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Alkali Silica Reactivity Surveying and Tracking Guidelines

July 2012

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7. Author(s) Thomas, M.D.A., Fournier, B., Folliard, K.J., Resendez, Y.A.		8. Performing Organization Report No.
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16. Abstract

This document is intended to serve as guidelines for State highway agencies (SHAs) to survey and track transportation infrastructure affected by alkali-silica reactivity (ASR). The focus of the guidelines is to assist engineers, inspectors, and users in tracking and surveying ASR-induced expansion and cracking in bridges, pavements, and tunnels. The guidelines are simple and are intended to collect, quantify, and rank typical signs of ASR distress, based primarily on visual inspection.

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SI* (MODERN METRIC) CONVERSION FACTORS

APPROXIMATE CONVERSIONS TO SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
in	inches	25.4	millimeters	mm
ft	feet	0.305	meters	m
yd	yards	0.914	meters	m
mi	miles	1.61	kilometers	km
		AREA		
in^2	square inches	645.2	square millimeters	mm^2
ft^2	square feet	0.093	square meters	m^2
yd^2	square yard	0.836	square meters	m^2
ac	acres	0.405	hectares	ha
mi^2	square miles	2.59	square kilometers	km^2
		VOLUME		
fl oz	fluid ounces	29.57	milliliters	mL
gal	gallons	3.785	liters	L
ft^3	cubic feet	0.028	cubic meters	m^3
yd^3	cubic yards	0.765	cubic meters	m^3
		NOTE: volumes greater than 1000 L shall be shown in m^3		
		MASS		
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2000 lb)	0.907	megagrams (or "metric ton")	Mg (or "t")
		TEMPERATURE (exact degrees)		
^oF	Fahrenheit	5 (F-32)/9 or (F-32)/1.8	Celsius	^oC
		ILLUMINATION		
fc	foot-candles	10.76	lux	lx
fl	foot-Lamberts	3.426	candela/m^2	cd/m^2
		FORCE and PRESSURE or STRESS		
lbf	poundforce	4.45	newtons	N
lbf/in^2	poundforce per square inch	6.89	kilopascals	kPa

APPROXIMATE CONVERSIONS FROM SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
mm	millimeters	0.039	inches	in
m	meters	3.28	feet	ft
m	meters	1.09	yards	yd
km	kilometers	0.621	miles	mi
		AREA		
mm^2	square millimeters	0.0016	square inches	in^2
m^2	square meters	10.764	square feet	ft^2
m^2	square meters	1.195	square yards	yd^2
ha	hectares	2.47	acres	ac
km^2	square kilometers	0.386	square miles	mi^2
		VOLUME		
mL	milliliters	0.034	fluid ounces	fl oz
L	liters	0.264	gallons	gal
m^3	cubic meters	35.314	cubic feet	ft^3
m^3	cubic meters	1.307	cubic yards	yd^3
		MASS		
g	grams	0.035	ounces	oz
kg	kilograms	2.202	pounds	lb
Mg (or "t")	megagrams (or "metric ton")	1.103	short tons (2000 lb)	T
		TEMPERATURE (exact degrees)		
^oC	Celsius	1.8C+32	Fahrenheit	^oF
		ILLUMINATION		
lx	lux	0.0929	foot-candles	fc
cd/m^2	candela/m^2	0.2919	foot-Lamberts	fl
		FORCE and PRESSURE or STRESS		
N	newtons	0.225	poundforce	lbf
kPa	kilopascals	0.145	poundforce per square inch	lbf/in^2

*SI is the symbol for the International System of Units. Appropriate rounding should be made to comply with Section 4 of ASTM E380.
(Revised March 2003)

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1.0 INTRODUCTION AND SCOPE

This document is intended to serve as guidelines for State highway agencies (SHAs) to survey and track transportation infrastructure affected by alkali-silica reaction (ASR). The primary focus of these guidelines is the tracking and surveying of ASR-induced expansion and cracking in bridges, pavements, and tunnels; however, some of the information/guidance provided may be applicable to other assets, such as harbors or ancillary structures (high-mast lights, signs, etc.).

These guidelines are intended to provide the framework by which ASR-induced damage can be tracked by existing tools already being used by most, if not all, SHAs, specifically bridge and pavement management systems, and are written with SHA inspectors and consultants as the primary audience. Tunnel management systems are less mature than bridge and pavement management systems, but the development of these systems can be based on commonly used approaches already commonly used in bridge management systems, and as such, ASR-related defects can be tracked in a similar manner.

It is recognized that routine bridge, pavement, and tunnel inspections are not detailed enough to capture many of the features (substantial and subtle) that are indicative of ASR. As such, the guidelines are simple and are intended to collect, quantify, and rank typical signs of ASR distress, based primarily on visual inspection. However, it is generally not possible to diagnose ASR without more detailed evaluations, particularly petrographic evaluations, performed on cores extracted from said structures. When a given highway bridge or pavement section exhibits "high" values of ASR-related distress (e.g., cracking, joint deterioration, etc.), SHAs can use this information to select certain structures for more advanced study. A separate Federal Highway Administration (FHWA) report developed by the same authors as the current guidelines provides detailed and comprehensive guidance on how to diagnose and prognose ASR in transportation infrastructure (Fournier et al., 2010) and serves as an effective follow-up tool to evaluate structures that visually exhibit significant distress.

To complement both the visual guidelines for surveying ASR-affected structures (presented herein) and the more advanced diagnosis/prognosis (Fournier et al., 2010), the same authors have recently developed an updated version of the Strategic Highway Research Program (SHRP) ASR Handbook (Stark, 1991), titled "Alkali-Silica Reactivity Field Identification Handbook" (2012). The Field Identification Handbook provides more detailed coverage on the causes and effects of ASR and a wide range of photographs illustrating common symptoms of ASR-induced expansion and cracking.

The overall objective of these guidelines is to provide - for the first time - the ability to track and survey ASR-affected structures and pavements and to do so in an implementable, efficient manner. For conciseness, the guidelines presented herein will be referred to for simplicity as **STAR** (**S**urveying and **T**racking of **A**lkali-Aggregate **R**eaction) and will describe what data/information/observation should be collected to effectively track ASR; SHAs would then implement these guidelines using their management system of choice.

2.0 OVERALL APPROACH

The STAR guidelines presented next focus primarily on bridge, pavement, and tunnel management, but similar approaches can be followed for tracking other transportation-related structures.

