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Effect of External Loading on Durability Properties of Pre-Stressed Concrete Girders with Microcracking

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ABSTRACT

Over the last fourteen years, very early in the service life of pre-stressed concrete girders, unexplained microcracks have been observed. Their presence led to concerns about the future integrity of the girders, with one of the major concerns being corrosion of pre-stressing strands. As such, a comprehensive study aimed at understanding the effects these microcracks have on the service life of the girders was initiated. Eight in-service girders, under external loads, and five rejected girders, not under external loads, were selected for the study. In this paper, we present work on the temporal evolution of the cracks during a one-year period. Two field visits were conducted to each girder, approximately one year apart, and the cracking index, crack width, strain measurements, surface resistivity and ultrasonic pulse velocity were measured. It was expected that the effects of external loads would lead to a more significant loss in durability. However, the results showed that exposure conditions and presence of pre-existing cracks had a more significant impact on the loss in durability than the presence of external loading.

Keywords: Early-Age Microcracks, In-Service Girders, Low Water-Cementitious Ratio Concrete, Cracking Index, Durability, Pre-Stressed

1.0 INTRODUCTION

Over the last fourteen years, microcracks have appeared in numerous in-service, pre-stressed concrete girders across Texas at relatively early ages, e.g., within thirteen to eighteen months of casting. The crack pattern initially appeared in a "starburst" pattern and with continued exposure to the environment progressed into map cracking (Stacy, 2016; Tiburzi, Drimalas, & Folliard, 2017). Figure 1 shows a typical example of the microcracks.

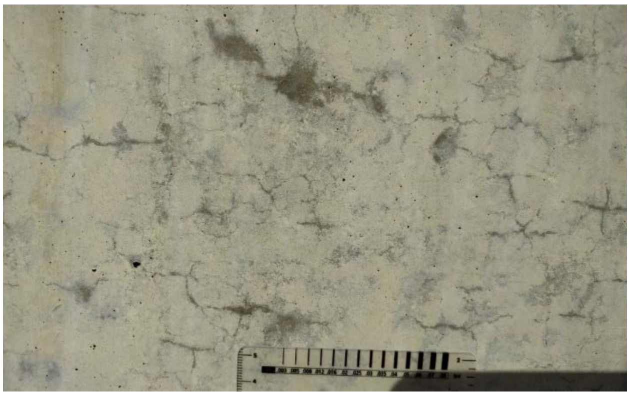

Fig. 1. Typical micro-cracks exhibited in girders with a crack ruler shown in the bottom of the photo

Cracking in concrete occurs as a result of volumetric changes being restrained which causes the stresses induced by the cracks to exceed the intrinsic strength of the concrete. Thus, understanding the mechanism responsible for volumetric changes (e.g., shrinkage, alkali-aggregate reaction, settlement, corrosion, etc.) is essential to prevent it. The mechanism behind the cracks found in Fig. 1 is not fully understood yet. The cracks appeared outside of the regular time-period of plastic shrinkage cracks, and they did not show the telltale signs of an alkali-silica reaction and corrosive products were negligible (Tiburzi *et al.*, 2017). Due to the low water-to-cementitious-material (w/cm) ratio of these concrete girders, the influence of autogenous shrinkage was studied and subsequently ruled out as a possible cause (Stacy, 2016).The cause of cracking is most likely material-related, as the microcracks developed before the girders were put in-service and had occurred while still in the pre-cast yards. Presence of microcracks has been shown to accelerate the ingress of deleterious material into the concrete and in turn accelerate the deterioration process of concrete structures (Benoit, Marc-André, Kevin, & Thomas, 2010; Wang & Bai, 2016). Regardless of the driving mechanism, the presence of the cracks led to concerns about the future integrity of the girders and questions about whether the maintenance program (in both schedule and cost) of pre-cast girders in-service needs to be changed have arisen.

American Concrete Institute's Building Code (ACI 318, 2017) defines structural cracks as cracks wider than 3 mm. The effects of structural cracks have been studied extensively (Allam, Shoukry, Rashad, & Hassan, 2012; Ospina, 2012). The temporal behavior of microcracks on in-service pre-cast concrete girders with low w/cm ratios have not been studied as much.

Various definitions for *microcracks* have been used in literature. According to the American Concrete Institute Committee 224R-01 report on Control of Cracking in Concrete Structures (ACI 224R, 2001), the term *microcracking* is used to refer to cracks that form at coarse-aggregate boundaries (bond cracks) and propagate through the surrounding mortar (mortar cracks). Other researchers have defined microcracks as cracks with crack widths smaller than 50 μm (Bisschop & Van Mier, 2002; Shiotani, Bisschop, & Van Mier, 2003). The RILEM committee on microcracking and lifetime performance of concrete suggested the use of the term microcracks for cracks with a crack width of less than 10 µm (Damgaard Jensen & Chatterji, 1996). F.O. Slate (Slate, 1983) defined an upper limit of 0.1 mm width, and a lower limit would be the smallest crack-like discontinuity that can be detected (approximately 6 μm). For this study microcracks were defined as cracks with crack widths ranging from 6 to 50 μm.

Researchers have shown that durability of concrete can worsen when subjected to cyclic and/or sustained loading (Otieno, Beushausen, & Alexander, 2016; Yu, François, Dang, L'Hostis, & Gagné, 2015). The goal of this study was to investigate the change in magnitude and extent of cracks, strain and ultrasonic pulse velocity and surface resistivity, over approximately one year, of girders that were under "external loads" and girders not under external loads. "External loads" in this context was used to express vehicular, pedestrian, and other live loads generally subjected to in-service girders. The relative change in the durability parameters can be used to assess if the loss in durability would be exacerbated under external loading.

2.0 MATERIALS AND METHODS

The following section describes the selection process for girders and tests conducted on the girders.

2.1 Selection of Girders

The girders tested were selected based on accessibility and extent of cracking. The goal was to select girders exposed to different exposure conditions and degrees of cracking across Texas, USA. Two rounds of field visits were conducted approximately one year apart, and non-destructive tests performed on each test girder. Only non-destructive tests such as measurement of crack width and number of cracks, change in strain, pulse velocity and surface resistivity were conducted, as coring was prohibited for safety reasons and to avoid damage to the girder's structural integrity. It was expected that the change in crack width and count, strain, pulse velocity and surface resistivity over one year would indicate the difference in the condition of the girders.

