WALKER
RESTORATION CONSULTANTS

Foundation Performance Association

ASR and DEF in Concrete Structures
"It's not as Bad as it Seems"

Al Bustamante, P.E.
September 13, 2017

OUTLINE

- Learning objectives
- ASR and DEF Overview
- Case Study
- Questions

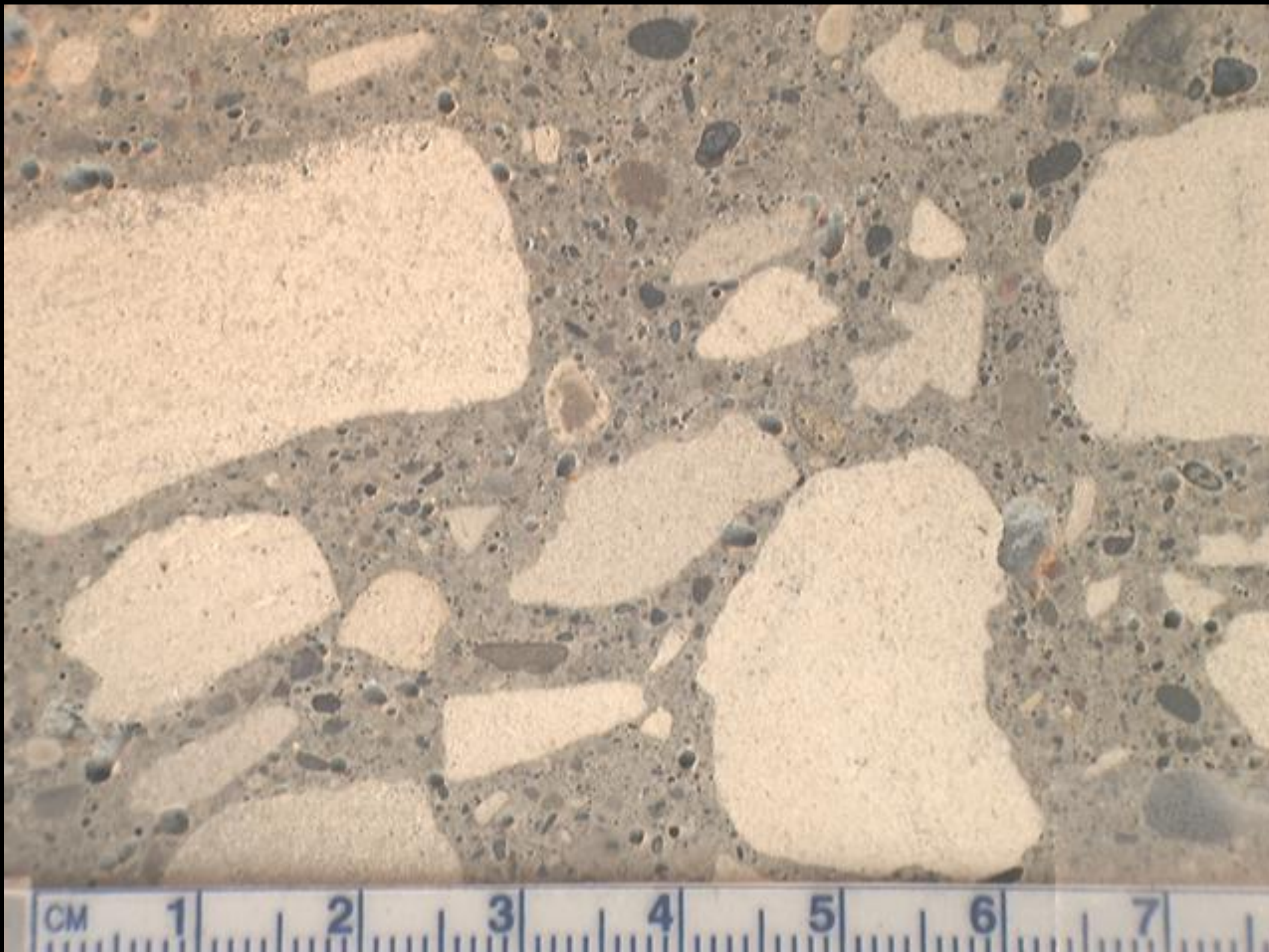
LEARNING OBJECTIVES

LEARNING OBJECTIVES

- Understand the concepts of ASR and DEF
- Learn the approach to investigate a structure with ASR and DEF issues
- Learn the general causes of ASR and DEF
- Understand the general repair program to address existing concrete columns with ASR and DEF

