FINAL REPORT ON SHRINKAGE-CRACKING CHARACTERISTICS OF STRUCTURAL LIGHTWEIGHT CONCRETE

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PREFACE

The primary objective of the synthetic aggregate research being conducted by the Texas Transportation Institute is to develop a recommended acceptance criterion for synthetic aggregates for use in all phases of highway construction.

This is the thirteenth report issued under Research Study 2-8-65-81, one of the synthetic aggregate research studies being conducted at the Texas Transportation Institute in the cooperative research program with the Texas Highway Department and the Federal Highway Administration. The first twelve reports are:

"Correlation Studies of Fundamental Aggregate Properties with Freeze-Thaw Durability of Structural Lightweight Concrete," by W. B. Ledbetter, *Research Report 81-1,* Texas Transportation Institute, August, 1965.

"Effect of Degree of Synthetic Lightweight Aggregate Pre-Wetting on the Freeze-Thaw Durability of Lightweight Concrete," by C. N. Kanabar and W. B. Ledbetter, *Research Report 81-2,* Texas Transportation Institute, December, 1966.

"Aggregate Absorption Factor as an Indicator of the Freeze-Thaw Durability of Structural Lightweight Concrete," by W. B. Ledbetter and Eugene Buth, *Research Report 81-3,* Texas Transportation Institute, February, 1967.

"Flexural Fatigue Durability of Selected Unreinforced Structural Lightweight Concretes," by J. C. Chakrabarti and W. B. Ledbetter, *Research Report 81-4,* Texas Transportation Institute, July, 1967.

"Suitability of Synthetic Aggregates Made from Clay-Type Soils for Use in Flexible Base," by W. M. Moore, Richard S. Van Pelt, F. H. Scrivner, and George W. Kunze, *Research Report 81-5,* Texas Transportation Institute, February, 1968.

"Performance Studies of Synthetic Aggregate Concrete," by C. E. Buth, H. R. Blank, and R. G. McKeen, *Research Report 81-6,* Texas Transportation Institute, March, 1969.

"Fundamental Factors Involved in the Use of Synthetic Aggregate Portland Cement Concrete," by W. B. Ledbetter, C. E. Sandstedt, and A. H. Meyer, *Research Report 81-7,* Texas Transportation Institute, October, 1969.

"A Sandblast Abrasion Test for Synthetic Aggregate Evaluation," by James T. Houston and W. B. Ledbetter, *Research Report 81-8,* Texas Transportation Institute, October, 1969.

"Studies of the Thermal Transformation of Synthetic Aggregates Produced in a Rotary Kiln," by James T. Houston, H. R. Blank, and George W. Kunze, *Research Report 81-9,* Texas Transportation Institute, November, 1969.

"Effect of Synthetic Aggregate Thermal Transformation on Performance of Concrete," by James T. Houston, and W. B. Ledbetter, *Research Report 81-10,* Texas Transportation Institute, October, 1969.

"Evaluation of Shrinkage-Cracking Characteristics of Structural Lightweight Concrete," by R. G. McKeen and W. B. Ledbetter, *Research Report 81-11,* Texas Transportation Institute, October, 1969.

"Fired-Clay Aggregates for Use in Flexible Bases," by W. M. Moore, *Research Report 81-12,* Texas Transportation Institute, November, 1970.

In addition, a special report has been published under this research study The report is:

"A Recommended Synthetic Coarse Aggregate Classification System (Revised August 1969)," by W. B. Ledbetter, B. M. Gallaway, W. M. Moore, and Eugene Buth, *Special Report,* Texas Transportation Institute, August, 1969.

The authors wish to thank all members of the Institute who assisted in this research.

The authors wish to acknowledge the guidance and assistance given by the advisory committee for this study. The members are as follows: (a) Texas Highway Department personnel—Mr. Kenneth D. Hankins, Study Contact Representative and Research Area Representative; Mr. H. A. Sandberg, Jr., Materials and Tests Division Representative; and Mr. Clarence R. Rea, Bridge Division Representative; (b) Federal Highway Administration personnel—Mr. Edward V. Kristaponis, Division Representative; and Mr. W. J. Lindsay, Regional Representative.

ABSTRACT

Structural lightweight concrete, made with two types of coarse aggregate and with two types of cement (I and III) were subjected to two curing periods followed by a prolonged exposure in a 140°F - 25 percent relative humidity environment. Unrestrained drying shrinkage and restrained cracking were determined. Significant findings included (1) prolonging moist curing resulted in a marked reduction in drying shrinkage, (2) although the use of Type III cement resulted in *less* unrestrained drying shrinkage, it caused *more* restrained cracking and (3) the complete elimination of shrinkage cracks appears to be practically impossible.

SUMMARY

Two structural lightweight concretes and one regular weight concrete were made with two types of cement (I and III) and subjected to two different curing periods and two different exposures. Unrestrained drying shrinkage, water loss, and restrained cracking were determined. Significant conclusions drawn were:

1. On the lightweight concrete specimens, increasing the moist curing from one day to six days before placing the concrete specimens in the 140°F-25 percent R. H. environment resulted in reducing the shrinkage approximately fifty percent.

2. The use of Type III cement with lightweight aggregate reduced unrestrained shrinkage, but did *not* reduce restrained cracking. Thus the use of Type III cement would appear to be detrimental with respect to cracking of concrete due to restrained volume changes.

3. Concretes subjected to the mild College Station environment shrank very little; nor did they crack when restrained. However, concretes which were not moist cured exhibited approximately 200 micro in. per in. more shrinkage than concretes allowed to moist cure for 6 days. Thus the importance of an adequate curing period is verified, even for the relatively humid and mild climate in College Station, Texas.

From these conclusions the following recommendations are made:

1. A shrinkage requirement should not be placed on lightweight aggregate concrete used in pavements.

2. The curing of concrete pavement should be closely controlled.

3. The use of Type III cement should be discouraged in those places where cracking may cause a problem.

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1. Introduction

1.1 Purpose

In 1969 a study was undertaken to relate restrained and unrestrained shrinkage characteristics of various types of structural lightweight concrete to the cracking characteristics of those concretes. A report was prepared, *Research Report 81-11* (1), summarizing the results of that study. The purpose of this investigation was to continue the study of the shrinkage-cracking characteristics of those concretes to determine if a shrinkage requirement should be recommended for portland cement concrete pavements made with synthetic lightweight aggregates.

Inasmuch as the background concerning shrinkage and cracking of concrete is fully described in *Research Report 81-11,* it will not be repeated here.

1.2 Objectives

The objectives of this research were:

1. To determine the effect of coarse aggregate type, cement type, and curing environment on unrestrained volume changes and restrained shrinkage cracking behavior in structural lightweight concrete.

2. To determine if a shrinkage requirement should be recommended for synthetic aggregate concrete used in pavements.

3. To compare the results of this investigation with those of the previous study (*81-11*) and develop methods of predicting cracking characteristics of the materials studied.

1.3 Conclusions

The following conclusions relate only to the experimental investigation reported herein.

