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# CRACKING POTENTIAL IN HIGH-PERFORMANCE CONCRETE (HPC) UNDER RESTRAINED CONDITIONS

## PODATNOŚĆ NA PĘKANIE BETONÓW WYSOKOWARTOŚCIOWYCH W WARUNKACH SKURCZU OGRANICZONEGO

**Abstract** This paper presents a direct method for measuring the strain development up to cracking failure in the concrete ring using Vibrating Wire Strain Gages (VWSG). The AASHTO test (PP 34÷99, The Passive or Restrained Ring Test) is employed to measure the cracking potential of various HPC mixes under restrained conditions. For each mix, additional tests were performed to determine the corresponding mechanical properties. The effect of pozzolanic material and the potential of cracking for various HPC mixes are also reported. The results of the study are used in correlating restrained shrinkage from ring tests with measured free shrinkage. In general, this study shows that coarse to fine aggregate ratio as well as amount and type of coarse aggregate is a major factor affecting shrinkage behavior of HPC.

**Streszczenie** Niniejszy artykuł przedstawia metodę bezpośredniego pomiaru odkształceń powstających w betonowym pierścieniu za pomocą tensometrów wibracyjnych (z ang. Vibrating Wire Strain Gages, VWSG). Norma opracowana przez AASHTO Nr. PP 34÷99 „Metoda pierścienia pasywnego lub ograniczonego” (*z ang. The Passive or Restrained Ring Test*) została wykorzystana do pomiaru podatności na pękanie różnych mieszanek wykonanych z betonów wysokowartościowych, a poddanych skurczowi ograniczonemu. Dla każdej z mieszanek wykonano dodatkowo pomiary właściwości mechanicznych. Wpływ domieszek pucolanowych na podatność na pękanie został także uwzględniony i udokumentowany. Wyniki badań pozwalają na korelację wyników skurczu uzyskanego w metodzie pierścieniowej z wynikami uzyskanymi w pomiarze skurczu swobodnego. Uogólniając, artykuł ten dowodzi, iż stosunek kruszywa grubego do piasku, a także ilość i rodzaj kruszywa grubego mają decydujący wpływ na skurcz betonów wysokowartościowych.

## 1. Introduction

Over the last decade, the use of High Performance Concrete (HPC) has emerged as an important alternative to deal with the deteriorating infrastructure. Many State Departments of Transportation implemented HPC into their infrastructure applications but with varying results in bridge deck performance to resist cracking. Many State Engineers have observed that a number of HPC bridge decks exhibited cracking and sometimes soon after being poured. Additionally, concrete in bridge decks is considered restrained and there is a need to examine the behavior of HPC mixes under restrained conditions. Thus, test results from free drying shrinkage alone are not sufficient to fully understand the cracking behavior of HPC.

Concrete cracking is one of the most critical issues that lead to deterioration of bridge decks, increasing maintenance costs, and shortening the overall service life. Although bridge deck cracking can be attributed to various causes (e.g., concrete deck pouring sequence, negative moment region in continuous bridges, improper curing and/or construction practices, etc.), in many cases, concrete shrinkage is considered the main contributor. Shrinkage cracking is not only related to the amount of concrete shrinkage but also to concrete's modulus of elasticity, tensile strength, and creep. Additionally, concrete in bridge decks is considered restrained and there is a need to examine the behavior of HPC mixes under restrained conditions. Thus, test results from free drying shrinkage alone are not sufficient to fully understand the cracking behavior of HPC.