The following girders were selected for the study:

- Four *rejected* girders (R1, R2, R3, and R4 in Table 1) were selected for observation. The girders were rejected by clients and/or by Texas Department of Transportation engineers for use in projects due to the presence of extensive microcracking visible to the naked eye. Tests on the girders were conducted at the pre-cast yard they were cast at and stored. These girders were not under external loads.
- Six *in-service* girders (I1, I2, I3, I4, I5, and I6 in Table 1) that are currently in use and were examined in the field at the location where they were installed. These girders had visible cracking and were under external loads. It was unclear as to when the cracks appeared, however, these girders were found to exhibit microcracking during inspections conducted by Texas Department of Transportation engineers.
- One rejected girder (RC in Table 1) and two in-service girders (IC1 and IC2 in Table 1) exhibiting negligible cracking were also selected to serve as control specimens. These girders with negligible cracking are henceforth referred to as *un-cracked*.

2.2 Visual Survey

A thorough visual survey was conducted on each girder according to American Concrete Institute's *Guide for Conducting a Visual Inspection of Concrete in Service* (ACI 201.1R, 2016). Photographs were taken to document the visible changes in the girder's condition.

Table 1 gives information regarding exposure conditions, test dates, as well as details about locations, mixture designs, and constituents of each girder. Photographs were taken during both site visits to compare significant changes in cracking magnitude and pattern. Additionally, the following data were recorded for each girder:

- Description of structure: location, type, size, and loading conditions
- Materials: mix design, admixtures, aggregate, and cementitious materials used
- Environmental condition: exposure, orientation, drainage, and soil conditions
- Distress indicators: cracking, staining, surface deposits, and leaking
- Cracking: location and frequency, type of cracking, crack map, width, and pattern

2.3 Selection of Testing Locations on Girders

<u>Rejected Girders</u>
Six locations on each girder were selected for further non-destructive testing. As detailed in Table 1, the youngest rejected girder was 6.9 years old while the

Table 1. Description of Girders and Exposure Conditions

Girder Type	Rejected					In-Service							
Girder	**R1**	**R2**	**R3**	**R4**	**RC**	**I1**	**I2**	**I3**	**I4**	**I5**	**I6**	**IC1**	**IC2**
Age (Years)	13.8	8.5	6.9	7.0	10.9	11.5	10.8	11.5	11.5	10.8	10.8	11.5	10.8
Years in Service	-	-	-	-	-	8	7	8	8	7	7	8	7
Extent of Cracking	Extensive	Extensive	Extensive	Extensive	Negligible	Extensive	Extensive	Extensive	Extensive	Extensive	Extensive	Negligible	Negligible
Climate[1]	Humid	Semi-Arid	Humid	Semi-Arid	Humid	Humid-Subtropical	Semi-Arid	Humid-Subtropical	Humid-Subtropical	Semi-Arid	Semi-Arid	Humid-Subtropical	Semi-Arid
Visit Interval (Days)	344	315	252	315	252	366	345	366	366	345	345	366	345
Girder Type[2]	Tx54	Type IV	Type IV	Tx54	Type IV	Type IV	Type IV	Type IV	Type IV	Type IV	Type IV	Type IV	Type IV
W/CM	0.28	0.28	0.30	0.30	0.28	0.36	0.33	0.36	0.36	0.33	0.33	0.36	0.33
Cementitious Materials[3]	T3 FA	T3+FA	T3+FA	T3+FA	T3+FA	T3	T3	T3	T3	T3	T3	T3	T3
Aggregate Type[4]	RG	RG	RG	LS	RG	RG	RG	RG	RG	RG	RG	RG	RG
HRWR oz/100lbs[5]	6	6	5.25	5.25	10	9	10	9	9	10	10	9	10
Retarder oz/100lbs[6]	3	2.5	1.25	1.5	3	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5

1. As obtained from the National Centers for Environmental Information (NCEI, 2017)
2. Tx54, Type IV – Girder types as specified by Texas Department of Transportation (TxDOT, 2017)
3. T3- Type III Cement as specified by *ASTM C150-2017, Standard Specification for Portland Cemen*t (ASTM C150, 2017)
   FA – ASTM Class F Fly Ash as specified by *ASTM C618-2017, Standard Specification for Coal Fly Ash and Raw or Calcined Natural Pozzolan for Use in Concrete* (ASTM C618, 2017)
4. RG – River Gravel
   LS - Limestone
5. HRWR - Polycarboxylate based high range water reducer and superplasticizer as specified by *ASTM C494-2017, Standard Specification for Chemical Admixtures for Concrete* (ASTM C494, 2017)
6. Retarder - Water-reducer and retarder as specified by *ASTM C494-2017, Standard Specification for Chemical Admixtures for Concrete* (ASTM C494, 2017)

oldest rejected girder was 13.8 years old. Upon arriving at the pre-cast yards, it was found that the girders were stored in such a way that one side was exposed to the environment (Fig. 2a), while the other side was relatively protected from the elements by neighboring elements (Fig. 2b). The pre-cast yards were requested to maintain this exposure condition for all girders selected for monitoring. As such, the side exposed to the environment was referred to as "Exposed" and the other side as "Sheltered." However, it must be noted that the tops of the rejected girders were exposed to the environment. Each girder was further divided into "End" and "Middle" sections (Fig. 3c). The ends of the girders had pre-stressing release cracks, typically found in the end regions of precast beams due to the highly localized force applied to the girder during the release of the pre-tensioned forces (Okumus & Oliva, 2013). Fig. 3b shows a typical rejected girder with pre-stressing release cracks on the girders, traced in red (Fig. 3a). Fig. 3c shows a typical rejected girder with test locations marked as "End" and "Middle".

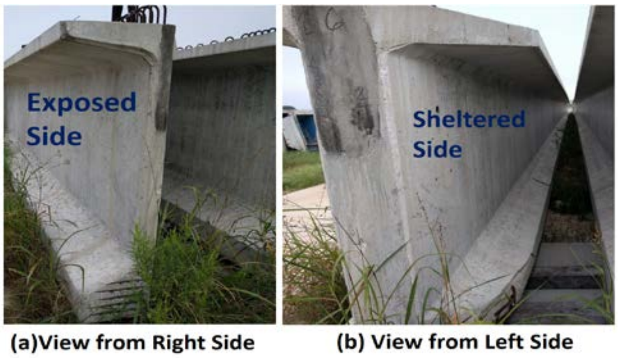

Fig. 2. Photos of a typical rejected girder showing (a) exposed side and (b) sheltered sides

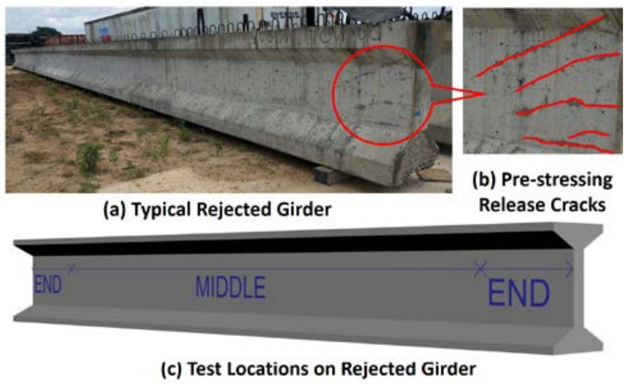

Fig. 3. (a) Typical Rejected Girder showing (b) prestressing release cracks and (c) pictorial representation of end and middle sections of girder