1. On the lightweight concrete specimens, increasing the moist curing from one day to six days before placing the concrete specimens in the 140°F-25 percent R. H. environment resulted in reducing the shrinkage approximately fifty percent.

2. Unrestrained shrinkage of concrete, when subjected to a 140°F-25 percent R. H. environment, can be very high. In one case shrinkage in excess of 2800 micro in. per in. was recorded.

3. The use of Type III cement with lightweight aggregate reduced unrestrained shrinkage, but did *not* reduce restrained cracking. Thus, the use of Type III cement would appear to be detrimental with respect to cracking of concrete due to restrained volume changes.

4. Concretes subjected to the mild College Station environment shrank very little; nor did they crack when restrained. However, concretes which were not moist cured exhibited approximately 200 micro in. per in. more shrinkage than concretes allowed to moist cure for six days. Thus the importance of an adequate curing period is verified, even for the relatively humid and mild climate in College Station, Texas.

5. Due to the variation in water loss associated with type of curing, water loss measurements should *not* be used in lieu of shrinkage measurements.

6. The complete elimination of shrinkage cracks appears to be practically impossible. If elimination is desired, then shrinkage would have to be limited to less than around 400 micro in. per in.

1.4 Recommendations

Based on the conclusions reached in this investigation, the following recommendations are offered:

1. A shrinkage requirement should *not* be placed on lightweight aggregate concrete used in pavements.

2. The curing of concrete pavement should be closely controlled.

3. The use of Type III cement should be discouraged in those places where cracking may cause a problem.

1.5 Implementation Statement

The Highway Department specifications could be changed to require either (1) a curing time longer than the specified minimum for concrete pavements when, in the opinion of the engineer, the environmental conditions would be conducive to rapid concrete drying following the curing period, or (2) membrane curing only.

The foregoing statement represents the combined opinions of the Study Contact Representative and the authors and should not be construed as departmental policy.

2. Experimental Methods

2.1 Strength Tests

Compressive strength tests were made on four, 6 x 12 in. cylinders from each batch of concrete (see Table 4-1 in the Appendix). Two cylinders were tested at seven days, and two at 28 days. All specimens were cured one day in the mold and moist cured until tested. Testing was performed according to ASTM C39-64 specifications. These data were taken to provide a base for comparison with normal strength properties for the materials tested.

2.2 Variables

2.2.1 Coarse Aggregates

Three types of coarse aggregates were used, designated R, D, and H. They were combined with the same fine aggregates (a regular weight sand). Two synthetic lightweight aggregates were used. Aggregate R is a semicoated expanded shale which has lower water absorption characteristics. Aggregate D is an uncoated expanded shale with high water absorption characteristics. Aggregate H is a natural siliceous gravel of known service record which was included primarily as a reference.

The synthetic lightweight coarse aggregates were immersed in water prior to batching for a period of time sufficient for the aggregate to reach a saturation of internal voids of 25 percent. See *Research Report 81-6* (2) for a complete discussion of saturation.

2.2.2 Cement

The nominal cement factors for each batch were six sacks per cubic yard and coincided with the previous study (*81-11*). The cement factor varied from 5.8 to 6.0 sacks per cubic yard.

Two types of cement of the same brand (manufactured in Texas) were used—Type I and Type III.

2.2.3 Environmental Conditions

The previous study (*81-11*) involved four different curing conditions, all prefaced by an initial one day in the molds followed by a four-day moist curing period. In this present study additional curing conditions were employed. These conditions were:

Initial Curing	Long Term Curing Conditions	Abbreviation
One day in molds	140°F-25% R. H.*	NMC—Hot
One day in molds	Outside	NMC—Outside
One day in molds, then moist cured for six days	140°F-25% R. H.*	MC—Hot
One day in molds, then moist cured for six days	Outside	MC—Outside

*A description of the environmental facilities used is given in Section 5.2 of *Research Report 81-11* (1).

2.3 Test Descriptions

2.3.1 Unrestrained Shrinkage Specimens

Specimens used for unrestrained shrinkage measurements were 3 x 3 x 11.25 in. prisms with a 10 in. gage length between stainless steel studs mounted in the ends according to ASTM Method C157-67T (3). Equipment used for measurements and the method used for measuring were those suggested in ASTM Method C157-67T.

2.3.2 Restrained Cracking Specimens

Specimens used for restrained cracking measurements were 4 x 4 x 48 in. prisms with a one in. diameter deformed reinforcing bar imbedded along the specimens centerline. Specimens were mixed and placed in the molds according to ASTM C192-66 (3). Cracks in the specimens were detected through visual inspection. Both transverse and longitudinal cracks were recorded (see Table 4-2 in the Appendix for a sample data sheet).

2.3.3 Constants

The following parameters were the same as previously reported in *Research Report 81-11* and were kept as constant as possible throughout the mixing, casting, curing, and testing program:

Mixing Procedure

Fine Aggregate Type—a regular weight siliceous sand

Coarse Aggregate Type (D, R, H)

Cement Brand

The concrete mix data are given in the Appendix in Table 4-1.

3. Results and Discussion

3.1 Results

3.1.1 General

The data to be presented were obtained from three test methods. They were: a) unrestrained volume change determinations similar to that specified by the ASTM Method C157-67T (3), b) weight change determinations, and c) restrained cracking determinations. The coarse aggregate type, cement type, and environment were deliberately varied while other parameters were maintained as constant as practicable.

3.1.2 Statistical Considerations

Since constants cannot be held absolutely invariant, some measure of their variability must be provided in the evaluation of experimental data. The statistical measures of standard deviation (σ) and coefficient of variation (C. V.) are shown in Table 3-1 for several of the constants of this study.

The values shown in the table were computed using the following standard statistical equations:

$$\bar{x} = \frac{\Sigma x_i}{n} \quad \text{.......} (3.1)$$

where $\bar{x}$ = mean of observations x_i where i = 1, 2, 3 . . . n

where n = number of observations.

$$\sigma = \left[\frac{\Sigma(x_i{}^2) - (\Sigma x_i)^2/_n}{(n-1)}\right]^{1/2} \quad \text{.......} (3.2)$$

where σ = standard deviation.

$$\text{C.V.} = \frac{\sigma}{\bar{x}}\ (100\%) \quad \text{.......} (3\text{-}3)$$

TABLE 3-1. STATISTICAL DATA

PARAMETER	n	$\bar{x}$	σ	C.V. (percent)
Specimen Gage Length (in.)	48	10.0726	0.216	2.15
Unit Water Content (lbs/cu yd)	6	341	38.0	11
Air Content (percent abs. vol.)	6	4.2	0.44	10
Slump (in.)	6	2.8	0.6	15
Total Aggregate Content (percent abs. vol.)	6	65.1	2.3	4
Cement Factor (sk/cu yd)	6	5.9	0.1	2

It was assumed that the data were normally distributed. Thus the standard deviation represents the amount of scatter in the data about the mean value for all measurements. The coefficient of variation represents the standard deviation expressed as a percent of the mean value.

