FHWA Workshop

Alkali-Aggregate Reaction

Session 07: Diagnosis and Prognosis of Alkali-Aggregate Reaction

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Slide 1

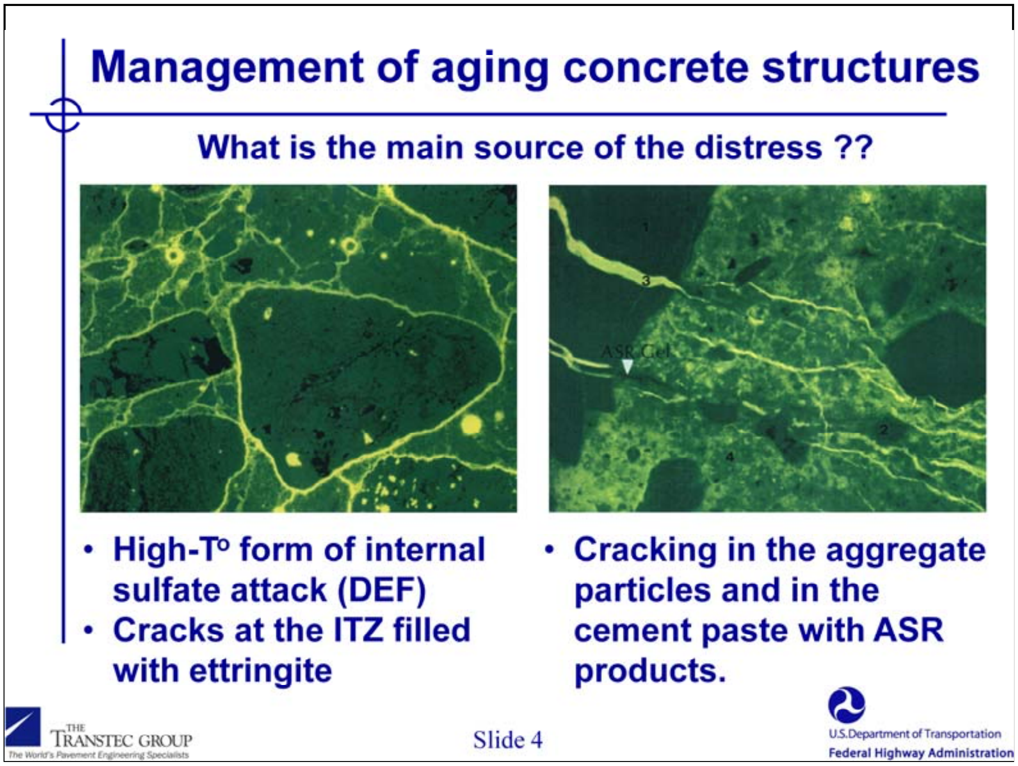
This Session present a summary of the most recent approaches/strategies for the determination of the current condition (*Diagnosis*) and the potential for future degradation (*Prognosis*) of AAR in concrete structures.

Slide 2

The management of aging concrete structures is indeed one of the major challenges for engineers. In order to select the most appropriate remedial measures for such structures, it is important to determine what is (are) the main cause(s) of deterioration and how severe is the deterioration affecting the structure investigated, as for this bridge structure illustrated which is badly affected by ASR.

Slide 3

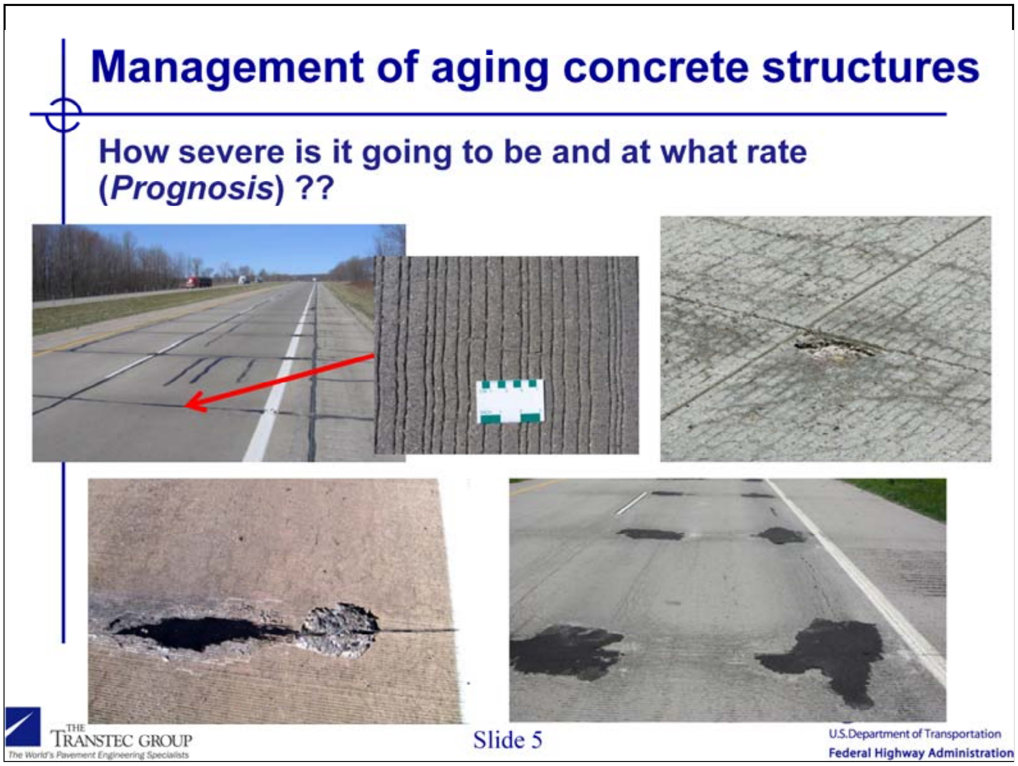
It is particularly a challenge for concrete structures that may be affected by more than one deleterious mechanism. This is the case of a number of railway ties manufactured in the 1990's in the Northeastern USA. Other than the legal case that went on to determine the group responsible for the deterioration, it is critical to identify the source of the problem to apply the proper remediation strategy.



Slide 4

In the case of the railway ties... the micrograph on the left illustrates signs of deterioration that are consistent with *Delayed Ettringite Formation* (DEF), which is a high-temperature form of internal sulphate attack of concrete. It is characterized by the presence of a network of cracks filled with *ettringite* in the cement paste and typically in the interfacial transition zone between the aggregate particles and the cement paste.

The micrograph on the right illustrates signs of ASR, i.e. cracks filled with alkali-silica reaction products extending from the aggregate particles into the cement paste.



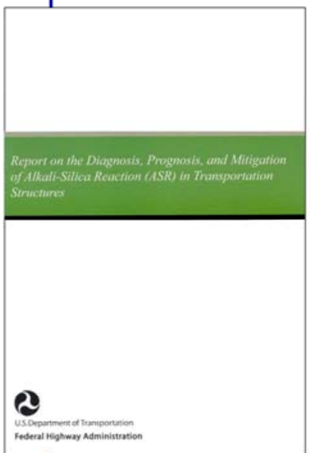
Slide 5

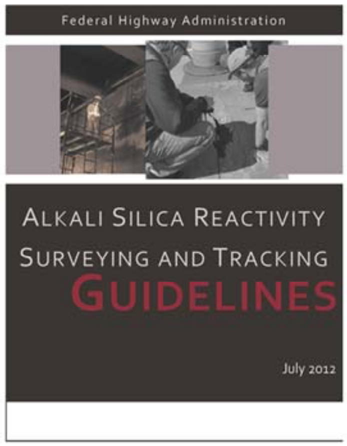
Another critical question is how severe is the damage possibly/likely going to be in the future and at what rate is the damage going to increase. This is illustrated in the various pictures showing the typical progress of ASR damage in concrete pavement sections, starting with expansion and fine cracking in the pavement sections and preferentially close to the joints, and progressing into spalls at joints becoming more and more severe with time.

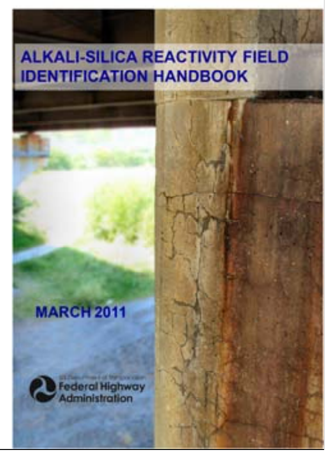
Slide 6

The situation can be particularly critical in Northern states or countries where the effects of cracking initiated by ASR are exacerbated by freeze-thaw cycles, which will largely accelerate the progress of deterioration.

Tools for the management of aging concrete structures (ASR)







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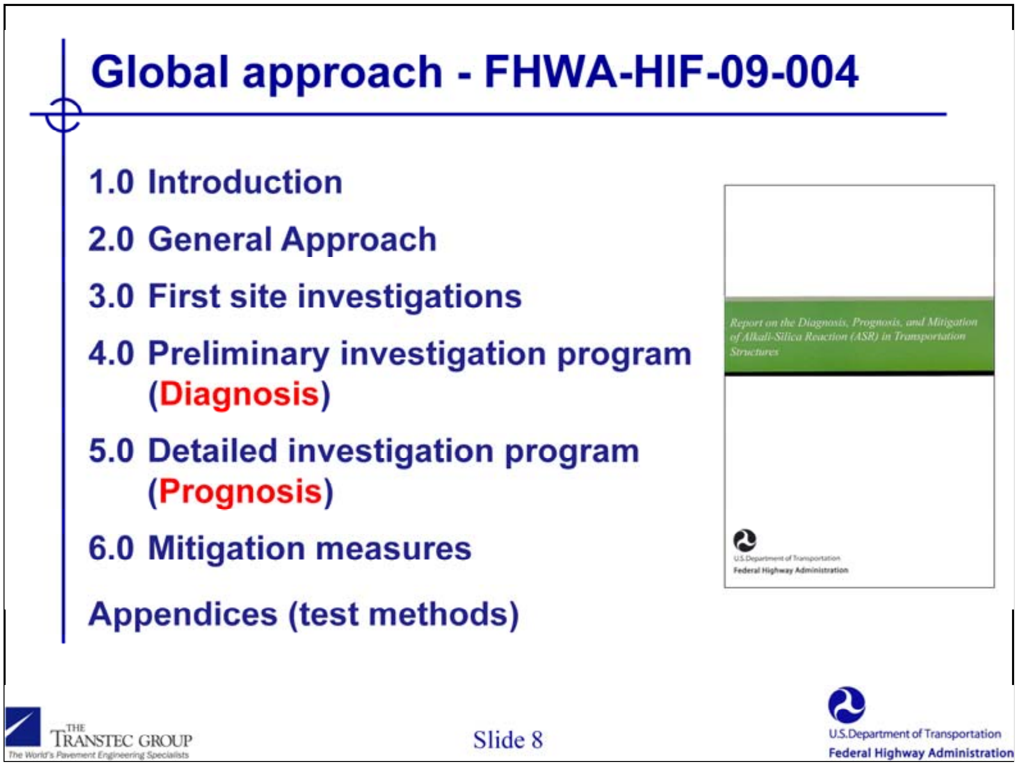
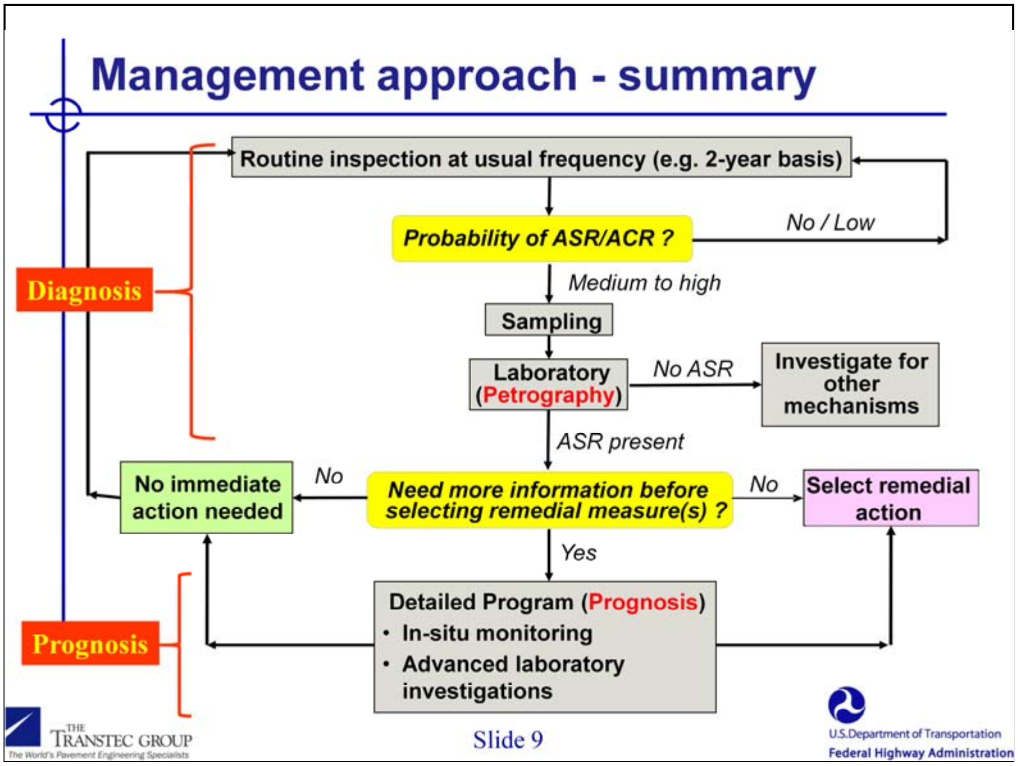


Slide 8

A global approach for the management of AAR in concrete structures was recently developed under Federal Highway's ASR Development and Deployment program. This Report on the *Diagnosis, Prognosis and Mitigation of ASR in Transportation Structures* is available on FHWA's website and presents procedures for field and laboratory investigations for the Diagnosis and Prognosis of AAR in transportation structures.



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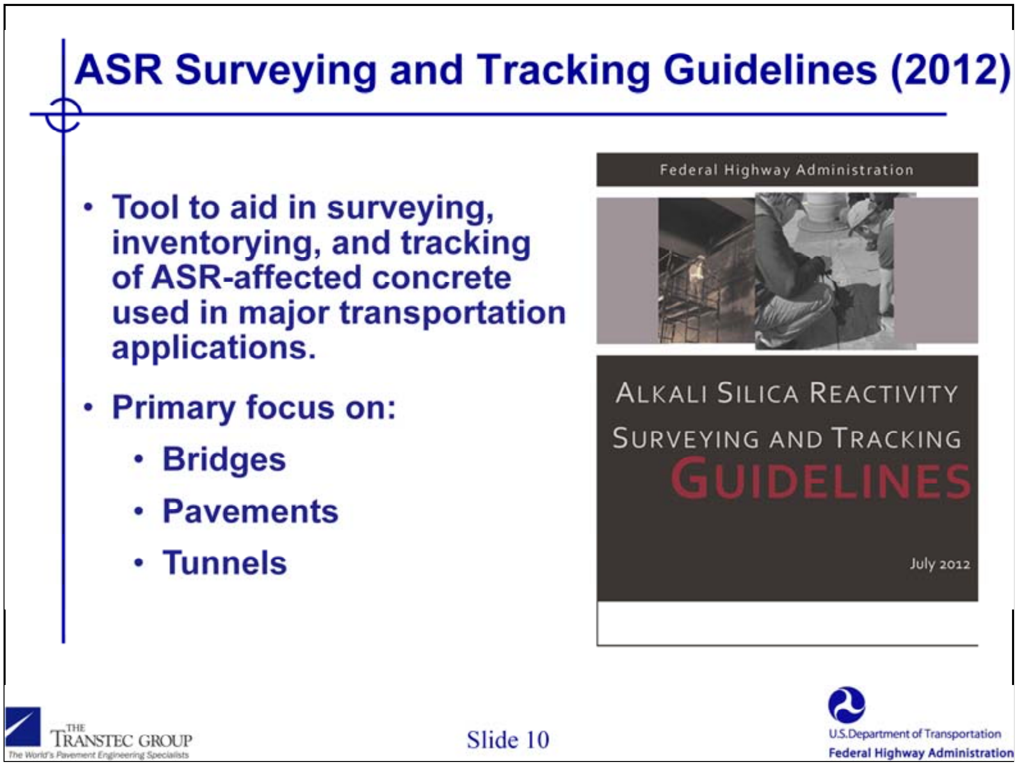
This flowchart presents a step-by-step approach aiming at evaluating the cause of concrete distress (**diagnosis**) and the potential for future expansion/damage (**prognosis**), both elements providing information for the selection of appropriate mitigation measures for ASR-affected structures.

The extent to which each of the various methods proposed in the above approach will need to be implemented in a particular case will depend on different factors, including the nature/extent of the problem, the criticality of the structure, the potential impact on the safety of users, etc.

Signs of premature deterioration in transportation concrete structures that could be related to ASR can generally be detected during *routine inspections* of concrete structures that are carried out by inspectors on a regular basis.



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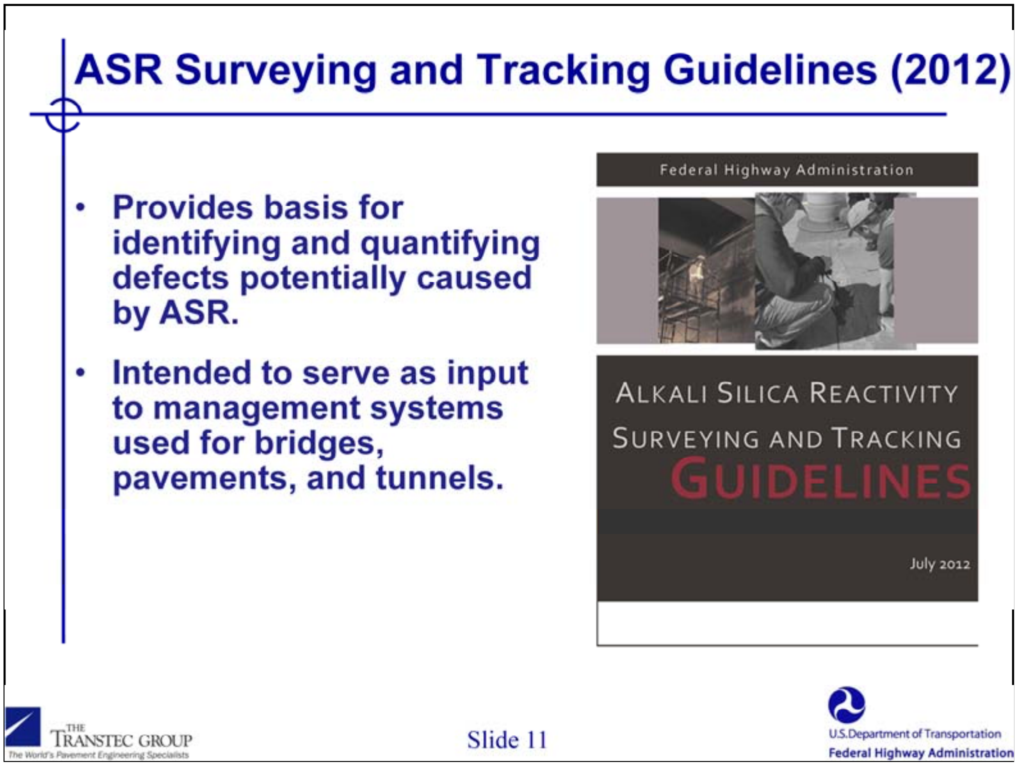
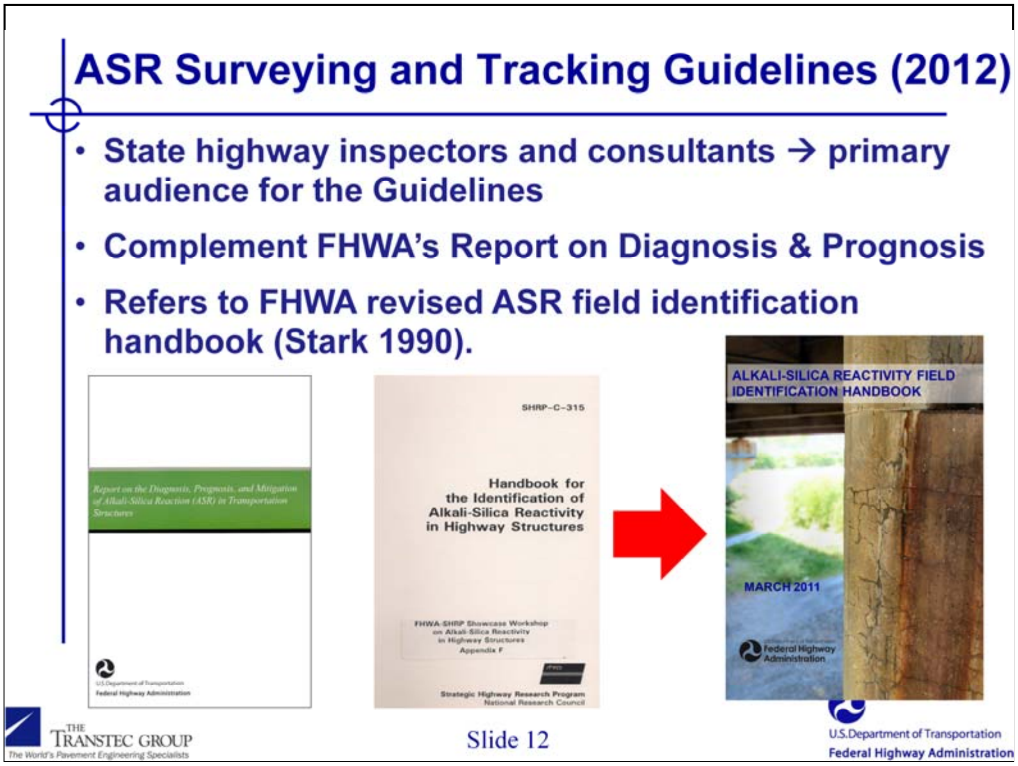
The *Alkali-Silica Reactivity Surveying and Tracking Guidelines* were developed as part of Federal Highway's ASR Development and Deployment program; they are intended to assist engineers and inspectors in tracking and monitoring ASR-induced features of deterioration in bridges, pavements, and tunnels.



Slide 11

The document provides the basis for identifying and quantifying defects potentially caused by ASR. It is expected to serve as input to management systems used for bridges, pavements, and tunnels.



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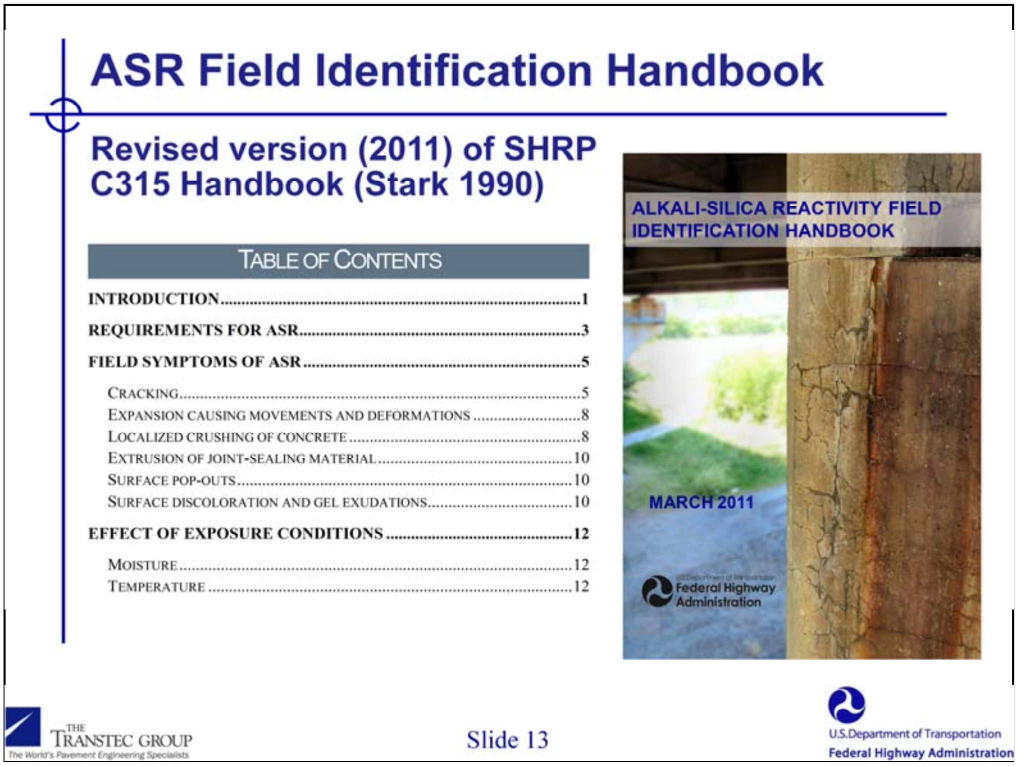
State Highway inspectors and consultants form the primary audience for the Guidelines, which are intended to complement FHWA's Report on the *Diagnosis, Prognosis and Mitigation of ASR in Transportation Structures.*

It also refers to the *ASR field identification handbook*, which is an updated version of the handbook developed by Stark and co-workers under the SHRP program in the late 1980's.