There are four main types of shrinkage cracks: 1) autogenous, 2) drying, 3) carbonation, and 4) plastic shrinkage. Autogenous shrinkage is associated with the loss of water due to the hydration process of concrete at early-age and is considered relatively small compared to drying shrinkage. However, for HPC, autogenous shrinkage contributes quite significantly and in some cases (HPC with high volume silica fume) it could be as high as drying shrinkage [1÷5]. Thus, the autogenous shrinkage could no longer be disregarded for HPC. Drying shrinkage is the volume change in concrete due to drying and it occurs as soon as concrete is exposed to air. Drying shrinkage is unavoidable but the amount of drying shrinkage could be controlled by reducing the amount of cementitious material in the mix. Carbonation shrinkage occurs when the cement hydrate reacts with carbon dioxide present in the air. Carbonation shrinkage is very small and only occurs at early-age to fresh concrete. It could be controlled by covering the fresh concrete with protective plastic so that the cement hydrate would not react to carbon dioxide. Plastic shrinkage occurs when the rate of evaporation exceeds the bleeding rate or in other words the concrete dries too fast due to the combination of heat and wind of the surrounding area. Plastic shrinkage is more critical for HPC because HPC typically has a very low bleeding rate. However, it could be controlled by applying proper curing practice, i.e. moist curing [1].

The shrinkage cracks found on bridge decks are combinations of these types of shrinkage, i.e., early-age (autogenous, plastic, and carbonation) and long-term drying shrinkage, and can be measured under either restrained or unrestrained conditions. The unrestrained or free shrinkage is an easy measurement since there is no secondary component. The concrete specimen could be simply cast in a prism mold and the shrinkage could be obtained by measuring the change in length of the top to bottom of the specimen using a strain gage or any other measuring devices. On the other hand, restrained shrinkage requires secondary component to restrain the concrete specimens. There are many methods that have been developed to restrain the concrete [2÷10], but only the ring method has been adopted by the American Association of State Highway and Transportation Officials (AASHTO PP 34) because of its simplicity. However, this test is not as straight forward in comparison to the free shrinkage test since there is no readily available manufacturer of the test apparatus. Moreover, the test does not quantitatively describe the properties of concrete but rather just an indicator of the age that the concrete cracks. Thus, an attempt is made in this paper to quantify the stress development in the restrained concrete ring as well as determining the relationship between the unrestrained and restrained shrinkage such that the unrestrained shrinkage can be used for quality control.

The objective of this paper is to present results of a study [11] employed to define and compare the cracking potential of common high performance concrete (HPC) mixes used in bridge decks by the New Jersey Department of Transportation (NJDOT). This study provides guidance and recommendations to selecting HPC mixes with lower cracking potentials. Basic properties to be investigated include compressive strength, tensile splitting strength, modulus of elasticity, unrestrained (i.e., free) drying shrinkage and restrained shrinkage. A total of 16 mixes from various bridge deck projects are selected and provided by NJDOT. The water to binder ratio ranges between 0.34÷0.40 and the majority of the mixes have slag as a replacement for cement. Mixes are grouped according to the cement replacement percentages. Two main groups are 30% and 40% slag replacement. Remaining mixes have varying percentages of slag, silica fume and fly ash as cementitious replacements. Also, source of coarse and fine aggregates, as well as type and manufacturer of chemical admixtures are varied within groups of mixes. This forms a complex matrix of variables by which the effects of most sensitive parameters can be determined.

## 2. Experimental program

To measure restrained shrinkage, concrete is cast around a steel ring in accordance with the test method of AASHTO PP34. Figure 1 shows the schematic diagram and picture of the test setup, respectively. The steel ring has an inner diameter of 279 mm (11 in.), an outer diameter of 305 mm (12 in), and a height of 152.5 mm (6 in). The concrete wall thickness is 75 mm (3 in.). The concrete is cast around the steel ring, such that as the concrete shrinks, a compressive stress is developed in the steel ring and balanced by a tensile stress in the concrete ring. If this tensile stress is greater than the allowable tensile stress of the concrete, it cracks. The cracks in the ring are monitored daily using a crack microscope. In addition, four foil strain gages (FSG) are instrumented at mid-height of the inner surface of the steel ring (Fig. 1a) so that abrupt changes in the steel strain can signal the age of cracking. The strain readings are recorded by using a data acquisition system. Moreover, two arrangements for the vibrating wire strain gages (VWSGs) are installed at the top surface of the concrete ring using threaded bolts. The configuration shown in Figures 1a and 1b included placing six VWSG's in a closed hexagon-shape configuration. The six-VWSG arrangement was used in the majority of the mixes since it was found to be more encompassing and accurate in recording the crack location and in measuring the strain in the concrete.

