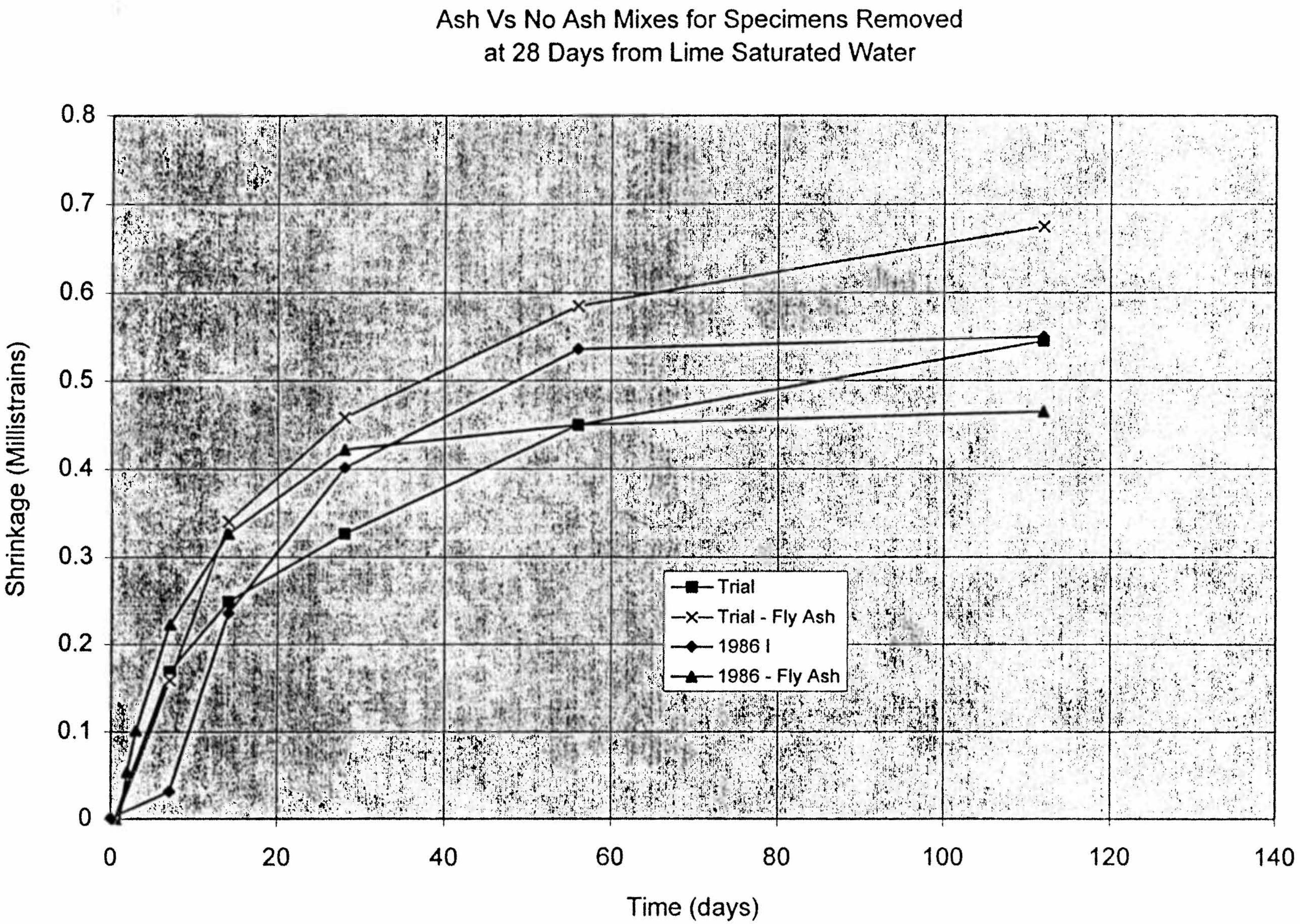

Ash Vs No Ash Mixes for Specimens Removed at 28 Days from Lime Saturated Water
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
Shrinkage (Millistrains)
0
20
40
60
80
100
120
140
Time (days)
Trial
Trial - Fly Ash
1986 I
1986 - Fly Ash