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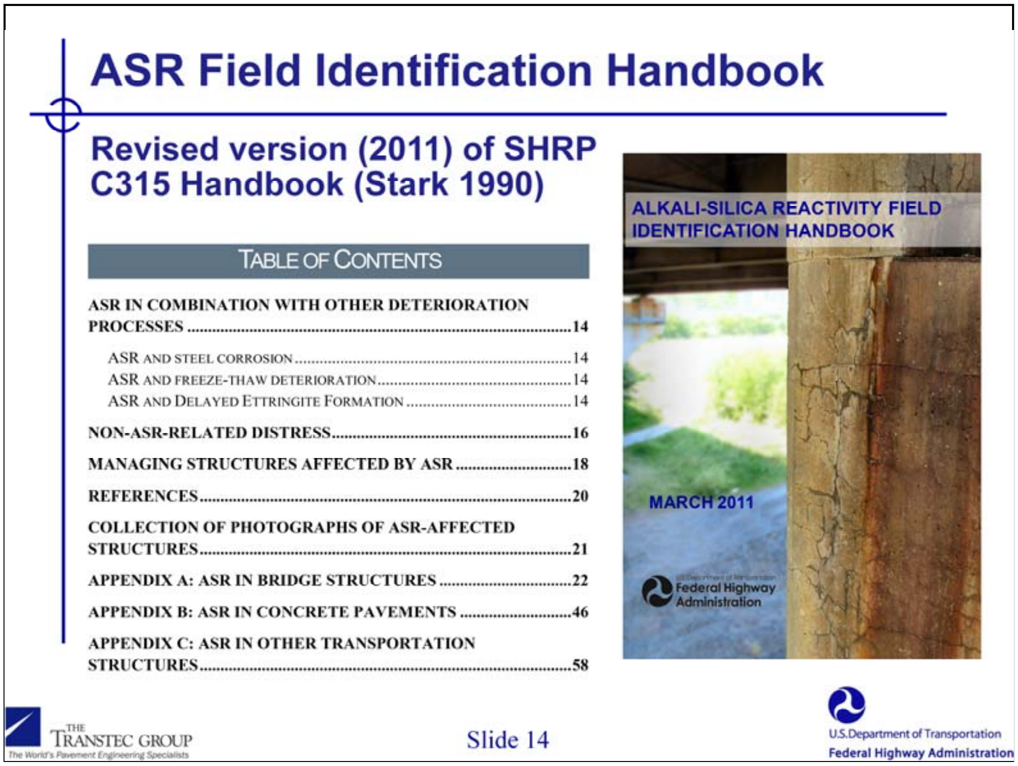
In this new handbook, the common field symptoms of ASR are presented, such as cracking, expansion and deformations, localized crushing of concrete due to excessive expansions, etc. Also, the effects of the exposure conditions (temperature and humidity) on ASR are discussed.



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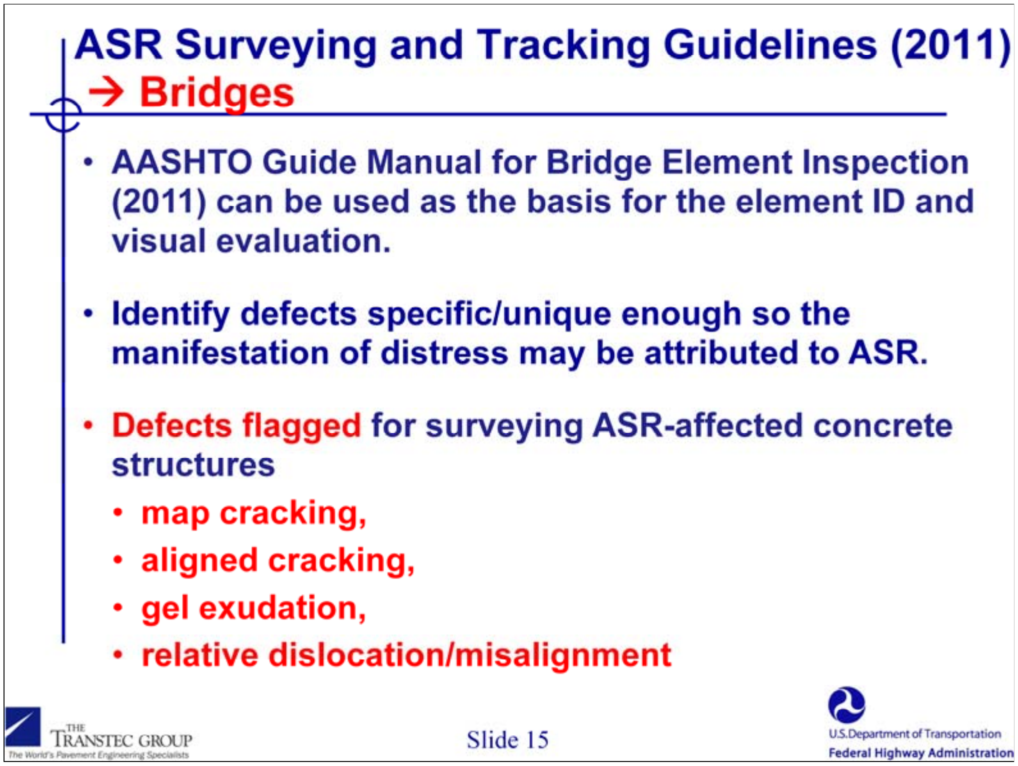
Examples of deterioration due to ASR, in combination with other deleterious mechanisms such as corrosion of reinforcing steel, freezing and thawing and delayed ettringite formation, are presented, discussed and compared to non-ASR related distresses.

Finally, the handbook presents a large number of pictures of typical symptoms of ASR in bridges structures, pavements and other transportation structures.



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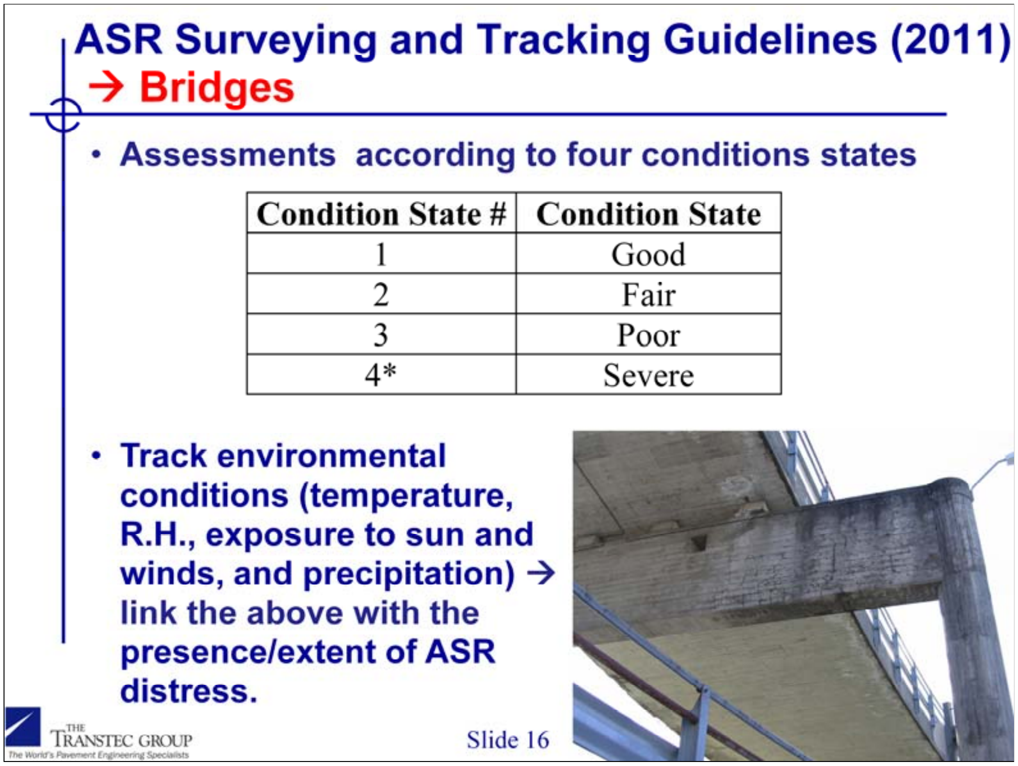
In the case of *bridge structures*, basic inspection data, such as element ID and visual evaluation, can first be collected in accordance with the AASHTO Guide Manual for Bridge Element Inspection that was published in 2011.

The concept is to identify defects that are specific/unique enough so the manifestation of distress may be attributed to ASR.

Such features consist of *map cracking*, *aligned cracking*, *gel exudation*, and *relative dislocation/ misalignment* of adjacent sections.



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The presence and extent of ASR-related defects are then noted and quantified in accordance to the four conditions states described in the Table below, i.e. from 1 (good) to 4 (severe).

In addition, environmental conditions, especially temperature, relative humidity, exposure to sun and winds, and precipitation, can be tracked and coupled with other inspection findings to attempt linking the specific climatic conditions (especially the availability of moisture) to the presence and extent of ASR.

ASR Surveying and Tracking Guidelines (2011) → Bridges

Defect	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 element or bridge, or both
Aligned Cracking	None to hairline	Narrow size or density, or both	Medium size or density, or both	
Gel Exudation	None	Moderate	Severe (with gel staining)	
Relative dislocation/ misalignment	None	Tolerable	Approaching or exceeding limits (including causing local crushing)	

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This Table summarizes the proposed ASR-related defects, defect descriptions, and criteria/ threshold for bridge element types using a similar approach as in the AASHTO guide manual (2011). For example, in the case of map cracking, the condition state 1 corresponds to the presence of hairline cracks in the worst case, while the identification of medium-size cracks will result in classifying the concrete in the condition state 3.

It is important to note that Condition 4, which 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.

ASR Surveying and Tracking Guidelines (2011)
→ ASR-related defects to be tracked in Bridges

Defect	Hair-line Minor	Narrow - Moderate	Medium - Severe
Map cracking	Crack width < 0.0625" (1.6mm) % Map cracking < 5%	Crack width of 0.0625" (1.6mm) – 0.1250" (3.2mm) % Map cracking 5 to 25%	Crack width > 0.1250" (1.6mm) % Map cracking > 25%
Aligned cracking	Crack width < 0.0625" (1.6mm)	Crack width of 0.0625" (1.6mm) – 0.1250" (3.2mm)	Crack width > 0.1250" (1.6mm)
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 sealant at joints, or local crushing)	Movement is visible, with loss of clearance, exudation of sealants at joints, or local crushing

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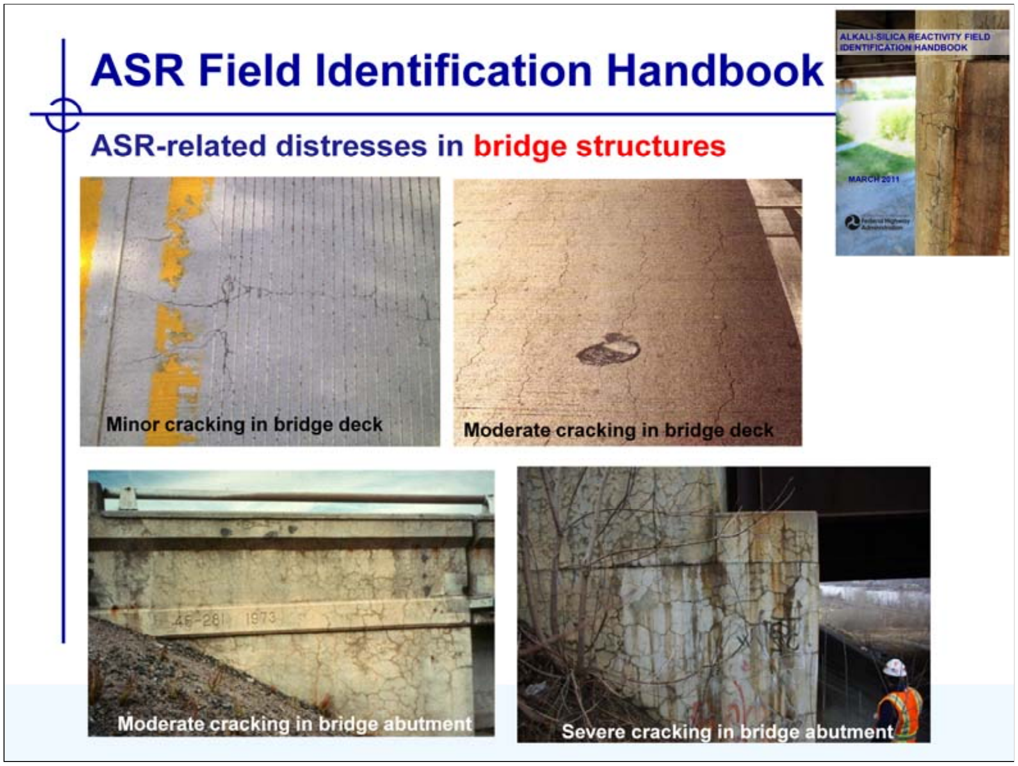
More detailed descriptions of the above defects are provided in this Table. For example, in the case of the *map cracking*, the defect is evaluated in terms of *crack width*, ranging from minor (0.0625 in.) to severe (> 0.1250 in.) as well as the *surface area affected*, ranging from minor (< 5%) to severe (>25%).

The *relative dislocation/misalignment* will range from minor to medium/severe, where movement is visible, with loss of clearance, exudation of sealants at joints, or local crushing.



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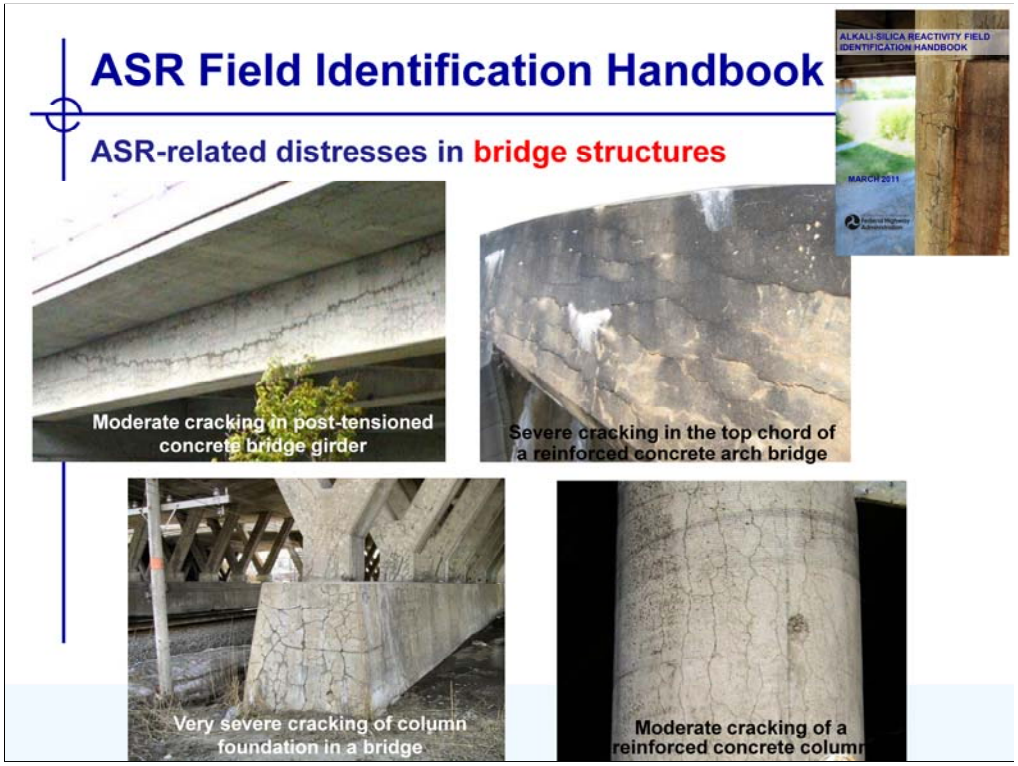
The *Alkali-Silica Reactivity Field Identification Handbook* provides a wide range of photographs illustrating the above features of ASR, as well as examples of condition states (or severity ratings) to help inspectors in rating the condition of the bridge elements.

For instance, examples are given here of minor and moderate cracking in bridge decks, moderate to severe cracking in abutment walls of bridge structures.



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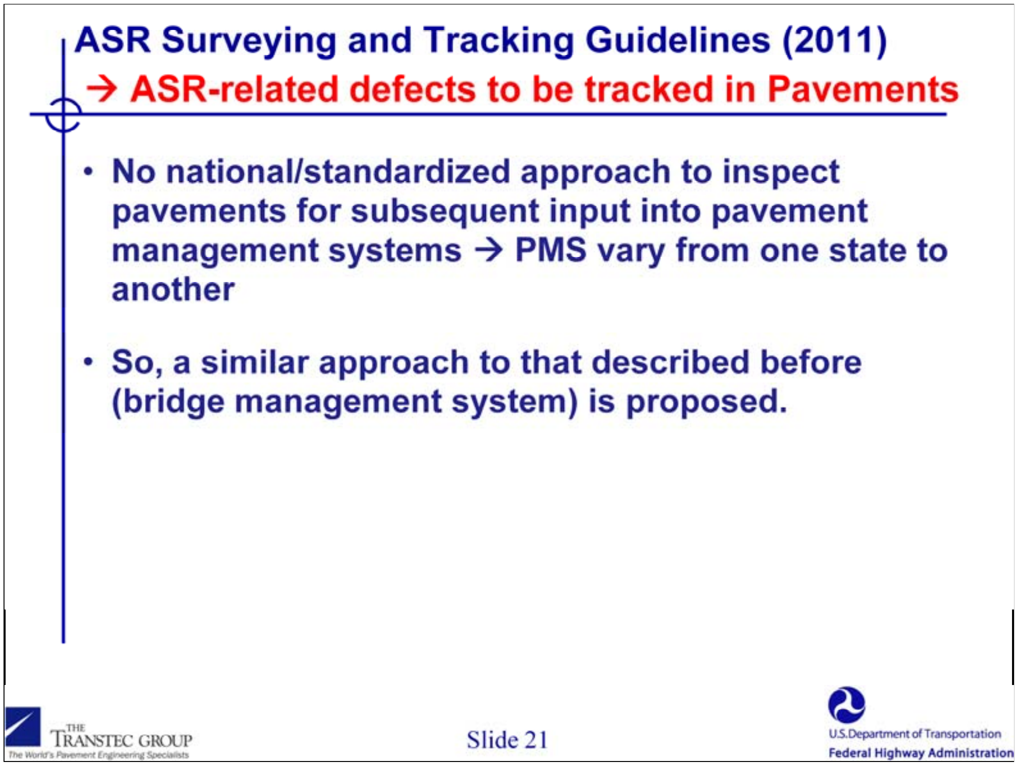
Other examples are given in this slide, i.e. moderate cracking in post-tensioned concrete bridge girder, severe cracking in the top chord of a reinforced concrete arch bridge, very severe cracking in the foundation block of columns in a bridge structure, and moderate cracking in a reinforced concrete column.



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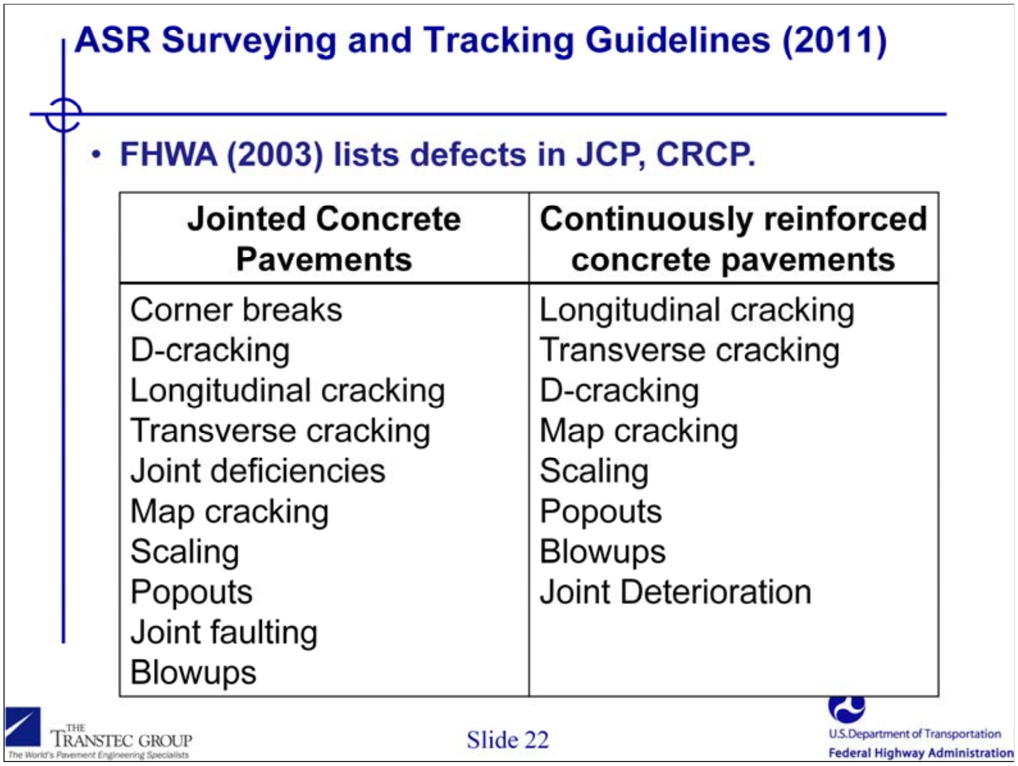
In the case of concrete pavements, there is no national/standardized approach to inspect pavements for subsequent input into pavement management systems, such systems vary from one state to another. So, a similar approach to that proposed for bridges can be adopted.



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According to FHWA's Distress Identification Manual for the Long-Term Pavement Performance, published in 2003, this table lists the defects that can be identified in Jointed Concrete Pavements and continuously reinforced concrete pavements.

ASR Surveying and Tracking Guidelines (2011)

→ ASR-related defects to be tracked in Pavements

- **FHWA (2003) lists defects in JCP, CRCP.**

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	

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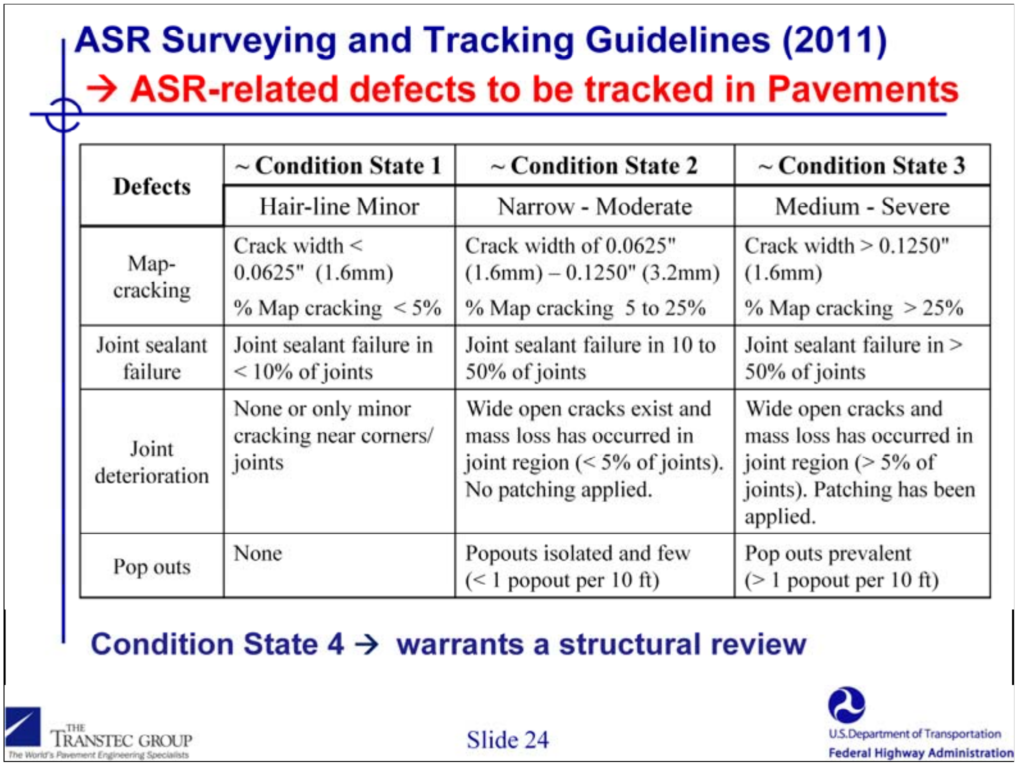
During routine field surveys, the inspectors will give special attention to the features suggestive of ASR, which are highlighted in this slide (name them).