2.1 BRIDGE INSPECTION AND MANAGEMENT

Pontis is an AASHTOWare™ product that is used by a number of State highway departments as part of their bridge management system. Most SHAs currently use Pontis to collect inspection elemental data as part of their bridge inspection programs and in accordance with the American Association of State Highway and Transportation Officials (AASHTO) Commonly Recognized (CoRe) Element Manual, which was superseded by the new AASHTO Guide Manual for Bridge Element Inspection (AASHTO, 2011). A small number of SHAs use the repair or replacement programming features in Pontis, while other states use commercially available software packages or have developed their own state-specific management systems.

To ensure efficient implementation of these guidelines into bridge management systems, such as Pontis, the AASHTO Guide Manual for Bridge Element Inspection (2011) will serve as a basis in terms of overall approach to element identification, quantification, and evaluation. This AASHTO Guide Manual, in its first edition, facilitates bridge inspection on an elemental level and includes two element sets, National Bridge Elements (NBE) and Bridge Management Elements (BME), which together comprise the entire AASHTO element set. Note that the two element sets are treated identically with regard to inspection and management. The elements, whether they are NBE or BME, are used in inspection and bridge management in a standardized fashion, as shown in Figure 1; this same procedure is recommended for inspecting and managing elements potentially affected by ASR.

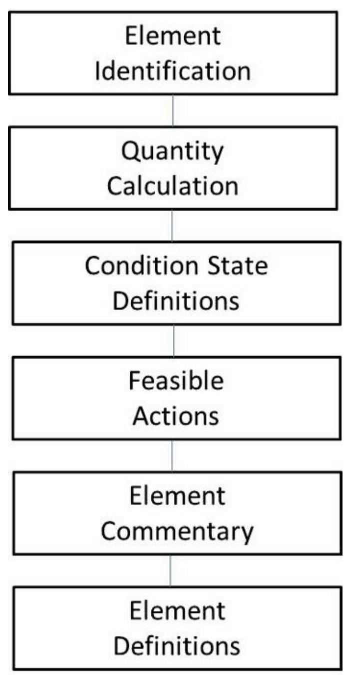

Figure 1 – Elements Used in Inspection and Bridge Management (after AASHTO, 2011)

Table 1 summarizes the NBE and BME elements that are either reinforced or precast concrete elements. As one would expect, only these elements will be included in these guidelines focusing on surveying ASR. Table 1 also lists the element number (as per AASHTO 2011), as well as the unit of measure/payment (used in quantity calculations).

Table 1 – Reinforced and Prestressed Concrete Bridge Elements (after AASHTO, 2011)

Element Number	Element Description	Unit of Measure
Decks/Slabs		
12*	Reinforced Concrete Deck	ft^2 (m^2)
15*	Prestressed/Reinforced Concrete Top Flange	ft^2 (m^2)
38*	Reinforced Concrete Slab	ft^2 (m^2)
Bridge Rail		
331*	Reinforced Concrete Bridge Railing	ft (m)
Superstructure		
104*	Prestressed Concrete Closed Web/Box Girder	ft (m)
105*	Reinforced Concrete Closed Web/Box Girder	ft (m)
109*	Prestressed Concrete Girder/Beam	ft (m)
110*	Reinforced Concrete Girder/Beam	ft (m)
115*	Prestressed Concrete Stringer	ft (m)
116*	Reinforced Concrete Stringer	ft (m)
143*	Prestressed Concrete Arch	ft (m)
144*	Reinforced Concrete Arch	ft (m)
154*	Prestressed Concrete Floor Beam	ft (m)
155*	Reinforced Concrete Floor Beam	ft (m)
Substructure		
204*	Prestressed Concrete Column/Pile Extension	Each
205*	Reinforced Concrete Column/Pile Extension	Each
226*	Prestressed Concrete Submerged Pile	Each
227*	Reinforced Concrete Submerged Pile	Each
233*	Prestressed Concrete Pier Cap	ft (m)
234*	Reinforced Concrete Pier Cap	ft (m)
220*	Reinforced Concrete Pile Cap/Footing	Each
241*	Reinforced Concrete Culvert	ft (m)
215*	Reinforced Concrete Abutment	ft (m)
Bridge Approach Slabs		
320**	Prestressed Concrete Approach Slab	ft^2 (m^2)
321**	Reinforced Concrete Approach Slab	ft^2 (m^2)

** National Bridge Element (NBE)*

*** Bridge Management Elements (BME)*

For each of the elements listed in Table 1, the presence and extent of defects are noted and quantified, based on AASHTO (2011). Table 2 shows the defects and defect descriptions for reinforced or prestressed concrete elements, grouped by element type. Within AASHTO (2011), specific criteria are set forth for each of these defects, including specific crack width ranges and sizes of spalls. For conciseness, the specific defect criteria are not included herein, but specific ASR-related defects, descriptions, and criteria will be presented later in these guidelines.

Table 2 – Defects and Defect Description for Element Types

Defect	**Defect Description**
Decks/Slabs	
Cracking	Crack width; Crack density
Spalls/Delaminations/Patched Areas	Spall depth; Spall diameter; Rebar exposed
Efflorescence	Surface white; Surface build-up (w/ or w/o rust)
Bridge Rail	
Cracking	Crack width; Crack density
Spalls/Delaminations/Patched Areas	Spall depth; Spall diameter; Rebar exposed
Efflorescence	Surface white; Surface build-up (w/ or w/o rust)
Superstructure	
Cracking	Crack width; Crack density
Spalls/Delaminations/Patched Areas	Spall depth; Spall diameter; Rebar exposed
Exposed Rebar	Corrosion without section loss*
Exposed Prestressing	Present without section loss*
Efflorescence	Surface white; Surface build-up (w/ or w/o rust)
Substructure	
Cracking	Crack width; Crack density
Spalls/Delaminations/Patched Areas	Spall depth; Spall diameter; Rebar exposed
Exposed Rebar	Corrosion without section loss*
Exposed Prestressing	Present without section loss*
Efflorescence	Surface white; Surface build-up (w/ or w/o rust)

** Section loss automatically assigned Condition State 4*

For each of the defects shown in Table 2, one of four conditions states must be assigned. The four condition states, shown in Table 3, are defined based on the presence and severity of defects relevant to the specific element type. Condition state 4 (severe) is typically reserved for conditions that warrant safety concerns and that are beyond the range of defects described in condition states 1 through 3; in essence, each defect has three commonly used condition states (good, fair, and poor).