3.1.3 Control Tests

Seven-day and 28-day compressive strength tests of two 6 x 12 in. cylinders were made for each batch to provide a means of detecting irregularities in the materials used. Data are given in the Appendix in Table 4-1.

The compressive strengths obtained all compared favorably with those of the previous set of tests.

All cylinders were cured one day in mold and then moist cured up to the point of testing.

3.1.4 Unrestrained Volume Changes

The unrestrained volume changes (shrinkage) with time are shown on Figures 3-1 and 3-2. Each curve represents the average shrinkage of three specimens.

Note in Figure 3-1 a six-day moist curing period on the lightweight concretes reduced the shrinkage approximately fifty percent when compared to only one day of curing. The aggregate D concrete exhibited higher shrinkage than the aggregate R concrete, which is as expected (see *81-11*). However, note that the use of Type III cement, with the lightweight aggregate concrete resulted in an overall reduction in unrestrained shrinkage. This was not expected! Furthermore, this anomaly was not experienced with the regular weight concrete made with aggregate H. However, a hypothesis can be offered as a possible explanation for this phenomenon. Shrinkage is dependent on the amount of moisture lost during the hydration of the cement paste. The lightweight concretes contain more water than regular weight concrete, and Type III cement hydrates more rapidly, thereby forming a surface skin more quickly than Type I cement. This surface skin reduces water loss, thereby reducing shrinkage. Weight loss determinations were made and this hypothesis is partially verified in the next section.

One curve, the HIII-NMC, has been omitted from Figure 3-2. This omission was due to the erratic shrinkage behavior experienced by the three specimens of the aggregate H concrete that were cured in the 140°F-25% R. H. without any initial moist curing. This behavior negated the results and no unretrained shrinkage-time relationship could be obtained.

Another finding of this study was that all the shrinkage exhibited was fairly high—up to 2800 micro in. in one case (Figure 3-1). All concretes were batched with a nominal cement factor of 6 sks per cu yd. In *Research Report 81-11,* the concrete contained 5 sks of cement per cu yd of concrete. A comparison of the 28- and 120-day shrinkage values (Tables 3-2) indicates that, for Type I cement, an increase in the cement factor (from 5 to 6) resulted in almost doubling the amount of shrinkage. Increases in shrinkage with increased cement has been reported by other researchers (4, 5, 6) and thus was expected.

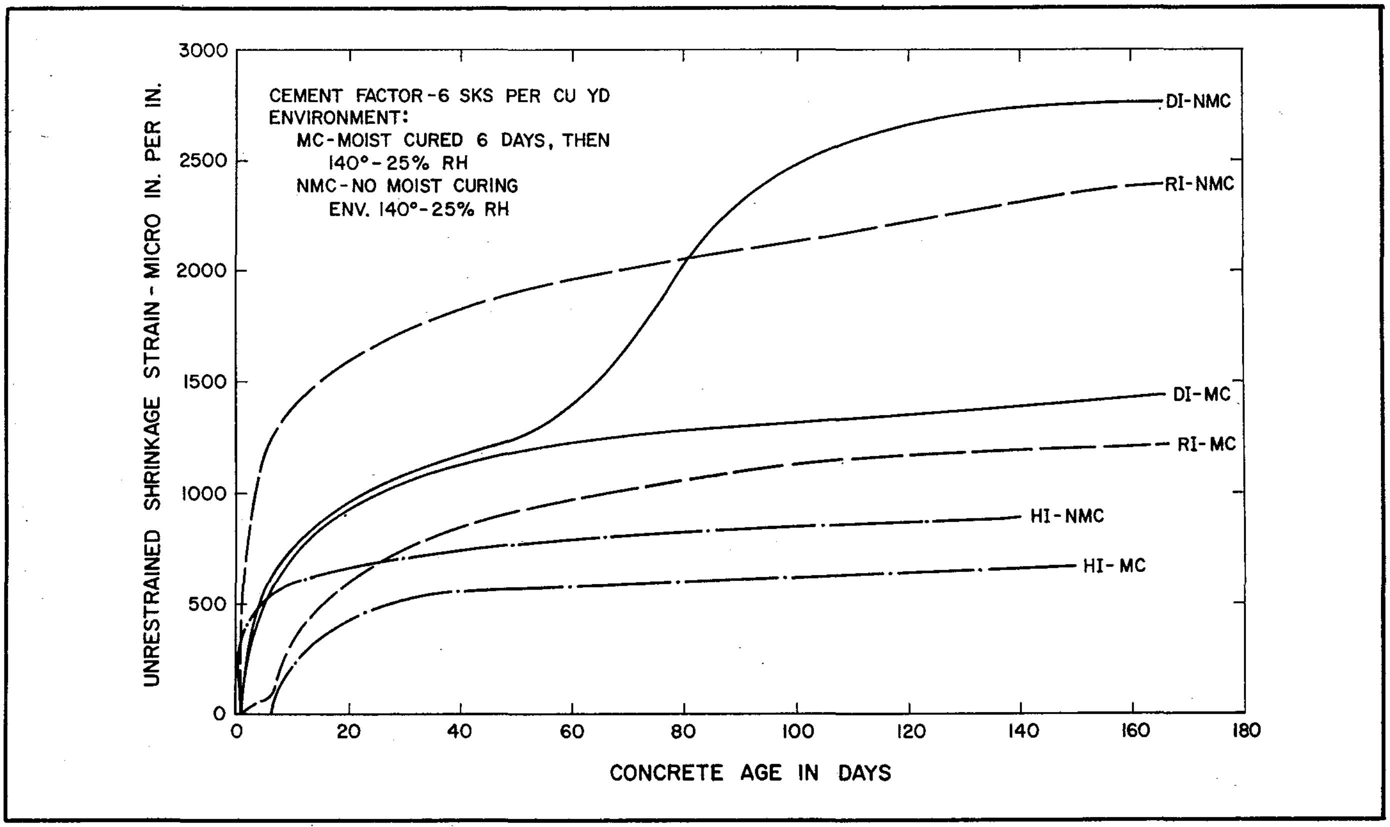


Figure 3-1. Unrestrained volume change versus time for concretes with Type I cement.