ASR Surveying and Tracking Guidelines (2011)

→ ASR-related defects to be tracked in Pavements

Defects	~ Condition State 1	~ Condition State 2	~ Condition State 3
	Hair-line Minor	Narrow - Moderate	Medium - Severe
Map-cracking	Crack width < 0.0625" (1.6mm) % Map cracking < 5%	Crack width of 0.0625" (1.6mm) – 0.1250" (3.2mm) % Map cracking 5 to 25%	Crack width > 0.1250" (1.6mm) % Map cracking > 25%
Joint sealant failure	Joint sealant failure in < 10% of joints	Joint sealant failure in 10 to 50% of joints	Joint sealant failure in > 50% of joints
Joint deterioration	None or only minor cracking near corners/ joints	Wide open cracks exist and mass loss has occurred in joint region (< 5% of joints). No patching applied.	Wide open cracks and mass loss has occurred in joint region (> 5% of joints). Patching has been applied.
Pop outs	None	Popouts isolated and few (< 1 popout per 10 ft)	Pop outs prevalent (> 1 popout per 10 ft)

Condition State 4 → warrants a structural review

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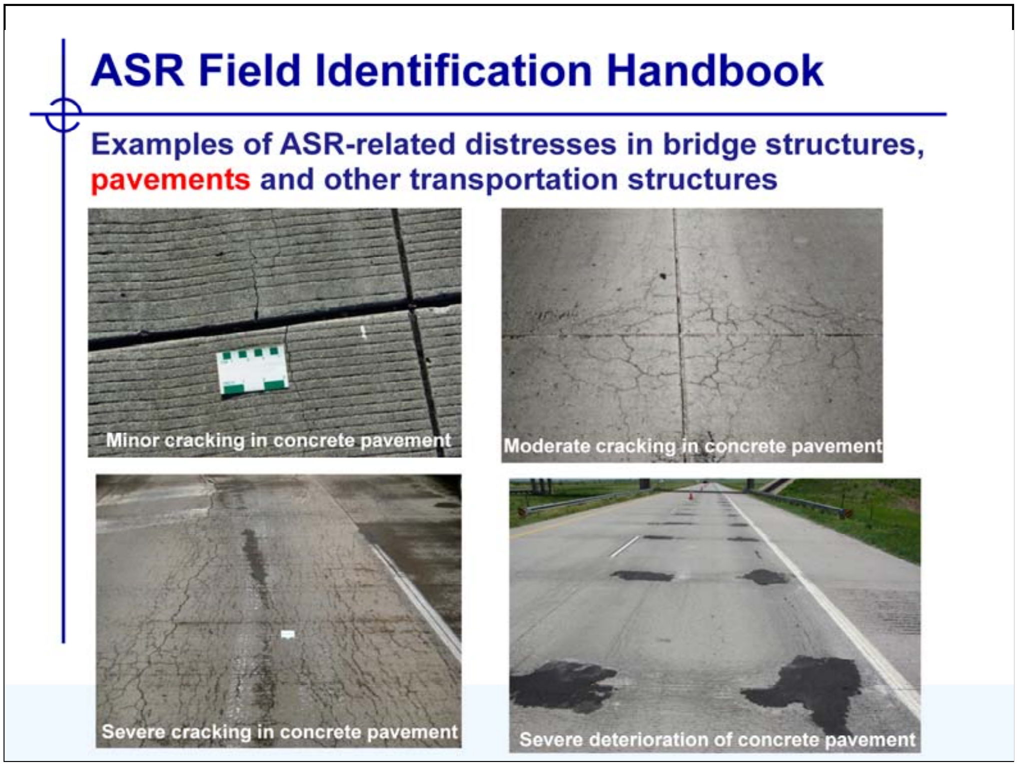
Similarly to bridge structures, the *Alkali-Silica Reactivity Surveying and Tracking Guidelines* present detailed descriptions to help inspectors for quantifying the severity of the various defects suggestive of ASR.

For example, in the case of the *map cracking*, the defect is evaluated in terms of *crack width*, ranging from minor (0.0625 in.) to severe (> 0.1250 in.) as well as *surface area affected*, ranging from minor (< 5%) to severe (>25%).

Joint deterioration will range from minor cracking near corners/joints (condition state 1) to wide opened cracks and mass loss occurring in joint region (> 5% of joints)(condition state 3).

Once again, Condition 4, which is beyond the limit state of Condition State 3, warrants a structural review to determine the strength or serviceability of the element.



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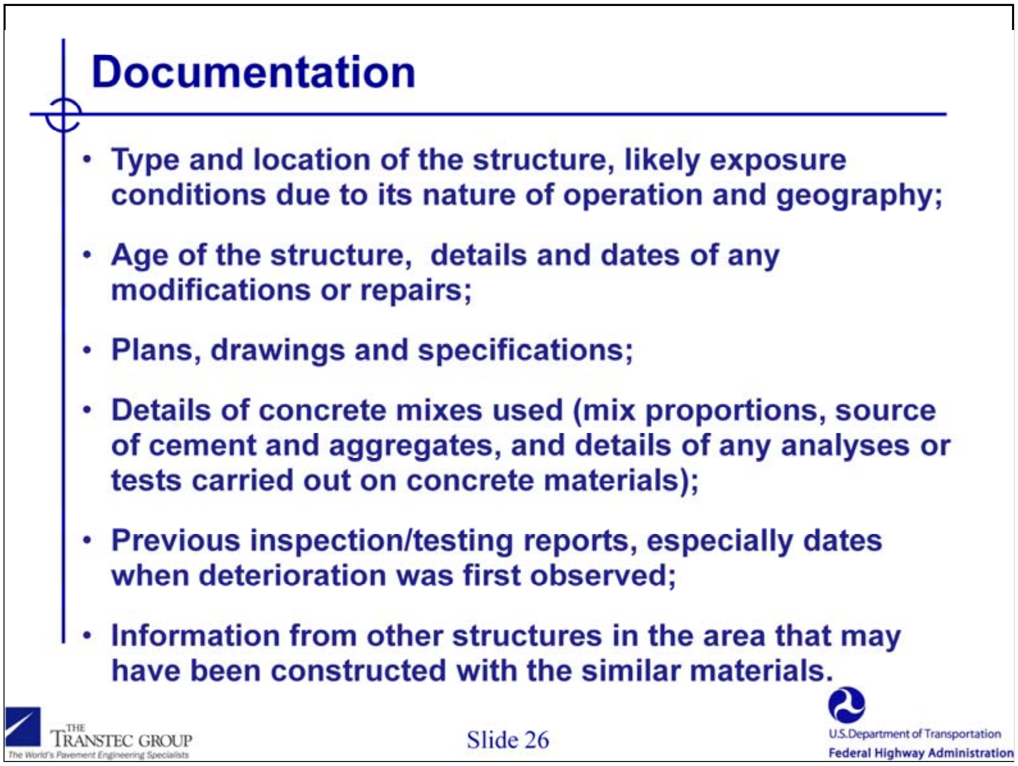
The *Alkali-Silica Reactivity Field Identification Handbook* provides a wide range of photographs illustrating the above features of ASR, as well as examples of condition states (or severity ratings) to help inspectors in rating the condition of the pavement sections.

For instance, examples are given here of minor, moderate and severe cracking/deterioration in pavement sections, with patching required to repair spalling at joints.



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When the information collected by the inspectors, as part of the routine field inspection, has highlighted the possibility of ASR, either during a first cycle or a subsequent cycle of the routine inspection program, it may be useful to gather additional information on the structure in question to help for the interpretation of the observations. The information that could be useful includes the following:

Type and location of the structure, likely exposure conditions due to its nature of operation and geography;

Age of the structure, details and dates of any modifications or repairs;

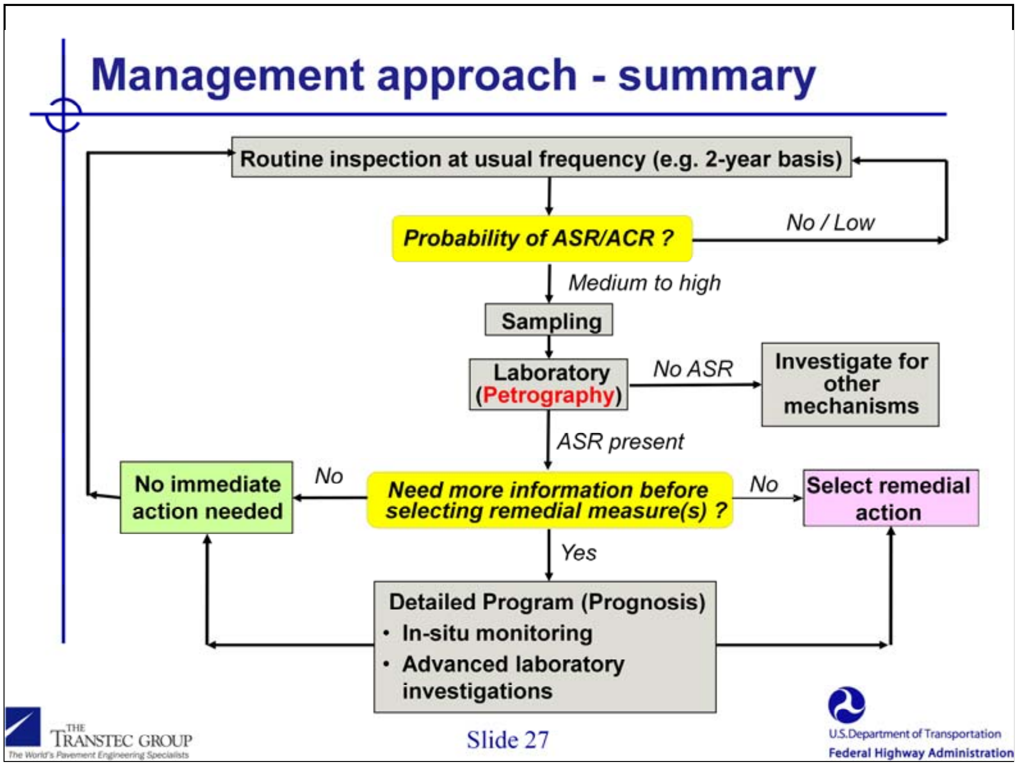
Plans, drawings and specifications;

Details of concrete mixes used (mix proportions, source of cement and aggregates, and details of any analyses or tests carried out on concrete materials);

Previous inspection/testing reports, especially dates when deterioration was first observed;

Information from other structures in the area that may have been constructed with the similar materials.

Details regarding the concrete materials, especially the composition and proportion of the cement and the type of aggregate used, are most useful when assessing the likelihood of ASR. It is recognized that information of this nature is often not available or lacks specific details in the case of many structures; however, it is important to collect whatever data are available.



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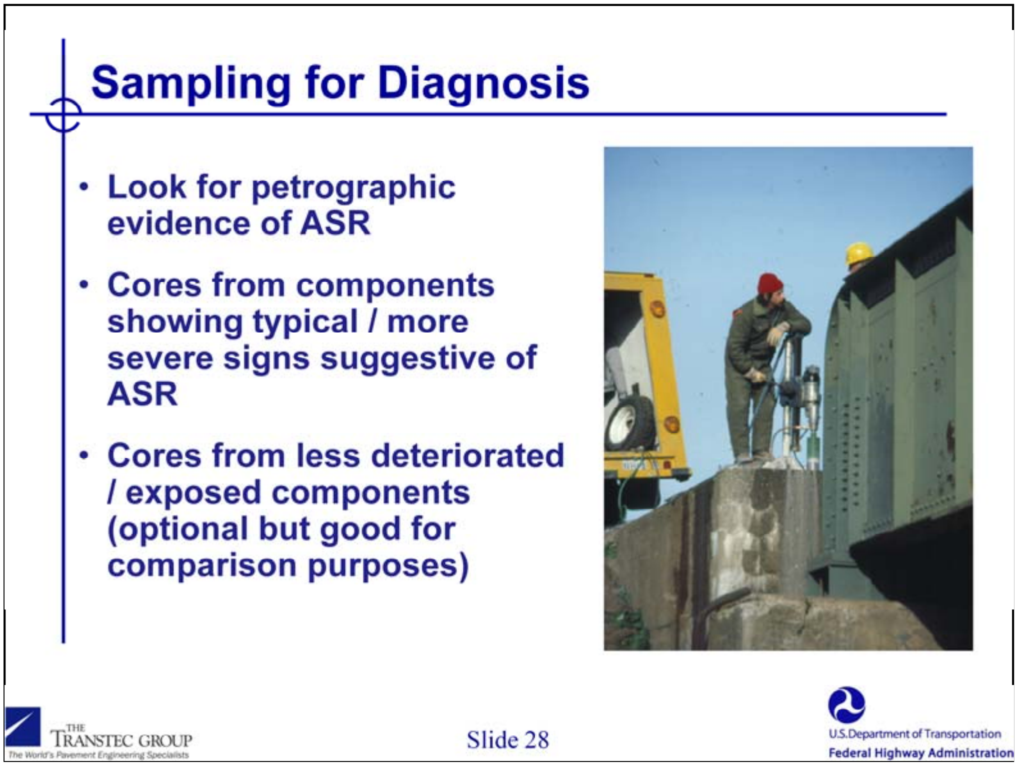
If the probability of ASR is low or no visual signs suggestive of ASR are noted during the routine inspection program, further work can probably be postponed until the next cycle of inspection. However, when the visual signs of deterioration observed on the structure(s) examined are such that AAR is a possibility, sampling of the structure under evaluation is recommended to confirm the first diagnostic obtained from the visual survey.



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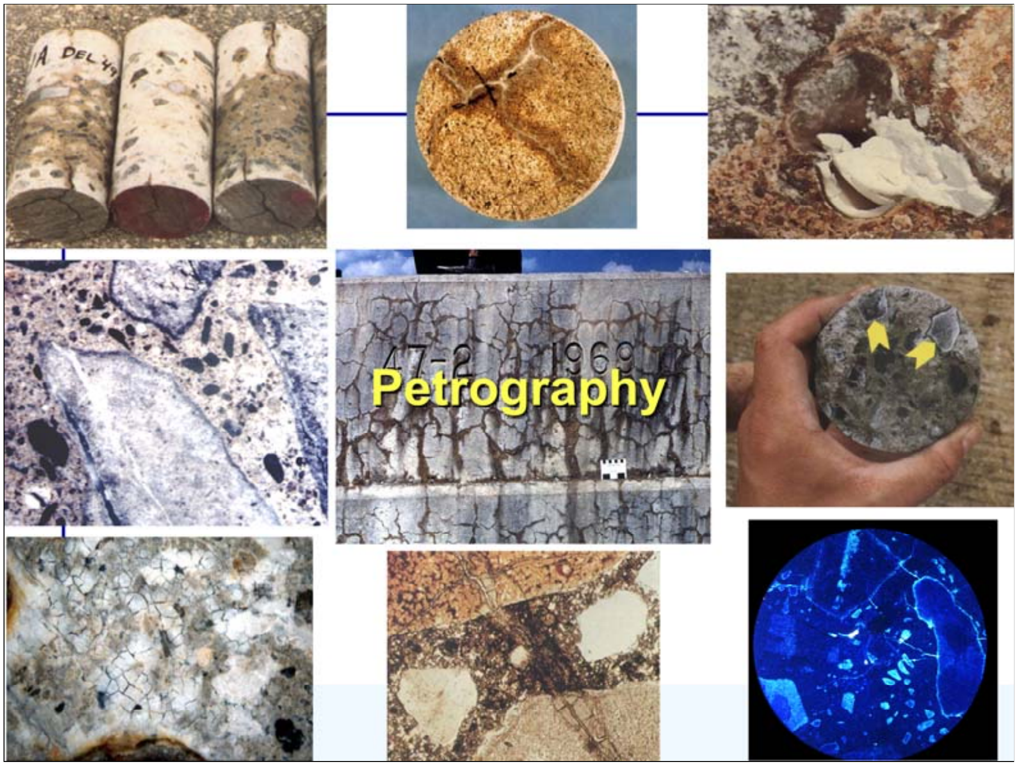
At this stage of the program, sampling is carried out on component(s) of the structures showing typical defects suggestive of ASR, which most often correspond to structural components exposed to a constant or renewable supply of moisture.

This is essentially done to determine whether or not the concrete contains petrographic evidence of ASR.

For comparison purposes, it will also be useful/appropriate to collect cores from structural components that are less or not deteriorated, or not exposed to the severe environmental elements.



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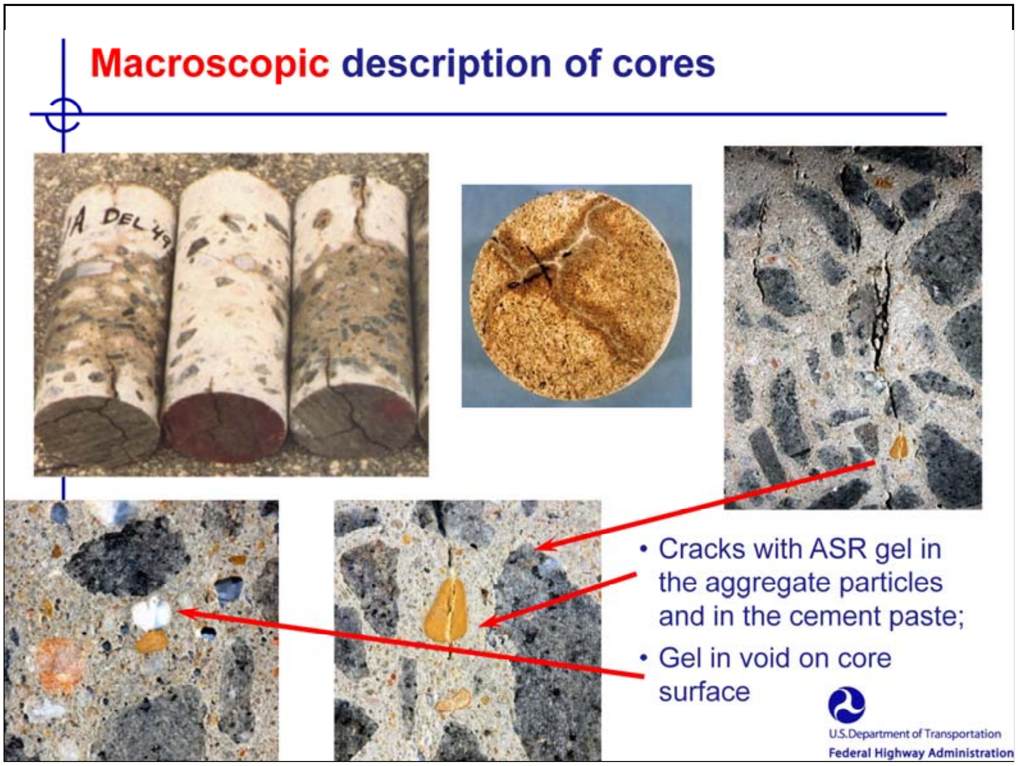
Petrographic examination is a powerful technique for the diagnosis of the cause of concrete deterioration. Petrographic features of ASR can be detected on various types of specimens prepared from the drilled cores (e.g. polished sections or slices, broken (fresh) surfaces, and thin sections). Although not necessarily exclusive to ASR, these features generally consist of the following:

Microcracking in aggregates and/or cement paste.

Reaction product “gel”.

Reaction rims.

Loss of the cement paste-aggregate bond.



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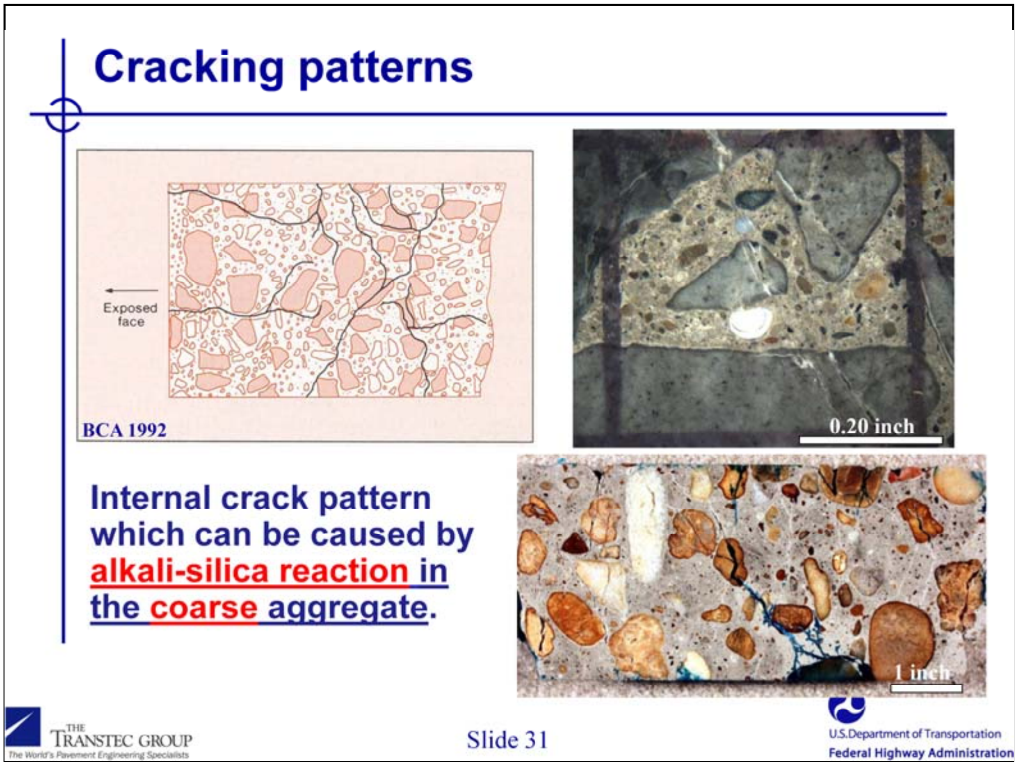
Macroscopic signs of concrete deterioration due to ASR (but sometimes not exclusively) can be detected by examining the cores immediately after their extraction or back in the laboratory.

Such features can consist of macrocracks in the outer portion (or "skin" of the concrete member turning into microcracking in the "internal" part of the concrete member), gel staining surrounding surface cracks, dark reaction rims at the periphery of reacted aggregate particles, cracks within reactive aggregate particles sometimes extending into the cement paste (with/without reaction products gels), alkali-silica gel in air voids of the cement paste, etc.