Table 3 – Standard Condition States for Defects in Bridge Elements (after AASHTO, 2011)

Condition State #	**Condition State**
1	Good
2	Fair
3	Poor
4	Severe

2.1.1 INTEGRATION OF ASR INTO BRIDGE INSPECTION AND MANAGEMENT

When considering the defects, defect descriptions, and defect criteria as summarized in Tables 2 and 3, some relevant and important discussions with regard to the current scheme are warranted in order to extend the capabilities to include ASR. Some of the salient points are as follows:

- The identification and quantification of defects are performed based on symptoms of distress but no inherent linkage is provided between cause (e.g., corrosion, freeze thaw, sulfate attack, shrinkage cracking) and effect (cracking, spalling, etc.).
- The level of effort required to identify and quantify defects is based on typical, visual inspection with simple measurements required for certain defects (e.g., crack width, crack density, spall size).
- Diagnosis of causes of defects is beyond the scope of a typical inspection.

Some of the defects already included in AASHTO (2011) and integrated in Pontis are also those that are typically caused by ASR, specifically cracking, efflorescence (or in the case of ASR gel extrusion and carbonation), and spalling. With regard to AASHTO (2011), these defects are often caused by corrosion and sometimes by other forms of distress, namely shrinkage cracking and freeze-thaw damage. Nevertheless, to some extent, ASR-induced distress may already be detected in some bridges, and relevant information captured under existing bridge management systems, but such effects would only be captured if ASR-induced damage was significant, leading to crack widths/densities exceeding prescribed thresholds or gel exudation/efflorescence. To provide a more accurate and specific tracking index, some other features characteristic of ASR must be included, as described next.

ASR is an internal reaction within the concrete that results in expansion, cracking, and other related actions (misalignment of elements, loss of clearance, etc.). The Field Identification Handbook (2012) serves as a useful tool in aiding inspectors in identifying typical characteristics of ASR-induced distress. It is recommended that this Handbook be available to inspectors to increase their knowledge of ASR, factors affecting the progression of the reaction, and the manifestation of ASR in bridges and pavements. However, the Field Identification Handbook is not intended to serve the specific purposes required for bridge inspection and management. That is, specific defects are not quantified, nor are standard condition states defined. Diagnosis of causes of defects is beyond the scope of typical inspections.

The approach described herein attempts to bridge the gaps between existing bridge inspection/management manuals/systems (AASHTO, 2011; Pontis) and ASR-specific tools developed or under development by the same authors of these guidelines. Essentially, the concept is to identify specific defects that are "typical" of ASR, but are unique enough that the manifestation of distress may be attributed to ASR. Examples of these types of defects include map cracking, aligned cracking, gel exudation, and relative dislocation/misalignment of adjacent sections. None of these defects are currently identified or tracked within Pontis or included in AASHTO (2011). Furthermore, there have been no standards/protocols developed to specifically include ASR-induced distress into other types of infrastructure management systems. As such, the guidelines presented herein should be considered an initial step in this direction, and it should be noted that the definitions/criteria used to quantify ASR-related defects have not yet been calibrated or validated in field applications. Most defects described and defined herein will be consistent with the level of detail as is currently presented in AASHTO (2011), such as thresholds for crack widths and density. However, in some cases, when feasible, examples of specific defects are presented in the form of photographs showing different levels/severity of the defects. Each of these defects is discussed next, along with definitions of condition states and associated criteria. A summary of how these defects will be integrated into the various element types is provided.

The remainder of this section provides guidelines on the definition and quantification of defects that have a reasonable probability of being caused by ASR. As stated earlier, it is not technically possible to diagnose a bridge as being affected by ASR through routine visual inspections, and in some cases, a more detailed evaluation is required. Fournier et al. (2010) have developed a guide to diagnose and prognose ASR-affected structures; this document provides significant detail on how to perform a more detailed evaluation, including guidance on how to measure internal relative humidity in concrete or measure the in-situ expansion of concrete elements.

Table 4 summarizes the defects, defect descriptions, and criteria/threshold for each element type using a similar approach as AASHTO (2011). Descriptions of the defects in Table 4 are provided in Table 5, followed by selected photographs of the defects, some with varying degrees of severity.

Table 4 – Recommended Defects and Condition States for Element Types Potentially Affected by ASR

<table>
<tr><th>Defect</th><th>Condition State 1</th><th>Condition State 2</th><th>Condition State 3</th><th>Condition State 4</th></tr>
<tr><td>Map Cracking</td><td>None to hairline</td><td>Narrow size or density, or both</td><td>Medium size or density, or both</td><td rowspan="4">The condition is beyond the limit state of Condition State 3, warrants a structural review to determine the strength or serviceability of the element or bridge, or both</td></tr>
<tr><td>Aligned Cracking</td><td>None to hairline</td><td>Narrow size or density, or both</td><td>Medium size or density, or both</td></tr>
<tr><td>Gel Exudation</td><td>None</td><td>Moderate</td><td>Severe (with gel staining)</td></tr>
<tr><td>Relative dislocation/misalignment</td><td>None</td><td>Tolerable</td><td>Approaching or exceeding limits (including causing local crushing)</td></tr>
</table>

Table 5 – Recommended Defects and Defect Description for Element Types Potentially Affected by ASR

Defect	Hairline-Minor	Narrow-Moderate	Medium-Severe
Map Cracking	Crack width < 0.0625" (1.6 mm) % Map Cracking < 5%	Crack width: 0.0625" (1.6 mm) – 0.1250" (3.2 mm) % Map Cracking: 5 to 25%	Crack width > 0.1250" (3.2 mm) % Map Cracking > 25%
Aligned Cracking	Crack width < 0.0625" (1.6 mm)	Crack width: 0.0625" (1.6 mm) – 0.1250" (3.2 mm)	Crack width: > 0.1250" (3.2 mm)
Gel Exudation	None	Gel visible on surface (<20% of concrete surface, with no build-up of gel)	Gel build-up on surface (>20% of concrete surface), typically at or near cracks; gel staining visible (especially once structure dries after a rain event)
Relative dislocation/misalignment	None	Tolerable (movement is visible but no loss of clearance, exudation of sealants at joints, or local crushing)	Movement is visual, with loss of clearance, exudation of sealants at joints, or local crushing

Figure 2 – Map cracking on bridge abutment (Condition State 3)