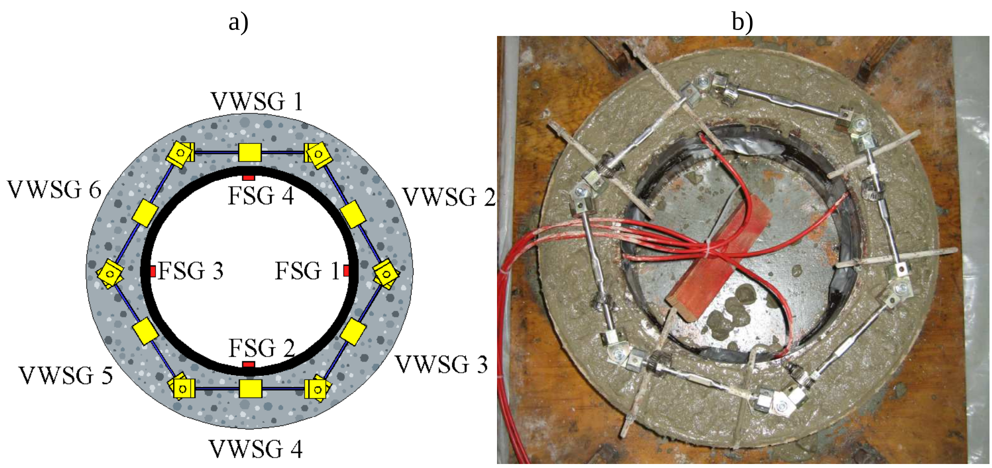


Figure 27 Ring Test Set-up: a) Schematic diagram, and b) picture of the restrained shrinkage test setup with six VWSG Arrangement

The advantage of using VWSGs is that the early-age shrinkage of concrete is also being monitored and therefore, if the concrete does not crack the concrete stress development can be quantified.

In addition to the restrained shrinkage tests, free shrinkage and other tests to measure the concrete properties are also conducted. The free shrinkage test is conducted in accordance with American Society of Testing and Materials (ASTM) C157 using three 76×76×279 mm (3×3×11 in) prism molds. Other tests are compressive strength, modulus of elasticity, and tensile splitting tests, which are all performed in accordance to ASTM standards, i.e., ASTM C39, ASTM C469, and ASTM C496.

Table 1 shows typical mix parameters used in Group 1. Group 1 has three mixes with 40% slag and various percentages of coarse aggregate. Other mixes (13) were also considered but are not shown in this paper for brevity.

***Data Collection and Analysis***

Data collection is done using a data acquisition system (DAS) manufactured by Campbell Scientific, Inc. Figure 2 shows the DAS that is installed permanently into the environmental chamber where all the specimens are stored and monitored at a controlled relative humidity of 50% and temperature of 23°C (74°F). It is equipped with strain gage modules that are able to monitor 12 rings simultaneously. For the specified mixes, the DAS was programmed to collect data at 5 minutes intervals and to download the data to a permanent computer every 24 hours.

Table 4 Group 1 Mix Design Proportions

| (kg/cu.m) | | | |
|---|---|---|---|
| Mix Designation | G1M1 | G1M2 | G1M3 |
| Portland Cement | 285 | 234 | 235 |
| Type | I | I | I |
| Silica Fume | 0 | 0 | 0 |
| Fly Ash Class F | 0 | 0 | 0 |
| Slag | 190 | 156 | 157 |
| | 40% | 40% | 40% |
| Total Cementitious Content | 475 | 390 | 392 |
| Course Agg. (No. 57) | 979 | 1700 | 1875 |
| Fine Agg. | 736 | 711 | 709 |
| Course Agg./Fine Agg. | 1.33 | 1.42 | 1.57 |
| Water (liters) | 145.0 | 118.1 | 120.0 |
| W/(C+P) | 0.4 | 0.4 | 0.4 |
| Water Reducer (oz/cwt) | 2.3 | | 3.5 |
| Retarder | | | |
| Superplasticizer (oz/cwt) | 19.9 | 8.4 | 13.4 |
| AEA (oz/cwt) | 1 | 0.7 | 1 |
| Slump (in) | 152.4 | 139.7 | 203.2 |
| Air Content (%) | 6.4 | 7.5 | 4 |