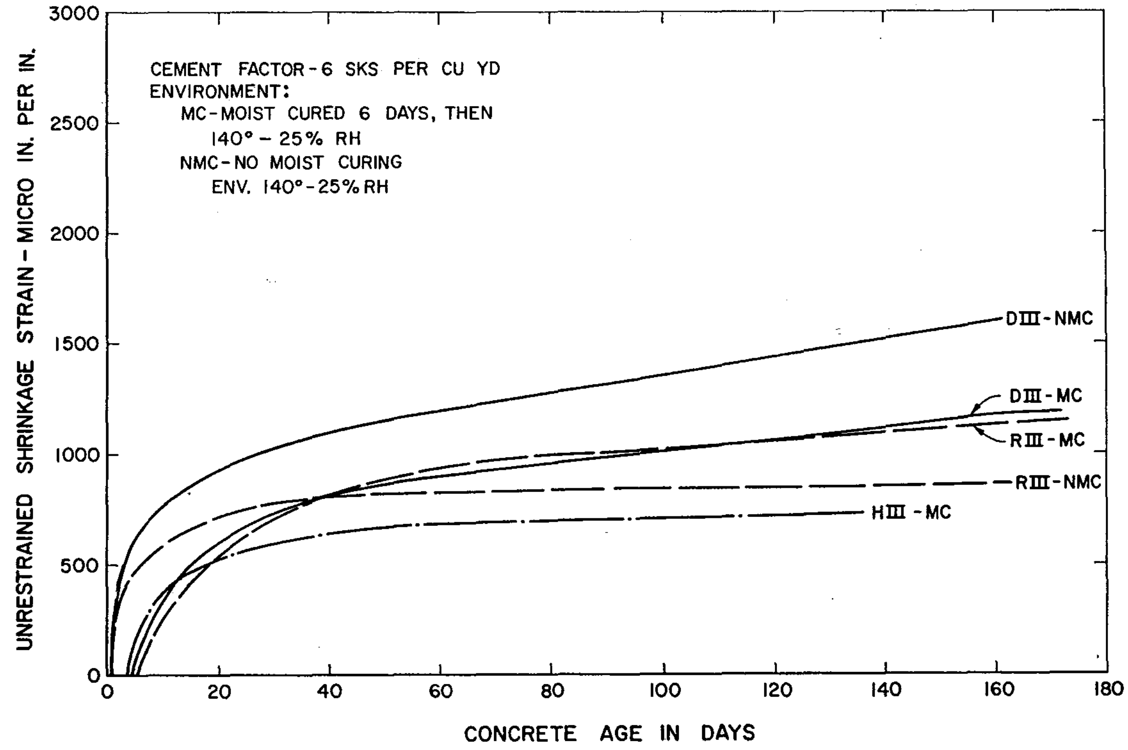


Figure 3-2. Unrestrained volume change versus time for concretes made with Type III cement.

In contrast to the high shrinkages experienced in the severe environment those specimens stored outside exhibited relatively little volume change. And this volum change fluctuated according to the weather conditions. Data for the DIII concrete (which exhibited the greatest volume changes) are shown in Figure 3-3, along with the outside temperature and humidity profile for the same period. As the volume change data were not corrected for thermal differences, the volume change reflects both shrinkage and thermal change. It can be concluded that, in the environment around College Station, Texas, shrinkage would be very slight. The effect

TABLE 3-2. AVERAGE SHRINKAGE VALUES AND NUMBER OF FULL-DEPTH CRACKS FOR CONCRETES SUBJECTED TO 140°F-25 PERCENT RELATIVE HUMIDITY

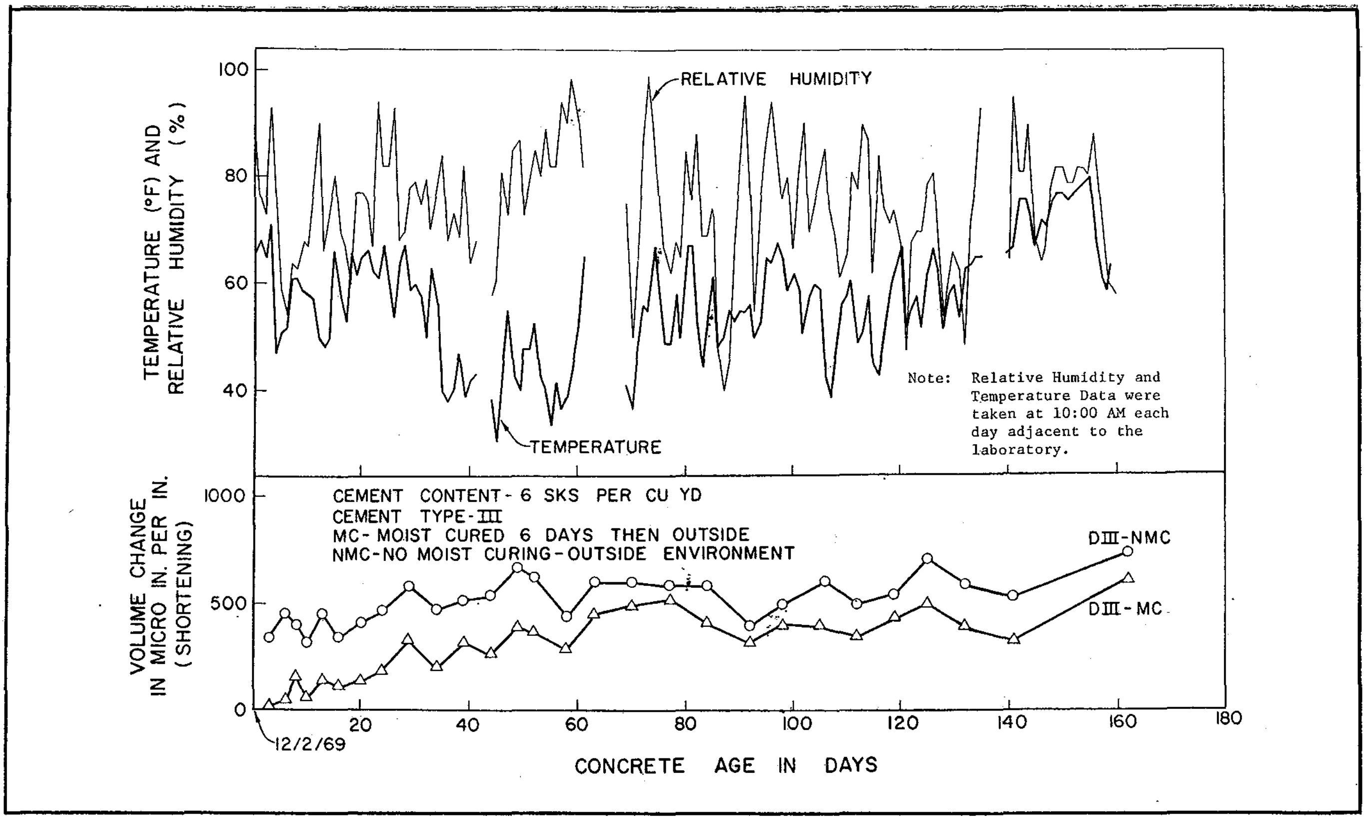
				Shrinkage (micro in./in.)				Number of Cracks		
Aggr. Code	Cement Type	Nominal Cement Factor (sks/cu yd)	Curing pd[1] (days)	@ 28 Days	@ 40 Days	@ 80 Days	@ 120 Days	@ 40 Days	@ 80 Days	@ 120 Days
R	I	5	4	480[2]	480[2]	480[2]	480[2]	2.0[3]	3.0[3]	3.6[3]
R	I	6	6	730	800	1050	1160	0	0.5	0.5
R	I	6	1	1700	1830	2050	2200	0	0	0
D	I	5	4	580[2]	570[2]	590[2]	600[2]	5.5[3]	7.1[3]	7.9[3]
D	I	6	6	1020	1120	1280	1350	4.6	6.2	6.8
D	I	6	1	1050	1170	2020	2650	0	0	0
H	I	5	4	450[2]	440[2]	470[2]	500[2]	0[3]	0[3]	0.5[3]
H	I	6	6	500	550	600	640	0	0.4	1.2
H	I	6	1	580	740	820	860	0	0	0
R	III	6	6	680	810	1000	1060	0.4	2.4	3.3
R	III	6	1	750	800	830	850	2.1	3.0	4.4
D	III	6	6	710	810	950	1060	6.2	8.4	10.0
D	III	6	1	1000	1100	1270	1440	3.4	5.4	6.9
H	III	6	6	580	640	700	720	0.2	1.4	2
H	III	6	1	[4]	[4]	[4]	[4]	1.3	2.3	2.8

[1] After an initial 24-hour period in molds.