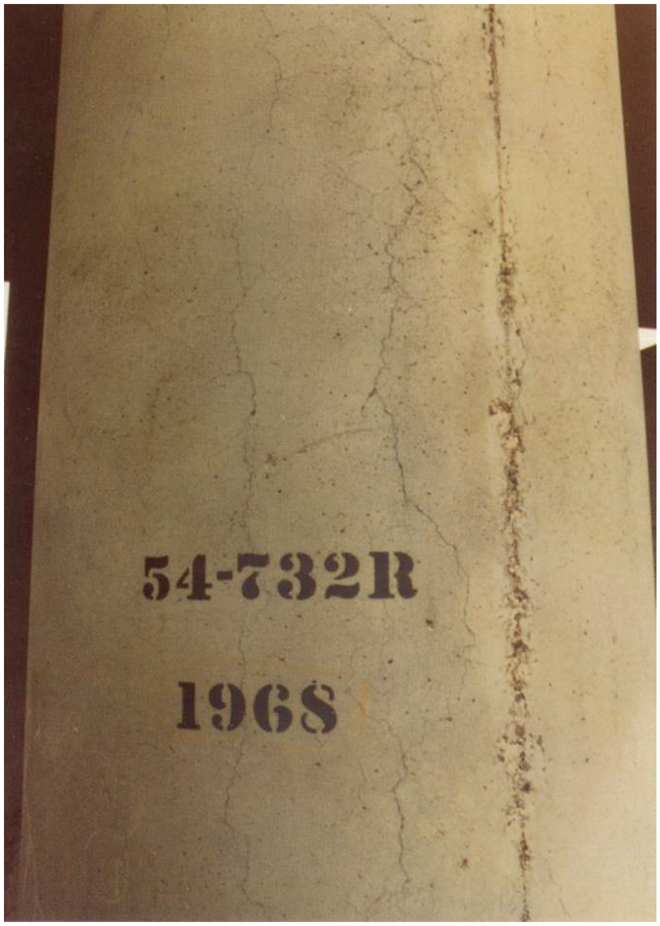

Figure 3 – Aligned cracking on column (Condition State 2)

Figure 4 – Aligned cracking in beam (Condition State 3)

Figure 5 – Gel Exudation (Condition State 3)

Figure 6 – Relative dislocation/misalignment, leading to loss of clearance and cracking (photo from SHRP C-315, 1991) (Condition State 3)

For each of the above defects that have been added specifically to track ASR in bridges, the standard approach recommended by AASHTO (2011) with regard to feasible action is followed, as shown in Table 6.

Table 6 – Feasible Actions for Defects

Condition State 1	Condition State 2	Condition State 3	Condition State 4
Do Nothing Protect	Do Nothing Protect	Do Nothing Protect Repair Rehab	Do Nothing Rehab Replace

AASHTO (2011) also provides for the use of "smart" or "defect" flags. Currently, concrete cracking (element number 359) and concrete efflorescence (element number 360) are the only two elements that are included in this defect flag approach. Future considerations should include whether certain ASR-specific defects (map cracking, aligned cracking) could be included in select defect flags aimed at surveying ASR-affected structures. These flags would most likely be assigned, developed and tracked by individual SHAs, based on familiarity with their local situation and awareness of factors that most significantly affect the longevity of ASR-affected structures. In addition, environmental conditions, especially temperature, relative humidity, and precipitation, can be tracked and coupled with other inspection findings to attempt to link the specific climatic conditions to the progress of ASR.

2.2 PAVEMENT INSPECTION AND MANAGEMENT

Whereas there is a general trend towards SHAs using Pontis for bridge management, there is no single product that has emerged to help SHAs manage their pavement inventories. Pavement management systems (PMS) tend to vary widely among States. There is also no national standardized approach or manual to inspect pavements for subsequent input into PMS. Given the lack of common approaches/systems for tracking pavements, a similar approach and format as was taken for bridge management will be followed here. That is, characteristics of ASR in pavements will be identified, ranked, and ultimately quantified. The data collected could then be input into PMS used by individual SHAs. Whenever possible, the data collected should be compatible with data collected under the Long-Term Pavement Performance (LTPP) Program.

There has been considerable work done to attempt to understand the key defects (or more commonly referred to as distresses in pavement community) that affect concrete pavement performance, as summarized in Table 7 (as per FHWA, 2003). Jointed concrete pavements (JCP) are the most common in the United States, but some states, particularly Texas and Illinois, prefer continuously reinforced concrete pavements (CRCP). To draw parallels to bridge management, JCP and CRCP can be considered "element types" to be tracked in an infrastructure management system, typically on a lane-mile basis.

Table 7 – Distress Types in Concrete Pavements (after FHWA, 2003)

Jointed Concrete Pavements	Continuously Reinforced Concrete Pavements
Corner Breaks	Longitudinal Cracking
D-Cracking	Transverse Cracking
Longitudinal Cracking	D-Cracking
Transverse Cracking	Map Cracking
Joint Deficiencies	Scaling
Map Cracking	Popouts
Scaling	Blowups
Popouts	Joint Deterioration
Joint Faulting	
Blowups	

2.2.1 INTEGRATION OF ASR INTO PAVEMENT INSPECTION AND MANAGEMENT

Of the distress mechanisms shown in Table 7, several may serve as potential indicators of ASR-induced expansion and cracking. The distresses most commonly associated with ASR from Table 7 include map cracking, joint deficiencies/deterioration, and in some cases, popouts. It is not possible to determine based solely on a visual observation whether these signs of distress are in fact due to ASR for a given pavement. Nevertheless, visual signs can be potential indicators; there are many documented cases of ASR that have resulted in such distress. Table 8 summarizes the aforementioned distress types and assigns condition states to each, as per AASHTO (2011) for bridge inspection/management. Table 9 provides detailed description/criteria for the distress types, followed by selected photographs of the defects, some with varying degree of severity. Figures 7 through 9 show manifestations of ASR-induced expansion and cracking in pavements.