<u>In-Service Girders</u>

These girders are being used in the superstructure of in-service bridges. Due to limited accessibility (e.g., accessing the middle of a beam is difficult when it is on a high overpass), four locations on each in-service girder were selected for non-destructive testing. Some girders were exterior girders and were exposed to the elements more readily than the interior girders (Fig. 4a). Each girder was further divided into "End" and "Middle" sections (Fig. 4b). Like the rejected girders, the ends of the girders have pre-stressing release cracks. It was found that the outside surfaces of the exterior girders were painted (Fig. 5a). In this paper, the measurements taken on the exposed side of the exterior girders are referred to as "Exposed" whereas the measurements taken on interior girders and the un-exposed side of the exterior girders are referred to as "Sheltered" (Fig. 5b).

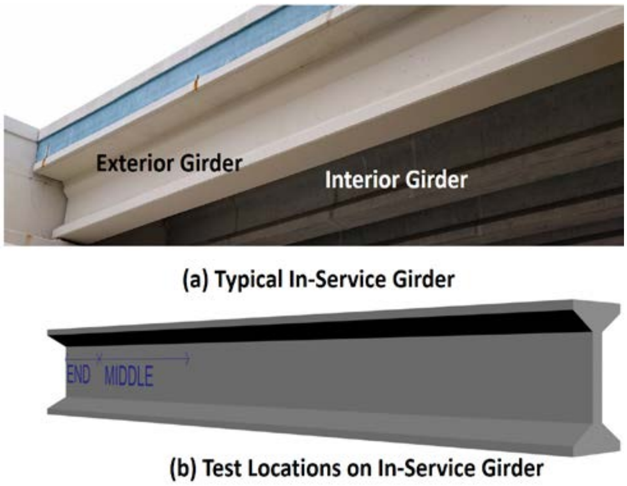

Fig. 4. Typical In-Service Girder showing exterior and interior girders

Fig. 5. In-service girder showing (a) exposed side and (b) sheltered side. Notice the exposed girder has been painted.

2.4 Crack Indexing and Strain Measurement

The extent of surface cracking in concrete elements is related to the overall amount of expansion or shrinkage reached by the affected concrete member (Shah & Chandra, 1968). Multiple studies using crack width to indicate cracking severity have been conducted; however, measuring only crack width cannot provide accurate data on the extent of cracking. FHWA HIF-09004 report on ASR mitigation (Benoit *et al.*, 2010) suggests a method for evaluating the extent of cracking and volumetric change in concrete members by calculating the "cracking index", calculating the average crack width, and measuring the change in strain using a demountable mechanical (DEMEC) gauge.

200 x 200 mm cracking index grids were set up at each test location on the girders, and the cracking index and average crack width were calculated, according to the method prescribed in the FHWA HIF-09004 (Benoit *et al.*, 2010) report. Change in strain was measured by installing DEMEC points at the corners of each cracking index grid, and strain measurements were made using a DEMEC strain gauge, according to the FHWA HIF-09004 report (Benoit *et al.*, 2010). Fig. 6 shows typical regions on an (a) extensively cracked girder and a (b) negligibly cracked girder at 50X magnification.

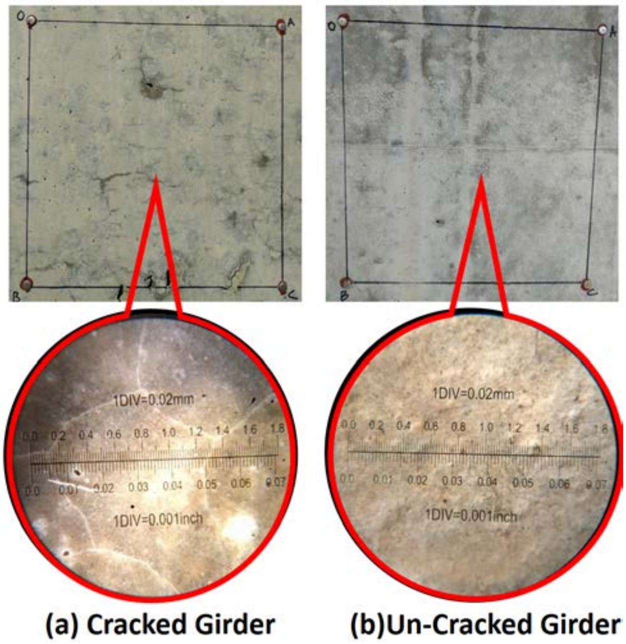

Fig. 6. Typical regions on an (a) extensively cracked and (b) un-cracked girder as visible to the naked eye (top row of photos) and at 50X magnification (shown in the circled call-out)

2.5 Ultrasonic Pulse Velocity (UPV)

While the in-situ condition of concrete is best determined by sampling cores and laboratory testing, coring is not always feasible, as in this case. As per ASTM C597, Standard Test Method for Pulse Velocity Through Concrete (ASTM C597, 2016), the pulse velocity of longitudinal stress waves in a concrete mass is related to its elastic properties and density. Studies have shown that UPV can be used an indicator of Modulus of Elasticity and Compressive Strength of concrete (Chien-Chih Wang & Her-Yung Wang, 2017). Other studies have shown the effectiveness of using UPV as a measure of in-situ concrete quality (Angelo Masi & Vincenzo Manfredi, 2016). The UPV test method can also be used to assess the uniformity and relative quality of concrete;

to indicate the presence of voids and cracks and changes in the properties of concrete; and in the survey of structures, to estimate the severity of deterioration or cracking. Higher pulse velocity in concrete indicates better homogeneity, i.e., higher quality concrete will have shorter wave travel time and subsequently higher velocity. The test can also be used to monitor changes in condition over time when test locations can be marked on the structure and tests are repeated at the same positions (ASTM C597, 2016). UPV measurements were taken at the location of each cracking index grid according to the ASTM C597, Standard Test Method for Pulse Velocity Through Concrete (ASTM C597, 2016).