Figure 9

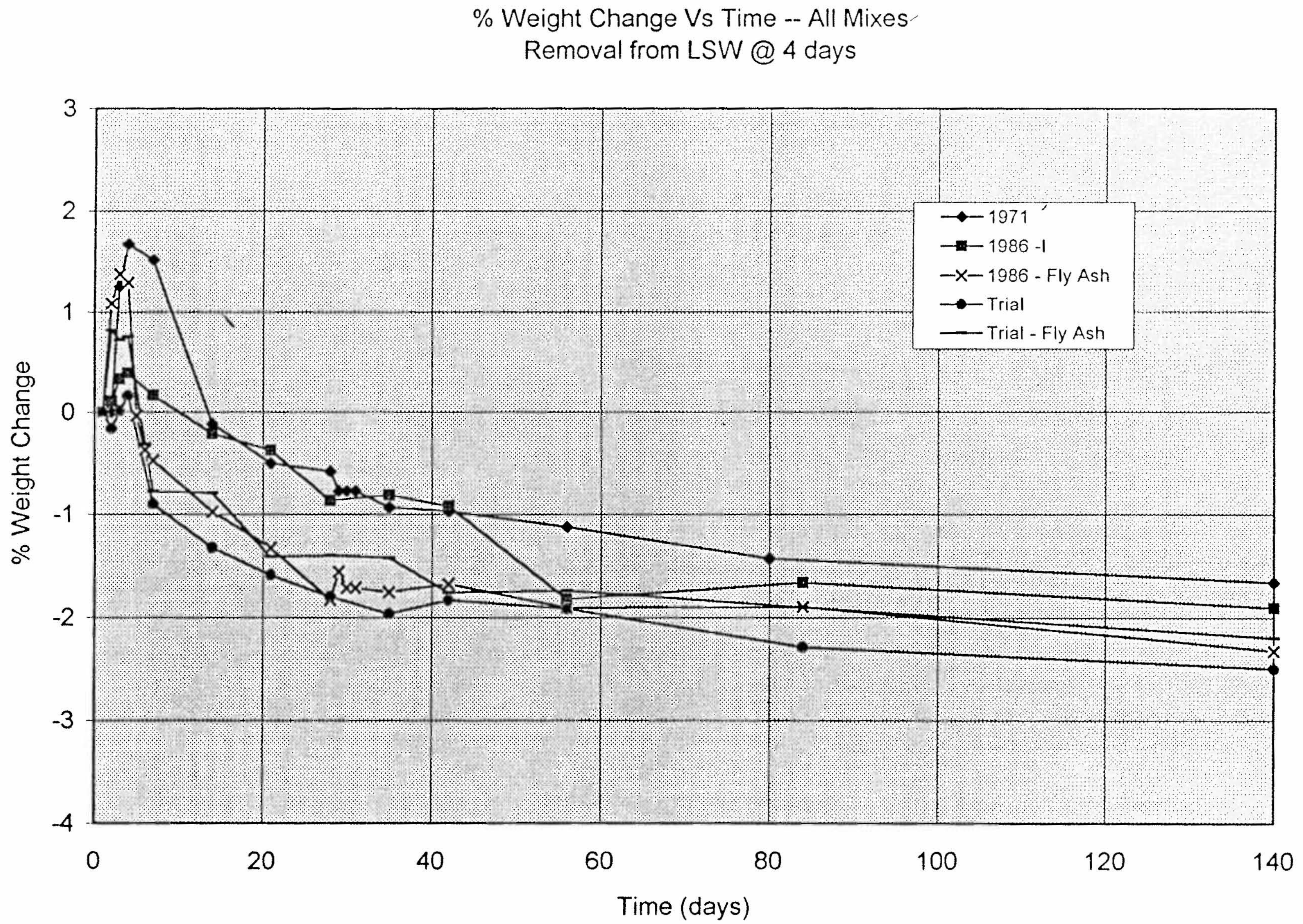

% Weight Change Vs Time -- All Mixes
Removal from LSW @ 4 days
% Weight Change
3
2
1
0
-1
-2
-3
-4
0
20
40
60
80
100
120
140
Time (days)
1971
1986 -I
1986 - Fly Ash
Trial
Trial - Fly Ash