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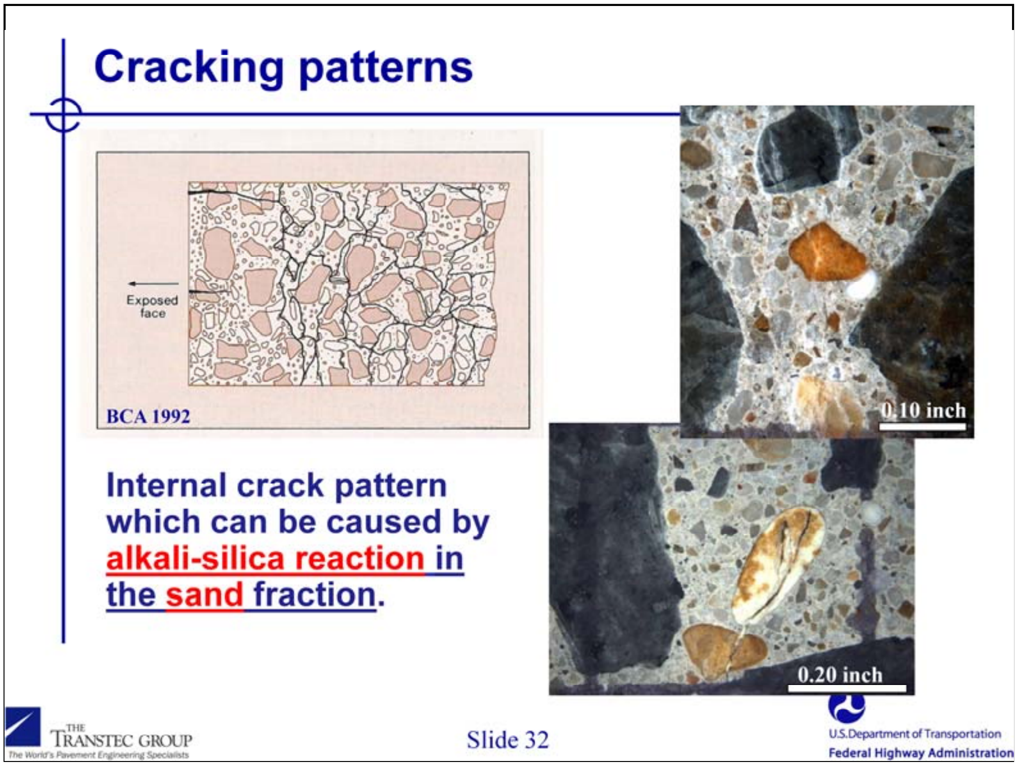
St. John and co-authors in the late 1990’s compared “idealized” cracking patterns in concrete specimens affected by various deleterious mechanisms. In the case of concrete affected by ASR where the reactive fraction is in the coarse aggregate, a network of microcracks develops in the inner part of the concrete, with only a few “macrocracks” being observed in its outer (superficial) portion.

The microcracks typically run through the particles. Cracks in the aggregate particles and in the cement paste are filled or lined with alkali-silica reaction products depending on the degree or severity of the reaction/expansion.



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Similarly, when the reactive fraction is in the sand, a network of microcracks also develops in the inner part of the concrete, which are found connecting and running through the fine aggregate particles. Again, only a few "macrocracks" are generally observed in its outer (superficial) portion of the concrete element.

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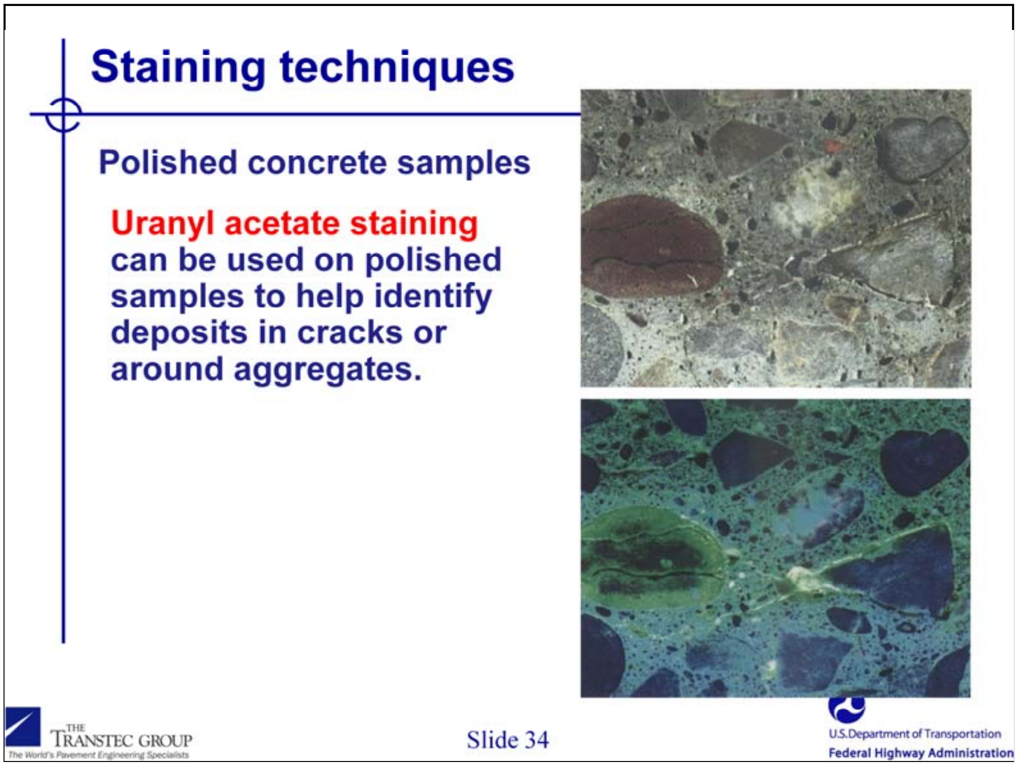
ASR generates secondary reaction products containing silica, alkalis and calcium as typical constituents. The so-called "alkali-silica gel" will be found filling/lining cracks within the aggregate particles and in the cement paste, as well as air voids.



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The confirmation of the presence and of the nature of reaction products is not necessarily easy. Staining techniques have been proposed to help identifying the reaction product gel in concrete affected by ASR.

Natesaiyer and co-workers proposed, in the early 1990's, a method that consists in applying an uranyl acetate solution on polished or fresh broken surfaces of concrete specimens to be examined followed by a visual observation of the section under a UV light.

By applying the uranyl acetate solution to a surface containing the gel, the uranyl ion substitutes for the alkalis in the gel, thereby imparting a characteristic yellowish-green glow when viewed in the dark using short wavelength ultraviolet light. ASR gel fluoresces much brighter than cement paste due to the greater concentration of alkali and, subsequently, uranyl ions in the gel.

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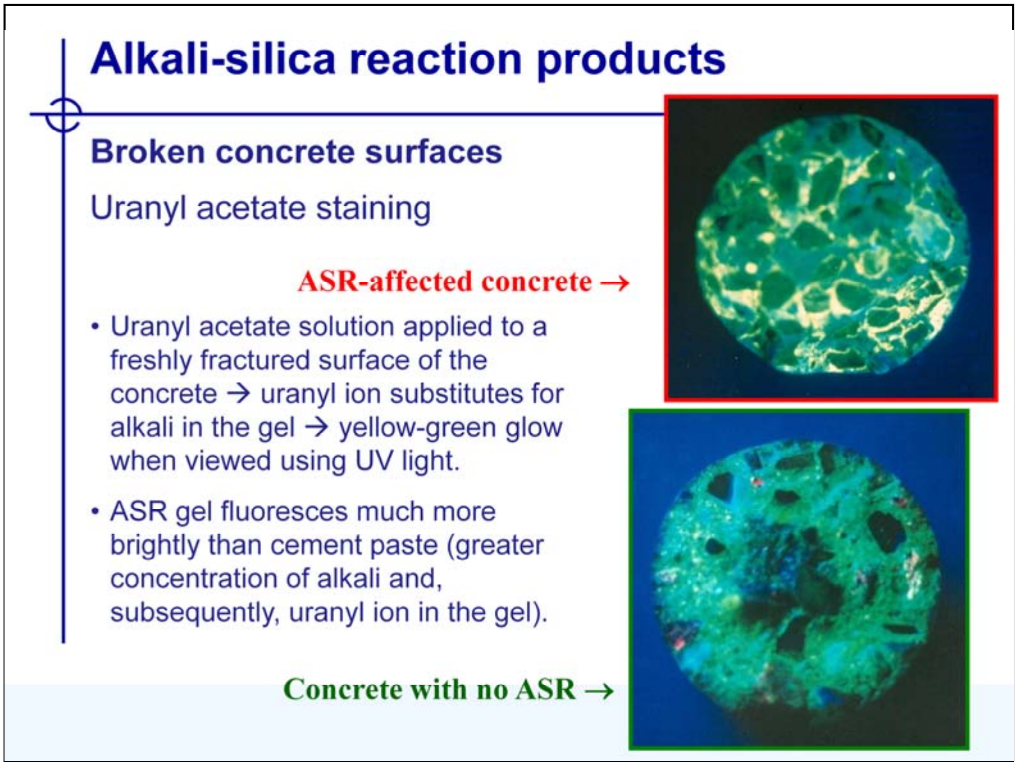
On broken concrete surfaces, the alkali-silica reaction products will be found lining or filling voids and fractured surfaces of the cement paste and the aggregate particles. These deposits will cover more or less important surfaces depending on many factors, such as the extent of the reaction-expansion processes that have occurred, the availability of water, etc



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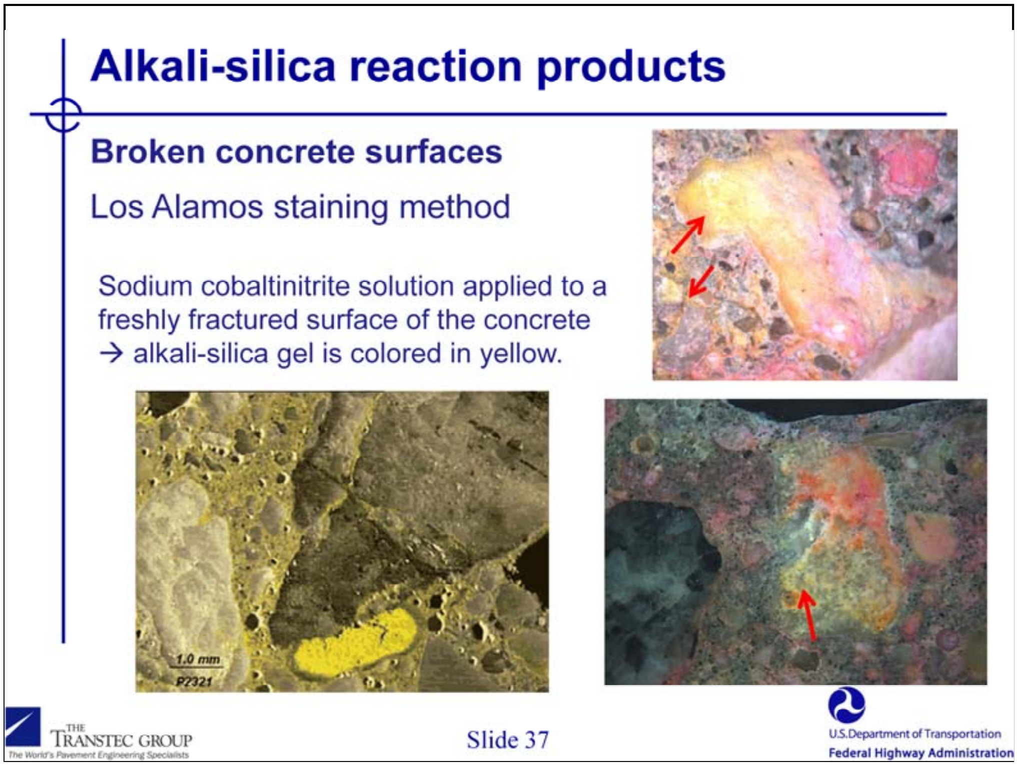
The uranyl acetate solution method can also be used on broken surfaces of concrete cores or laboratory specimens to help identifying the presence and, to some extent, the relative abundance of alkali-silica gel.

This technique should be used with great care following appropriate health and safety procedures because of the potentially hazardous nature of the product. Also, technically speaking, the results of the test should be interpreted with great care since some aggregates fluoresce naturally, which can incorrectly suggest the presence of alkali-silica gel through macroscopic or microscopic examinations.



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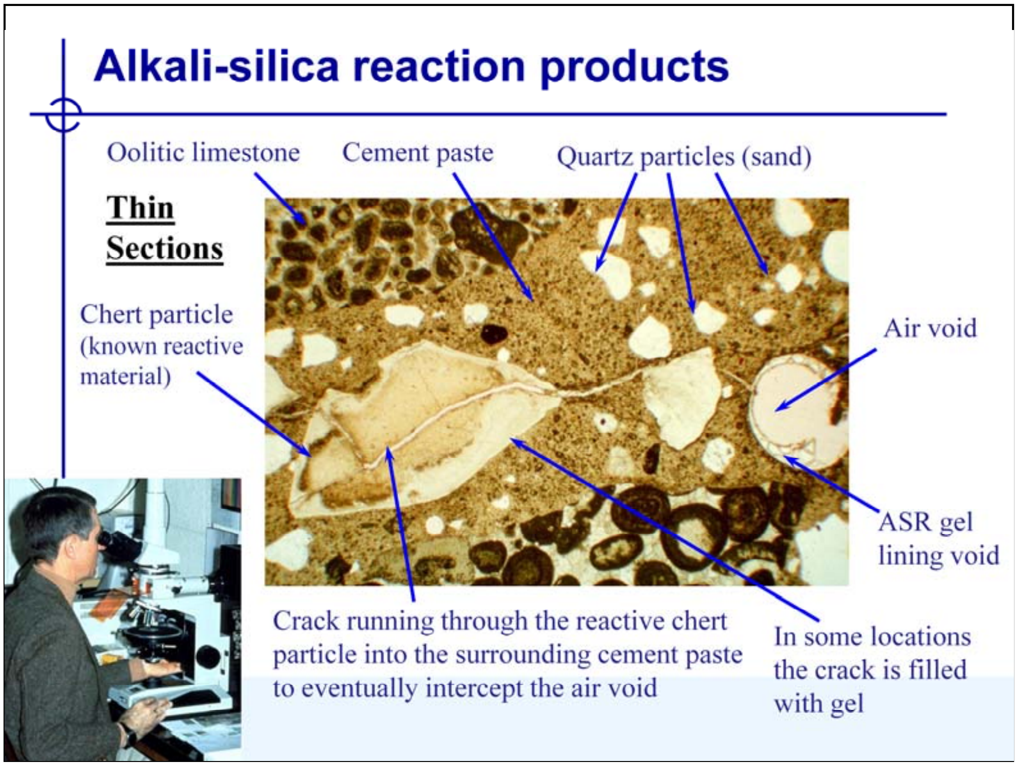
In the late 1990's, Guthrie and Carey from the Los Alamos research Station proposed an alternative method that consists in treating fresh concrete surfaces to successive applications of Sodium Cobaltinitrite and Rhodamine B.

Upon treatment, regions affected by ASR stain either yellow or pink. According to the above author, yellow staining would be associated with massive ASR-related precipitate with gel-like morphology as well as granular precipitate consisting of crystals that have grown from the gel.



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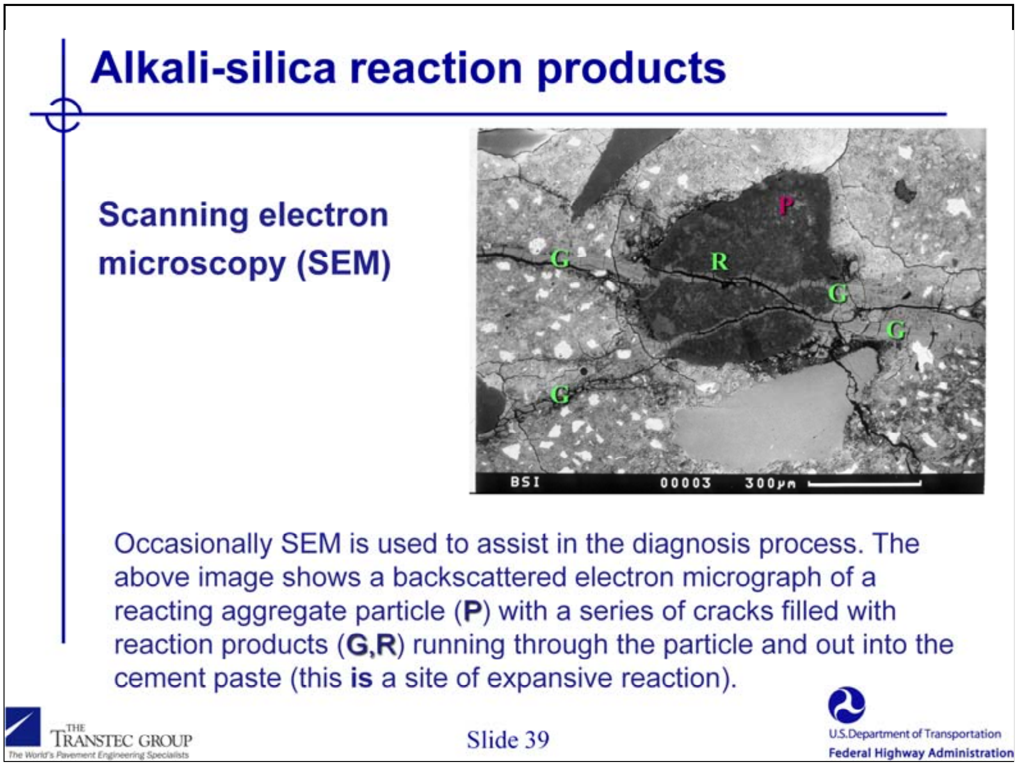
Thin sections prepared from the concrete cores can be examined under the petrographic microscope. The petrographer will look more specifically for "sites of expansive reactions" where microcracks, which have formed within reactive aggregate particles, have extended into the cement paste and also contain secondary ASR products. (Point out on the micrograph the cracks running from the aggregate particle into the cement paste and the air void filled with gel).



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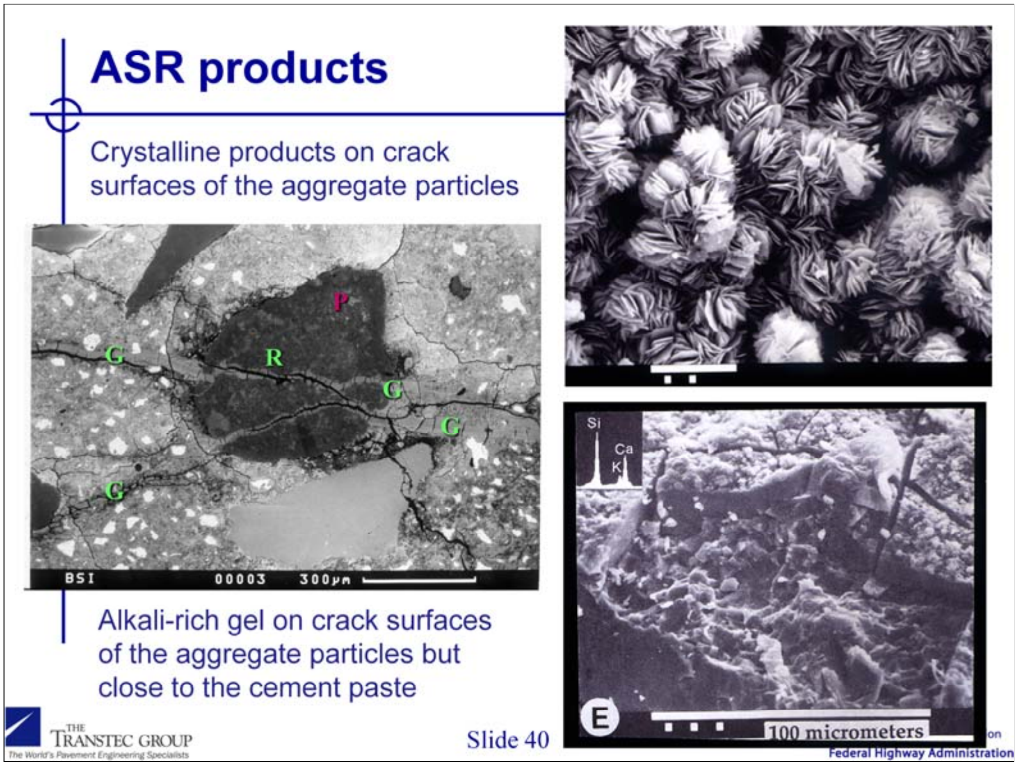
Occasionally, the scanning electron microscope (SEM), equipped with chemical analysis capabilities, is used to assist in the diagnosis process.

The micrograph shows a backscattered electron micrograph of a reacting aggregate particle (P) with a series of cracks filled with reaction products (G,R) running through the particle and out into the cement paste (this is a site of expansive reaction).



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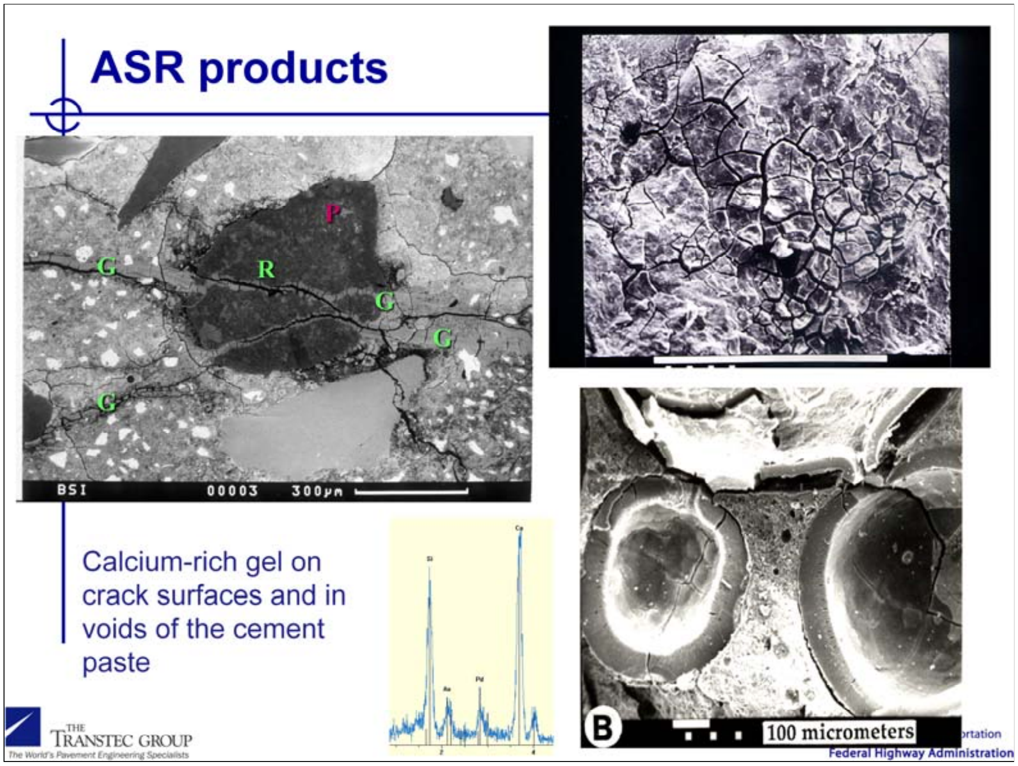
The SEM with energy dispersive X-Ray analysis capabilities will allow identifying / confirming the nature and the composition of the secondary reaction products, which can be a critical step in the diagnosis process.

This micrograph (top right) shows crystalline reaction products (with rosette-like morphology) that can be typically found on cracked surfaces through reactive aggregate particles and, sometimes, in air voids of the cement paste.

The micrograph below shows a layer of alkali-silica gel, containing some calcium, that can be found on the cracked surface of the aggregate particles, at the boundary with the cement paste.



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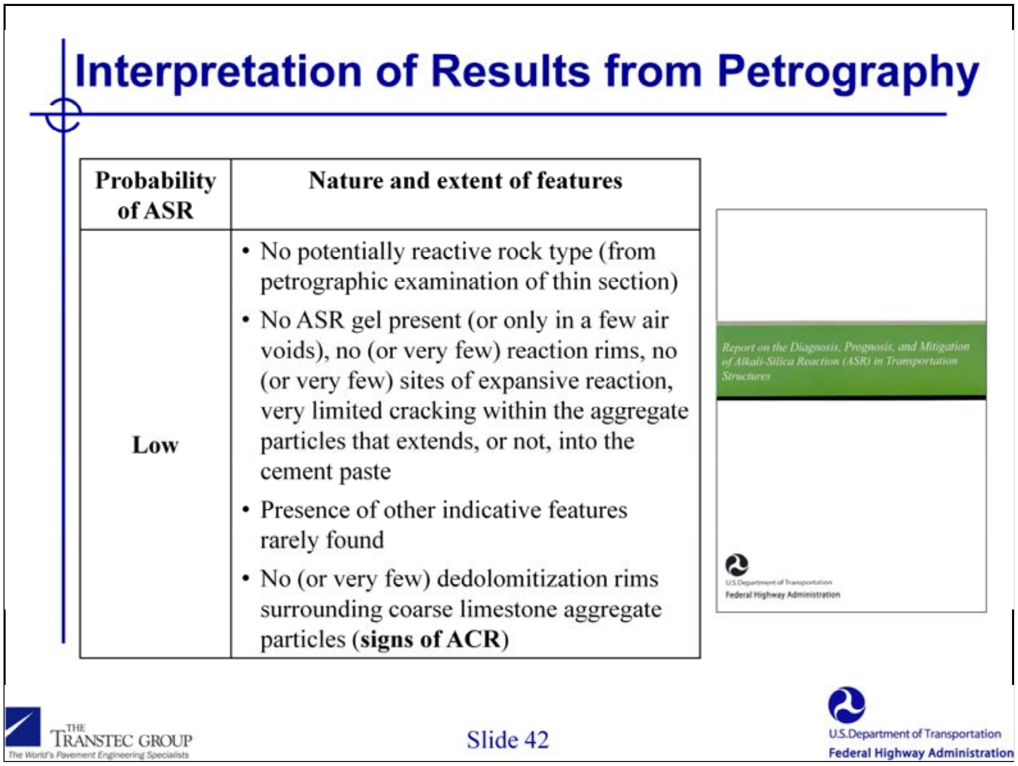
These micrographs show calcium-rich gel deposits on cracked surfaces and in voids of the cement paste.