[2] Taken from Figure 4-2 of *Research Report 81-11* (1).

[3] Taken from Figure 4-10 of *Research Report 81-11* (1).

[4] Data not obtained.



Note: Relative Humidity and Temperature Data were taken at 10:00 AM each day adjacent to the laboratory.

Figure 3-3. Unrestrained volume change for agg. D concrete stored outside and the outside environmental readings.

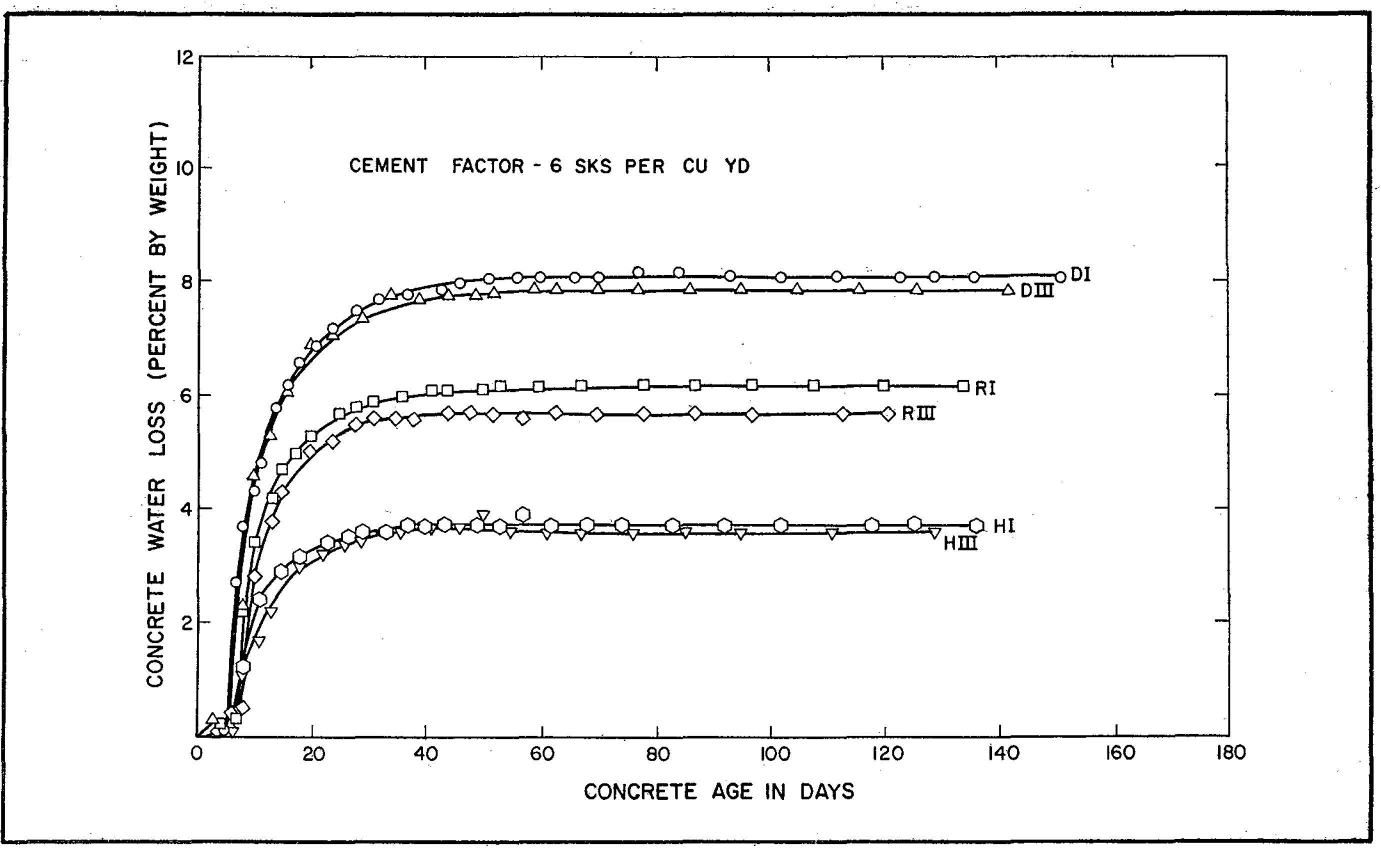


Figure 3-4. Concrete water loss in 140°F-25% R. H. after 6 days moist curing.