Figure 10

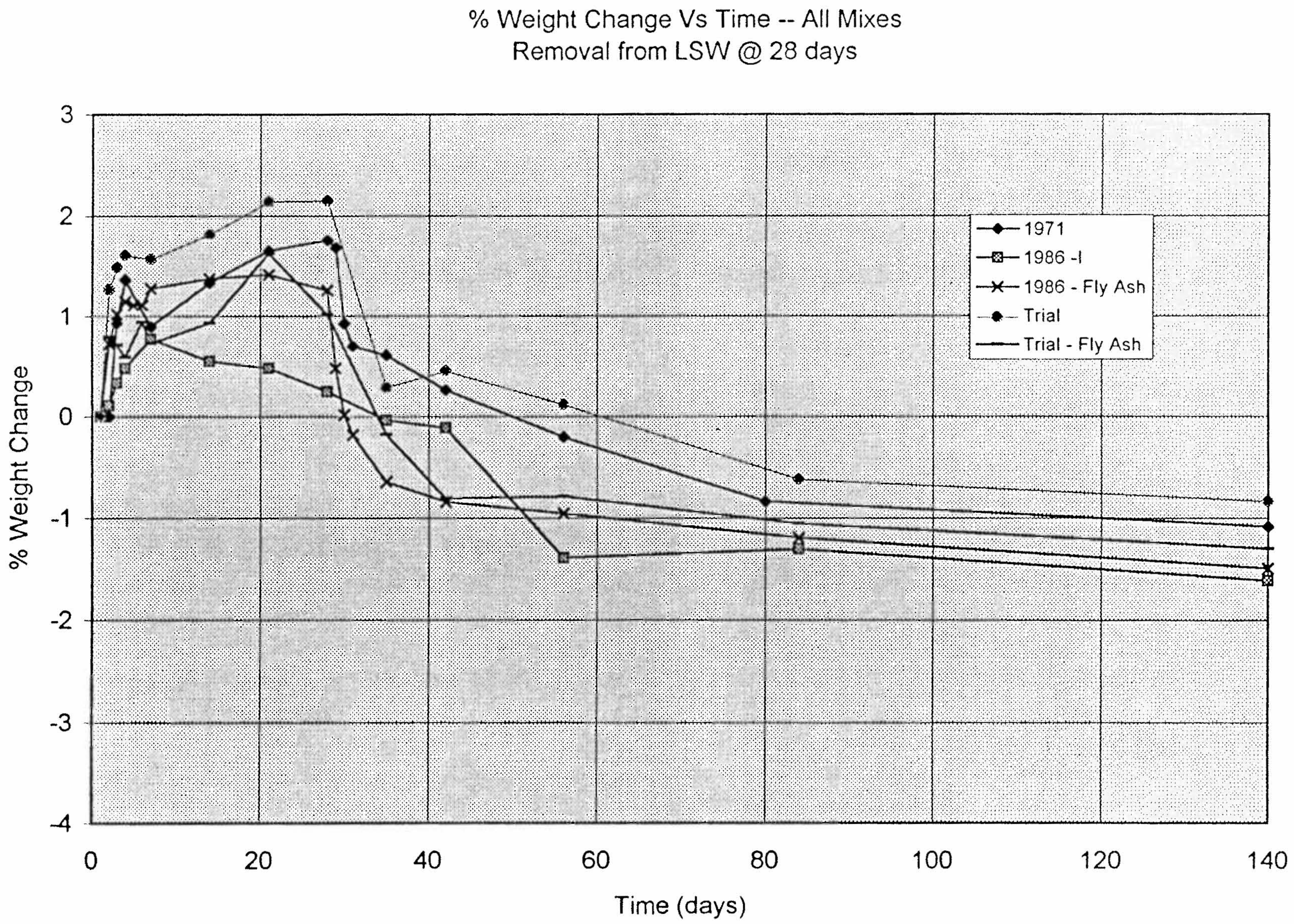
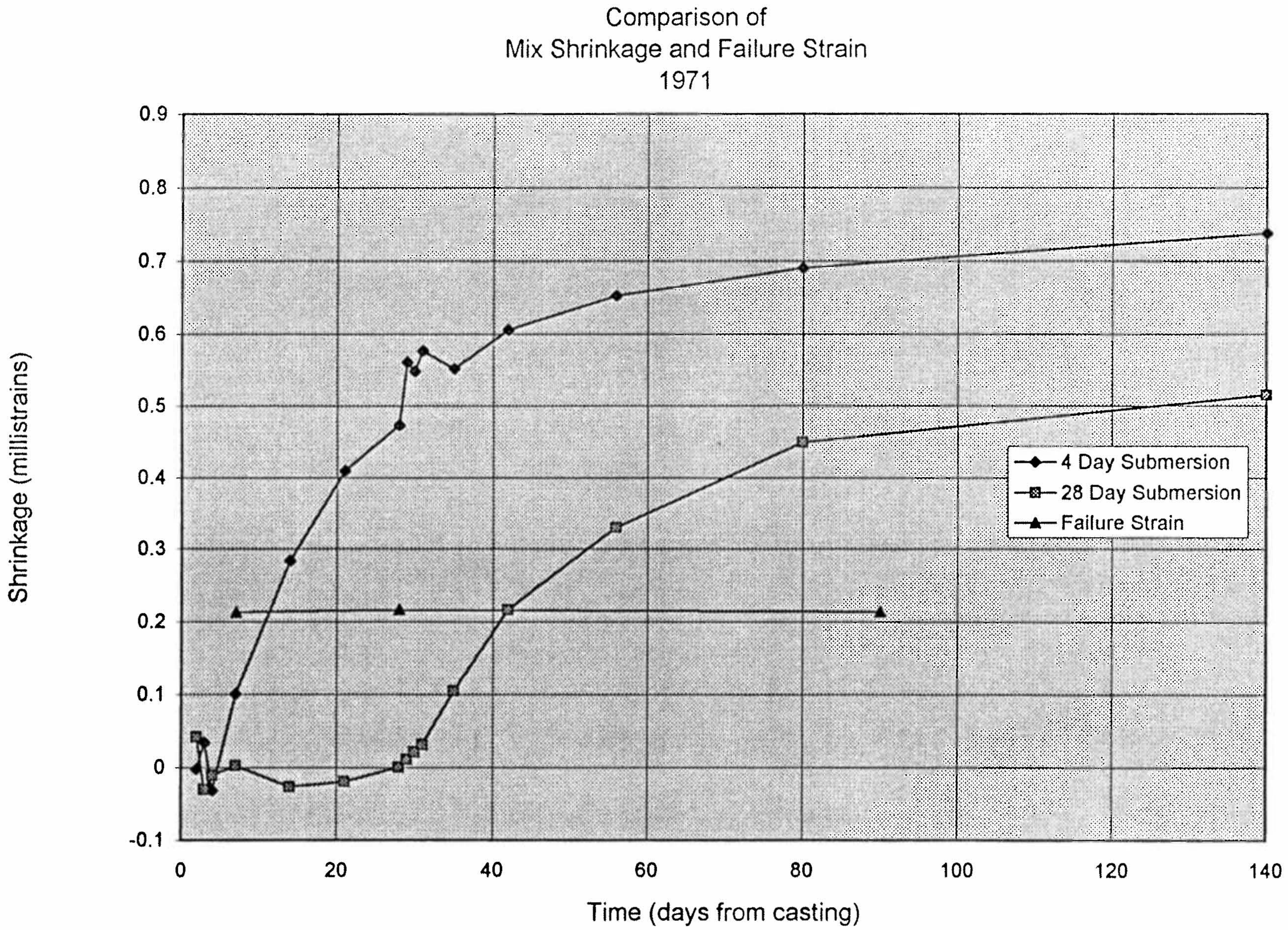