Typically, ASR gel will be richer in calcium when found in cracks of the cement paste because of an ion exchange process with the hydrates from the cement paste, which can return a part of the alkalis (from the gel) to the concrete pore solution.



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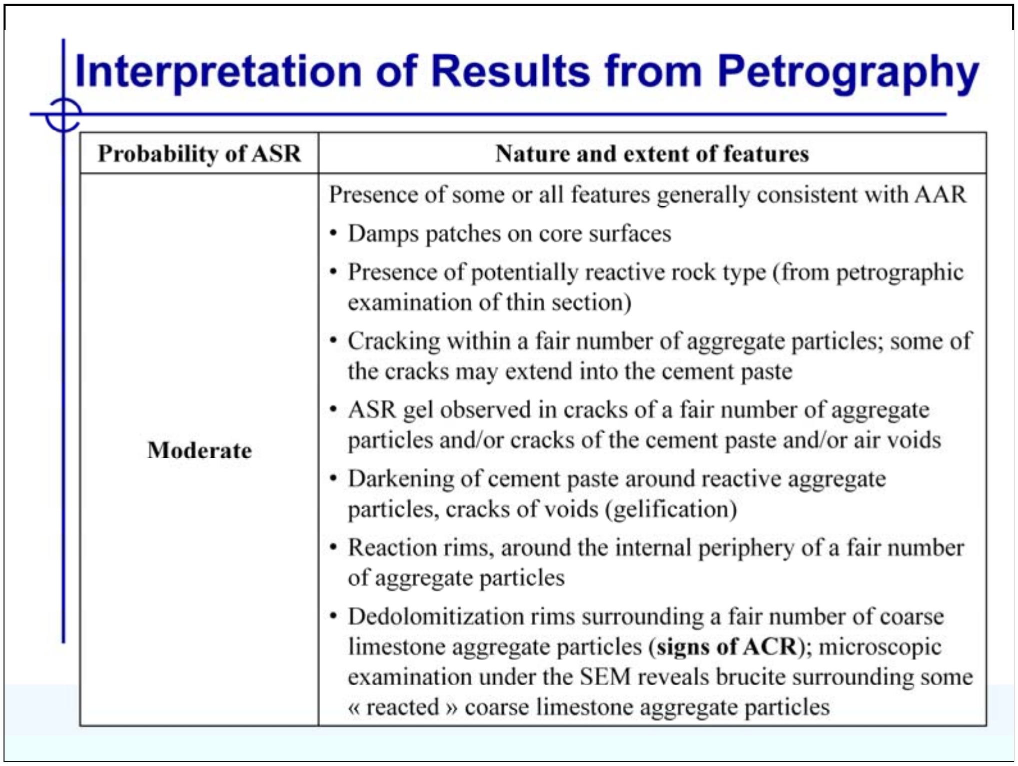
Federal Highway's Report on the *Diagnosis, Prognosis and Mitigation of ASR in Transportation Structures* includes a number of tables that will help the petrographer and the engineers for interpreting the results of petrographic examination.

All the observations obtained from the macroscopic description, and the examination of polished concrete sections and broken surfaces of the core specimens can be gathered and analyzed to determine whether the probability of ASR is low...



Interpretation of Results from Petrography

Probability of ASR	Nature and extent of features
Moderate	Presence of some or all features generally consistent with AAR • Damps patches on core surfaces • Presence of potentially reactive rock type (from petrographic examination of thin section) • Cracking within a fair number of aggregate particles; some of the cracks may extend into the cement paste • ASR gel observed in cracks of a fair number of aggregate particles and/or cracks of the cement paste and/or air voids • Darkening of cement paste around reactive aggregate particles, cracks of voids (gelification) • Reaction rims, around the internal periphery of a fair number of aggregate particles • Dedolomitization rims surrounding a fair number of coarse limestone aggregate particles (**signs of ACR**); microscopic examination under the SEM reveals brucite surrounding some « reacted » coarse limestone aggregate particles

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Moderate...

Interpretation of Results from Petrography

Probability of ASR	Nature and extent of features
High	• Presence of extensive signs of AAR (as described above; larger quantities) • Evidence of sites of expansive reactions, i.e. location within the concrete where evidence or emanation of swelling pressure can be positively identified, and/or • Presence of gel in cracks and voids associated with several reactive particles and readily visible to the unaided eye or under low magnification

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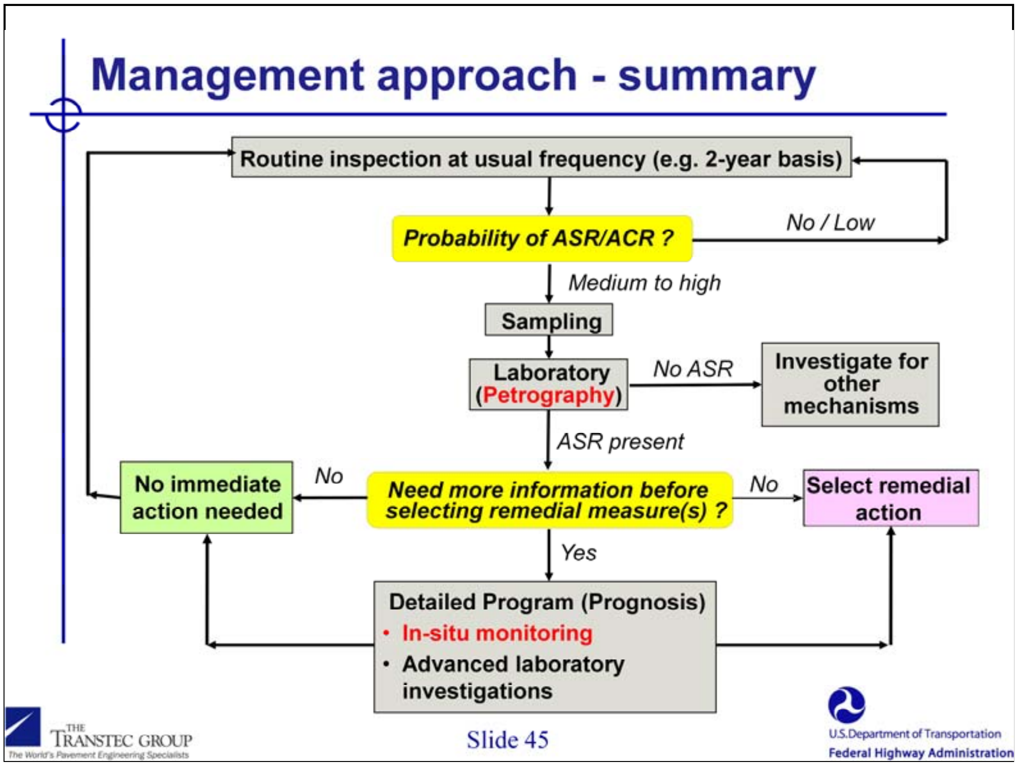
Or high in the concrete specimens.



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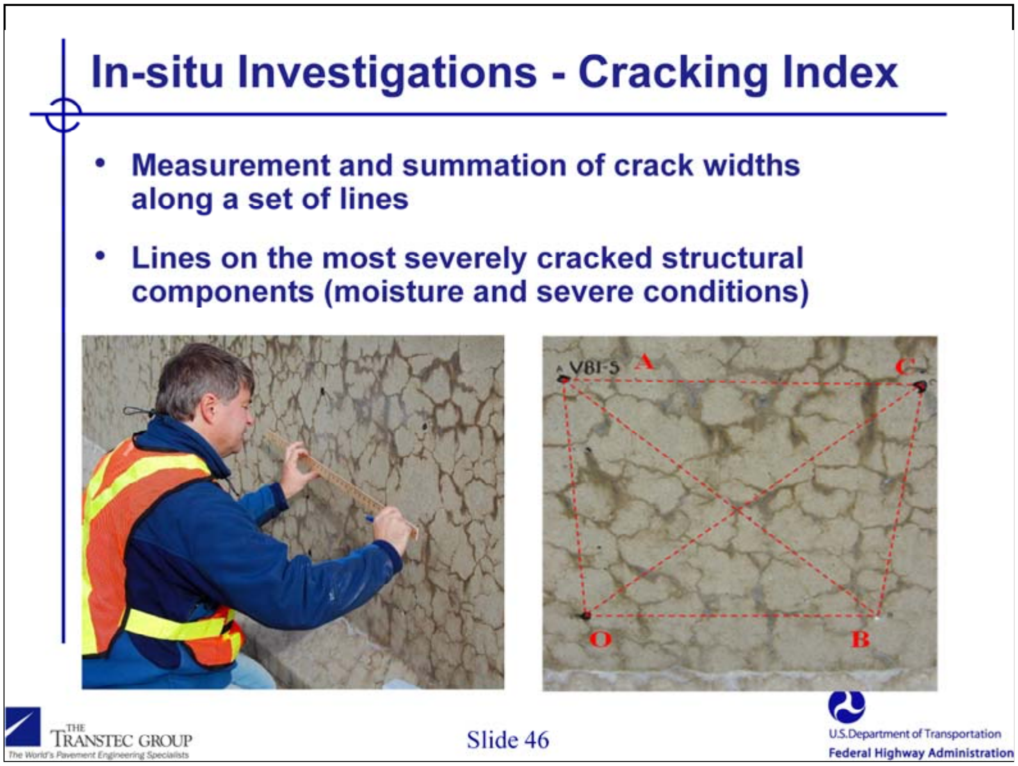
If the results of the petrographic examination indicate that ASR is likely not the main factor or a significant contributor to the damage observed on the structure, further investigations may be necessary to identify the deleterious mechanism involved in the deterioration.

However, when petrographic evidence of ASR is confirmed, a decision on further steps to be taken can be based on factors such as the severity of the damage and the "criticality" of the structure.

In some cases, it may be decided that additional “technical” investigations are not required and some remedial actions could/should already be implemented. Examples of such cases will be given in the next presentation on remedial actions.

On the other hand, the extent of the damage may be such that no immediate action is needed; the structure will then be re-examined as part of the routine condition survey.

However, in the case of “critical” structures, such as large size / major highway bridges and pavements, hydraulic dams, etc. or when the extent of deterioration is significant, a detailed in-situ and/or laboratory investigation program may be desirable/necessary to determine the potential for the progress of ASR in the structure (prognosis), which can provide additional information for selecting the best remedial action.



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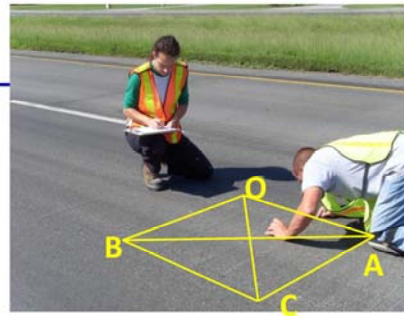
The extent of surface cracking on severely exposed/cracked sections of concrete elements is somewhat related to the overall amount of expansion reached by the affected member. The *Cracking Index* method consists in the measurement and summation of crack widths along a set of lines drawn perpendicularly on the surface of the concrete element investigated.

Cracking Index



	1	2	3	4	5	Base Length (m)	# cracks	Crack opening (mm)			
Interval	6	7	8	9	10			Total sum	Avg. /crack	Avg. /m	C.I. mm/m
OA	0.1, 0.1	0.2	--	--	0.6	0.5	6	1.8	0.3	3.6	3.2
	0.4	--	--	0.4	--						
BC	0.1	0.4	--	0.1	0.1	0.5	7	1.4	0.2	2.8	
	--	0.3	0.2	0.2	--						
OB	--	--	0.3, 0.5	0.4	0.3	0.5	7	2.8	0.4	5.6	4.6
	0.4	0.3	--	--	0.6						
AC	0.5	0.2	--	--	0.3	0.5	8	1.6	0.2	3.6	
	0.05	0.05	0.1, 0.2	--	0.2						

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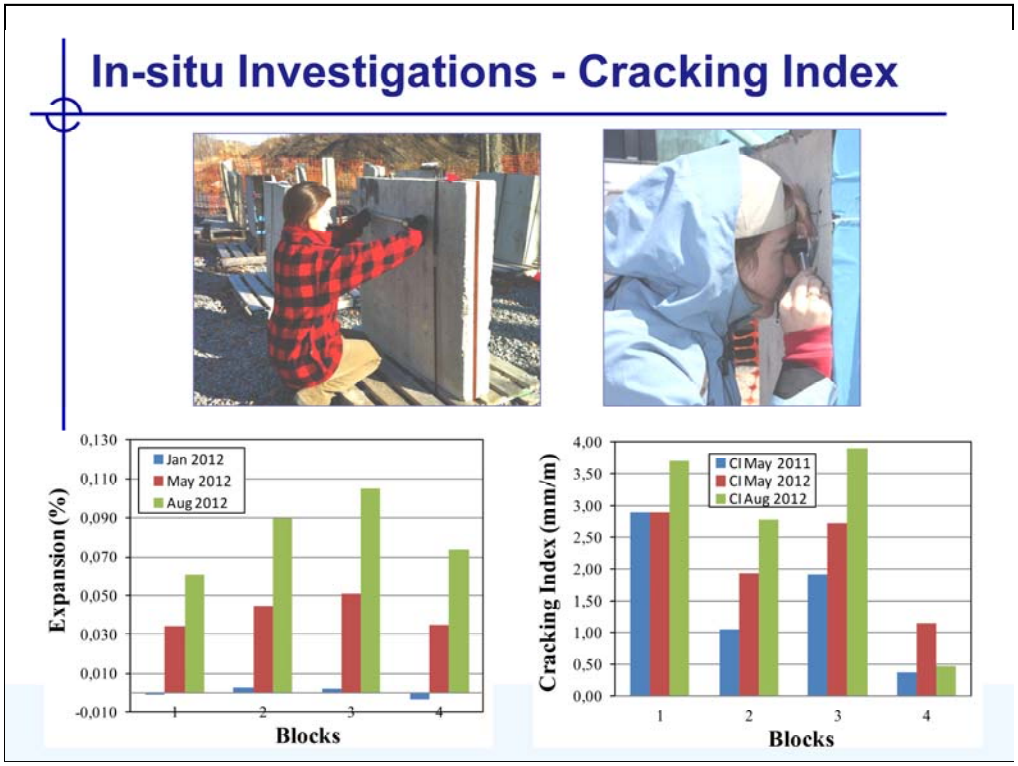
The data are used to calculate the *Cracking Index* value, which increases with increasing expansion and cracking.

The method can provide a quantitative assessment of the extent of cracking in structural members, either punctually (when obtained at a specific time) or as a progressive process when performing the measurements on a regular basis at the exact same location (rate of expansion – prognosis).



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For example, Francoeur and co-workers, recently used the Cracking Index method to study the progress of expansion and cracking in metric size concrete blocks exposed outdoors and suffering from deleterious aggregate's reactions. The graphs show a good correlation between the expansion of the concrete blocks and the progress of surface cracking measured through the Cracking Index method.

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Measurements of expansion/deformation can be performed using demec points or metallic references drilled into the surface of selected structural members and extensometers. As part of the *Federal Highway's ASR Development and Deployment program*, grid systems with demec points were installed on selected ASR-affected and non-deteriorated concrete members, which served for both Cracking Index and expansion measurements.

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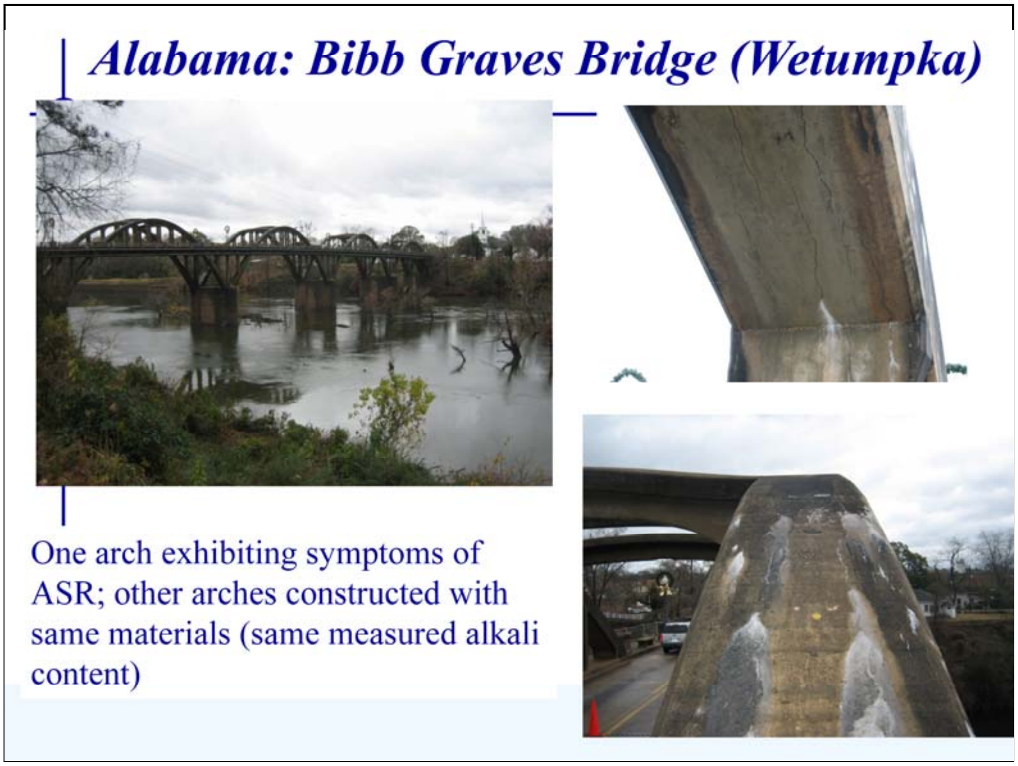
Such a set-up is versatile and can be used on various types of concrete members, such as pavements, barrier walls, abutment walls in bridges, columns, etc.



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This slide shows an historical bridge structure located in Alabama, which has been selected as part of *Federal Highway's ASR Development and Deployment program*. The structure, constructed in 1930 and 1931, is composed of ten concrete arches, with one of them exhibiting significant deterioration. Other arches were constructed with the same materials (same measured alkali content) but are in good condition.

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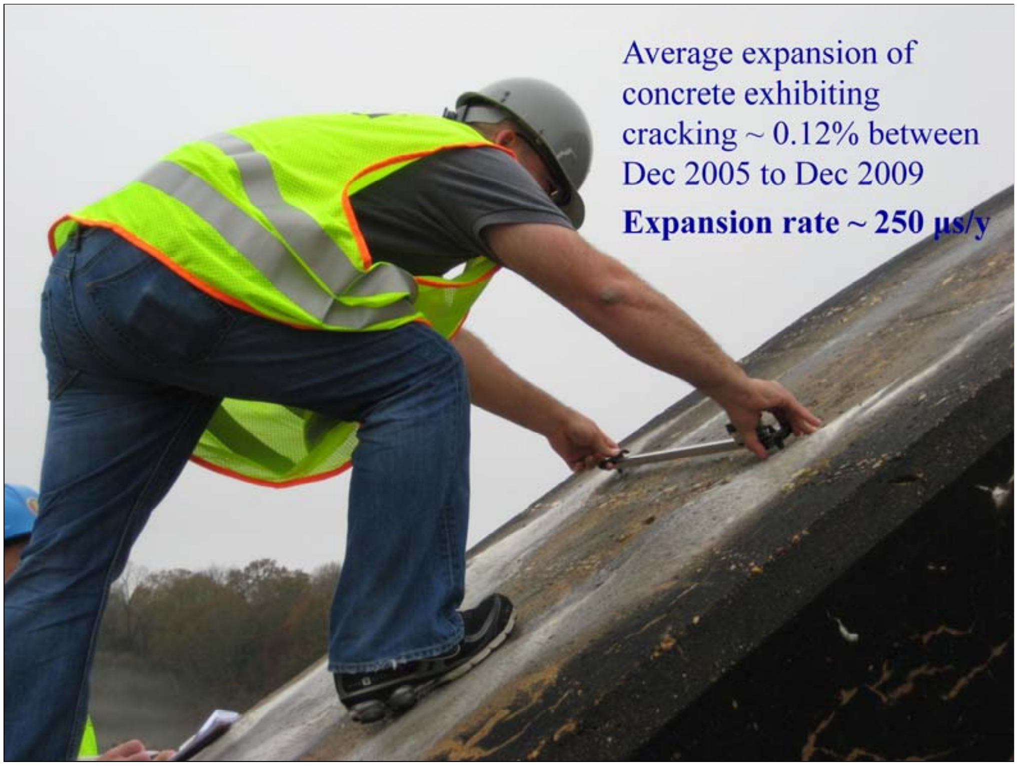
Petrographic symptoms of deterioration included extensive cracking both in the aggregate particles and in the cement paste. Cracks were found to be filled by alkali-silica gel along with large amounts of ettringite in cracks of the cement paste.



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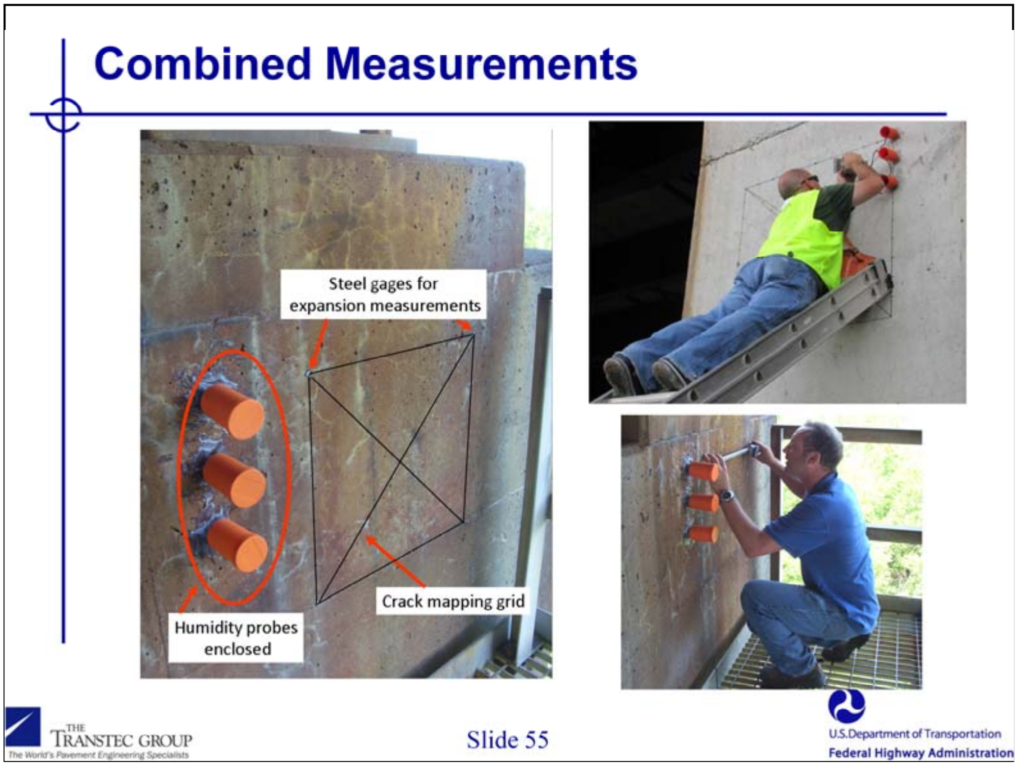
Expansion monitoring at various locations on the bridge revealed an average expansion of the concrete arch exhibiting cracking of about 0.12% between December 2005 and December 2009, which corresponds to an expansion rate of about 250 microstrains per year.