2.6 Surface Resistivity

The electrical resistivity of a material describes its ability to withstand the transfer of charge. Resistivity represents the ratio between applied voltage and resulting current multiplied by a cell constant. Thus, a concrete member with higher resistivity would have a higher resistance to corrosion. However, measuring surface resistivity as an absolute value might not yield satisfactory results, due to the high scatter observed in correlation data between corrosion rate and resistivity (Hornbostel, Larsen, & Geiker, 2013). However, the test can be used to monitor changes in condition over time when test locations can be marked on the structure and tests are repeated at the same positions (Gowers & Millard, 1999). Surface resistivity has been used as an indicator of concrete durability for in-situ concrete members successfully by various researchers (Kevern *et al.*, 2016). Surface resistivity has been shown to have good correlations with bulk resistivity (Ghosh & Tran, 2015) and rapid chloride penetration test values (Ramezanianpour, Pilvar, Mahdikhani, & Moodi, 2011). Surface resistivity was measured according to AASHTO TP119-15, Standard Method of Test for Surface Resistivity Indication of Concrete's Ability to Resist Chloride Ion Penetration (AASHTO TP119, 2015). While the standard was prescribed for use on cylinders and cores, the method was modified according to the method suggested by Gowers and Millard (Gowers & Millard, 1999) for the surface of the girders. The girder was sprayed with one liter of water before each measurement to achieve surface saturation.

2.7 Data Analysis

Increase in cracking index, average crack width, and shrinkage indicate the increase in overall cracking in the girder. In this study, decrease of pulse velocity has been used an indicator of deterioration in elastic properties and density of concrete while decrease in surface resistivity has been used as an indicator of reduction in corrosion potential.

Due to logistical reasons, it was not possible to collect the temporal data precisely one year apart. To account for this difference in time intervals between field visits, as well as the variations in the material properties arising from different ages and compositions, the following method of data analysis was used:

- Average values for each parameter (i.e., cracking index, average crack width, change in strain, UPV and surface resistivity) were calculated.
- The average values for the parameter of interest vs. time interval curves were created, and the slope of the curve was calculated.
- The slope represents the average value of the parameter per day (i.e., parameter/day) was then used as an indicator of the effective change in the parameter over the time interval.

3.0 RESULTS AND DISCUSSIONS

This section reports the temporal changes in cracking index, average crack width, strain measurements, surface resistivity, and ultrasonic pulse velocity of the test girders.

3.1 Comparison of Rejected and In-Service Girders

All girders showed an increase in the cracking index and average crack width indicating that the microcracks were widening and increasing in number with time as seen in Fig. 7. The girders also showed a decrease in the pulse velocity and surface resistivity indicating a loss in durability as seen in Fig. 8. Change in strain showed that there was shrinkage in all girders, as seen in Fig. 9.

Fig.s 7, 8 and 9 use the following designations:

- R- Average values of all rejected cracked girders (R1, R2, R3, and R4).
- RC- Average values of the rejected control girder (RC).
- I- Average values of all in-service cracked girders (I1, I2, I3, I4, I5, and I6).
- IC- Average values of all in-service control girders (IC1 and IC2).

As the in-service girders were under the influence of external loads, they were expected to exhibit a higher loss in durability than the rejected girders, which were not under the influence of external loads. However, it was seen that in general, the rejected girders showed a higher loss in durability than the in-service girders. The rejected girders had a larger increase in cracking index (Fig. 7a) and average crack width (Fig. 7b). Additionally, the rejected girders also had a higher reduction in pulse velocity (Fig. 8a) and surface resistivity (Fig. 8b). Figure 9 shows that the rejected girders had higher shrinkage than the in-service girders. An increase in cracking index, average crack width and strain suggested an increase in overall cracking, the decrease in pulse velocity indicated a decrease in concrete quality, and the decrease in surface resistivity indicated a decrease in corrosion resistance.