% Weight Change Vs Time -- All Mixes
Removal from LSW @ 28 days
% Weight Change
Time (days)
3
2
1
0
-1
-2
-3
-4
0
20
40
60
80
100
120
140
1971
1986 -I
1986 - Fly Ash
Trial
Trial - Fly Ash

Figure 11



Comparison of
Mix Shrinkage and Failure Strain
1971

Figure 12

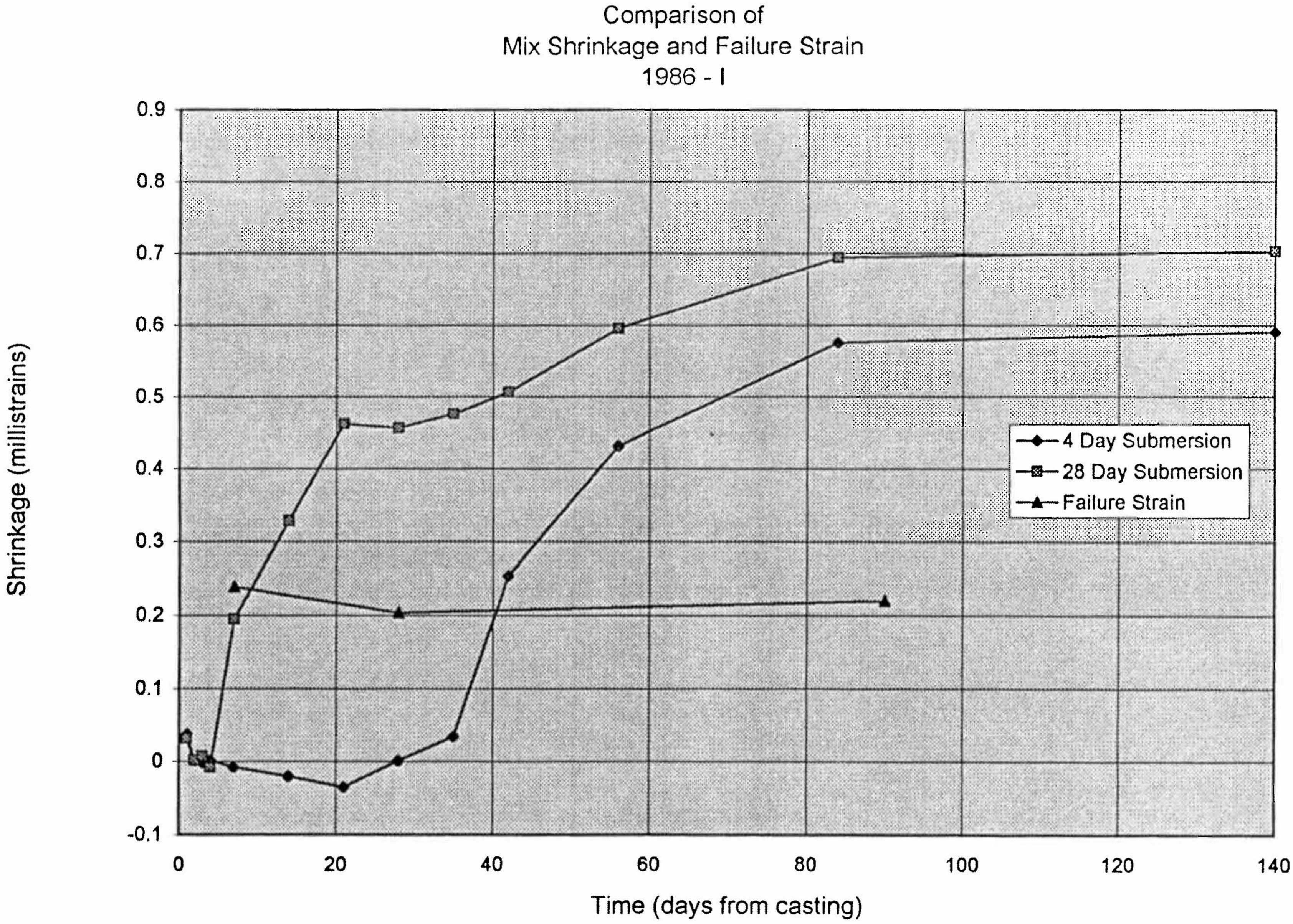

Comparison of
Mix Shrinkage and Failure Strain
1986 - I
Shrinkage (millistrains)
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
-0.1
0
20
40
60
80
100
120
140
Time (days from casting)
4 Day Submersion
28 Day Submersion
Failure Strain