Slide 54

The extent and rate of ASR expansion is temperature-dependant; also, the relative humidity is one of the essential conditions to maintain ASR in a concrete structure; relative humidity can be measured over time with depth or at different locations in concrete elements using various techniques, for example wooden stick and portable or permanent probes.

Wooden sticks are first calibrated in the laboratory under different RH conditions and then installed in structural members for monitoring over time.



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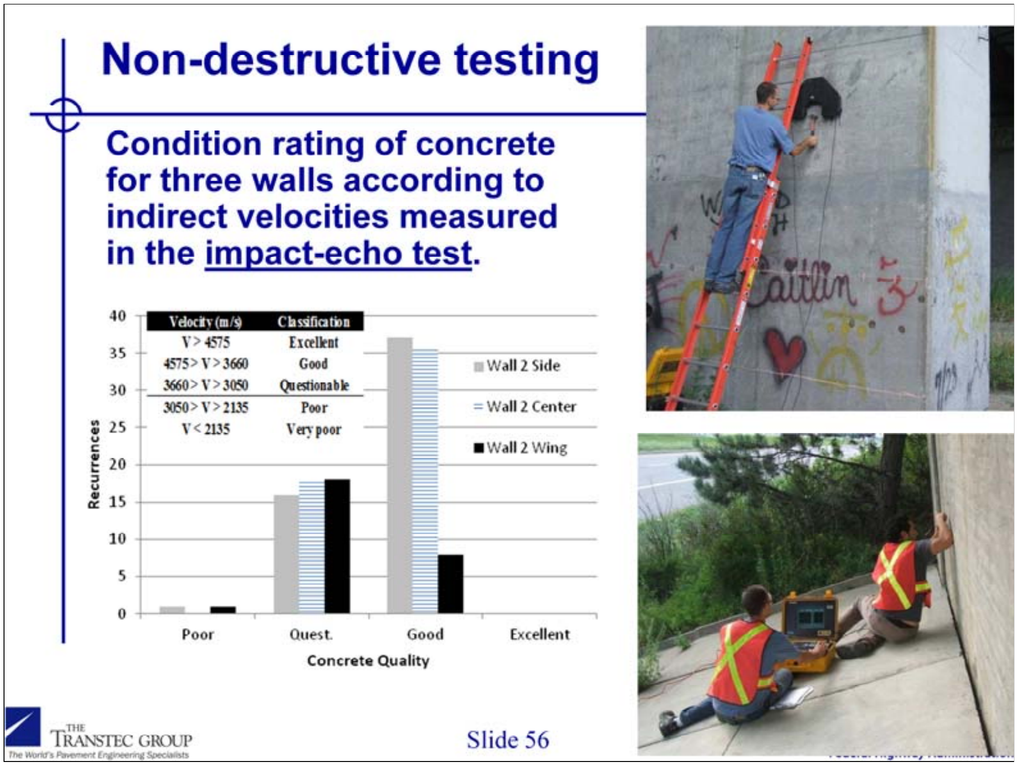
As part of *Federal Highway's ASR Development and Deployment program*, relative humidity and temperature measurements are being carried in the close vicinity of the grids used for crack and expansion monitoring in order to provide additional information for interpretation of the behavior of different treatments for mitigating ASR expansion.



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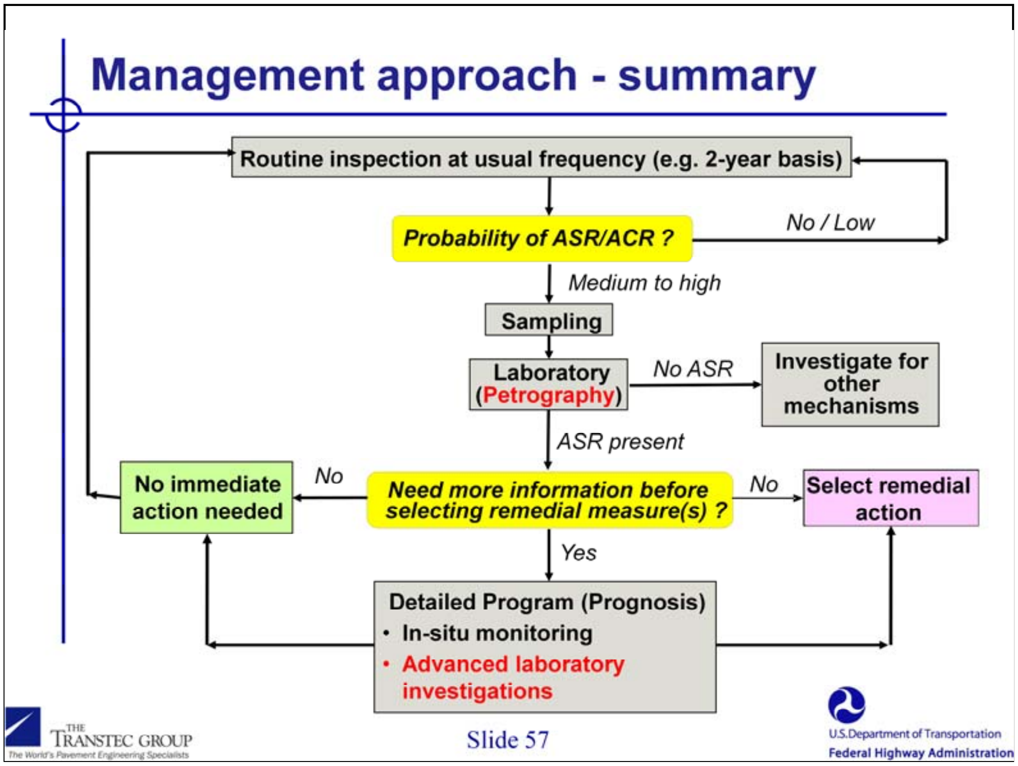
As part of *Federal Highway's ASR Development and Deployment program*, advances are being made to evaluate the reliability of various non-destructive techniques, such as pulse velocity, impact echo (illustrated on the slide), and acoustic methods, for evaluating the progress of ASR in ASR-affected structure treated or not with surface sealers.

The chart on the left shows an example of a condition rating based on impact echo results obtained on three walls (abutment, side and center; wing wall). It is clear that the wing wall, which is exposed to moisture and displays higher visual damage, has a much lower number of measurement spots classified as "good concrete" compared to the other walls. The center (unexposed) wall has no spots classified as "poor concrete", while the other areas exhibit some. None of the three walls felt in the "excellent" category for concrete quality.



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A series of tests can be performed on core samples extracted from structural members showing different degrees of deterioration and/or of exposure conditions. The data will provide information for further evaluating the current concrete condition, the expansion reached to date, the current rate of expansion, and the potential for future expansion of the concrete.

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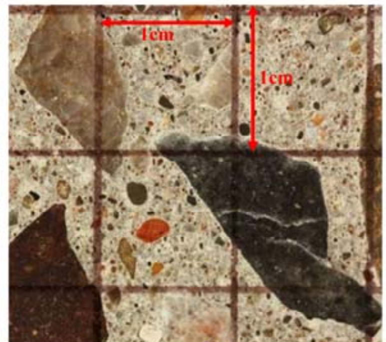
The *Damage Rating Index* is a semi-quantitative petrographic technique that evaluates the condition of polished sections of concrete under the stereomicroscope, at about 16x magnification.

Damage Rating Index
(Grattan-Bellew & Danay, 1992)

- Petrographic signs of ASR are identified and counted on 25 x 25 mm areas
- Weighting factors proposed for each sign
- Sum of the counts for each sign normalized for area of 100 cm^2

Petrographic feature	Abbre.	Factor
Coarse aggregate with crack	CA	0.25
Open crack in coarse aggregate	OCA	4
Coarse aggregate with crack and gel	CA+G	2
Debonding coarse aggregate	DCA	3
Reaction rim	RR	0.5
Cement paste with crack	CP	2
Cement paste with crack and gel	CP+G	4
Gel in air void	V+G	0.5



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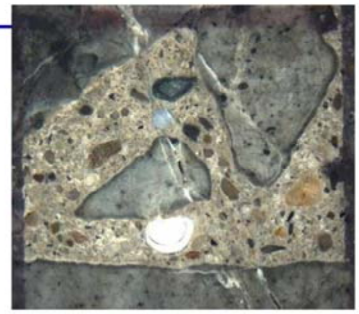
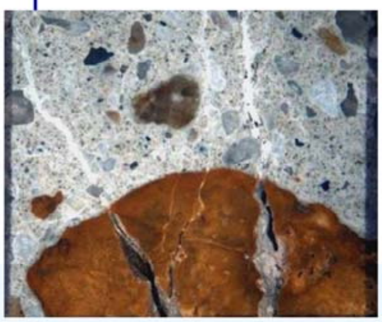
In this method, the number of typical petrographic features of ASR, for example cracks in the aggregate particles and in the cement paste, with or without secondary reaction products, are counted in a grid system drawn at the surface of polished concrete sections.

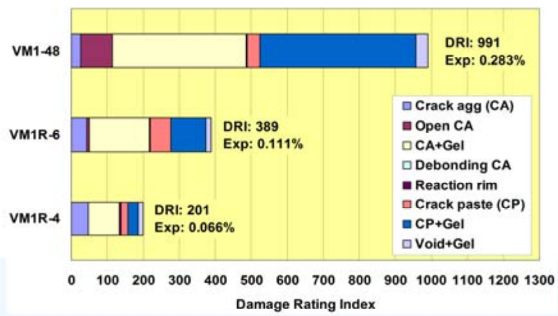
The DRI represents the normalized value, to a 100 mm^2 surface area, of the presence of these features after the count of their abundance over the surface examined has been multiplied by weighing factors representing their relative importance in the overall deterioration process. The weighing factors range from 0.25 or 0.5 (low importance) to 4 (high importance).

Damage Rating Index (DRI)

Petrographic feature	Abbreviation	Factor
Coarse aggregate with crack	CA	0.25
Open crack in coarse aggregate	OCA	4
Coarse aggregate with crack and gel	CA+G	2
Debonding coarse aggregate	DCA	3
Reaction rim	RR	0.5
Cement paste with crack	CP	2
Cement paste with crack and gel	CP+G	4
Gel in air void	V+G	0.5



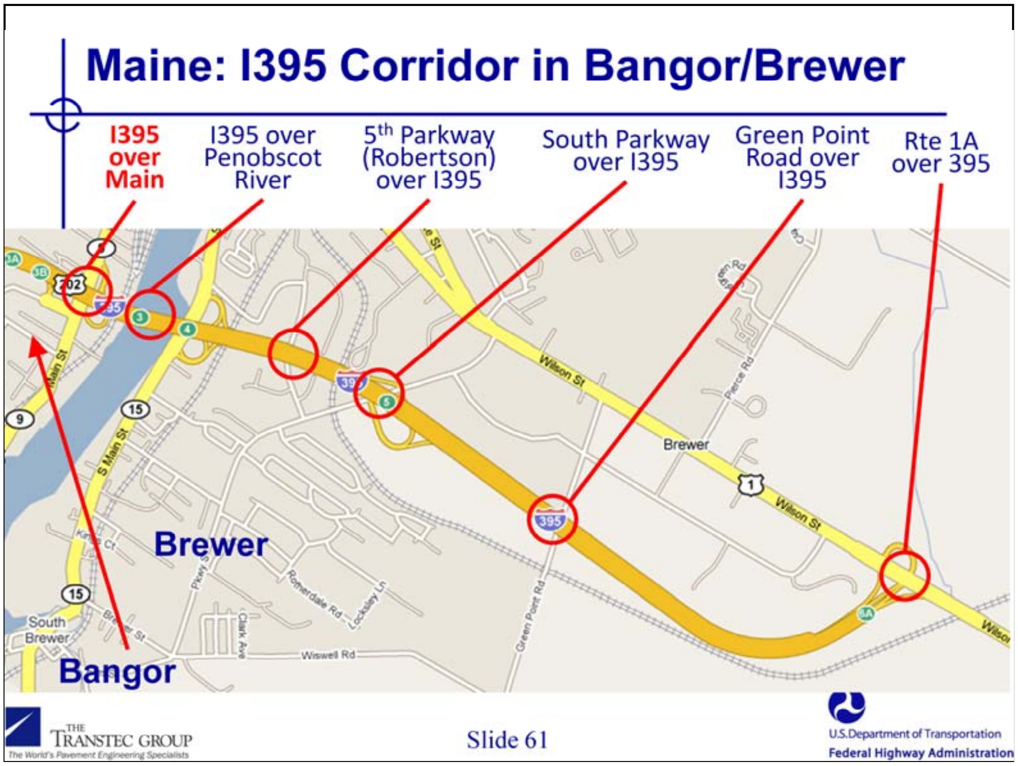




Slide 60

This slide illustrates the typical petrographic symptoms of ASR in a 1cm^2 grid. Cracks can be seen running though the cement paste, from aggregate particles to aggregate particles. The cracks are filled with alkali-silica reaction products. We can also see reaction products of two different textures in air voids of the cement paste, i.e. bluish vitreous gel (point in the upper air void) and whitish and chalky reaction product (point in the lower air void).

The results of the DRI can be presented using bar charts illustrating the relative contribution of each petrographic features of deterioration in the overall DRI values. Graphs can include the DRI results obtained for a number of cores, thus allowing direct comparison of the data from one core to another.



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As part of *Federal Highway's ASR Development and Deployment program*, a condition (visual) survey was carried out on six bridge structures along the Interstate 395 (I-395) in Maine. A particular attention is given here on the I395 highway structure over Main Street.

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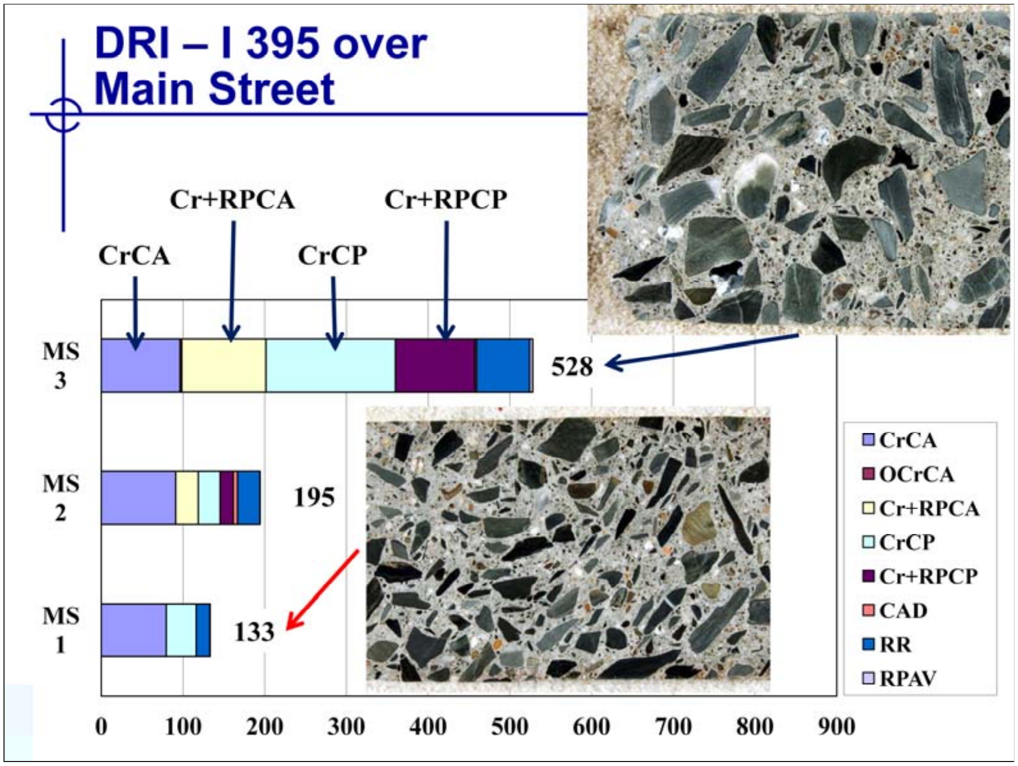
Sections or elements of the structures sheltered from direct exposure to rain and sun showed no or light visible cracking, while those exposed to the above elements (e.g. wing walls and exposed parts of the abutments) showed moderate to severe map/vertical cracking.

Cores were extracted from those different locations in order to determine the condition of the concrete through petrographic examination and mechanical testing.



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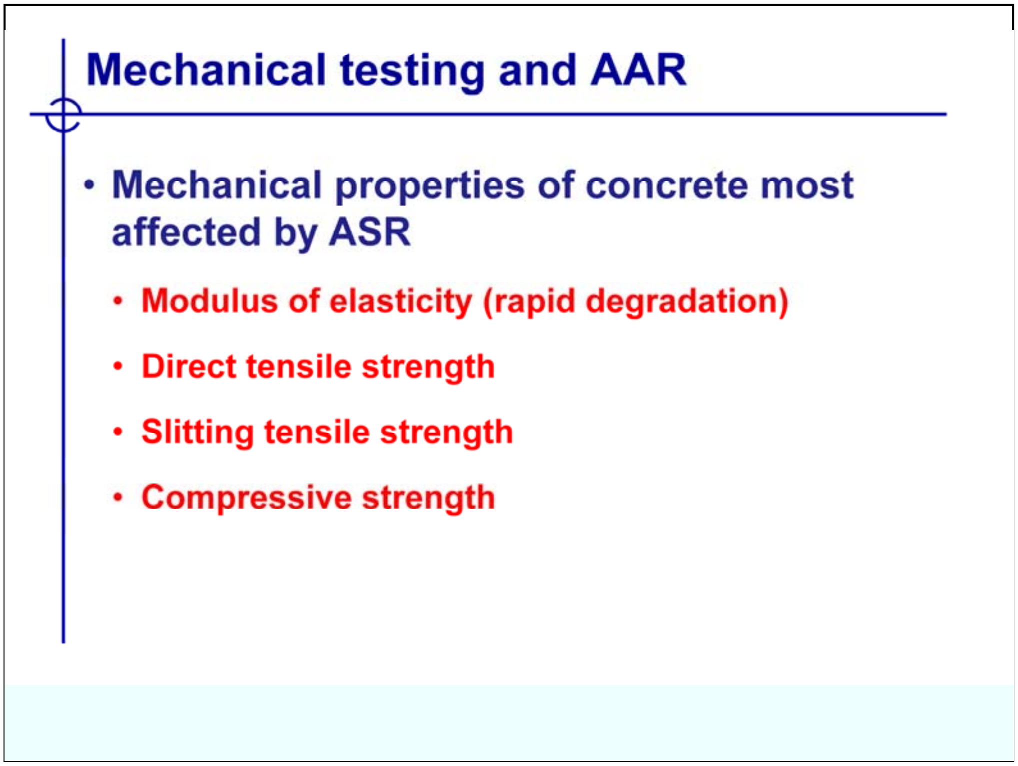
This bar chart presents the results of the Damage Rating Index method carried out on the cores. The petrographic examination of the cores confirmed the observations obtained from the visual survey of the concrete elements.

A high DRI value of 528 was obtained for the concrete core extracted from the wing wall showing significant map cracking. The main petrographic features of deterioration consist of cracking with alkali-silica reaction products in the reactive greywacke/argillite coarse aggregate particles as well as in the cement paste.

In the case of the core extracted from the sheltered portion of the abutment wall, a low DRI value of 133 was obtained, indicating a low degree of deterioration.

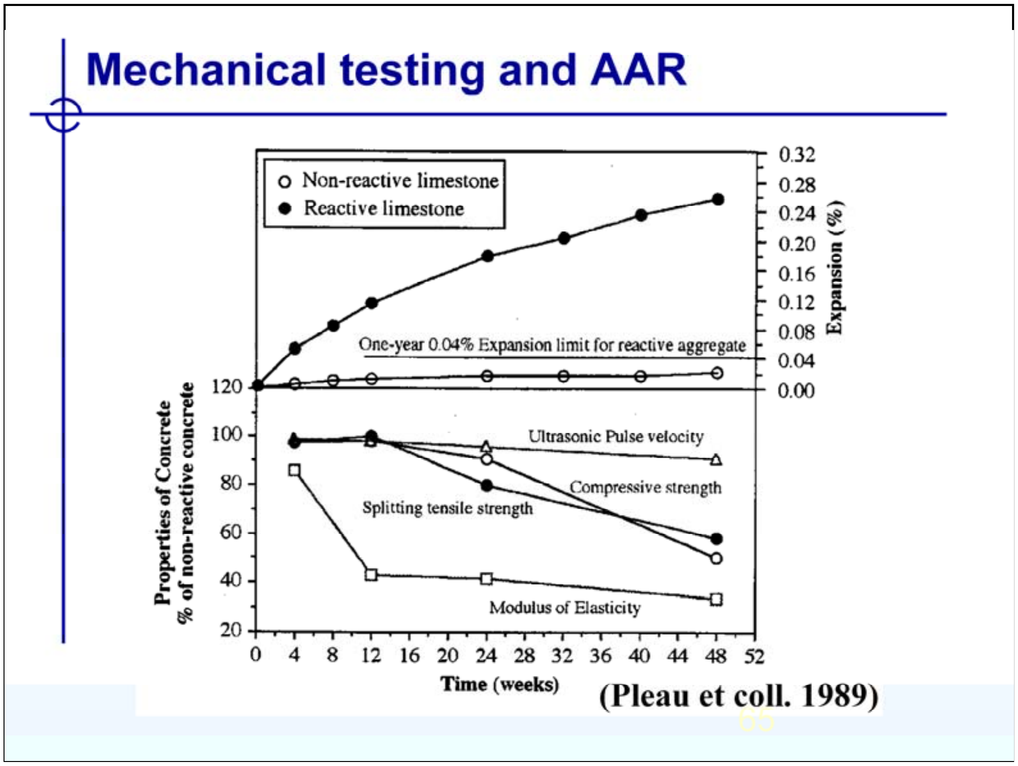
It is interesting to note that a significant portion of the damage corresponds to tight/closed cracks within the aggregate particles, which are common in the case of crushed aggregate material and likely related to processing operations in the quarry.

Overall, the DRI can provide a quantitative assessment of the extent of internal damage in structural concrete members, either punctually (i.e. at a specific time - diagnosis) or as a progressive process when performing the measurements on a regular basis on cores extracted at the same location (prognosis).



Slide 64

The results of several studies carried out on laboratory-made specimens or cores extracted from concrete structures affected by ASR have shown that, in general, the mechanical properties of concrete most affected by ASR are, in order of decreasing impact, the modulus of elasticity (rapid degradation), the direct tensile strength, the splitting tensile strength and, finally, the compressive strength.



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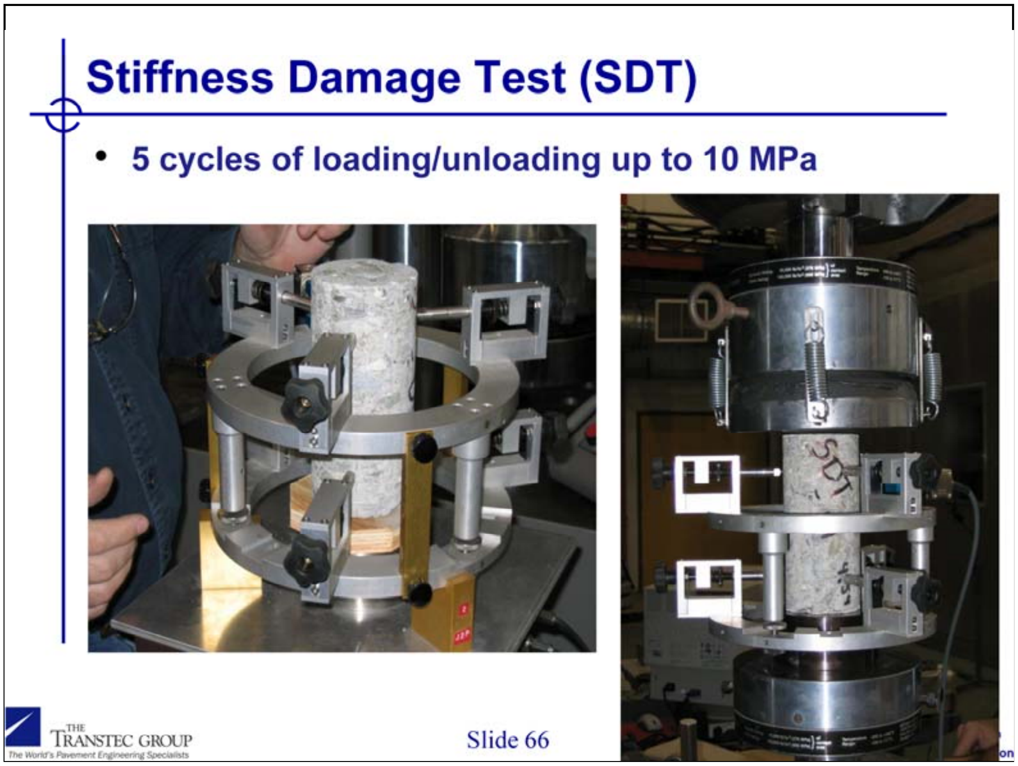
This is illustrated in this slide showing the results of laboratory investigations carried out by Pleau and coworkers at Laval University in Canada.