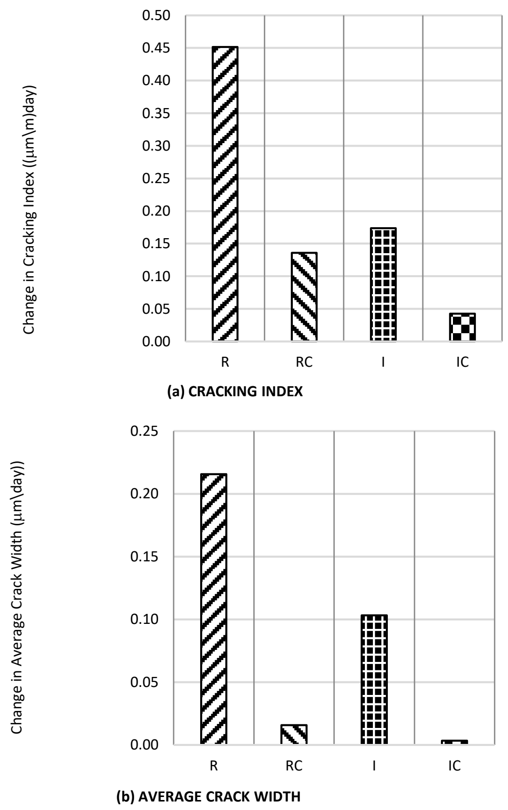

Fig. 7. Change in (a) Cracking Index and (b) Average Crack Width

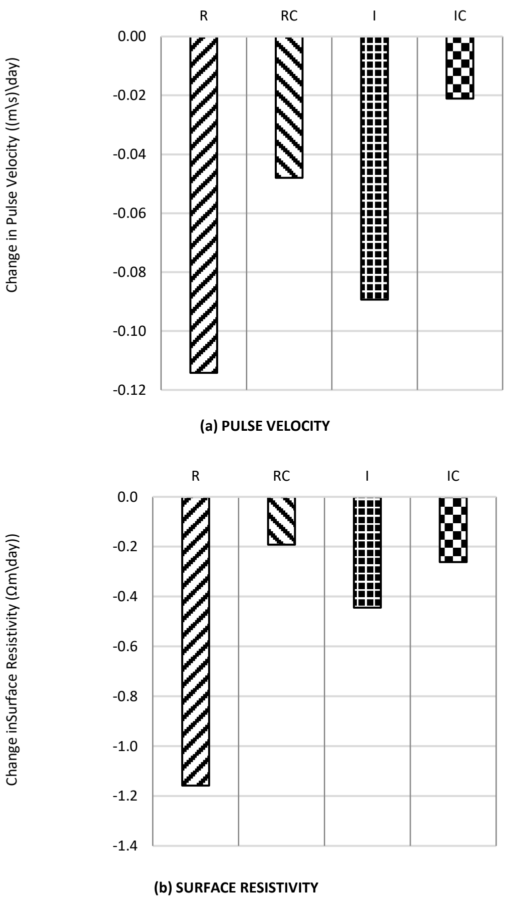

Fig. 8. Change in (a) Pulse Velocity and (b) Surface Resistivity

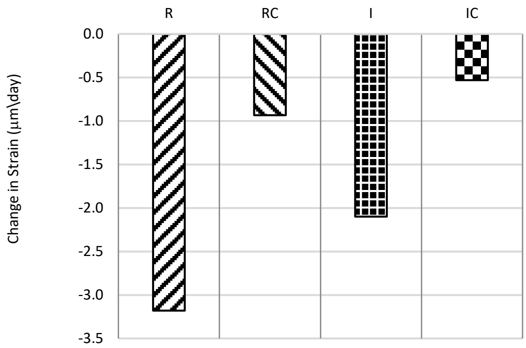

Fig. 9. Change in Strain

Some girders exhibited a higher increase in cracking index than in average crack width and vice versa. Figures 7a and 7b showed that the control girders (RC and IC) had a higher increase in cracking index than in average crack width. The higher change in cracking index in the control girders indicated that there was more of an increase in the formation of new cracks than an increase in crack width of existing cracks. Similarly, the in-service cracked girders exhibited a higher increase in average crack width than cracking index, indicating that there was more of an increase in the widths of the existing cracks than the formation of new cracks. The different rates of increase in cracking index and average crack width further support the importance of calculating both the cracking index and average crack width to measure the impact of cracking on durability accurately.

The rejected (RC) and in-service (IC) control girders also exhibited an increase in cracking index (Fig. 7a) and average crack width (Fig. 7b) values and a decrease in pulse velocity (Fig. 8a) and surface resistivity (Fig. 8b) during the period they were examined. The strain measurements also showed that the girders were exhibited shrinkage. However, the magnitude of change was lower than that of their cracked counterparts (compare R with RC and I with IC in Fig.s 7, 8 and 9). Like the trend exhibited by the cracked girders, the rejected control girder had a higher loss in durability than the in-service control girders.

From Figs. 7, 8 and 9, it was seen that the effect of external loading on the girders was minimal. To better understand these factors, further analysis was conducted based on considering the impact of exposure conditions, i.e., sheltered, or exposed (as shown in Figs. 2 and 4), on the girders and presence of pre-existing cracks (as shown in Figs. 3 and 5).

3.2 Effect of Exposure to the Environment

The effect of exposure conditions as defined in the sub-section titled "Selection of Testing Locations on Girder" was studied to understand the factors affecting loss in durability. The change in average crack width, cracking index, strain, and resistivity are discussed. The change in pulse velocity was not included as it is an indicator of bulk concrete properties rather than surface properties and hence, a comparison based on exposure conditions, that would affect just one face, would not accurately indicate the variation in pulse velocity. Figure 10 shows the change in average crack widths for all girders. Overall, the increase in average crack width was greater for the exposed sides than the sheltered sides in the cracked rejected girders (Fig. 10a). However, the exposed in-service girders did not exhibit this behavior (Fig. 10b). In-service girders I1 and I2 were exterior girders, each with one side exposed and one side sheltered. As the girders were painted, the change in average crack width was minimal. The sheltered sides of I1 and I2 and the interior in-service girders (I3, I4, I5, I6, IC1, and IC2) showed a lower increase in crack width when compared to the sheltered sides of the rejected girders.

Figure 11 shows the change in cracking index for all girders. Like the change in average crack width, there was an increase in cracking index in all girders. This indicated the formation of new cracks as well as an increase in crack widths.

Figure 12 shows the change in surface resistivity for all girders. The decrease in surface resistivity was higher for the exposed sides than the sheltered sides in all cracked rejected girders, which suggested that there were more cracks (i.e., damage) in the exposed sides than the sheltered sided. The decrease in surface resistivity in the exterior side of the in-service girders (I1 and I2) was higher than the sheltered sides of those girders and the interior in-service girders in the bridges, indicating that the exterior sides of the in-service girders had more defects than the sheltered sides of the girders and the interior girders. This contrasted with the change in average crack width and cracking index results (Figs. 10b and 11b), and thus the surface resistivity results indicated that the paint on the exposed side of the exterior girder did not have a major effect on the surface resistivity. The results from the change in cracking index and average crack width results for the exterior sides of the in - service girders (Fig. 10b and 11b) suggested that there was a decrease in cracking, but the surface resistivity results for these same girders indicated that the decrease in surface resistivity of the exposed side was higher than the sheltered side, indicating a higher loss of corrosion resistance. As such, the paint appears to be only preventing cracks from being observed and not the formation of cracks. If paint played a significant role in preventing the formation of cracks, this would have manifested as a lower decrease in surface resistivity in the exposed sides of the in-service exterior girders.

Fig. 13 shows the change in strain for all girders, with negative values indicating volumetric shrinkage and positive values indicating expansion. As such the results show that the girders predominantly exhibited