The recorded data is monitored and plotted every two to three days to check for sudden jumps in strain readings (which may signal cracking). In addition to data collected from the rings, ASTM tests such as compressive strength, tensile splitting strength, and elastic modulus tests are done at various ages (Day 3, 7, 14, 28 and 56). Also, gradual increase in strain is monitored and plotted against the cracking strain to quantify the cracking potential of each mix. Cracking strain of each mix is obtained from the results of standard cylinder tests as follows.

$$\varepsilon_t = \frac{f_t}{E}$$

$f_t$:Tensile splitting strength, $E$: Modulus of elasticity, $\varepsilon_t$: Cracking Strain

Figure 28 **Data Acquisition System**

After 91 day period ends, an evaluation is made whether to continue collecting readings from the rings or not. If the strain values in the foil gages and VWSG have stabilized it means that shrinkage has come to a stop and the test can be finalized. This can also be checked by examining the length comparator readings from the free shrinkage blocks. If the free shrinkage has ended and the concrete has not cracked after 91 days it is concluded that it will not crack. However, if the readings are changing and increasing strains are observed in the rings, the tests are extended beyond 91 days.

Figure 3 summarizes the restrained shrinkage test and data analysis procedure. Readings are obtained from DAS and graphed every two to three days. Any sensor which shows close to or higher than cracking strain signals a crack (In the case below VWSG 4 exceeds cracking strain first and the picture shows the observed crack). The first 7 days, where there is no tensile strain development, is the curing duration and when analyzing results strain measurements are started from initiation of drying.

## 3. Results

Figure 4 illustrates that although mixes G1M2 and G1M3 have the same amount of cement, there is a difference in their compressive strength which is attributed to the higher aggregate content included in mix G1M3. It was also observed that all the mixes attained 80% or more of their strength at day 14 with a 5% increase in strength beyond 28 days. This is typical for slag mixes since it is more reactive than ordinary cement.