Four-by-eight inch concrete cylinders were made with reactive and non-reactive limestone aggregates and subjected to accelerated curing conditions in the laboratory, i.e. 100^{o}F and 100% relative humidity. The upper graph shows the typical expansion curves obtained for the reactive and non-reactive concretes.

At selected expansion levels obtained with the reactive concretes, reactive and non-reactive test specimens were extracted from their curing conditions (i.e. non-reactive specimens were taken out at the same time as the reactive specimens) and tested for ultrasonic pulse velocity, compressive strength, splitting tensile strength and modulus of elasticity.

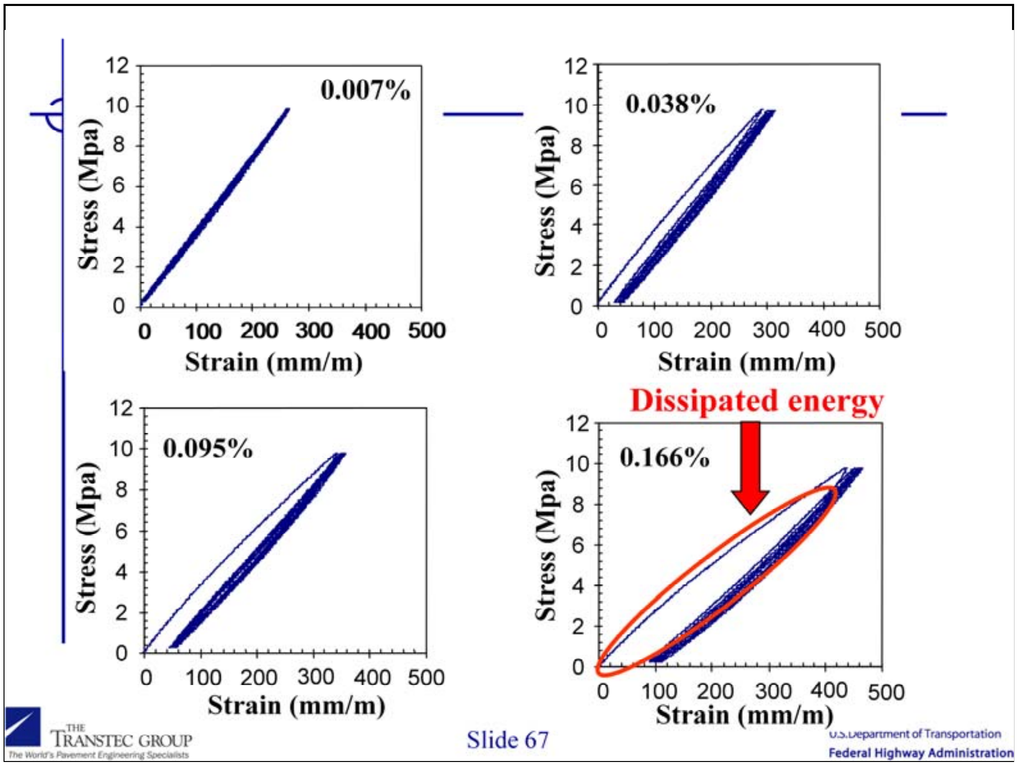
The bottom graph shows a plot of the test results expressed as a percentage of the results obtained for the non-reactive concretes at each testing period.

The results show that the ultrasonic pulse velocity was not significantly affected even for concrete specimens showing expansions reaching about 0.26%. The compressive strength and, to some extent, the splitting tensile strength, were affected significantly only at high levels of expansion. On the other hand, the modulus of elasticity was rapidly and drastically affected by the damage generated through ASR expansion, and showed progressive but lower degradation rate with increasing expansion afterwards.



Slide 66

The *Stiffness Damage Test (SDT)*, which consists in subjecting concrete cores to 5 cycles of uniaxial loading/unloading can be used for assessing the effect of ASR on the mechanical properties of concrete.



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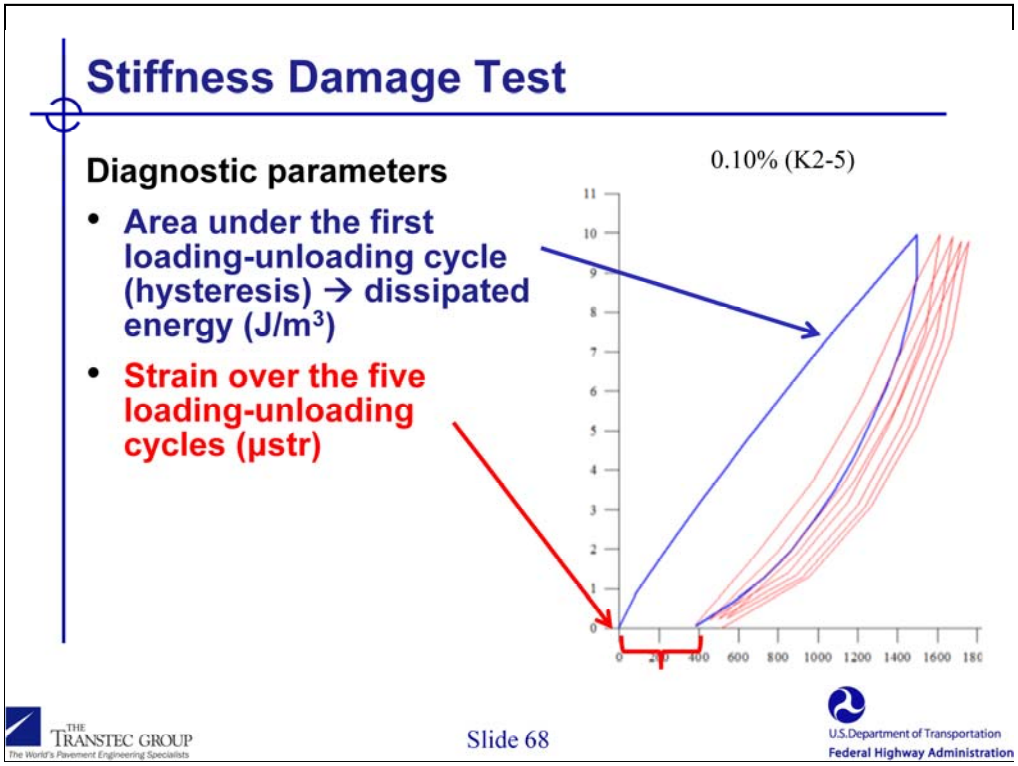
This slide shows a number of curves obtained for concrete cores tested by the SDT after they have reached selected expansion levels ranging from 0.007 to 0.166%.

One can see that as the expansion due to ASR increases, the area under the curve corresponding to the first cycle of loading/unloading increases. The area under the curve corresponding to the first cycle of loading/unloading corresponds to the energy dissipated in the system through the closure of the microcracks due to ASR.



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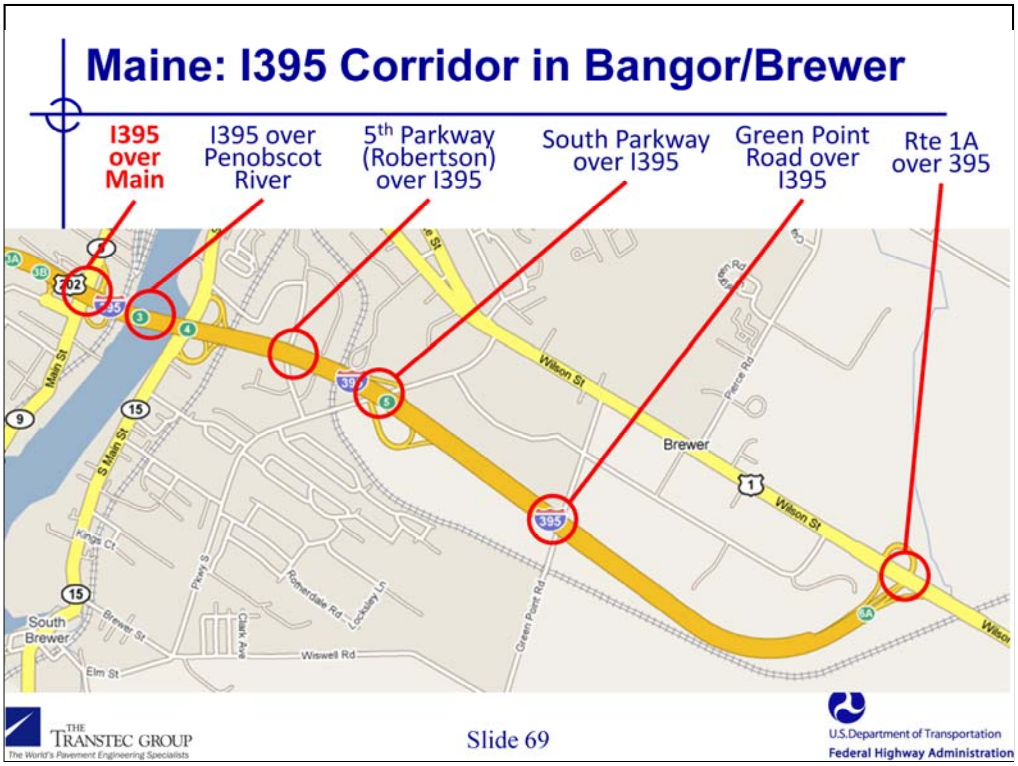
Various studies carried out recently have shown that the most diagnostic parameters from the SDT are the energy dissipated during the first cycle (hysteresis loop) and the accumulated plastic strain after the 5 load/unload cycles.

Recent research indicates that more accurate results are obtained when the SDT is carried out up to a maximum load corresponding to 40% of the design (28-day) strength.



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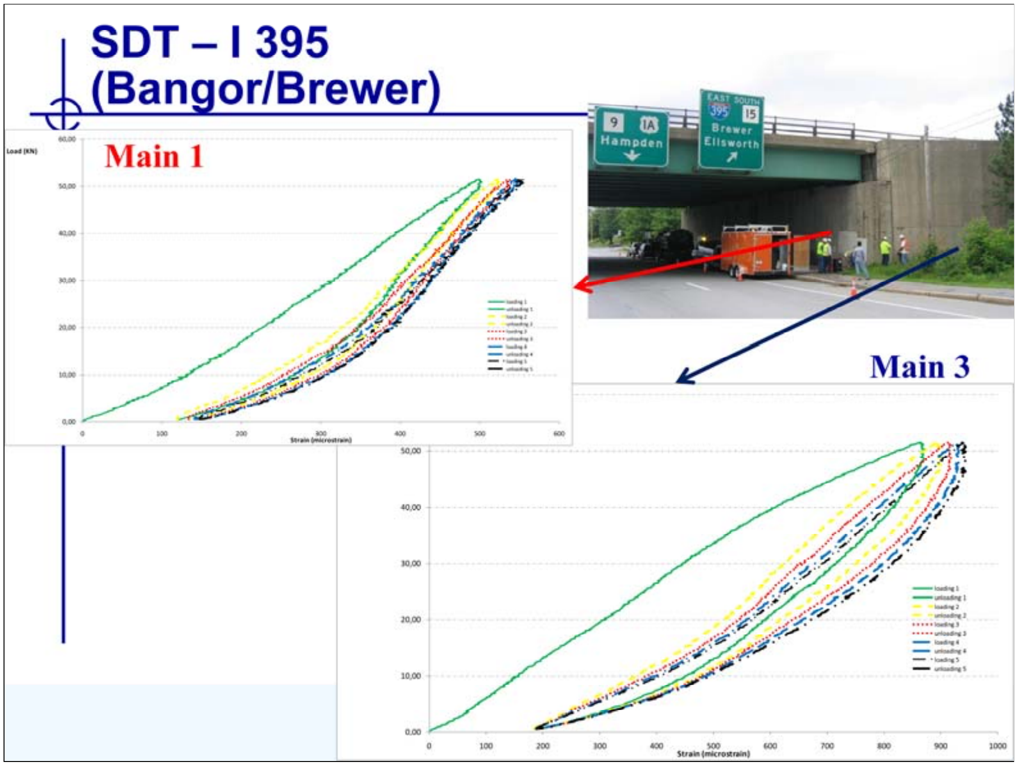
Let’s go back to the I395 highway structure over Main Street, In Maine.



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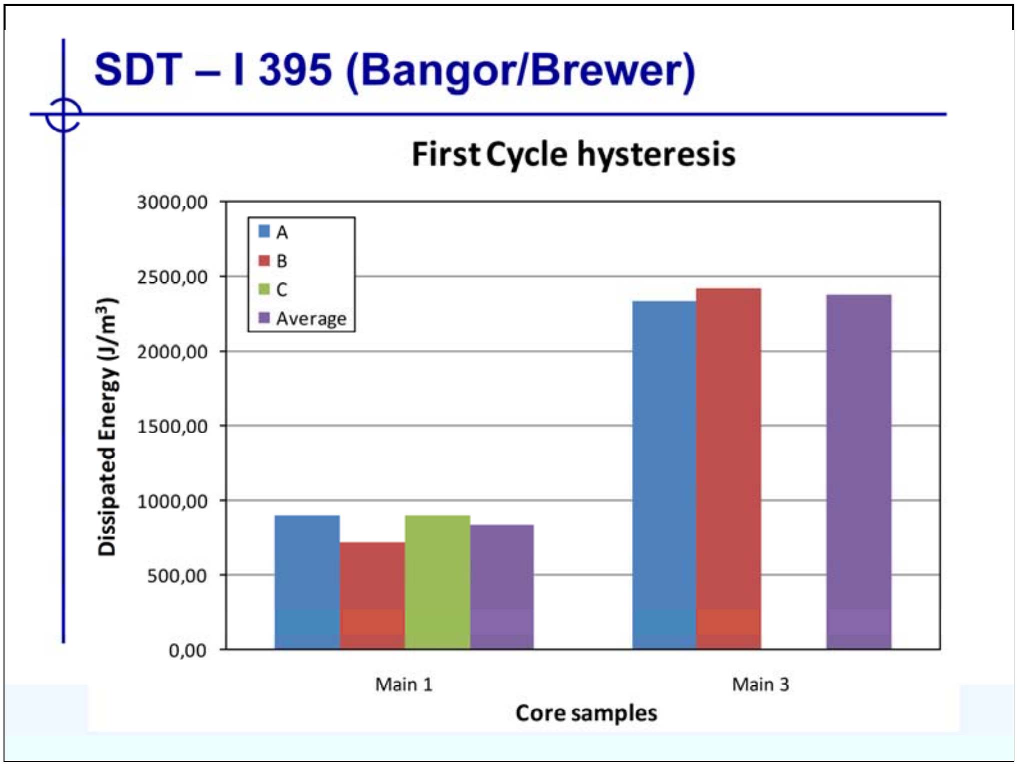
This slide shows typical SDT results obtained on concrete cores extracted from the section of the abutment wall sheltered from direct exposure to rain and sun (Main 1) and from the wing wall exposed to moisture and which showed moderate to severe map cracking (Main 3).



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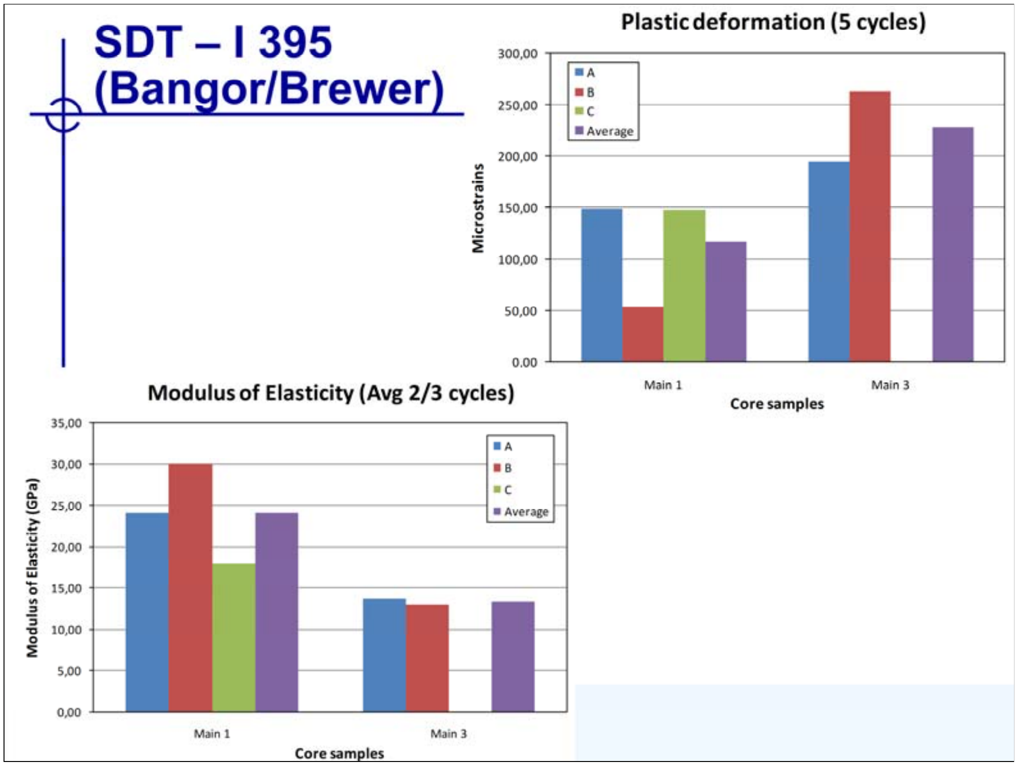
This graph shows the Dissipated Energy results obtained for cores extracted from the sites mentioned before. Once again, a good correlation was obtained between the visual condition of the concrete and the SDT results, the highest dissipated energy values (J/m^3) corresponding to the core samples extracted from severely exposed structural elements, i.e. Main 3.



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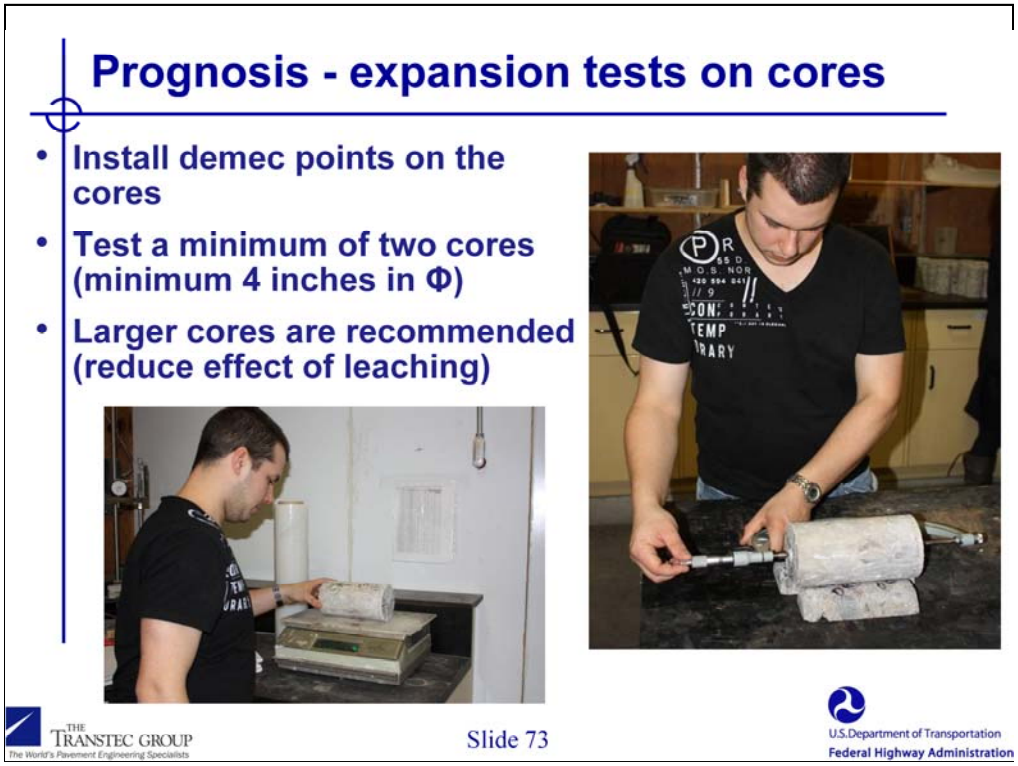
Similarly, higher deformations were obtained for concrete cores Main 3, while those cores also showed lower modulus of elasticity. The above results are indicative of higher degree of damage in the core samples extracted from the severely exposed and visually damaged wing walls.



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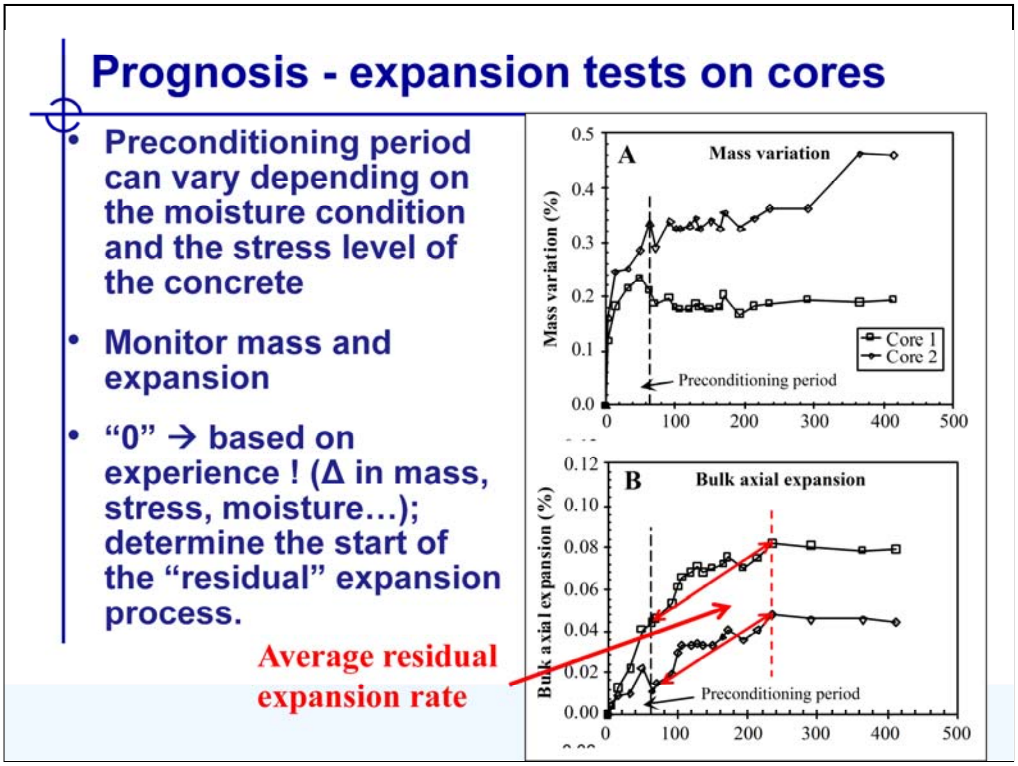
Expansion tests on cores can provide an "estimate" of the potential for further expansion (or prognosis) of ASR-affected concrete over a relatively short period of time, e.g. six months to one year.

For this test, demec points are installed at both ends of the concrete cores and the specimens are stored in air at > 95% R.H. and 100°F.

The test generally requires a minimum of two cores, of a minimum of four 4 inches in diameter, although larger cores are recommended to reduce the effect of alkali leaching and premature leveling of the expansion curves.



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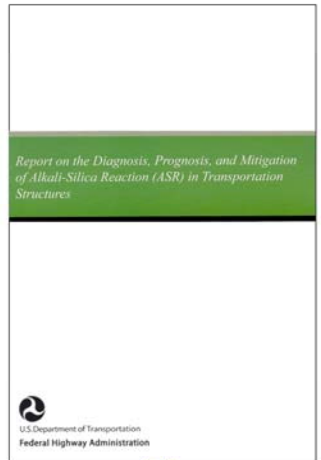
The preconditioning period of the core can vary depending on the moisture condition and the stress level of the concrete from which the cores have been extracted. In order to determine the start of the “residual expansion”, it is useful to monitor the mass variations in addition to the expansion.