Table 8 – Recommended Distress and Condition States for Pavements Potentially Affected by ASR

Distress	Condition State 1	Condition State 2	Condition State 3	Condition State 4
Map Cracking	None to hairline	Narrow size or density, or both	Medium size or density, or both	The condition is beyond the limit state of Condition State 3, warrants a structural review to determine the strength or serviceability of the pavement, or both.
Joint Sealant Failure	None	Moderate	Severe	
Joint Deterioration	None	Moderate	Severe	
Popouts	None	Moderate	Severe	

Table 9 – Recommended Distress and Distress Description for Pavements Potentially Affected by ASR

Defect	Hairline-Minor	Narrow-Moderate	Medium-Severe
Map Cracking	Crack width < 0.0625" (1.6 mm) % Map Cracking < 5%	Crack width: 0.0625" (1.6 mm) – 0.1250" (3.2 mm) % Map Cracking: 5 to 25%	Crack width > 0.1250" (3.2 mm) % Map Cracking > 25%
Joint Sealant Failure	Joint sealant failure in less than 10% of joints.	Joint sealant failure in 10 to 50% of joints.	Joint sealant failure in greater than 50% of joint
Joint Deterioration	None or only minor cracking near corners/joints	Wide, open cracks exist and mass loss has occurred in joint region (less than 5% of joints). No patching applied.	Wide, open cracks and mass loss has occurred in joint region (greater than 5% of joints). Patching has been applied.
Popouts	None	Popouts isolated and few [less than 1 popout per 10 ft]	Popouts prevalent [greater than 1 popout per 10 ft]

** Popout data generally not collected and not included in LTPP. Estimates are shown in [ ]*

Figure 7 – Map Cracking of Concrete Pavement (Condition State 3)

Figure 8 – Joint Sealant Failure in Concrete Pavement (Condition State 3)

Figure 9 – Joint Deterioration in Concrete Pavement (Condition State 3)

The information gathered from Tables 8 and 9 would be in addition to the typical distress data gathered using most pavement management systems (e.g., faulting, punchouts, crack spacing for CRCP, etc.), as well as other performance attributes typically tracked in PMS software, such as ride quality (roughness) and deflection data (e.g., falling weight deflectometer), which can serve as indirect indicators of ASR-induced expansion and cracking.

2.3 TUNNEL INSPECTION AND MANAGEMENT

Unlike bridge and pavement management systems, tunnel management systems are in their early stages of development and/or implementation. However, the development of tunnel management systems has been spurred and accelerated in recent years by increasing concerns over tunnel safety and by the need for a comprehensive inspection and management system for the nation's tunnel infrastructure (which is comprised of approximately 300 tunnels, with an average age of about 40 years). Efforts are underway to develop National Tunnel Inspection Standards (NTIS), along the same lines as National Bridge Inspection Standards (NBIS) in the early 1970's. Several FHWA products have been developed in recent years that are directed towards the development of NTIS, including:

- Highway and Rail Transit Tunnel Inspection Manual (HRTTIM) (FHWA, 2005);
- Highway and Rail Transit Tunnel Maintenance and Rehabilitation Manual (FHWA, 2005);
- ONE DOT Tunnel Management System (TMS) (FHWA, 2003).

The information from these three products above is currently being used to develop the FHWA's Tunnel Operations, Maintenance, Inspection and Evaluation (TOMIE) Manual. The guidelines presented next for tracking ASR in tunnels are intended for future incorporation into the TOMIE Manual once it is completed and implemented. A similar approach that was followed for the development of guidelines for ASR-affected bridges will be followed; that is, elements will be defined that may be susceptible to ASR, defects and defect descriptions will be presented, and condition states will be assigned that quantify the overall extent of the defects.

Before discussing how ASR will be incorporated into tunnel inspection and management, the basic approach of the 2005 Highway and Rail Transit Tunnel Inspection Manual (HRTTIM) is briefly described, as it will serve as the foundation from which ASR-related evaluations will be performed (in a similar way in which the AASHTO (2011) serves as the basis for identifying and quantifying defects potentially caused by ASR in bridge structures).

As per the HRTTIM (2005), highway and rail transit tunnels are evaluated per segment, with the segment defined by the user. It could be per panel or per specified length, such as every 100 ft (30 m) or 200 ft (60 m). Specific defects are identified and quantified within each segment, after which the overall condition of the tunnel can be assigned.

Tunnels are constructed primarily of concrete, steel, and masonry, with a small number constructed using timber. In addition to distinguishing tunnel elements based on material type, tunnels are characterized by shape, liner type, invert type, construction method, and tunnel finishes. For the purposes of surveying and tracking ASR in tunnels, it is assumed that any element composed of portland cement concrete could potentially be affected by ASR. Table 10 shows the liner types that are most commonly composed of concrete.

Table 10 – Tunnel Liner Types Commonly Composed of Concrete (FHWA, 2005)

Tunnel Liner Type	Description/Notes
Shotcrete	Can be used as temporary liner (with a surface liner applied over it) or as permanent liner.
Ribbed Systems	Consists of timber, steel, or precast concrete ribs, subsequently filled in between with cast-in-place concrete.
Segmental Lining	Prefabricated lining segments composed of concrete, steel, or cast iron, typically bolted together and compressed to prevent water penetration.
Cast-in-Place Concrete	Can be a final lining installed over various initial stabilization methods or a thin cover layer over a primary line (to provide a finished surface, for example). Can be reinforced or unreinforced. Can serve as either non-structural cover layer or as the main structural support for the tunnel.
Slurry Walls	Tremie concrete that is placed into excavation that was temporarily filled with drilling fluid. Typically reinforced concrete.

In addition to the tunnel liners, the inverts of tunnels are generally made from concrete and could potentially be affected by ASR. By definition, an invert is the slab on which the roadway or track bed is supported (FHWA, 2005). It can either rest on grade at the bottom of the tunnel (slab-on-grade concrete) or span a higher portion of the tunnel (structural reinforced concrete slab). In the latter slab type, an open space is created below the roadway/track bed that can be utilized for ventilation or other utilities.

The concrete tunnel liners (as described in Table 10), inverts, and other structural components are to be inspected as part of an overall tunnel inspection and management program, as per FHWA (2005). Defects specific to concrete elements are shown in Table 11, along with descriptions and criteria related to each defect. The inspection includes primarily a visual inspection of all exposed surfaces, but it may also include limited non-destructive testing, specifically to attempt to locate delaminations.

As per FHWA (2005), the presence and extent of the defects shown in Table 11 are to be recorded for the concrete tunnel elements (liners, inverts, other structural components). This information, coupled with inspection data for non-concrete components (e.g., steel, masonry, etc.), is then used to assign a condition code to the overall tunnel segment on a scale from 0 (worst) to 9 (best). Table 12 shows the general condition codes and concrete-specific condition codes.