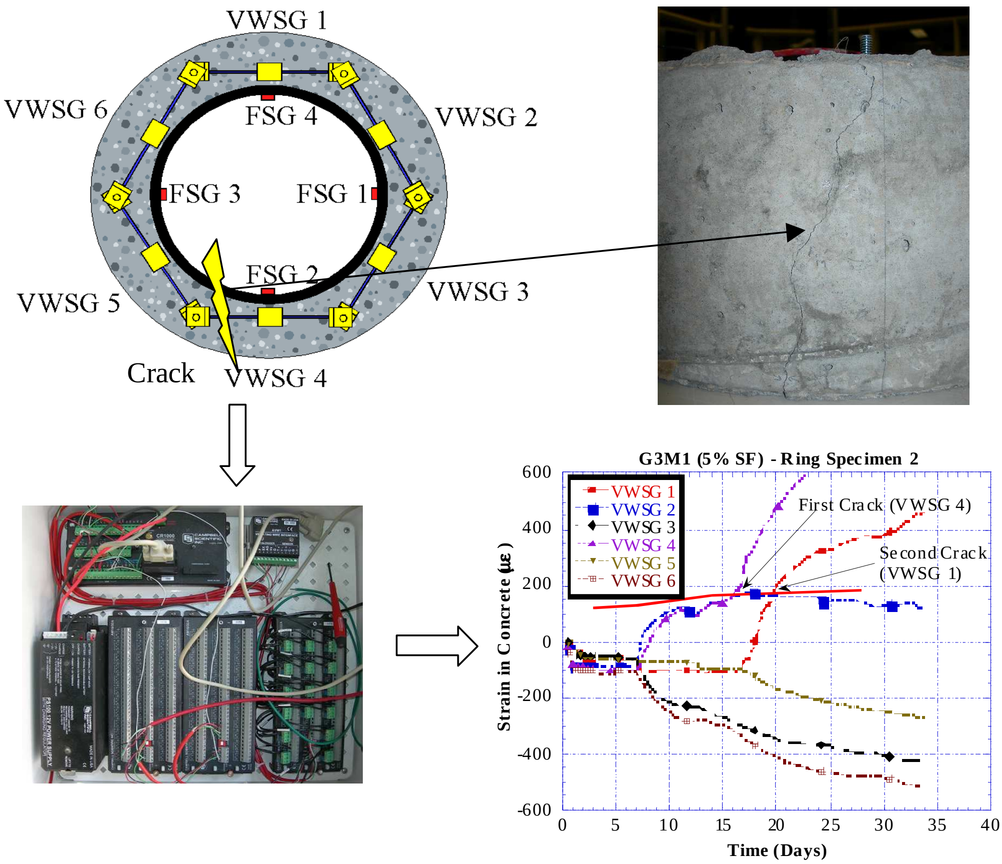


Figure 29 Schematic of the restrained shrinkage test setup, data collection schemes, and test results

It is also observed that the major factors affecting shrinkage are cementitious content, percentage of cementitious materials, w/c ratio, coarse aggregate content, and C/F ratio. Considering all these variables, it is expected that mix G1M2 would experience more shrinkage than mix G1M3 since the total aggregate content in its composition is lower.

Figure 5 shows the splitting tensile strength for all three mixes. The tensile strength has a similar in trend to that of the compressive strength.

G1M2 and G1M3 are 40% slag mixes and their mix proportions are shown in Table 1. The only difference between the two mixes is the amount of coarse aggregate used (therefore the C/F aggregate ratio). Figures 6 and 7 compare the free shrinkage, and average steel strain, respectively. Although the steel strains observed are similar as shown in Figure 7, the strain observed in the concrete is much different for the two mixes. G1M3 only used 37% of its capacity in tension where as G1M2 cracked at day 14 and strains continued to increase which means that the crack was expanding.