The selection of the “T_0” is often based on experience, looking at the variations in mass and expansion as a function of time.

Prognosis - expansion tests on cores

- Potential further expansion increases with increasing residual expansion of cores (Fournier et al. 2010)

Residual expansion rate (% / year)	Rating
< 0.003	Negligible
0.003 – 0.005	Very low
0.005 - 0.010	Low
0.010 – 0.020	Moderate
0.020 – 0.030	High
> 0.030	Very high



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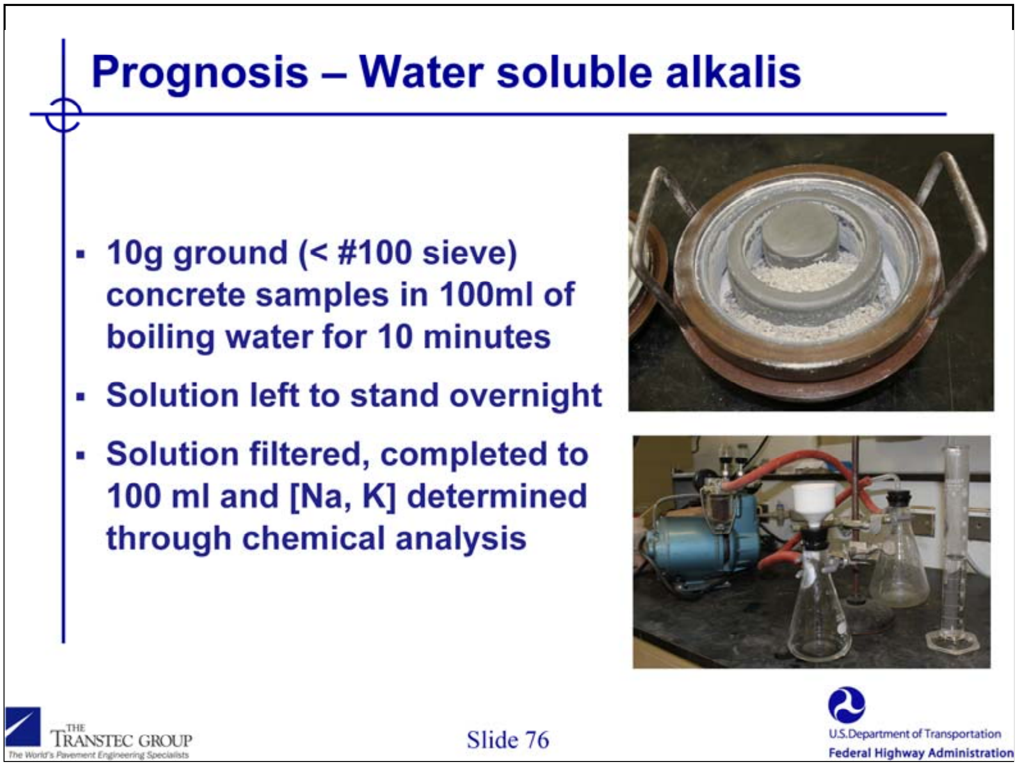
The Report on the *Diagnosis, Prognosis and Mitigation of ASR in Transportation Structures* provides additional information for the interpretation of the residual core expansion test, including this table with suggested ratings for the prognosis purposes. The ratings vary from negligible potential with residual expansion rates < 0.003% / year to very high for residual expansion rates > 0.030% / year.

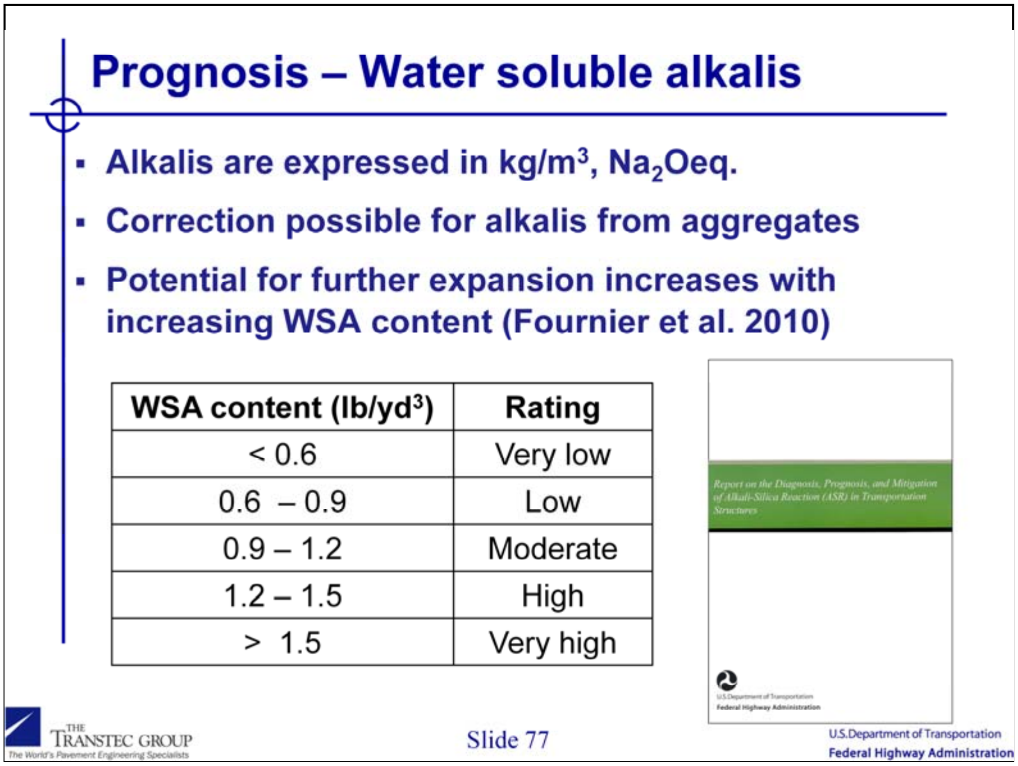
Although this method is commonly used, the correlation between the "free" expansion of cores (i.e. when extracted from their restraining environment) and the expansion of the corresponding structural element in the field is yet to be established.



Slide 76

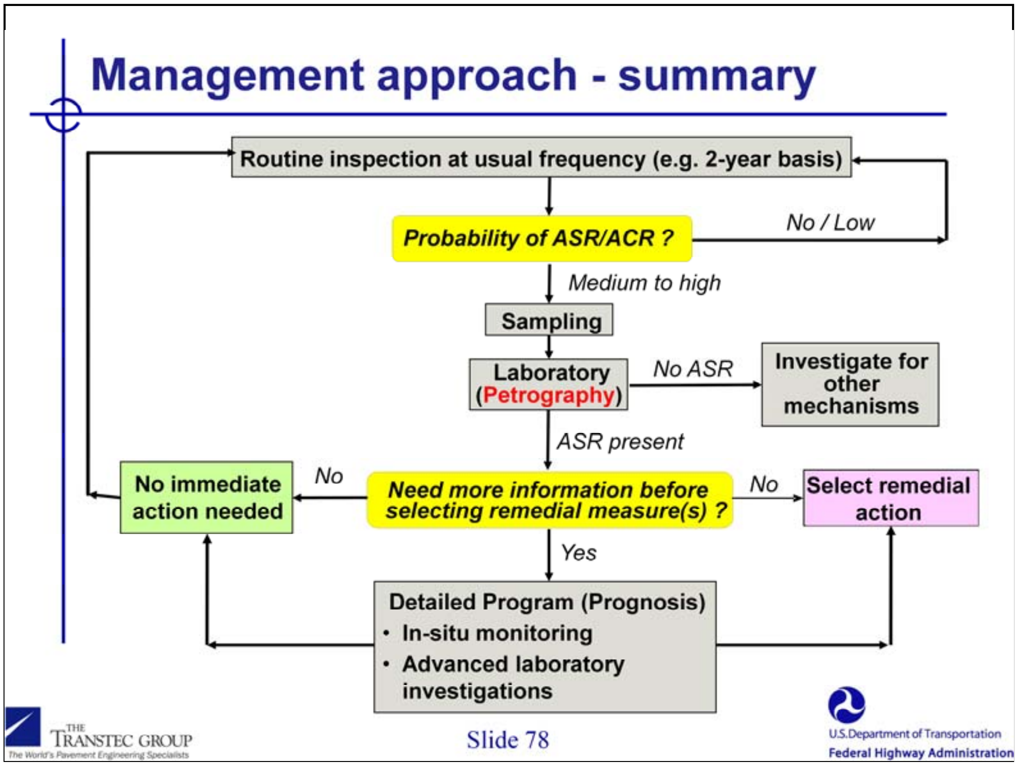
The measurement of the "available/residual" alkali content in concrete can yield interesting information in assessing whether the concrete tested contains sufficient alkalis to sustain this reaction (*prognosis*).

The "available/ residual" alkali content in concrete can be obtained by hot-water extraction. Ten-gram samples of ground concrete (< #100 sieve) are maintained in 100ml of boiling water for 10 minutes. The solution is then left to stand overnight and the solution is filtered, completed to 100 ml and the concentrations in sodium and potassium are determined through chemical analysis.



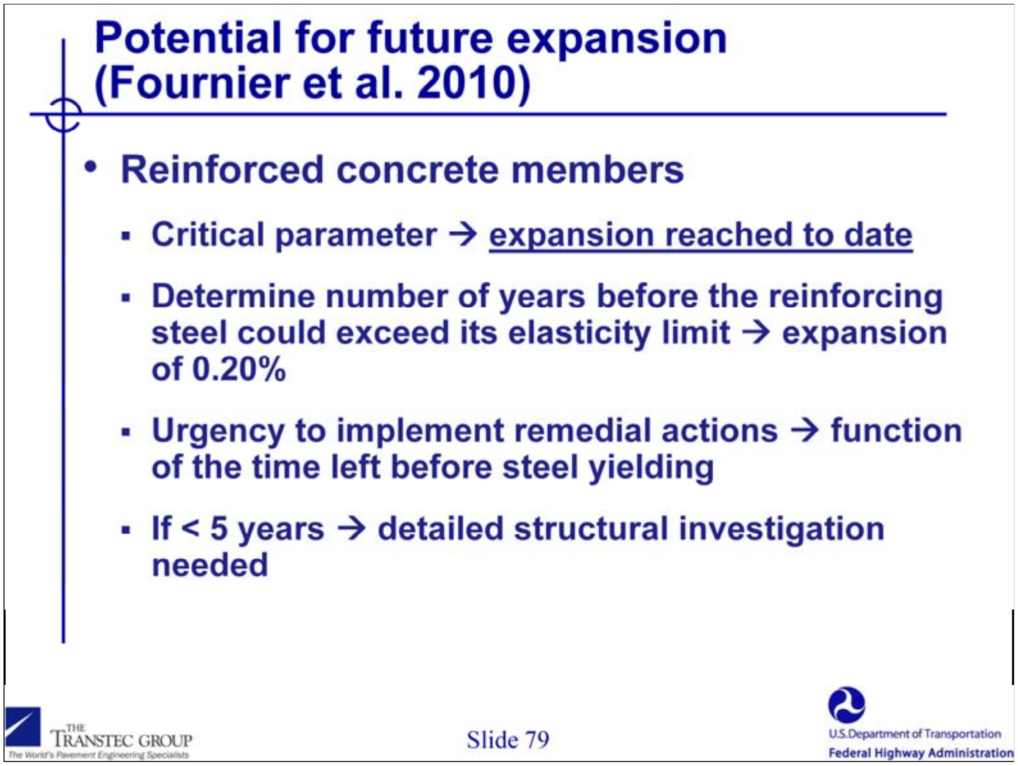
Slide 77

The Report on the *Diagnosis, Prognosis and Mitigation of ASR in Transportation Structures* provides additional information for the interpretation of the hot water alkali extraction test, including this table with suggested ratings for the prognosis purposes. The ratings vary from negligible potential for water soluble alkali contents < 0.6% lb/yd^3 to very high for water soluble alkali contents >1.5 lb/yd^3.



Slide 78

Based on the results of the detailed in-situ and laboratory investigations, decisions will be taken for selecting immediate appropriate remedial actions or to wait for further data from the monitoring program. This will be discussed further in the next session.



Slide 79

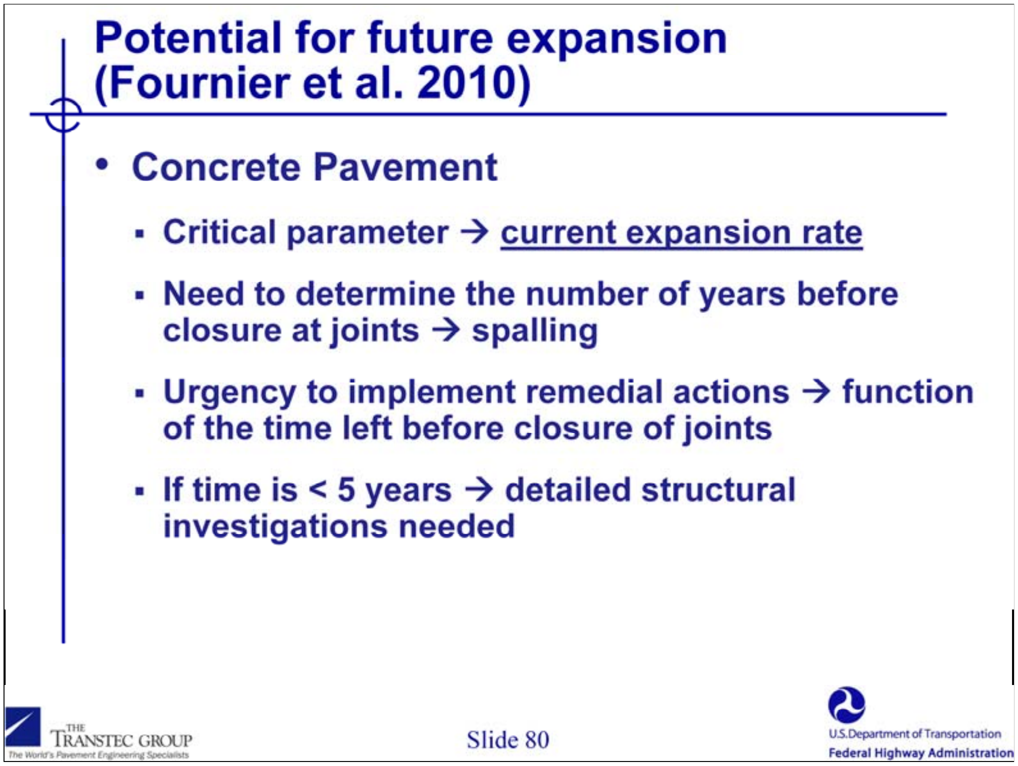
The Report on the *Diagnosis, Prognosis and Mitigation of ASR in Transportation Structures* provides a scheme for the analysis of the results obtained from the in-situ and laboratory investigations for prognostic evaluation of ASR.

In the case of reinforced concrete members (e.g. bridges), it is suggested that the critical parameter are the ***expansion attained to date*** and the ***current expansion rate*** in order to determine the number of years before the reinforcing steel yield (in the direction of lower or lack of restraint) could occur. The critical level of expansion is estimated to about 0.20%.

The urgency to implement remedial actions would then be a function of the time left before steel yielding, or to reach to 0.20% expansion.

If this time period is estimated to be less than 5 years, it is recommended to perform a structural assessment of the member/ structure.

Also, it would be appropriate to confirm an assessment that has been based essentially on expansion tests on cores rather than on in-situ monitoring.



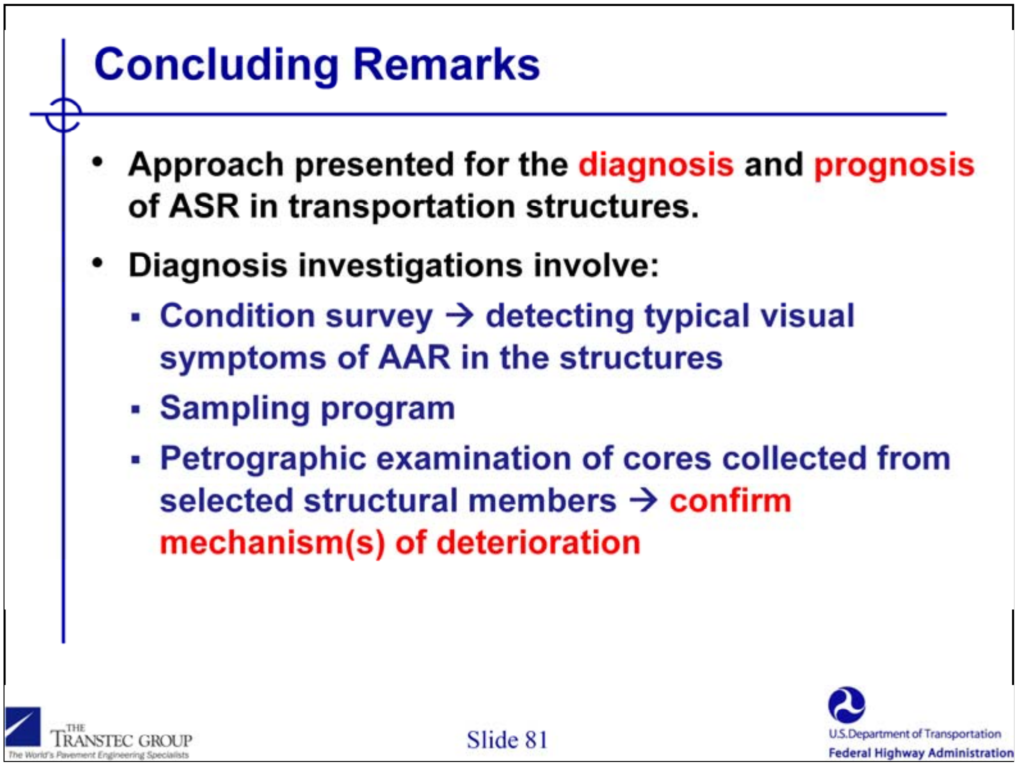
Slide 80

In the case of concrete pavements, it is suggested that the critical parameter is the *current expansion rate* in order to determine the number of years before the joints could close, thus increasing the risk of spalling at joints.

The urgency of applying remedial actions will then be partly based on the delay before the closure of expansion joints occur.

If this time period is estimated to be less than 5 years, it is recommended to perform a structural assessment of the member/ structure.

Once again, it would be appropriate to confirm an assessment that has been based essentially on expansion tests on cores rather than on in-situ monitoring.



Slide 81

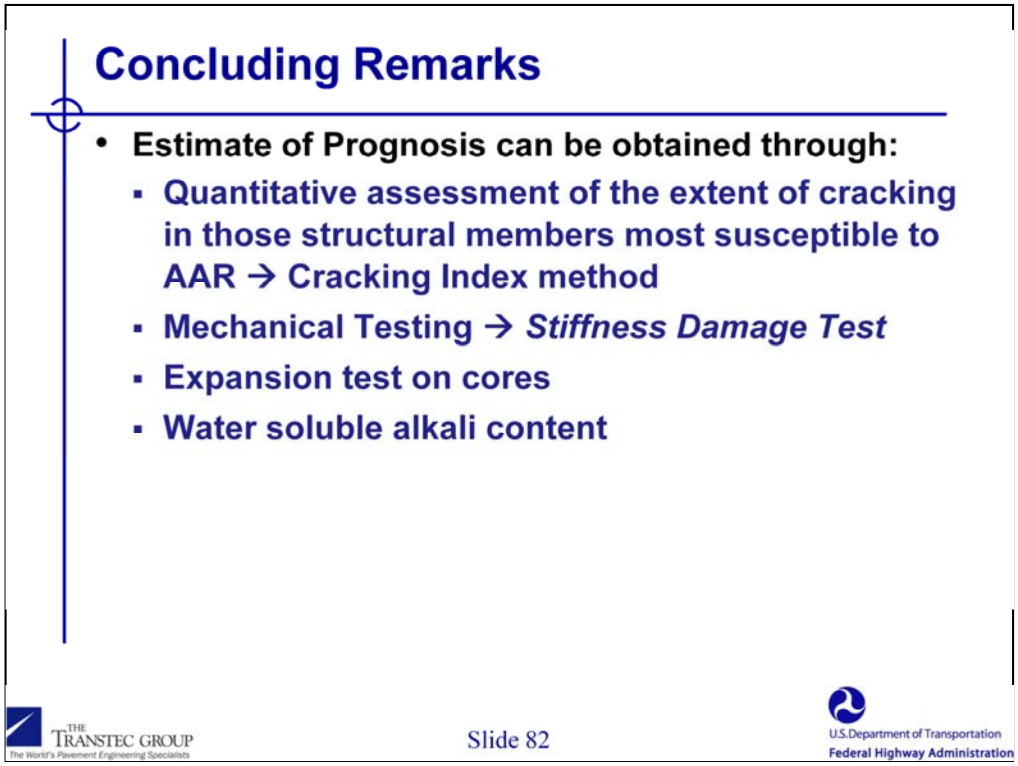
In this session, an approach was presented for the diagnosis and prognosis of ASR in transportation structures.

The diagnosis investigations involve the following activities:

A routine condition /field survey for detecting typical visual symptoms of AAR in the structures

A sampling program, especially in concrete structural elements showing symptoms of deterioration that could be indicative of ASR.

The petrographic examination of cores collected from selected structural members to confirm the mechanism(s) of deterioration in the structure investigated.



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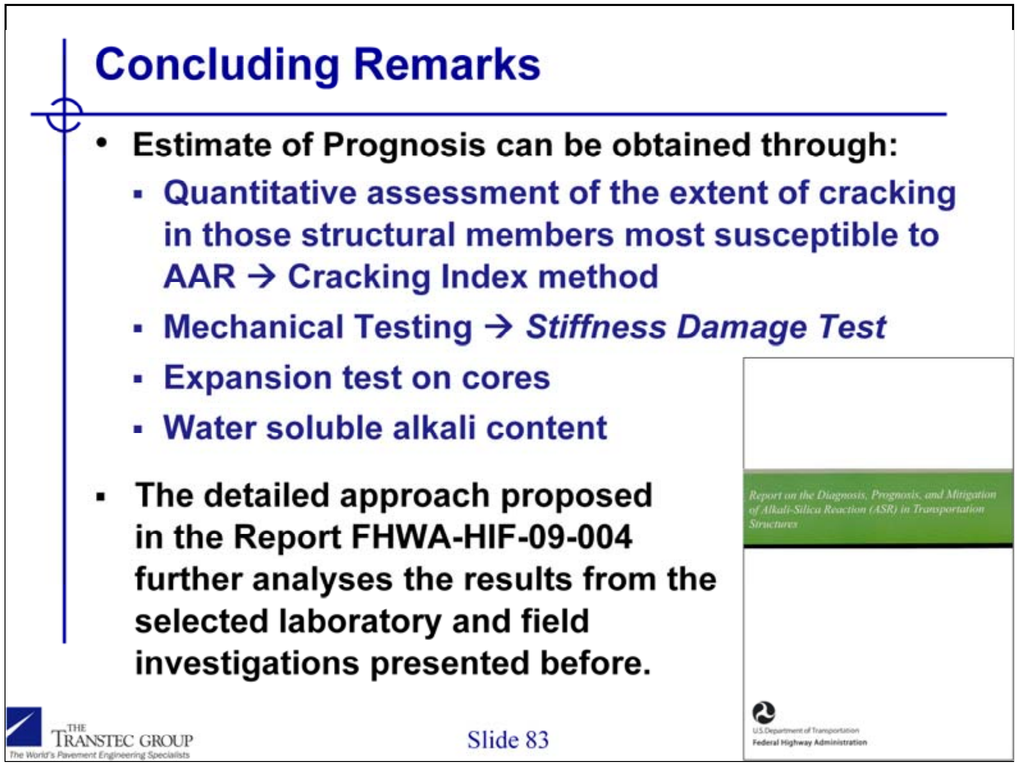
An estimate of the residual potential expansion (or Prognosis) can be obtained through the following activities:

A quantitative assessment of the extent of cracking in those structural members most susceptible to AAR through the Cracking Index method

Mechanical testing of concrete cores using a *Stiffness Damage Test*

Expansion testing on cores, and

Water soluble alkali content determinations.



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The detailed approach proposed in the Report FHWA-HIF-09-004 further analyses the results from the selected laboratory and field investigations presented before.