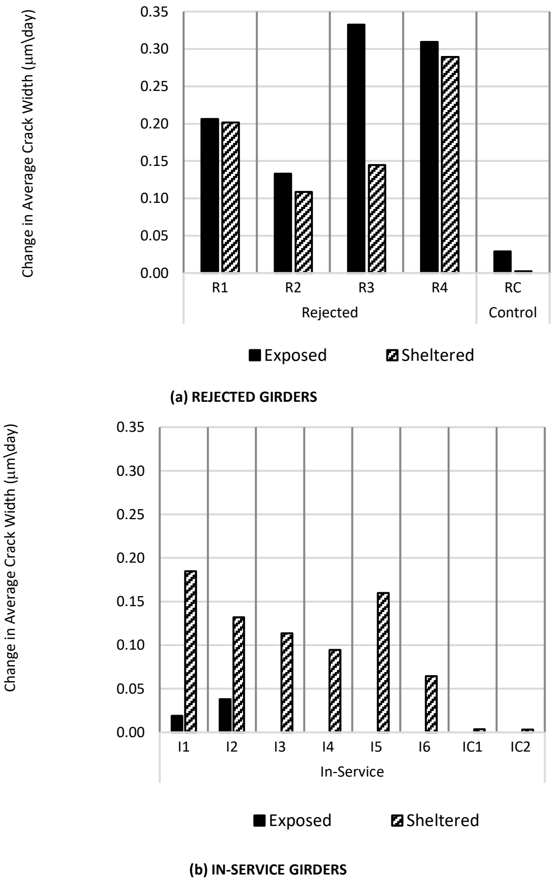

Fig. 10. Effect of Exposure Conditions on Change in Average Crack Width

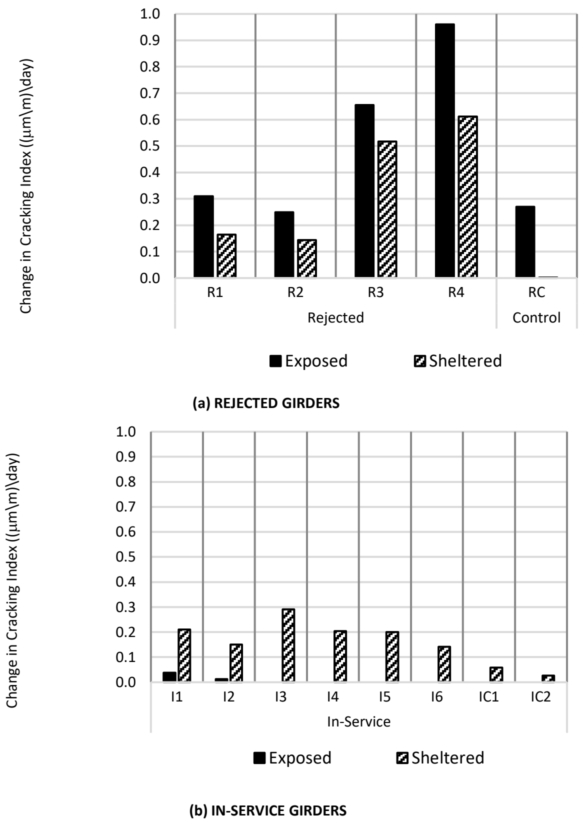

Fig. 11. Effect of Exposure Conditions on Change in Cracking Index

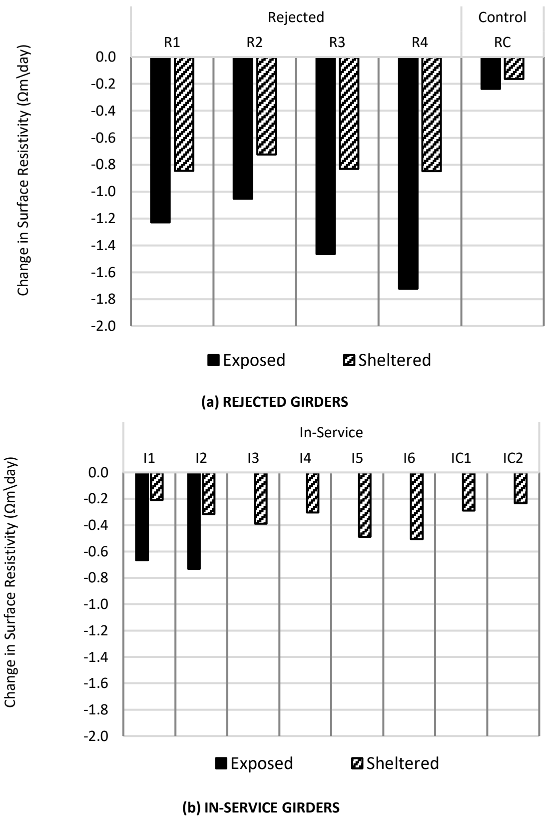

Fig. 12. Effect of Exposure Conditions on Change in Surface Resistivity

volumetric shrinkage. The shrinkage was higher for the exposed sides in all cracked rejected girders. Higher shrinkage was also measured in the exterior side of in-service girders (I1 and I2) as compared to the sheltered sides and the interior in-service girders. While this contrasted with the change in average crack width and cracking index, it was in line with the change in surface resistivity values. This showed that there was shrinkage in the exterior girders, further supporting the theory that the paint was only preventing cracks from being observed and not the formation of cracks. The rejected control girder exhibited lower shrinkage on the exposed side and an even lower shrinkage on the sheltered side. The in-service control girders had shrinkage values comparable to the rejected control girder, while still being lower than that of the cracked in-service girders.

3.3 Effect of Pre-Existing Cracks

The effect of pre-existing cracks as defined in the sub-section titled "Selection of Testing Locations on Girder" was studied to understand the factors affecting loss in durability. Upon visual survey of the girders, it was found that the end sections of the girders had higher levels of visible cracking due to the

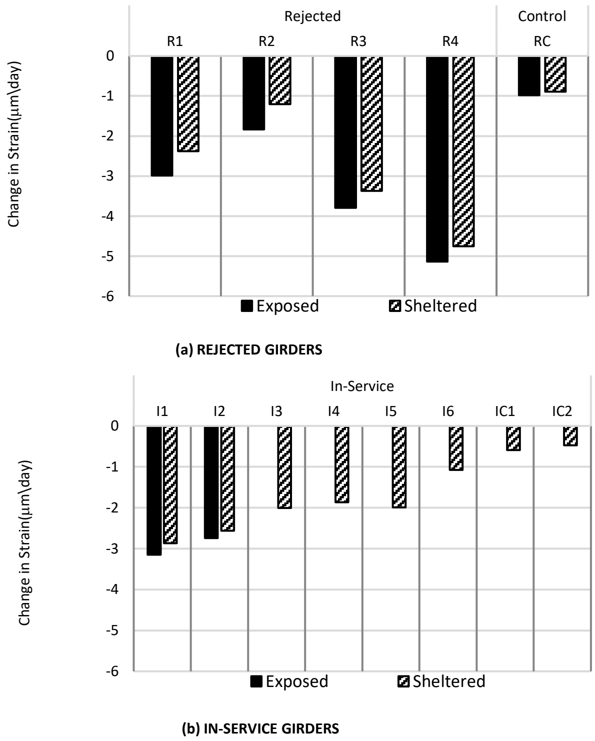

Fig. 13. Effect of Exposure Conditions on Change in Strain

formation of pre-stress release cracks (shown in Fig. 3). The change in average crack width, cracking index, strain, pulse velocity, and resistivity are discussed. Figure 14 shows the change in (a) cracking index, (b) average crack widths, and (c) strain (collectively referred to as cracking in this paragraph) for all girders. The increase in cracking was higher in the end sections in all cracked and un-cracked rejected girders when compared to the middle sections. Likewise, the increase in cracking in the end sections of all cracked and un-cracked in-service girders was higher when compared to the middle sections. The increase in cracking in the end sections of all control (rejected and in-service) girders was comparable to that of the in-service cracked girders. This showed that the presence of pre-existing cracks proved to be a significant factor affecting the increase in cracking (average crack width, cracking index, and strain).