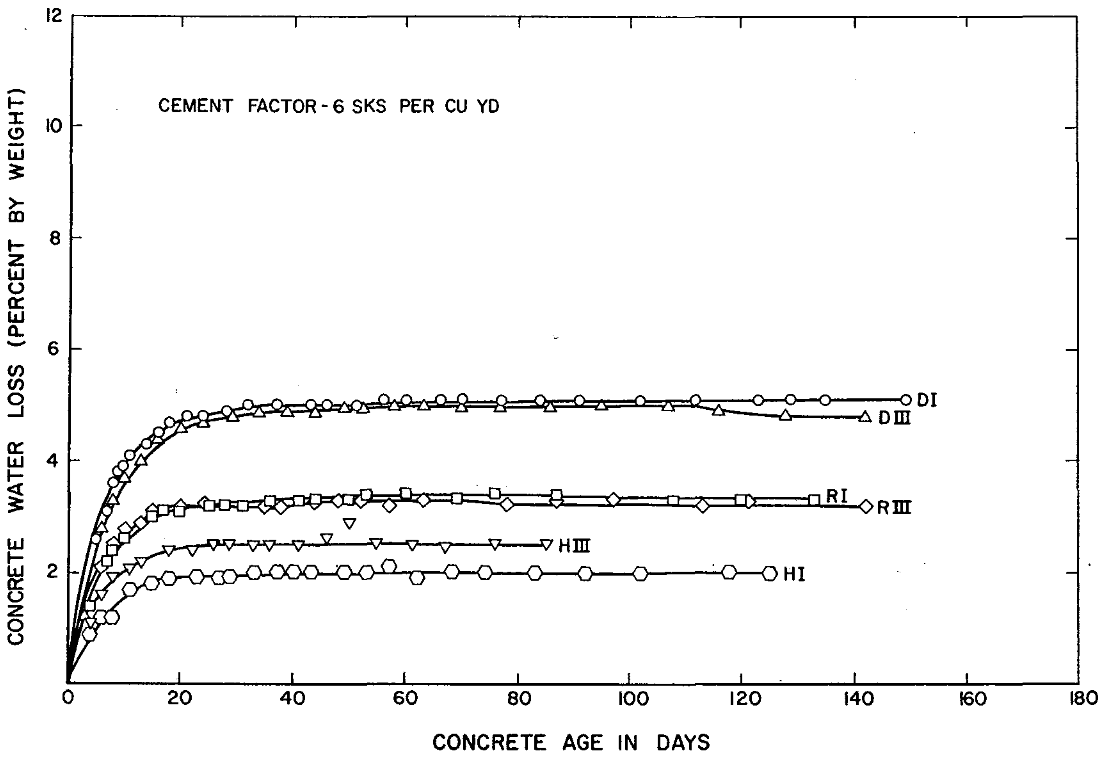


Figure 3-5. Concrete water loss in 140°F-25% R. H. without moist curing.

of six days of curing is seen to reduce shrinkage by about 200 micro in. per in. While this may not appear to be high when compared with the shrinkages exhibited in the hot environment, 200 micro in. per in. strain, if restrained, could result in concrete tensile stresses as high as 50 to 60 psi (see Figure 4-7 in *Research Report 81-11* (1)). Assuming the concrete has a tensile strength of 300 psi, this restrained shrinkage could reduce the concrete's tensile capacity by around 20 percent. Thus it would seem desirable to provide adequate curing during the early life of the concrete.

One additional comment may be made concerning the shrinkage data. There was an unusually large amount of data scatter from the specimens in the hot environment. This data scatter was due to the severe environment affecting each specimen differently and thus the conclusions drawn should be considered as qualitative only.

3.1.5 Concrete Water Loss on Drying

Concrete water loss versus age data are portrayed in Figures 3-4 and 3-5. Note that the concretes containing Type III cement exhibited less weight loss than the concretes containing Type I cement. This partially verifies the hypothesis presented in Section 3.1.4, explaining why the lightweight concretes containing Type III cement exhibited less shrinkage than those containing Type I cement. As expected, water loss following 6 days of moist curing was greater than the water loss on concretes not allowed to cure. This was caused by the gain of water in those concretes allowed to cure.

3.1.6 Concrete Cracking

Concrete cracking curves versus age for the concrete specimens subjected to the hot environment are given in Figures 3-6 and 3-7.

Transverse cracking of the specimens occurred almost exclusively in the hot environment cured specimens. Specimens made with the D aggregate showed the greatest number of full-width transverse cracks, followed by the R specimens and then the H specimens. In general for a given aggregate, specimens made with Type III cement developed more cracks than did specimens made with Type I cement. Moist curing produced fewer cracks for the specimens made with the R and H aggregates, whereas for the D aggregate specimens moist curing produced the most cracks.

Almost no full-width transverse cracks were developed by specimens cured outside, whether moist cured or not. However, several of the specimens stored outside did develop shallow small longitudinal cracks in the top specimen surface which was trowel finished after placing. These small cracks were only surface cracks in the skin as a result of the slight bleeding which occurred during finishing.

Here again, the cracking in the hot environment is believed to be the result of stresses incurred during rapid partial hydration of the surface skin producing a hard surface. Further moisture evaporation causes shrinkage in the specimen. Being restrained by the reinforcing bar, shrinkage could not occur evenly, stresses developed, and transverse tensile cracks developed along the length

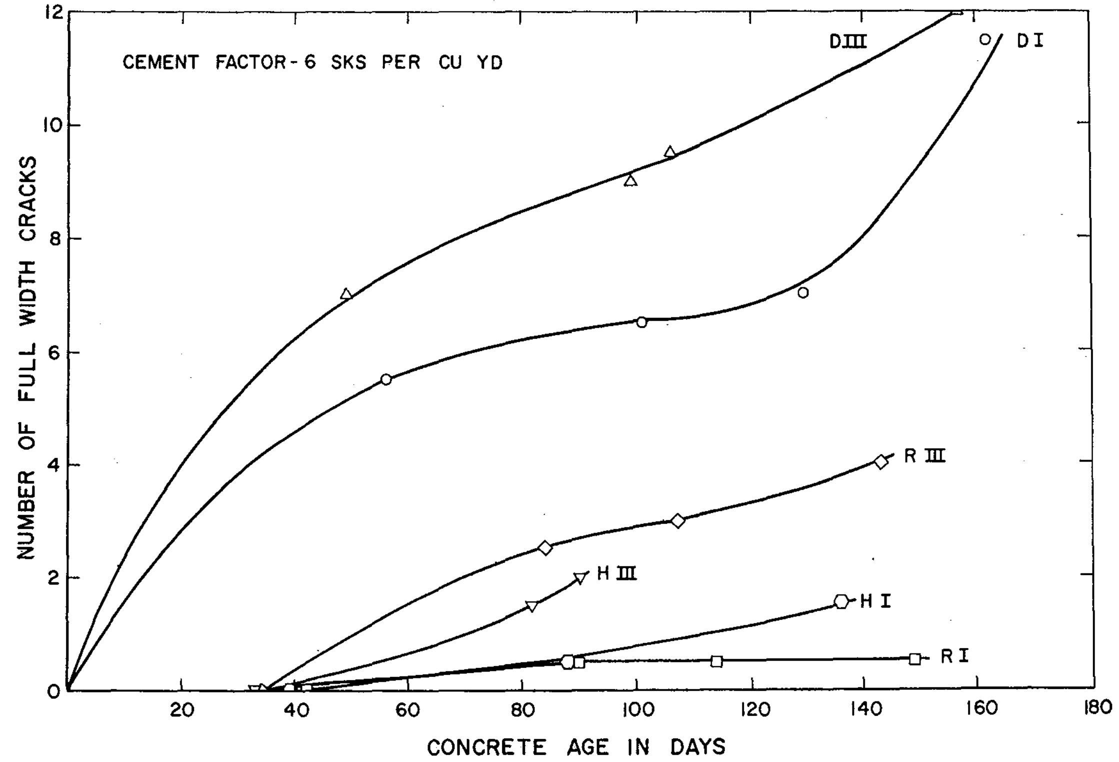


Figure 3-6. Concrete cracking in 140°F-25% R. H. after 6 days moist curing.