Figure 13

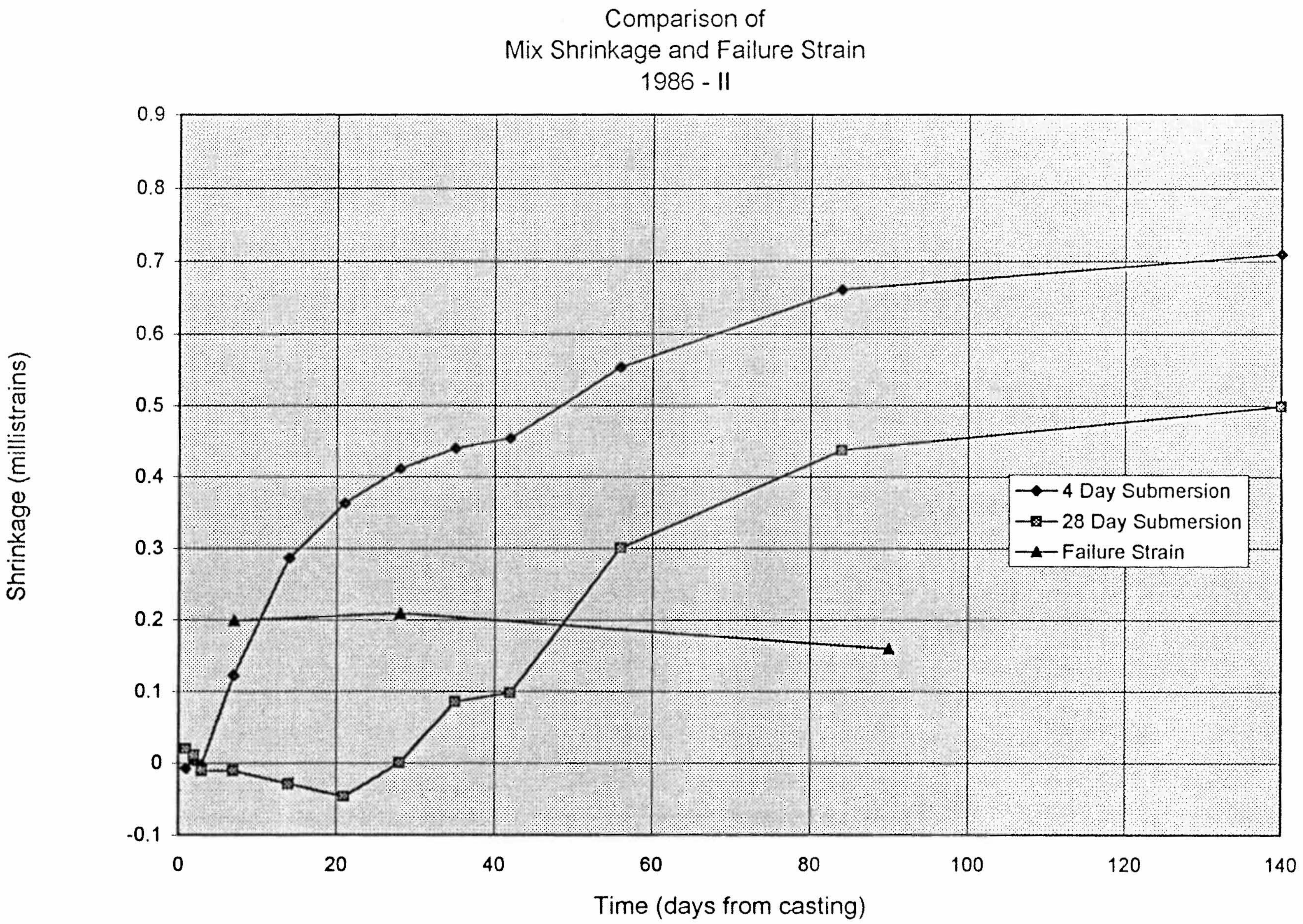

Comparison of
Mix Shrinkage and Failure Strain
1986 - II
Shrinkage (millistrains)
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
-0.1
0
20
40
60
80
100
120
140
Time (days from casting)
4 Day Submersion
28 Day Submersion
Failure Strain