Figure 15 shows the change in (a) pulse velocity and (b) surface resistivity for all girders. Presence of pre-existing cracks had the same effect on the decrease in pulse velocity and surface resistivity as it did on the increase in cracking. The decrease in pulse velocity and surface resistivity was higher in the end sections in all cracked and un-cracked rejected girders when compared to the middle sections. The decrease in pulse velocity and surface resistivity in the end sections of all cracked and un-cracked in-service girders was higher when compared to the middle sections. The decrease in pulse velocity and surface resistivity in the end sections of all control (rejected

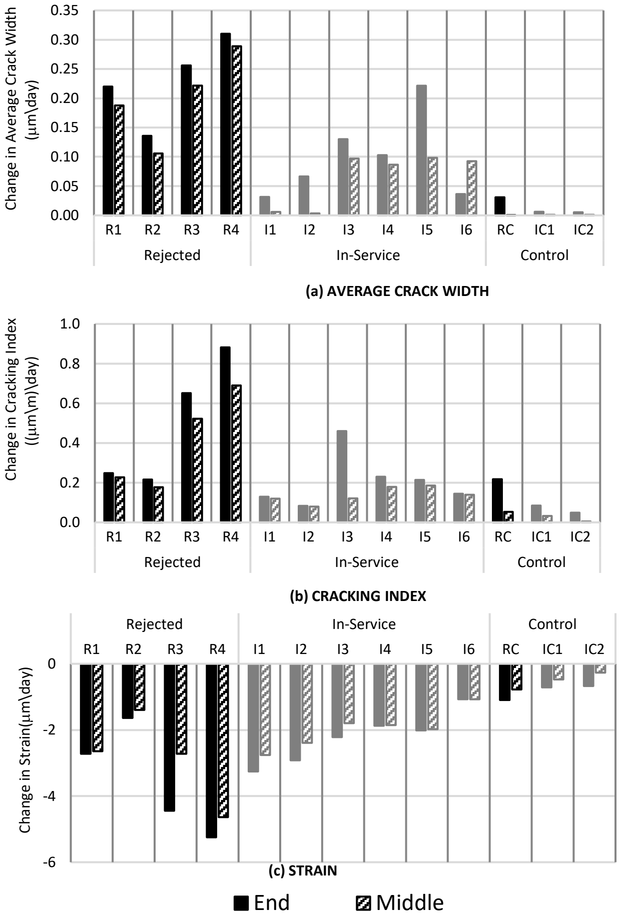

Fig. 14. Effect of Pre-Existing Cracks on (a) Cracking Index, (b) Average Crack Width, and (c) Strain. Change in Rejected girders are shown in black, whereas in-service girders are shown in grey.

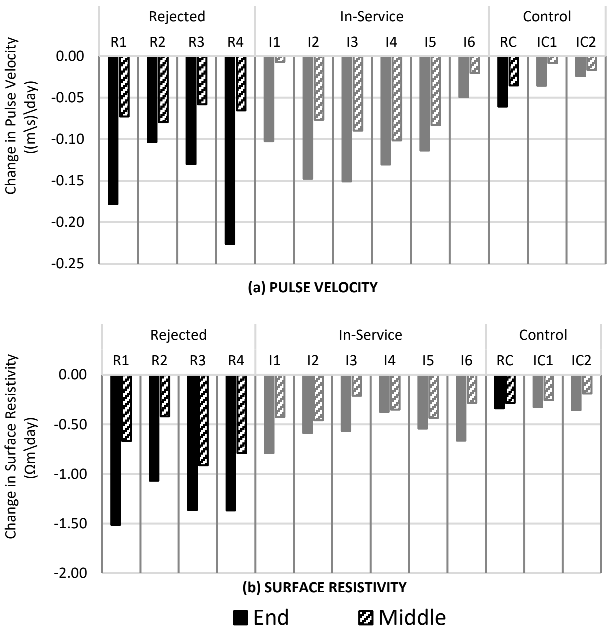

Fig. 15. Effect of Pre-Existing Cracks on Change in (a) Pulse Velocity and (b) Surface Resistivity. Rejected girders are shown in black, whereas in-service girders shown in grey.

and in-service) girders was comparable to that of the in-service cracked girders. This further supports the premise that the presence of pre-existing cracks proved to be a major factor affecting the integrity of the girders, and suggests that a more significant reduction in modulus of elasticity (as indicated by the decrease in pulse velocity) and corrosion resistance (as shown by the decrease in surface resistivity) occurred in the end regions of the girders as compared to the middle sections.

4.0 CONCLUSIONS

This study was conducted to determine the effect of external loads on the temporal changes in cracking index, crack width, strain measurements, surface resistivity and ultrasonic pulse velocity of pre-stressed concrete girders with low water/cementitious-material ratios. Four rejected, and six in-service girders exhibiting microcracking were selected for monitoring over approximately one year. Additionally, one rejected girder and two in-service girders with negligible cracking served as control specimens. The results indicates that a loss in durability occurred in the regions examined over a one-year period.

The research team initially theorized that, since the in-service girders were under the influence of external loads, they would exhibit a greater loss in durability than beams not in-service. However, the temporal results showed that the rejected girders showed a higher loss in overall durability. This indicated that external loading did not make as significant an impact as expected. However, as they are relatively early in their service life, it is possible that the girders have simply not manifested the effects of sustained loading yet. To better understand the factors that impacted the loss in durability the data obtained was analyzed based on the exposure conditions and presence of pre-existing cracks.

It was found that the exposed sides of the rejected girders showed the highest loss in durability. The exposed sides of the exterior in-service girders did not exhibit an increase in average crack width and cracking index. This was attributed to the layer of paint applied to the exposed in-service girders since the exposed sides of the exterior in-service exhibited a decrease in surface resistivity and an increase in shrinkage. Thus, it was possible that the paint layer only prevented the cracks from being visible and did not prevent their formation. The results also indicated that the end sections of the girders exhibited a higher loss in durability than the middle sections.

In conclusion, the results suggested that external loading had minimal impact on the temporal behavior of the microcracks studied. Instead, the presence of pre-existing cracks (pre-stress release cracks) and continued exposure to the environment showed a more significant impact on the increase in microcracking. It is expected that further studies on the effect of aging, exposure conditions (rainfall, temperature, number of wetting and drying cycles), material properties (mixture proportioning, age, and extent of hydration) will shed more light on the mechanism causing and propagating these microcracks.

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References

AASHTO TP119. (2015). *Standard Method of Test for Electrical Resistivity of a Concrete Cylinder Tested in a Uniaxial Resistance Test*. *American Association of State Highway and Transportation OfficialsA*.

ACI 201.1R. (2016). *Guide for Conducting a Visual Inspection of Concrete in Service*. *American Concrete Institute*.

ACI 224R. (2001). *Control of Cracking in Concrete Structures*. *American Concrete Institute*.