Table 11 – Defects and Defect Description for Concrete Tunnel Elements (FHWA, 2005)

Defect	**Defect Description**
Scaling	Minor: Loss of surface mortar < ¼" (6 mm). Moderate: Loss of surface mortar from ¼" (6 mm) to 1" (25 mm). Severe: Loss of surface mortar greater than 1" (25 mm) and loss of coarse aggregates.
Cracking	*For Non-Prestressed Concrete:* Minor: Crack widths up to 0.03" (0.80 mm). Moderate: Crack widths between 0.03" (0.80 mm) and 0.125" (3.20 mm). Severe: Crack widths greater than 0.125" (3.20 mm). *For Prestressed Concrete:* Moderate: Crack widths less than or equal to 0.003" (0.10 mm). Severe: Crack widths greater than 0.003" (0.10 mm).
Spalling	Minor: Less than ½" (12 mm) deep or 3 in (75 mm) to 6" (150 mm) in diameter. Moderate: ½" (12 mm) to 1" (25 mm) deep or approximately 6" (150 mm) in diameter. Severe: More than 1" (25 mm) deep and greater than 6" (150 mm) in diameter, and any spall that exposes reinforcing steel.
Joint Spalling	Spall occurring near or at joint; same criteria as above for *Spalling*.
Popouts	Minor: Leaving holes up to 0.40" (10 mm) in diameter. Moderate: Leaving holes between 0.40" (10 mm) and 2" (50 mm) in diameter. Severe: Leaving holes 2" (50 mm) to 3" (75 mm) in diameter. Pop-outs larger than 3" (75 mm) are considered spalls.
Mudballs	Small holes left in the surface by the dissolution of clayballs or soft shale particles; same criteria as *Popouts*.
Efflorescence	A combination of calcium carbonate leached out of the cement paste and other recrystallized carbonate and chloride compounds, which form on the concrete surface.
Staining	A discoloration of the concrete surface caused by the passing of dissolved materials through cracks and deposited on the surface when the water emerges and evaporates.
Hollow Area	An area of a concrete surface that produces a hollow sound when struck by a hammer, often referred to as delamination.
Honeycomb	An area of a concrete surface that was not completely filled with concrete during the initial construction.
Leakage	Minor: The concrete surface is wet although there are no drips. Moderate: Active flows at a volume less than 30 drips/minute. Severe: Active flows at a volume greater than 30 drips/minute.

Table 12 – Condition Codes (based on FHWA, 2005)

Rating	General Description	Cut-and-Cover Box Tunnels and Concrete/Shotcrete Inner Liners	Soft-Ground Tunnel Liners	Rock Tunnel Liners
9 (best)	Newly completed construction	Newly completed construction	Newly completed construction	Newly completed construction
8	***Excellent condition*** – No defects found	***Excellent condition*** – No defects found	***Excellent condition*** – No defects found	***Excellent condition*** – No defects found
7	***Good condition*** – No repairs necessary. Isolated defects found.	***Good condition*** – No repairs necessary although certain elements contain isolated minor deficiencies and minor presence of efflorescence. No delaminations or spalls are present.	***Good condition*** – No repairs necessary. Precast concrete liners have minor defects. Precast concrete liners and safety walk panels contain not more than one minor crack.	***Good condition*** – No repairs necessary. Concrete/shotcrete liner contains minor circumferential cracks at greater than 10 ft (3 m) intervals with a minor presence of efflorescence.
6	Shading between "5" and "7"	Shading between "5" and "7"	Shading between "5" and "7"	Shading between "5" and "7"
5	***Fair condition*** – Minor repairs required but element is functioning as originally designed. Minor, moderate, and isolated severe defects are present but with no significant section loss.	***Fair condition*** – Minor repairs required but element is functioning as originally designed. Concrete elements contain moderate cracks at 5 ft (1.5 m) to 10 ft (3 m) intervals with moderate presence of efflorescence and minor to moderate active leakage. Minor delaminations, spalls, map cracking, and staining exist on the concrete but no reinforcement is exposed.	***Fair condition*** – Minor repairs required but element is functioning as originally designed. Precast concrete liners have numerous minor defects. Precast concrete liners and safety walk panels have moderate spalls and more than two minor cracks.	***Fair condition*** – Minor repairs required but element is functioning as originally designed. Concrete/shotcrete liner contains minor circumferential cracks at 5 ft (1.5 m) to 10 ft (3 m) intervals, not more than one longitudinal moderate crack; moderate presence of efflorescence, minor to moderate active leakage. Minor delaminations, spalls, map cracking and staining are present but no reinforcement is exposed.
4	Shading between "3" and "5"	Shading between "3" and "5"	Shading between "3" and "5"	Shading between "3" and "5"

Table 12 (cont'd) – Condition Codes (based on FHWA, 2005)

Rating	General Description	Cut-and-Cover Box Tunnels and Concrete/Shotcrete Inner Liners	Soft-Ground Tunnel Liners	Rock Tunnel Liners
3	***Poor condition –*** Major repairs are required and element is not functioning as originally designed. Severe defects are present.	***Poor condition –*** Major repairs are required and element is not functioning as originally designed. Concrete elements contain numerous moderate cracks with extensive efflorescence, severe leakage, and staining. Delaminations and spalls are present over 50% of the concrete surface and exposed reinforcement has up to 15% section loss.	***Poor condition –*** Major repairs are required. Precast concrete liners exhibit extensive severe deterioration such that the liners can no longer achieve the full original design capacity, although still retaining some degree of their load-carrying capacity.	***Poor condition –*** Major repairs are required and element is not functioning as originally designed. Concrete/shotcrete liners have extensive longitudinal and circumferential cracks with extensive efflorescence, leakage, and staining. Delaminations and spalls are present over 50% of the concrete surface and exposed reinforcement has up to 15% section loss.
2	***Severe condition*** – Major repairs required immediately to keep structure open to highway or rail transit traffic.	***Severe condition –*** Major repairs are required immediately to keep structure open to highway or rail transit traffic. Concrete elements contain extensive severe cracks, delaminations, spalls, and leakage. Exposed reinforcement steel has up to 40% section loss.	***Severe condition –*** Major repairs are required immediately to keep structure open to highway or rail transit traffic. The precast concrete liners exhibit extensive, serious deterioration and are severely deflected such that the elements can no longer support the design loads without immediate repair. Severe active leakage is occurring at numerous locations within the tunnel segment.	***Severe condition –*** Major repairs are required immediately to keep structure open to highway or rail transit traffic. Concrete/shotcrete lining has extensive severe cracks, delaminations, spalls, and active leakage. Exposed reinforcement has up to 40% section loss.
1	***Critical condition –*** Immediate closure required. Study should be performed to determine the feasibility of repairing the structure.	***Critical condition –*** Immediate closure required. Study should be performed to determine the feasibility of repairing the structure.	***Critical condition –*** Immediate closure required. The precast concrete liner elements have major deterioration and have lost all capacity to sustain the original design loadings.	***Critical condition –*** Concrete/shotcrete lining has extensively cracked and deflected significantly. The lining has lost all capacity to sustain design loads.
0 (worst)	***Critical condition -*** Structure is closed and beyond repair.	***Critical condition -*** Structure is closed and beyond repair.	***Critical condition -*** Structure is closed and beyond repair.	***Critical condition -*** Structure is closed and beyond repair.