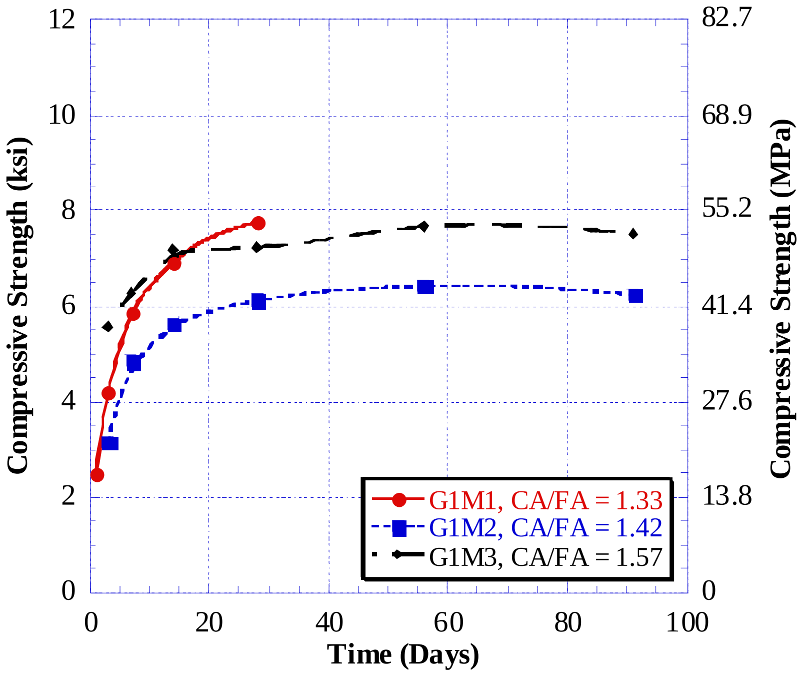


Figure 30 Compressive Strength of Group 1 Mixes

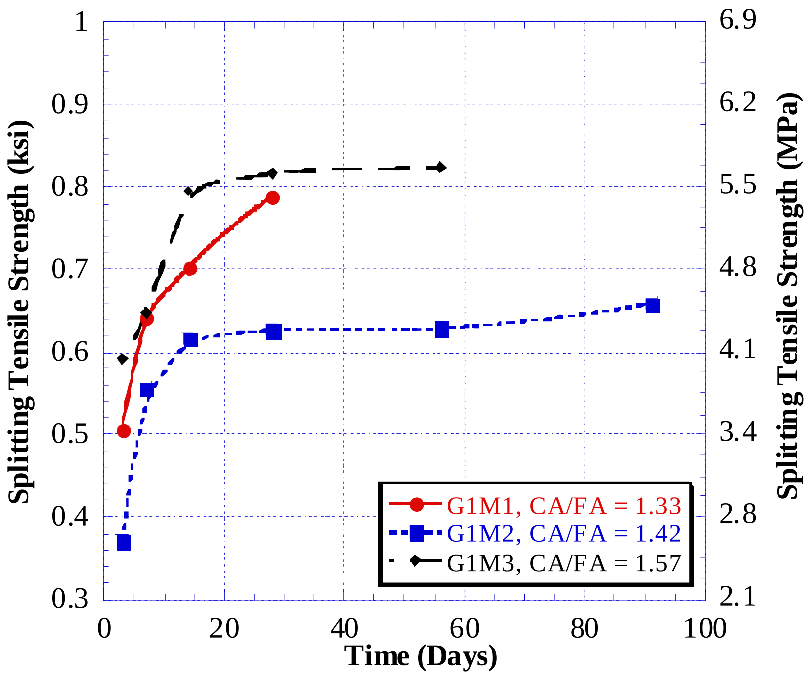


Figure 31 Splitting Tensile Strength of Group 1 Mixes

At the end of 150 days free shrinkage of G1M3 is considerably less than free shrinkage of G1M2. The affect of C/F aggregate ratio is therefore clear. For a given cementitious content and w/c ratio, increasing the total amount of coarse aggregate, and therefore the C/F ratio, will decrease the cracking potential of a concrete mix considerably. This point is further supported in Figure 9 which illustrates a comparison of the cracking potential of both mixes and suggests that the effect of the CA/FA ratio has a major effect on the restrained shrinkage.