ACI 318. (2017). Building Code Requirements for Structural Concrete. *American Concrete Institute*. http://doi.org/10.2307/3466335

Allam, S. M., Shoukry, M. S., Rashad, G. E., & Hassan, A. S. (2012). Crack width evaluation for flexural RC members. *Alexandria Engineering Journal*, *51*(3), 211–220. http://doi.org/10.1016/j.aej.2012.05.001

Angelo Masi, L. C., & Vincenzo Manfredi. (2016). Criteria for identifying concrete homogeneous areas for the estimation of in-situ strength in RC buildings. *Construction and Building Materials*, *121*, 576–587. Retrieved from https://ac-els-cdn-com.ezproxy.lib.utexas.edu/S095006181630945X/1-s2.0-S095006181630945X-main.pdf?_tid=beb508dc-ffa4-11e7-a2ca-00000aab0f01&acdnat=1516647058_61912021826f7d23c68aaa3a2c11b926

ASTM C150. (2017). *Standard Specification for Portland Cement*. *American Society for Testing and Materials*. Retrieved from https://compass-astm-org.ezproxy.lib.utexas.edu/download/C150C150M.12564.pdf

ASTM C494. (2017). Standard Specification for Chemical Admixtures for Concrete. *American Society for Testing and Materials*. http://doi.org/10.1520/C0494_C0494M-17

ASTM C597. (2016). *Standard Test Method for Pulse Velocity Through Concrete*. Retrieved from https://compass-astm-org.ezproxy.lib.utexas.edu/download/C597.17012.pdf

ASTM C618. (2017). *Standard Specification for Coal Fly Ash and Raw or Calcined Natural Pozzolan for Use in Concrete*. *American Society for Testing and Materials*. Retrieved from https://compass-astm-org.ezproxy.lib.utexas.edu/download/C618.31830.pdf

Benoit, F., Marc-André, B., Kevin, F., & Thomas, M. (2010). *Report on the Diagnosis, Prognosis, and Mitigation of Alkali- Silica Reaction (ASR) in Transportation Structures*. *FHWA-HIF-09-004*.

Bisschop, J., & Van Mier, J. G. M. (2002). *Drying shrinkage microcracking in cement-based materials*. *Technische Universiteit Delft*.

Chien-Chih Wang, & Her-Yung Wang. (2017). Assessment of the compressive strength of recycled waste LCD glass concrete using the ultrasonic pulse velocity. *Construction and Building Materials*, *137*, 345–353. Retrieved from https://ac-els-cdn-com.ezproxy.lib.utexas.edu/S095006181730154X/1-s2.0-S095006181730154X-main.pdf?_tid=f73381f2-ffa4-11e7-abfb-00000aab0f26&acdnat=1516647153_7ca6bfc7fa0612c0815bb60dcd9c2031

Damgaard Jensen, A., & Chatterji, S. (1996). State of the art report on micro-cracking and lifetime of concrete—Part 1. *Materials and Structures*, *29*(1), 3–8. http://doi.org/10.1007/BF02486001

Ghosh, P., & Tran, Q. (2015). Correlation Between Bulk and Surface Resistivity of Concrete. *International Journal of Concrete Structures and Materials*, *9*(1), 119–132. http://doi.org/10.1007/s40069-014-0094-z

Gowers, K. R., & Millard, S. G. (1999). Measurement of Concrete Resistivity for Assessment of Corrosion Corrosion Severity of Steel Using Wenner Technique. *ACI Materials Journal*, *September-*, 536–541. Retrieved from http://www.comsiru.uct.ac.za/sites/default/files/image_tool/images/333/Events/Gowers_and_Millard_1999_-_Measurement_of_Concrete_Resistivity_for_Assessment_of_corrosion_severitty_usin.pdf

Hornbostel, K., Larsen, C. K., & Geiker, M. R. (2013). Relationship between concrete resistivity and corrosion rate - A literature review. *Cement and Concrete Composites*, *39*, 60–72. http://doi.org/10.1016/j.cemconcomp.2013.03.019

Kevern, John T, Halmen, Ceki, Hudson, Dirk P, … Brett. (2016). Evaluation of Surface Resistivity for Concrete Quality Assurance in Missouri. *Transportation Research Record: Journal of the Transportation Research Board*, (2577), 53–59. http://doi.org/10.3141/2577-07

NCEI. (2017). https://www.ncei.noaa.gov/. Retrieved February 2, 2018, from https://www.ncei.noaa.gov/about

Okumus, P., & Oliva, M. G. (2013). Evaluation of crack control methods for end zone cracking in prestressed concrete bridge girders. *PCI Journal*, (Spring), 91–105.

Ospina, C. E. (2012). Serviceability Design of Reinforced Concrete Members with Emphasis in Marine Infrastructure. *ACI Special Journal*, 1–24.

Otieno, M., Beushausen, H., & Alexander, M. (2016). Chloride-induced corrosion of steel in cracked concrete—Part II: Corrosion rate prediction models. *Cement and Concrete Research*, *79*, 386–394. http://doi.org/10.1016/J.CEMCONRES.2015.08.008

Ramezanianpour, A. A., Pilvar, A., Mahdikhani, M., & Moodi, F. (2011). Practical evaluation of relationship between concrete resistivity, water penetration, rapid chloride penetration and compressive strength. *Construction and Building Materials*, *25*, 2472–2479. http://doi.org/10.1016/j.conbuildmat.2010.11.069

Shah, S. P., & Chandra, S. (1968). Critical Stress, Volume Change, and Microcracking of Concrete. *ACI Journal*, *65*(57), 770–780. http://doi.org/10.14359/7512

Shiotani, T., Bisschop, J., & Van Mier, J. G. . (2003). Temporal and spatial development of drying shrinkage cracking in cement-based materials. *Engineering Fracture Mechanics*, *70*(12), 1509–1525. http://doi.org/10.1016/S0013-7944(02)00150-9

Slate, F. (1983). Microscopic observation of cracks in concrete, with emphasis on techniques developed and used at Cornell University. *Elsevier Applied Science*, 75–83. Retrieved from https://scholar.google.com/scholar?hl=en&as_sdt=0%2C44&q=%27Microscopic+observation+of+cracks+in+concrete+with+emphasis+on+technique+developed+and+used+at+Comell+University+-+X-Ray&btnG=

Stacy, S. (2016). *Evaluation of ASTM C 494 Procedures for Polycarboxylate Admixtures used in Precast Concrete Elements*. University of Texas, Austin.

Tiburzi, N. B., Drimalas, T., & Folliard, K. J. (2017). Evaluation of precast bridge girder cracking: The role of volume change. *Cement and Concrete Research*, *101*, 55–67. http://doi.org/10.1016/j.cemconres.2017.08.024

TxDOT. (2017). Bridge Standards. Retrieved January 21, 2018, from https://www.dot.state.tx.us/insdtdot/orgchart/cmd/cserve/standard/bridge-e.htm

Wang, Y. C., & Bai, Y. (2016). Progress of Carbonation in Chloride Contaminated Concretes. In *International Conference on Durability of Concrete Structures* (pp. 317–327).

Yu, L., François, R., Dang, V. H., L'Hostis, V., & Gagné, R. (2015). Development of chloride-induced corrosion in pre-cracked RC beams under sustained loading: Effect of load-induced cracks, concrete cover, and exposure conditions. *Cement and Concrete Research*, *67*, 246–258. http://doi.org/10.1016/J.CEMCONRES.2014.10.007