Figure 14

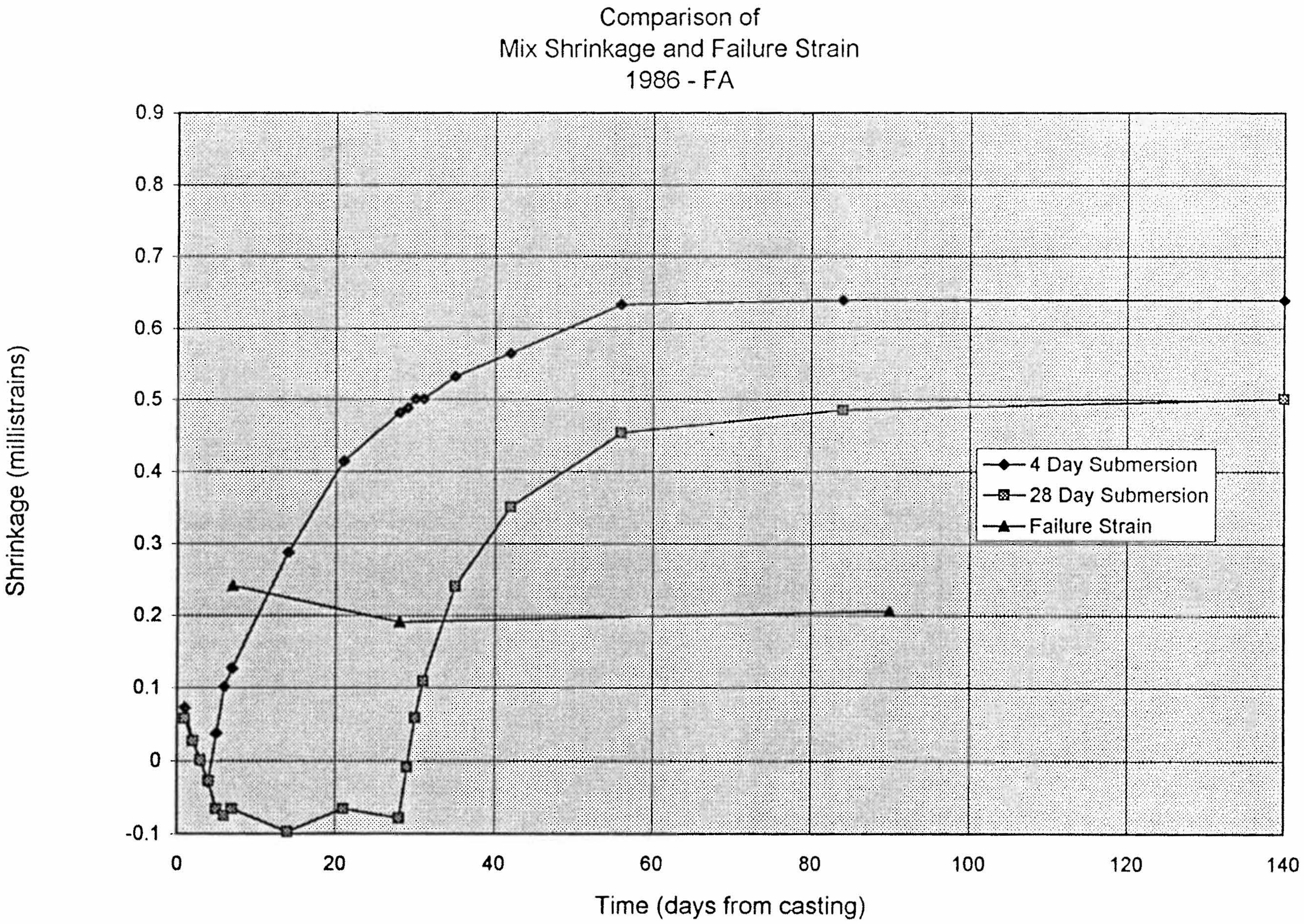

Comparison of
Mix Shrinkage and Failure Strain
1986 - FA
Shrinkage (millistrains)
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
-0.1
0
20
40
60
80
100
120
140
Time (days from casting)
4 Day Submersion
28 Day Submersion
Failure Strain