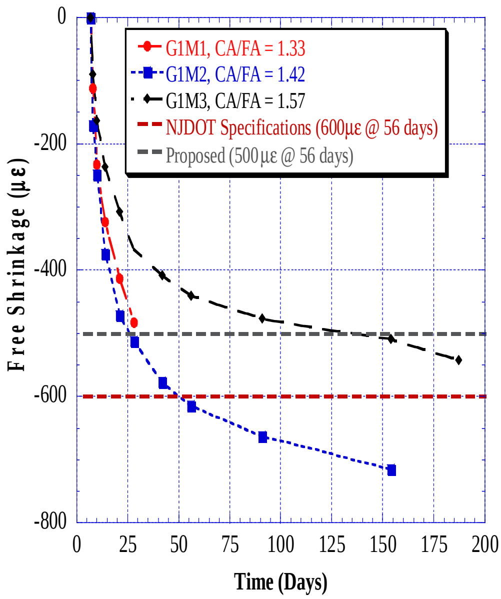


Figure 32 **Free Shrinkage Comparison of Group 1 Mixes**

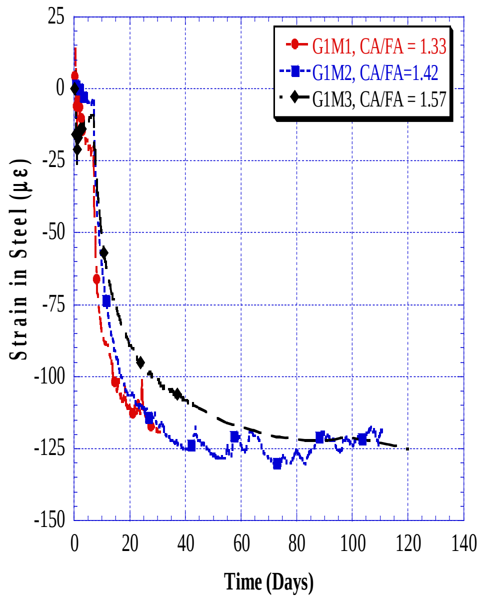


Figure 33 **Steel Strain Comparison of Group 1 Mixes**

Correlation of Cracking Potential with Aggregate Content and CA/FA RatioFigure 34 shows the relationship between CA/FA ratio and the Cracking Ratio under restrained shrinkage conditions is rather weak when all mixes are taken into account. Figure 9 shows that the majority of the mixes that did not crack have coarse aggregate contents of 1098 kg/cu.m (1850 lbs/cu.yd) or more, and almost all of the mixes which have 1038 kg/cu.m (1750 lbs/cu.yd) or less experienced cracking.

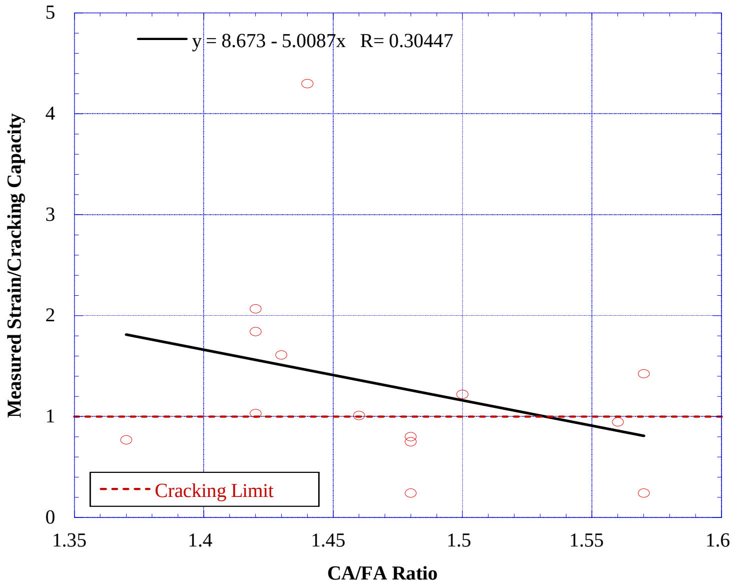


Figure 34 **CA/FA Ratio vs. Cracking Ratio**

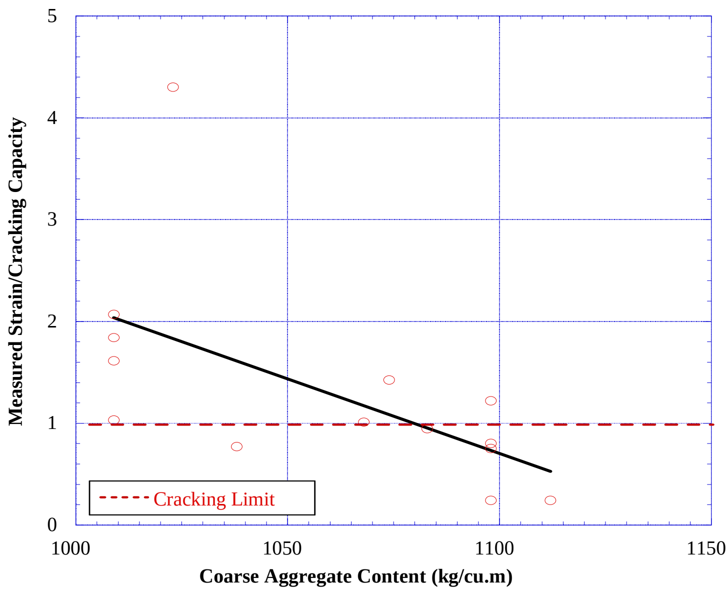


Figure 35 Coarse Aggregate Content vs. Cracking Ratio

## 4. Conclusions

This paper presents a qualitative method for measuring the concrete strains in the AASHTO PP34 restrained shrinkage test (Ring test). The modified method provides not only the day in which the concrete cracks but also the strain and stress levels in concrete at the onset of cracking. The following conclusions could be made:

1. The modified method presented in this paper can be used to detect concrete cracking age, as well as the cracking stresses.
2. The results show that the coarse aggregate content as well as the CA/FA ratio has the greatest effect on both free and restrained shrinkage. There was a significant reduction in free shrinkage of mixes having high CA/FA ratios and relatively high coarse aggregate contents (e.g., 1068 kg/cu.m (1800 lbs/cu.yd)) compared to similar mixes with lower ratios and total coarse aggregate content. Also, all mixes that did not exhibit any cracking in the restrained shrinkage test had coarse aggregate contents of 1098 kg/cu.m (1850 lbs/cu.yd) or more and the CA/FA ratio was equal to or higher than 1.48.
3. In the light of observations made in this study, to reduce the potential of restrained shrinkage cracking of an HPC mix, coarse aggregate content should be increased to give a high CA/FA ratio (preferably higher than 1.50). This would help in reducing the ultimate shrinkage and also would reduce the rate at which shrinkage takes place. Mixes that experience more than 500 micro-strains at 56 days are not recommended, since all such mixes cracked under restrained ring test shortly after initiation of drying. Also, maximum percentage of silica fume utilized in a mix should be limited to 5 percent.

## References

1. Nassif, H. H., Suksawang, N., Mohammed, M., “Effect of Curing Methods on Early-Age and Drying Shrinkage of High-Performance Concrete,” Transportation Research Record: Journal of the Transportation Research Board, No. 1834, TRB, National Research Council, Washington, D.C., 2003, pp. 48÷58.
2. Li, Z., Qi, M., Li, Z., and Ma, B., “Crack Width of High-Performance Concrete Due to Restrained Shrinkage,” Journal of Materials in Civil Engineering, Vol. 11, No. 3, August, 1999, pp. 214÷233.
3. Weiss, J. W., Yang, W., and Shah, S. P., “Shrinkage Cracking of Restrained Concrete Slabs,” Journal of Engineering Mechanics, Vol. 124, No. 7, July. 1998, pp. 765÷774.
4. Grzybowski, M., and Shah, S. P., “Model to Predict Cracking in Fiber Reinforced Concrete due to Restrained Shrinkage,” Magazine of Concrete Research, Vol. 41, No. 148, September, 1989, pp. 125÷135.
5. Kraai, P.P., “A Proposed Test to Determine the Cracking Potential due to Drying Shrinkage of Concrete,” Concrete Construction, Vol. 30, September 1985, pp. 775÷778.
6. Wiegrink, K., Marikunte, S., Shah, S. P., “Shrinkage Cracking of High Strength Concrete,” ACI Material Journal, Vol. 93, No. 5, Sep.-Oct., 1996, pp. 409÷415.
7. Mokarem, D.W., Weyers, R.E., and Lane, S. “Development of Performance Specification for Shrinkage of Portland Cement Concrete,” Transportation Research Record: Journal of the Transportation Research Board, No. 1834, TRB, National Research Council, Washington, D.C., 2003, pp. 40÷47.
8. Hossain, A. B., and Weiss, J., “Assessing Residual Stress Development and Stress Relaxation in Restrained Concrete ring Specimens,” Cement and Concrete Composite, Vol. 26, No. 5, July, 2004, pp. 531÷540.
9. Hossain, A. B., Pease, B., Weiss, J., “Quantifying Early-Age Stress Development and Cracking in Low Water-to-Cement Concrete,” Transportation Research Record: Journal of the Transportation Research Board, No. 1834, TRB, National Research Council, Washington, D.C., 2003, pp. 24-32.
10. Collins, F., and Sanjayan, J. G., “Cracking Tendency of Alkali Activated Slag Concrete Subjected to Restrained Shrinkage,” Cement and Concrete Research, Vol. 30, 2000, pp. 791÷798.
11. Nassif, H., Aktas, K., Suksawang, N., and Najm, H. (2007) “Concrete Shrinkage Analysis for bridge Decks,” FHWA-NJ-2007-010, Draft Report, New Jersey Department of Transportation, 96 pp.