2.3.1 INTEGRATION OF ASR INTO TUNNEL INSPECTION AND MANAGEMENT

When considering the defects, defect descriptions, and conditions as summarized in Tables 11 and 12, some relevant and important discussions with regard to the current scheme are warranted in order to extend the capabilities to include ASR. Some of the salient points are as follows:

- The level of effort required to identify and quantify defects is based on typical, visual inspection, with simple measurements required for certain defects (e.g., crack width, crack density, spall size). Only exposed surfaces are available for such visual inspections of tunnels, and defects in concrete only manifest themselves if the surface tiles show distress or allow leaching/efflorescence to escape from the underlying concrete.
- The identification and quantification of defects are performed based on symptoms of distress but no inherent linkage is provided between cause (e.g., corrosion, freeze thaw, shrinkage cracking) and effect (cracking, spalling, etc.). Diagnosis of causes of defects is beyond the scope of typical inspections.
- As stated earlier, it is not technically possible to diagnose a tunnel as being affected by ASR through routine visual inspections; in some cases, a more detailed evaluation is required. Fournier et al. (2010) have developed a guide to diagnose and prognose ASR-affected structures. This document provides significant detail on how to perform a more detailed evaluation, including guidance on how to measure internal relative humidity in concrete or measure the in-situ expansion of concrete elements.
- There is very little in literature on ASR-affected tunnels, and few photos exist that have identified ASR-related distress as being a factor.
- FHWA (2005) directs inspectors to refer to the American Concrete Institute (ACI) document ACI 201.1R-92 for representative photos of the concrete defects shown in Table 11.

Although not currently included in FHWA (2005), several of the defects shown in Table 11 may actually be caused by ASR, including:

- **Cracking** – ASR-induced expansion can lead to significant cracking, with the specific crack pattern determined by the magnitude of expansion and the amount of restraint provided internally (by reinforcing/prestressing steel) and/or externally (by adjacent elements). Cracking from ASR can range from discrete map cracking (especially for relatively unrestrained elements) to aligned cracking (where expansion is limited along the direction of highest restraint, resulting in increased expansion in the direction of least confinement). In such cases, the cracks become oriented in the same direction as the confining stresses (e.g., vertical cracks in columns, horizontal cracks in beams/girders, etc.). However, cracking can also be caused by a range of other causes, including shrinkage, corrosion, and applied loads.
- **Joint Spalling** – ASR-induced expansion can lead to significant expansion and cracking. As ASR advances, the concrete at or near joints tends to deteriorate preferentially, due to easier access to moisture at joints and reduced restraint near joints, which can lead to joint spalling. However, spalling can also be caused by freezing/thawing near joints or by corrosion above reinforcing steel.
- **Popouts** – ASR-susceptible aggregates that expand near the concrete surface may cause popouts, resulting in the detachment of a conical potion of the mortar overlying the aggregate in the bottom of the resulting conical recess. However, popouts can also be caused by freezing and thawing of certain aggregates, especially chert and argillaceous, clayey, or porous particles.
- **Efflorescence** – ASR-induced expansion and cracking can increase the tendency for leaching to occur from near the concrete surface, with calcium carbonate formed as a product, resulting in a white discoloration on the concrete surface. In addition, ASR gel products can also travel through cracked concrete to reach the concrete surface, resulting in staining around cracks, with cracks becoming increasingly discolored as damage progresses. However, other mechanisms can contribute to efflorescence, namely the normal leaching and subsequent carbonation that occurs at concrete surfaces. Also, freeze-thaw and sulfate attack can exacerbate efflorescence by physical and/or chemical attack, resulting in cracking and associated issues.

- **Staining** – Somewhat related to efflorescence, ASR-induced expansion and cracking can lead to staining on the surface of concrete. The staining is caused by the ASR gel products and calcium leaching exuded through cracks and staining the concrete surface, especially once the products react with the environment. Generally, a white exudation is observed first, which eventually turns into a colorless, jelly-like product readily identifiable as ASR gel (CSA, 2000). However, staining can also be caused by other distress mechanisms, such as corrosion, where staining is typically observed above reinforcing steel that is actively corroding.

As described above, ASR can cause defects (cracking, joint spalling, popouts, efflorescence, and staining) that are already set to be captured in FHWA (2005) and the TOMIE Manual. However, it is not possible to determine what portion, if any, of these defects are caused by ASR in a given tunnel segment without extracting cores and having them examined by a trained petrographer. Nevertheless, to some extent, ASR-induced distress will likely be detected in some tunnels and captured using FHWA (2005) or other tunnel inspection programs. To provide a more accurate and specific tracking index for ASR, some additional features must be noted and/or quantified during a visual tunnel inspection.

Table 13 shows the defects that should be included in the inspection process to track symptoms most associated with ASR-induced expansion and cracking. An assessment of cracking is already included in FHWA (2005), but to better identify and delineate cracking potentially caused by ASR, it is recommended that crack patterns defined specifically as **map cracking** or **aligned cracking** be noted, recorded, and tracked. Map cracking, as shown in Figure 2, can often be caused by ASR but can also occur due to drying shrinkage, as an example. Map cracking tends to occur most in elements that are minimally reinforced, and thereby have less of a confining effect on ASR-induced expansion, allowing for expansion to manifest in all directions. When expansion is restrained internally or externally, resultant cracks tend to follow the primary reinforcement or stress, as depicted in Figures 3 and 4. The same crack width criteria that are already included in FHWA (2005) are maintained for consistency. In essence, the inspector can measure and record cracks and crack widths as is typical, but he or she should note the presence of map cracking and aligned cracking and ensure that the relative amount of each of these crack patterns is quantified separately.