Figure 15

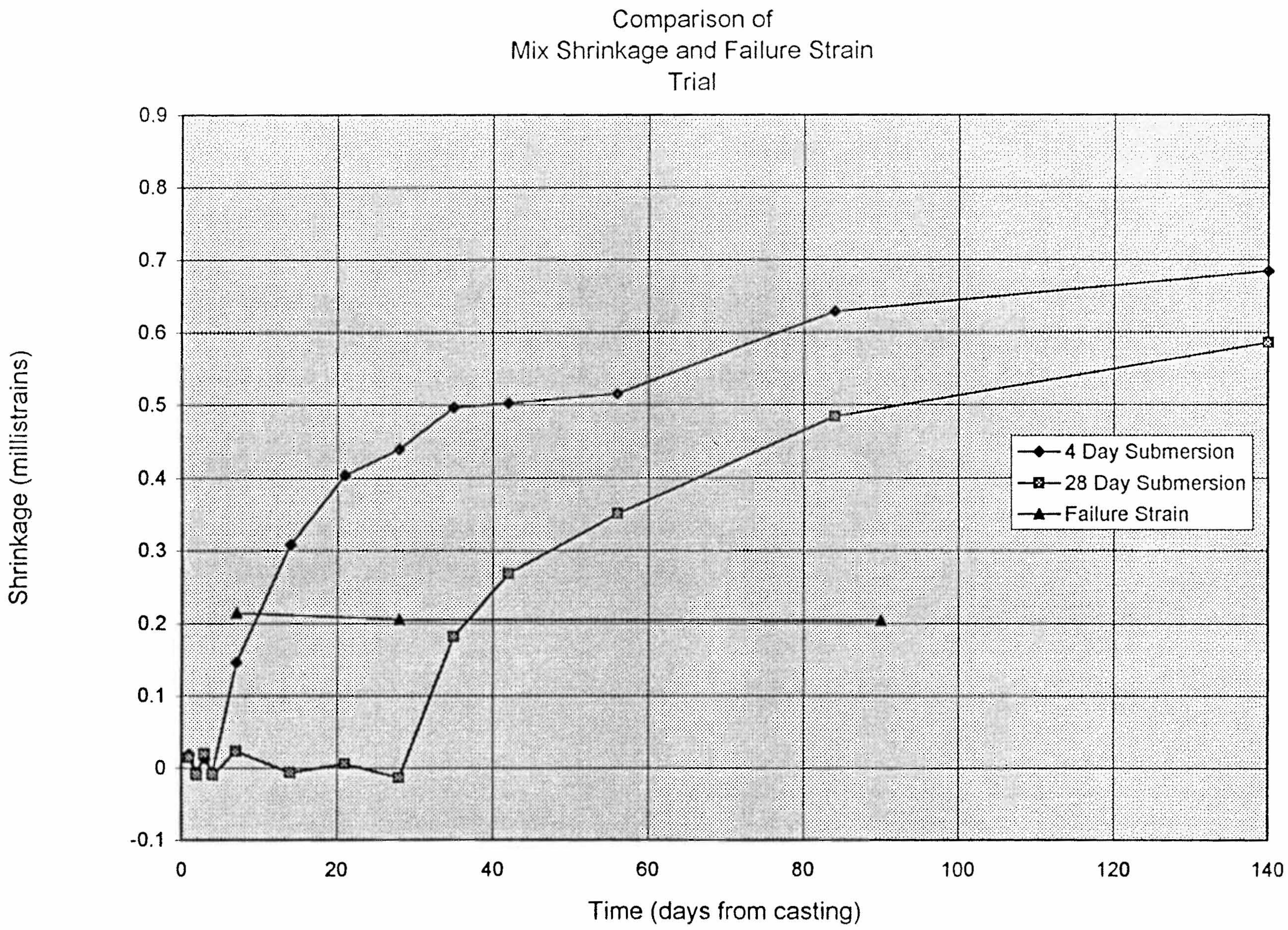

Comparison of
Mix Shrinkage and Failure Strain
Trial
Shrinkage (millistrains)
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
-0.1
0
20
40
60
80
100
120
140
Time (days from casting)
4 Day Submersion
28 Day Submersion
Failure Strain

Figure 16

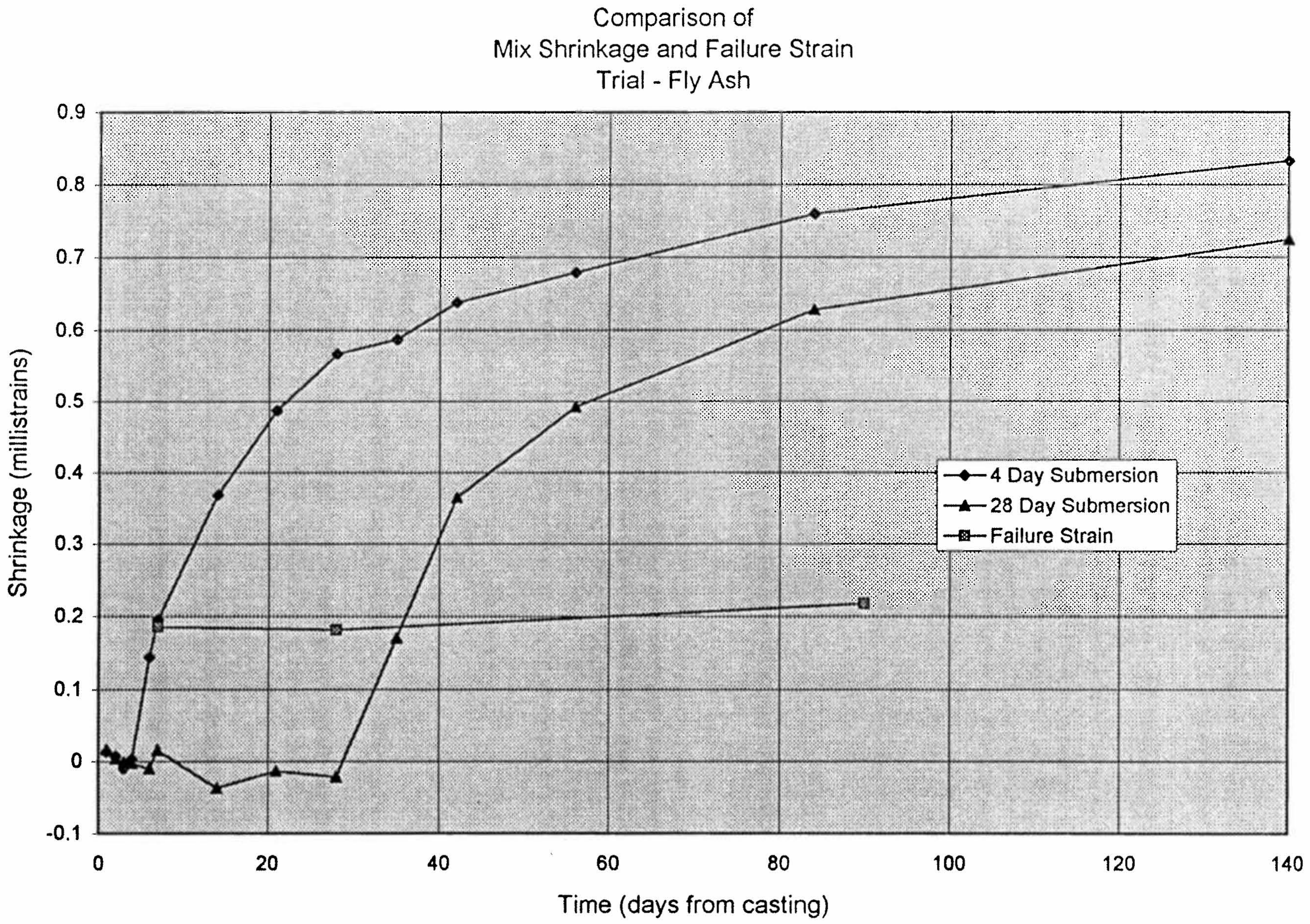

Comparison of
Mix Shrinkage and Failure Strain
Trial - Fly Ash
Shrinkage (millistrains)
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
-0.1
0
20
40
60
80
100
120
140
Time (days from casting)
4 Day Submersion
28 Day Submersion
Failure Strain