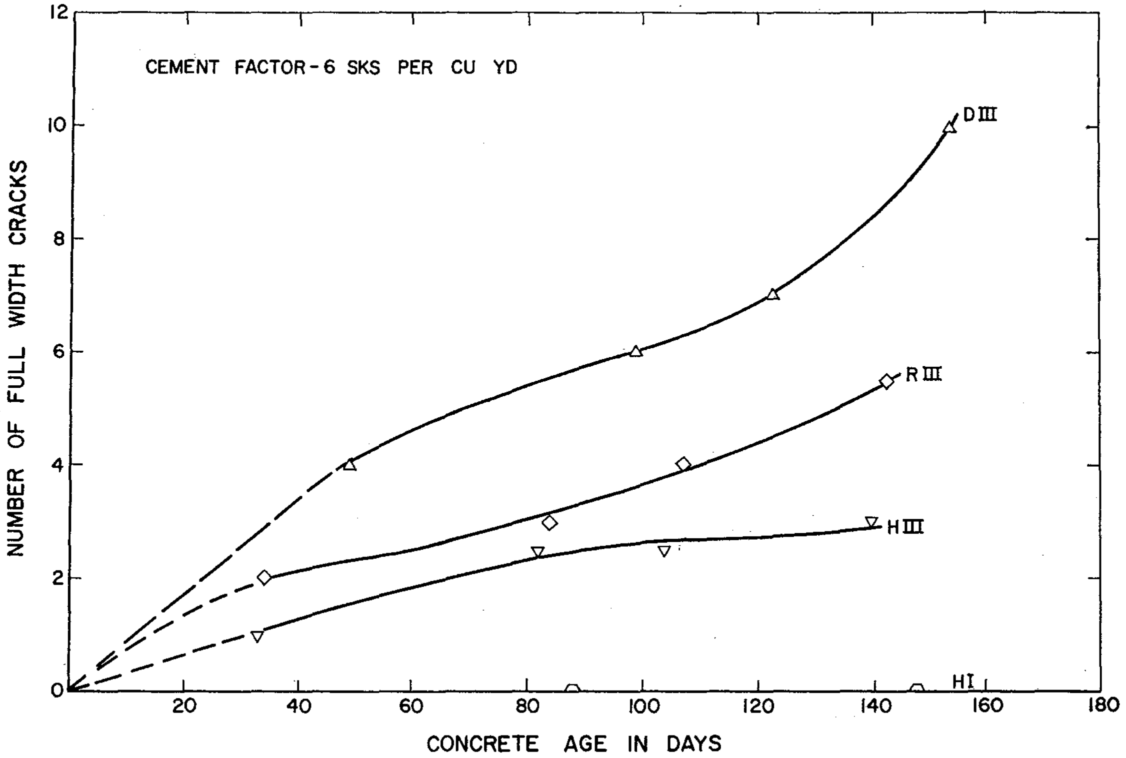


Figure 3-7. Concrete cracking in 140°F-25% R. H. without moist curing.

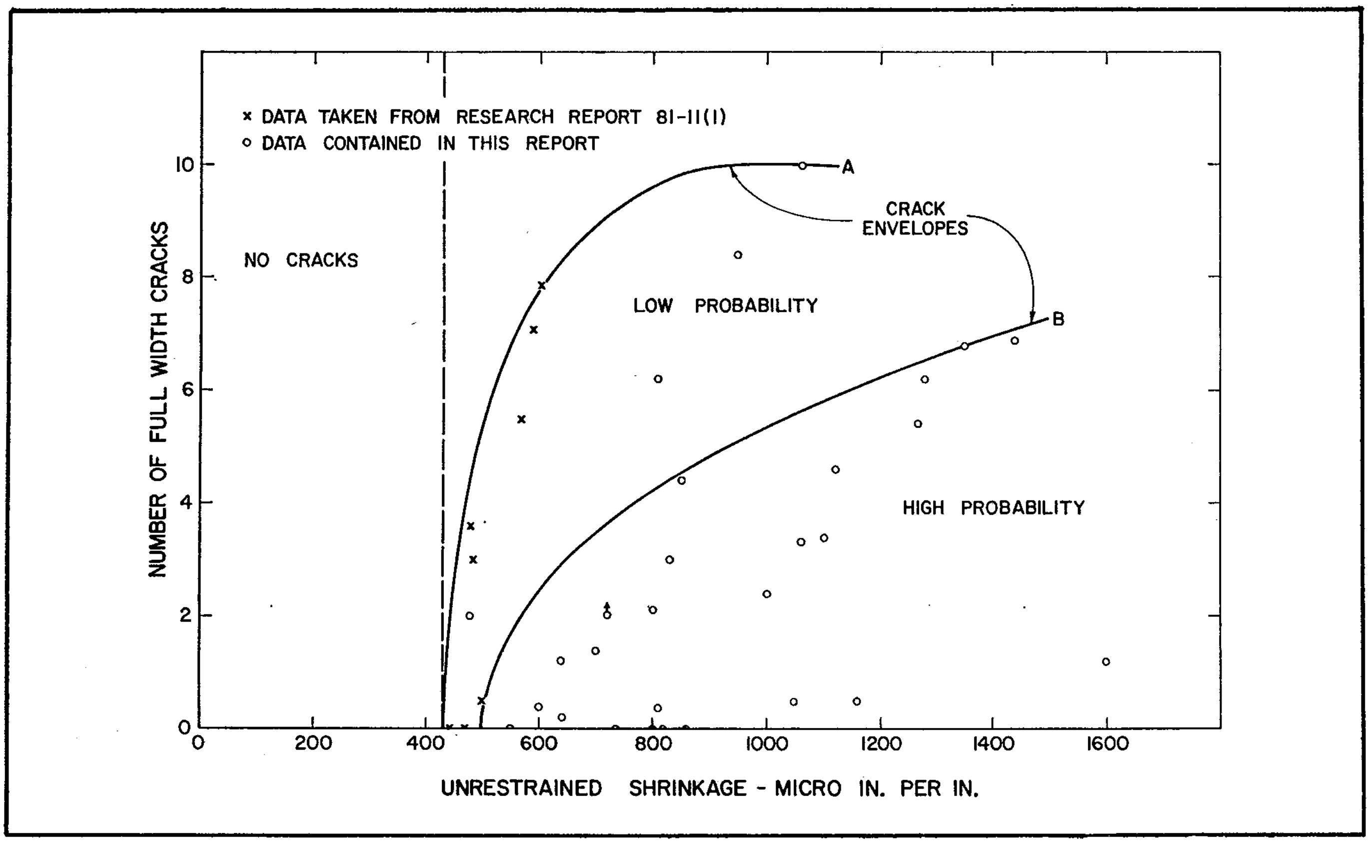


Figure 3-8. Number of full width cracks versus unrestrained shrinkage.

of the specimen. The greatest number of cracks developed at the center line and the third points. However, since rain and moisture in the air apparently provided enough water to prevent significant shrinkage in specimens cured outside, no cracks developed in these specimens.

3.2 Relationship Between Shrinkage and Water Loss

A definite relationship between unrestrained shrinkage and water loss was found and reported in *Research Report 81-11* (1). However, in the present investigation, this relationship was *not* verified. To the contrary, it was found that while the different types of curing and cement caused major variations in shrinkage, they did not cause major variations in water loss. Thus it is concluded that water loss, although easier to measure than shrinkage, should not be used in the place of shrinkage determinations.