Gel exudation (Figure 5) has been added as a defect to track ASR-affected tunnels. A more detailed, ASR-specific description has been added to aid in the quantification of ASR gel exudation and build-up and to differentiate this defect from typical efflorescence and staining, which may result from durability problems other than ASR, such as typical leaching, freezing and thawing, or sulfate attack.

Expansion or relative dislocation (Figure 6) has been added as a defect, along with defect criteria, to try to capture the manifestations of ASR-induced expansion that may have a significant effect on the serviceability and longevity of a given tunnel. ASR-induced expansion within a given tunnel element may result in various operating difficulties, whether the entire tunnel is expanding or certain elements are expanding relative to adjacent, non-expanding elements. As an example, expansion of precast tunnel liners can cause failure of the gaskets and bolts that clamp the sections together, potentially increasing the risk for concrete crushing at this interface or increased potential for leakage at joints. In addition, utilities that are contained in tunnels may be adversely impacted by ASR as the displacements and resultant misalignments can cause operational difficulties.

As stated earlier, there have been very few documented cases of ASR in tunnels. As such, references are made to the bridge photographs presented in Section 2.1.1 and the pavement photographs presented in Section 2.2.1. In addition to these, the Field Identification Handbook (2012) serves as a useful tool in aiding inspectors in identifying typical characteristics of ASR-induced distress, albeit not specifically to tunnels. FHWA (2005) recommended the use of ACI 201.1R-92 as a guide for inspectors to quantify defects in concrete. Since then, an updated Guide for Conducting a Visual Inspection of Concrete in Service (ACI 201.1R-08) has been released and is recommended as a resource for tunnel inspectors.

Table 13 – Recommended Defects and Defect Description for Tunnel Element Types Potentially Affected by ASR

Defect	**Defect Description**
Map Cracking	Minor: Crack widths up to 0.03” (0.80 mm) Moderate: Crack widths between 0.03” (0.80 mm) and 0.125” (3.20 mm) Severe: Crack widths greater than 0.125” (3.20 mm)
Aligned Cracking	*For Non-Prestressed Concrete:* Minor: Crack widths up to 0.03” (0.80 mm) Moderate: Crack widths between 0.03” (0.80 mm) and 0.125” (3.20 mm) Severe: Crack widths greater than 0.125” (3.20 mm) *For Prestressed Concrete:* Moderate: Crack widths less than or equal to 0.003” (0.10 mm) Severe: Crack widths greater than 0.003” (0.10 mm)
Gel exudation	Minor: White exudation visible; no visible gel Moderate: Colorless, jelly-like product visible but has not built up. Gel visible on less than 20 percent of surface. Severe: Colorless, jelly-like product visible and has built up on surface, usually near cracks. Gel visible on greater than 20 percent of surface.
Expansion or relative dislocation	Minor: Expansion is visible but no loss of clearance, relative dislocation, exudation of sealants at joints, or local crushing Moderate: Expansion is visible, clearance has been closed, but without local crushing. Sealants/gaskets may be compressed or exuded. Severe: Expansion is visible, clearance has been closed, and local crushing has occurred. Sealants/gaskets may be compressed or exuded.

Figure 10 summarizes the recommended defects to be tracked as part of tunnel inspection and management program. It is recommended that information/data/photos of these defects be collected and evaluated. An approach similar to what is used in bridge management systems, it is recommended that the defects in Figure 10 be “flagged” as potential indicators for ASR susceptibility. In addition to the defects shown in Figure 10, leakage is a global indicator of tunnel condition/performance, and it is recognized that ASR can cause expansion, cracking, and reduced watertightness.

Defects currently included in FHWA (2005)	**Additional defects recommended to track ASR**
Cracking Joint spalling Popouts Efflorescence Staining	Map cracking Aligned cracking Gel exudation Expansion and/or relative dislocation

Figure 10 – Defects to Track for Tunnel Elements Potentially Affected by ASR

As described in Section 2.3 and specifically in Table 12, a condition code is assigned for a given tunnel (on a 0-9 scale, 0 being worst, 9 being best), based on the assessment of the various structural elements. The additional ASR-related defects recommended to be tracked, as summarized in Table 13, should eventually be incorporated into the condition code of a given tunnel; however, insufficient data exist specifically on ASR in tunnels to relate ASR-related defects to overall tunnel health and performance. It is hoped that the guidance provided in this document will allow for the collection of relevant and important ASR information/data, and the knowledge gained will ultimately allow for incorporation into assigning a general condition code for a tunnel.

Although it is not recommended for formal inclusion into the assessment of condition code, it is worth noting that defects such as observed expansion and misalignment, as well as aligned cracking, are more of a concern than map cracking and popouts, which tend to be on a less severe scale in terms of deterioration. Given that crack widths are already being recorded and it is recommended that inspectors note the presence and extent of map and aligned cracking, one of the most important characteristics of ASR is in fact being tracked. Special attention should be paid to detecting relative dislocations and especially the more advanced forms that lead to operational difficulties or local crushing of concrete at interfaces. Map cracking, efflorescence, and staining, already included in FHWA (2005), are used to assign condition codes, and that data may prove to be a reasonable indicator that ASR is occurring in a given tunnel.

It should be noted that there have been no standards/protocols developed to specifically include ASR-induced distress into other types of infrastructure management systems. As such, the guidelines presented herein should be considered an initial step in this direction, and it should be noted that the definitions/criteria used to quantify ASR-related defects have not yet been calibrated or validated in field conditions (in general) and in tunnels (specifically).

2.4 OTHER ASSET MANAGEMENT

In addition to pavements, bridges, and tunnels, some SHAs have jurisdiction and assume the inspection/management responsibility for other assets, including:

- Transit agencies (e.g., light rail)
- Railways
- Airports
- Ports
- Wharfs/Piers/Ferry boat terminals
- Ancillary structures (high-mast lights, signs, etc.)
- Building structures (e.g., rail stops, etc.)

It is beyond the scope of this document to provide guidance on inspecting and managing these secondary structures, all of which may be affected by ASR. However, the guidance provided for bridges, pavements, and tunnels should serve as a foundation for evaluating other concrete components and structures.

3.0 SUMMARY

This document provides simple guidelines and recommendations for including ASR as a source of distress in bridges, pavements, and tunnels. These guidelines should be considered tentative at this point, as the data recommended for collection and the methods of quantifying overall distress are not calibrated or validated at this point in time. However, it is hoped that as more data are generated, a more accurate, calibrated methodology will emerge.

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