Figure 17

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98-4 Hot Bituminous Pavement QC & QA Project Constructed in 1997 Under QPM2 Specification
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98-9 Evaluation of Design Build Practice in Colorado - Construction Report
98-10 Whitetopping Thickness Design in Colorado

97-1 Avalanche Forecasting Methods, Highway 550
97-2 Ground Access Assessment of North American Airport Locations
97-3 Special Polymer Modified Asphalt Cement (Final Report)
97-4 Avalanche Detection Using Atmospheric Infrasound
97-5 Keyway Curb (Final Report)
97-6 IAUAC - (Interim Report)
97-7 Evaluation of Design-Build Practice in Colorado (Pre-Construction Report)
97-8 HBP Pilot Void Acceptance Projects Completed in 1993-1996 (Interim Report)
97-9 QC & QA Projects Constructed in 1996 Under QPM2 Specifications (Fifth Annual Report)
97-10 Loading Test of GRS Bridge Pier and Abutment in Denver, CO

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97-11 Faulted Pavements at Bridge Abutments

96-1 Long-Term Performance Tests of Soil-Geosynthetic Composites
96-2 Efficiency of Sediment Basins: Analysis of the Sediment Basins Constructed as Part of the Straight Creek Erosion Control Project.
96-3 The Role of Facing Connection Strength in Mechanically Stabilized Backfill Walls
96-4 Revegetation of MSB Slopes
96-5 Roadside Vegetation Management
96-6 Evaluation of Slope Stabilization Methods (US-40 Berthod Pass) (Construction Report)
96-7 SMA (Stone Matrix Asphalt) Colfax Avenue Viaduct
96-8 Determining Asphalt Cement Content Using the NCAT Asphalt Content Oven
96-9 HBP QC & QA Projects Constructed in 1995 Under QPM1 and QPM2 Specifications
96-10 Long-Term Performance of Accelerated Rigid Pavements, Project CXMP 13-006-07
96-11 Determining the Degree of Aggregate Degradation after Using the NCAT Asphalt Content Oven
96-12 Evaluation of Rumble Treatments on Asphalt Shoulders

95-1 SMA (Stone Matrix Asphalt) Flexible Pavement
95-2 PCCP Texturing Methods
95-3 Keyway Curb (Construction Report)
95-4 EPS, Flow Fill and Structure Fill for Bridge Abutment Backfill
95-5 Environmentally Sensitive Sanding and Deicing Practices
95-6 Reference Energy Mean Emission Levels for Noise Prediction in Colorado
95-7 Investigation of the Low Temperature Thermal Cracking in Hot Mix Asphalt
95-8 Factors Which Affect the Inter-Laboratory Repeatability of the Bulk Specific Gravity of Samples Compacted Using the Texas Gyratory Compactor
95-9 Resilient Modulus of Granular Soils with Fine Contents
95-10 High Performance Asphalt Concrete for Intersections
95-11 Dynamic Traffic Modeling of the I-25/HOV Corridor
95-12 Using Ground Tire Rubber in Hot Mix Asphalt Pavements

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95-13 Research Status Report
95-14 A Documentation of Hot Mix Asphalt Overlays on I-25 in 1994
95-15 EPS, Flowfill, and Structure Fill for Bridge Abutment Backfill
95-16 Concrete Deck Behavior in a Four-Span Prestressed Girder Bridge: Final Report
95-17 Avalanche Hazard Index for Colorado Highways
95-18 Widened Slab Study

94-1 Comparison of the Hamburg Wheel-Tracking Device and the Environmental Conditioning System to Pavements of Known Stripping Performance
1-94 Design and Construction of Simple, Easy, and Low Cost Retaining Walls
94-2 Demonstration of a Volumetric Acceptance Program for Hot Mix Asphalt in Colorado
2-94 The Deep Patch Technique for Landslide Repair
94-3 Comparison of Test Results from Laboratory and Field Compacted Samples
3-94 Independent Facing Panels for Mechanically Stabilized Earth Walls
94-4 Alternative Deicing Chemicals Research
94-5 Large stone Hot Mix Asphalt Pavements
94-6 Implementation of a Fine Aggregate Angularity Test
94-7 Influence of Refining Processes and Crude Oil Sources Used in Colorado on Results from the Hamburg Wheel-Tracking Device
94-8 A Case Study of concrete Deck Behavior in a Four-Span Prestressed Girder Bridge: Correlation of Field Test Numerical Results
94-9 Influence of Compaction Temperature and Anti-Stripping Treatment on the Results from the Hamburg Wheel-Tracking Device
94-10 Denver Metropolitan Area Asphalt Pavement Mix Design Recommendation
94-11 Short-Term Aging of Hot Mix Asphalt
94-12 Dynamic Measurements on Penetrometers for Determination of Foundation Design
94-13 High-Capacity Flexpost Rockfall Fences
94-14 Preliminary Procedure to Predict Bridge Scour in Bedrock (Interim Report)