3.3 Relationship Between Shrinkage and Cracking

Since one of the major objectives of this investigations was to determine whether or not a shrinkage requirement should be recommended for concrete pavement, unrestrained shrinkage versus number of full-width transverse cracks (for the restrained specimens) are plotted in Figure 3-8. Also drawn on the figure are two envelopes. These envelopes bound regions on the graph as indicated. For example, no restrained cracking occurred until the unrestrained specimens shrank at least 430 micro in. per in. For an unrestrained shrinkage of 500 micro in. per in., there were no specimens with more than 5.2 cracks (envelope A) and a large number of specimens still did not contain cracks. Thus it is concluded that for a shrinkage of 500 micro in. per in., there is only a slight probability of any cracking. If 800 micro in. per in. is selected, the data indicate there is a high probability of up to 4.2 cracks per specimen (envelope B), and a low probability of any specimens containing any more than 4.2 cracks.

Now, what does all this mean to the engineer? First, if the elimination of cracking is desired, then unrestrained shrinkage must be limited to less than around 400 micro in. per in. As most lightweight concretes shrink at least 400 micro in. per in. (1), the complete elimination of shrinkage cracks would appear to be practically impossible. Second, as shrinkage is so significantly affected by such factors as aggregate type, cement type, amount of cement and curing, environment, (and these factors cause so much data scatter), the imposition of an arbitrary shrinkage requirement would be difficult to defend. Therefore, rather than imposing a shrinkage requirement, those factors adversely affecting shrinkage should be closely controlled. Those factors are:

1. Cure the concrete as long as possible.
2. Use Type I cement unless it is necessary to use Type III.
3. Do not use any more cement than necessary for strength and durability as increasing the amount of cement adversely affects shrinkage.

4. Appendix

4.1 Laboratory Procedures

All materials were allowed to stabilize in the batching room for 24 hours prior to mixing. All concrete was mixed in a 6 cu ft capacity rotary drum mixer. Preceding each batch mixing, the drum was watered and "buttered" with a small charge of material of the same type used for the actual batch. Batching was begun by placing the coarse aggregate and a portion of the mixing water containing the air entraining agent in the mixer. After approximately ten minutes, the fine aggregate and the cement were added and then the remaining mix water which was used as a slump control. The ingredients were mixed about 10 minutes after addition of cement. At this point, tests for air content (ASTM C231-68) and slump (ASTM C143-66) were made. If the slump was too low, the materials used for the tests were placed back in the mixer, more water added, and the ingredients mixed for about two more minutes. Air and slump tests were again made. The batch was discharged and placed in the molds when the appropriate slump was attained.

As soon as the concrete was placed, the specimens were covered with polyethylene plastic sheets to prevent excess moisture loss during in-mold curing. At approximately 24 hours of age the specimens were removed from the molds, labeled, and placed in their respective curing environment.

4.2 Thermal Volume Changes

As the concretes were batched and cured at room temperature before being placed in the 140°F environment, they experienced a volume change as a result of the change in temperature. In order to correct the shrinkage readings to reflect these thermal volume changes, the specimens were subjected to temperature changes after completion of the shrinkage program (when the concretes were all over four months old). The resulting coefficients of thermal expansion are given in Table 4-3.

The method of making the corrections to the shrinkage data is fully described in Section 5.4 of *Research Report 81-11* (1).

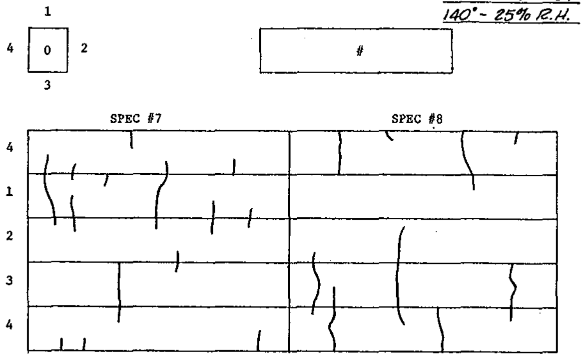
4.3 Data

The following data are included in this section:

Table 4-1	Concrete Mix Data
Table 4-2	Sample Restrained Cracking Data Sheet
Table 4-3	Concrete Thermal Properties

TABLE 4-2. SAMPLE RESTRAINED CRACKING DATA SHEET

Batch Design: R III
Date Batched:
Age:
Date: 4-1-1970
Curing Conditions: 1 DAY IN MOLDS FOLLOWED BY 6 DAYS MOIST-140°-25% R.H.



Evaluation:

Age	c_1	Range	c_2	Range	c_3	Range
	8.5	6-11	15.5	11-20	4	3-5

c_1 - Crack is counted as 1 when it appears on one or more faces. Value is average of 2 specs.

c_2 - Cracks on every face are added up and divided by 2 for spec. ave. (2 spec x 4 faces).

c_3 - Ave. no. of full width cracks.

4.4 References

1. McKeen, R. G., and Ledbetter, W. B., "Evaluation of Shrinkage-Cracking Characteristics of Structural Lightweight Concrete," *Research Report 81-11*, Texas Transportation Institute, Texas A&M University, College Station, Texas, October, 1969, 20 pp.

TABLE 4-1. CONCRETE MIX DATA

Batch Code[1]	Cement Factor sk/cu yd	Percent Absolute Volumes					Slump in.	Initial Unit Weight pcf	7 Day Comp. Strength psi	28 Day Comp. Strength psi
		Cement	Water	F.A.	C.A.	Air				
DI	5.8	10.3	22.3	30.7	31.9	4.8	3	115.6	3670	5620
DIII	6.0	10.6	22.8	29.9	32.7	4.0	1.5	113.6	4725	5810
RI	5.8	10.3	19.9	32.2	33.2	4.3	3	116.8	4430	5290
RIII	5.9	10.5	20.5	31.9	32.7	4.4	3	115.6	5110[2]	5770
HI	6.0	10.7	17.0	34.7	33.1	4.5	3.25	146.6	3455	4455
HIII	6.0	10.5	18.5	34.5	33.0	3.5	3	143.6	3770[3]	4530

[1] The letter refers to the coarse aggregate type used, and the Roman numerals refer to the type of cement used.
[2] 13-day strength.
[3] 8-day strength.

TABLE 4-3. CONCRETE THERMAL PROPERTIES

Batch Code	Curing Period (Days)	Coefficient of Thermal Expansion α(in./in./°Fx10^{-6})
RI	6	5.5
RI	1	5.6
DI	6	5.4
DI	1	4.9
HI	6	7.3
HI	1	5.8
RIII	6	6.1
RIII	1	5.2
DIII	6	6.0
DIII	1	6.3
HIII	6	7.9
HIII	1	8.9

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4. Powers, T. C., "Causes and Control of Volume Change," *Journal,* PCA Research and Development Laboratories, Vol. 1, No. 2, January, 1959, pp. 29-39.

5. Menzel, Carl A., "Strength and Volume Change of Steam Cured Portland Cement Mortar and Concrete," ACI Journal, *Proceedings,* Vol. 31, No. 2, November-December, 1934, pp. 125-148.

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