Alkali Silica Reaction (ASR)
Delayed Ettringite Formation (DEF)
Overview

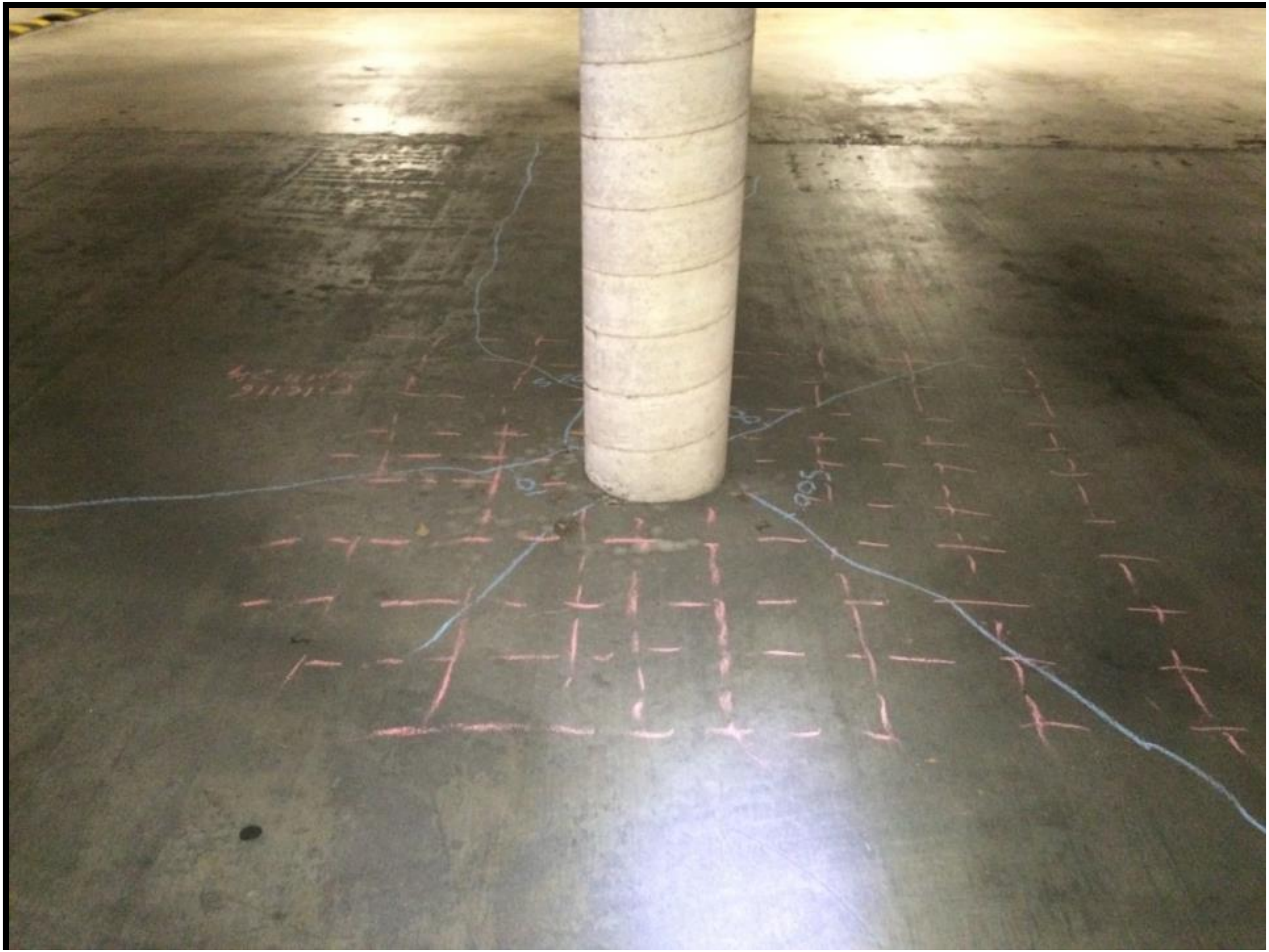
Macrostructure of Concrete

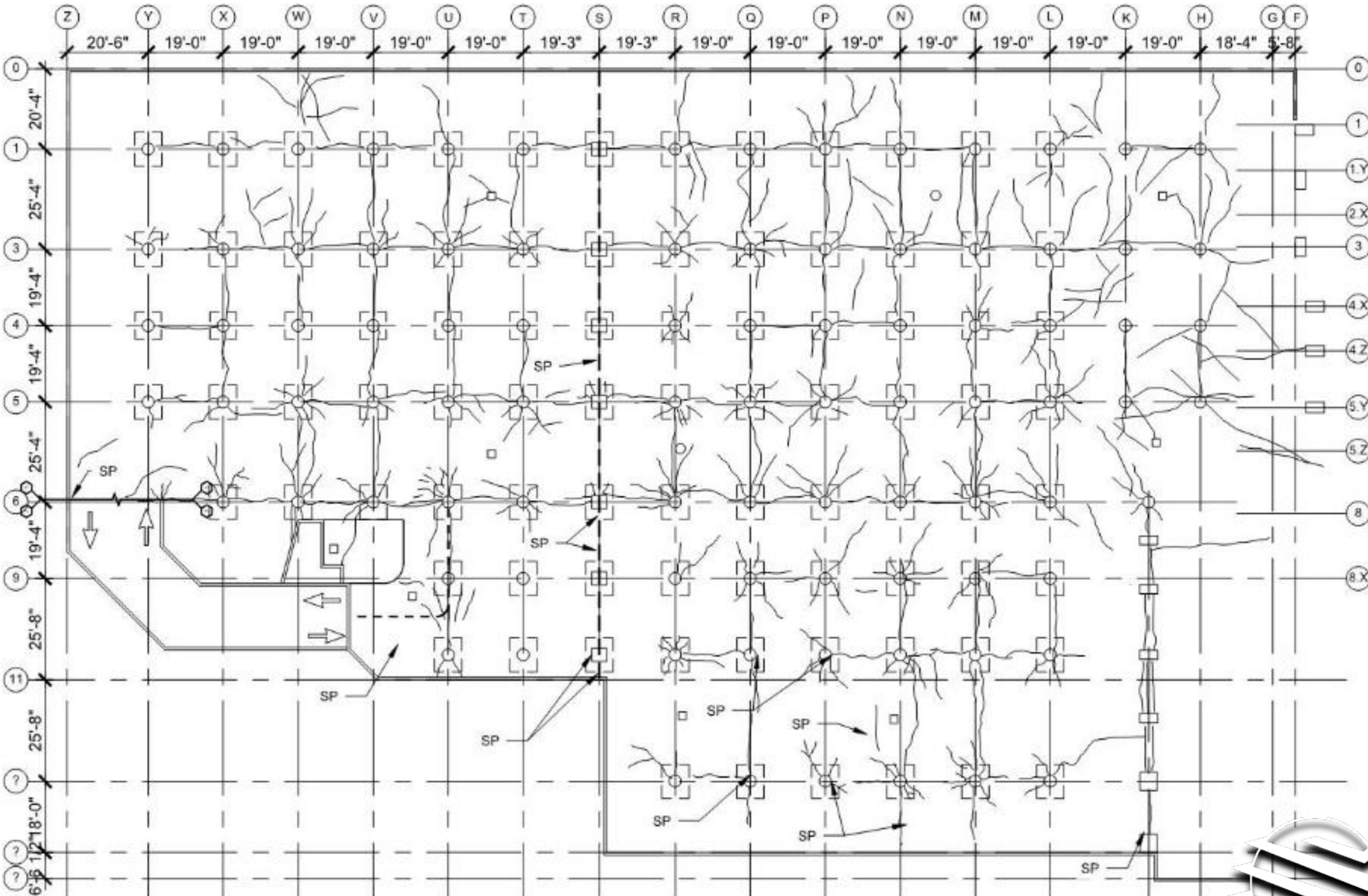


Structure of “damaged” Concrete

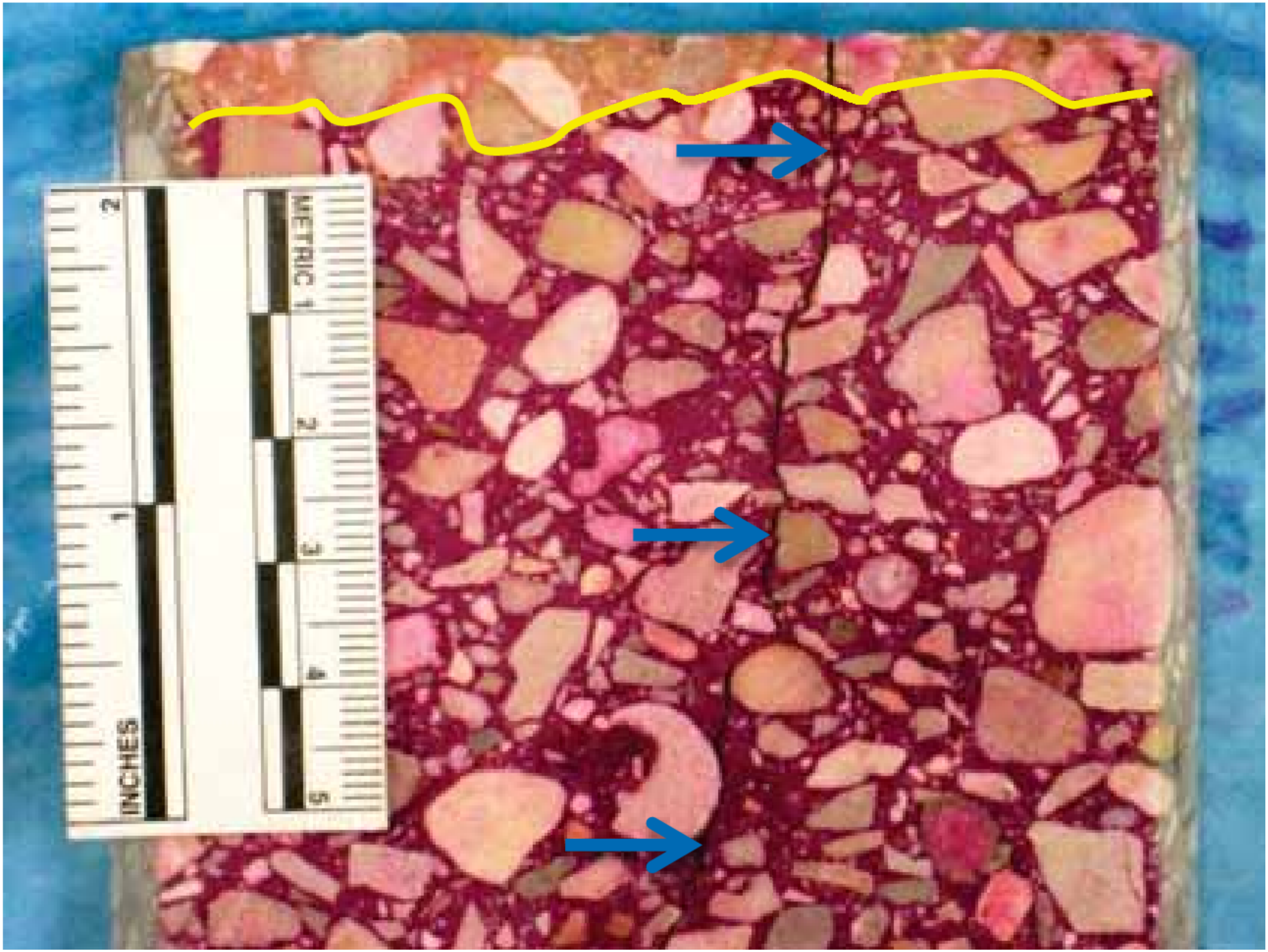
- Macrostructure
  - Visible cracks in hcp and aggregates due to volume change

    (to understand cause of cracks, we need to look at microstructure)
- Microstructure
  - Alkali-silica reaction:
    - Reaction product forms at ITZ and expands
  - Frost action:
    - Water freezes in capillary pores and expands
  - Sulfate attack:
    - reaction products form in hcp and expand





#WALKER_TOP_ASPS_Firm


INCHES
METRIC

Alkali Silica Reaction (ASR)

"The Cancer of Concrete"

- What causes ASR?
  - Chemical reactions involving:
    - **Alkali ions from portland cement**
    - **Hydroxyl ions**
    - **Siliceous constituents in aggregate**

$SiO_2 + 2NaOH + H \rightarrow Na_2SiO_{32}H$

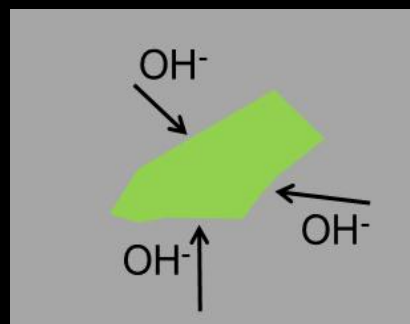
Silica   alkali   water   alkali-silica gel

Alkalis
\+
Reactive Silica
\+
Moisture

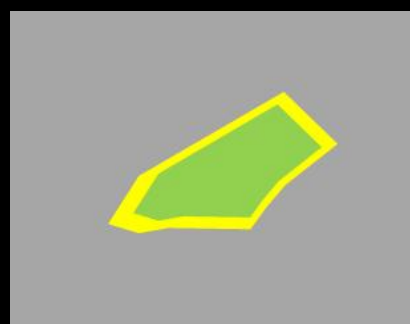
⇨ ASR Gel which expands ⇨ Concrete cracking

ASR Formation and Necessities

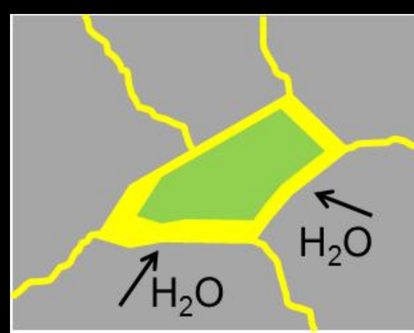
1. Silica dissolution



2. Silica gelation



3. Swelling of gel



Reactive Silica

High pH

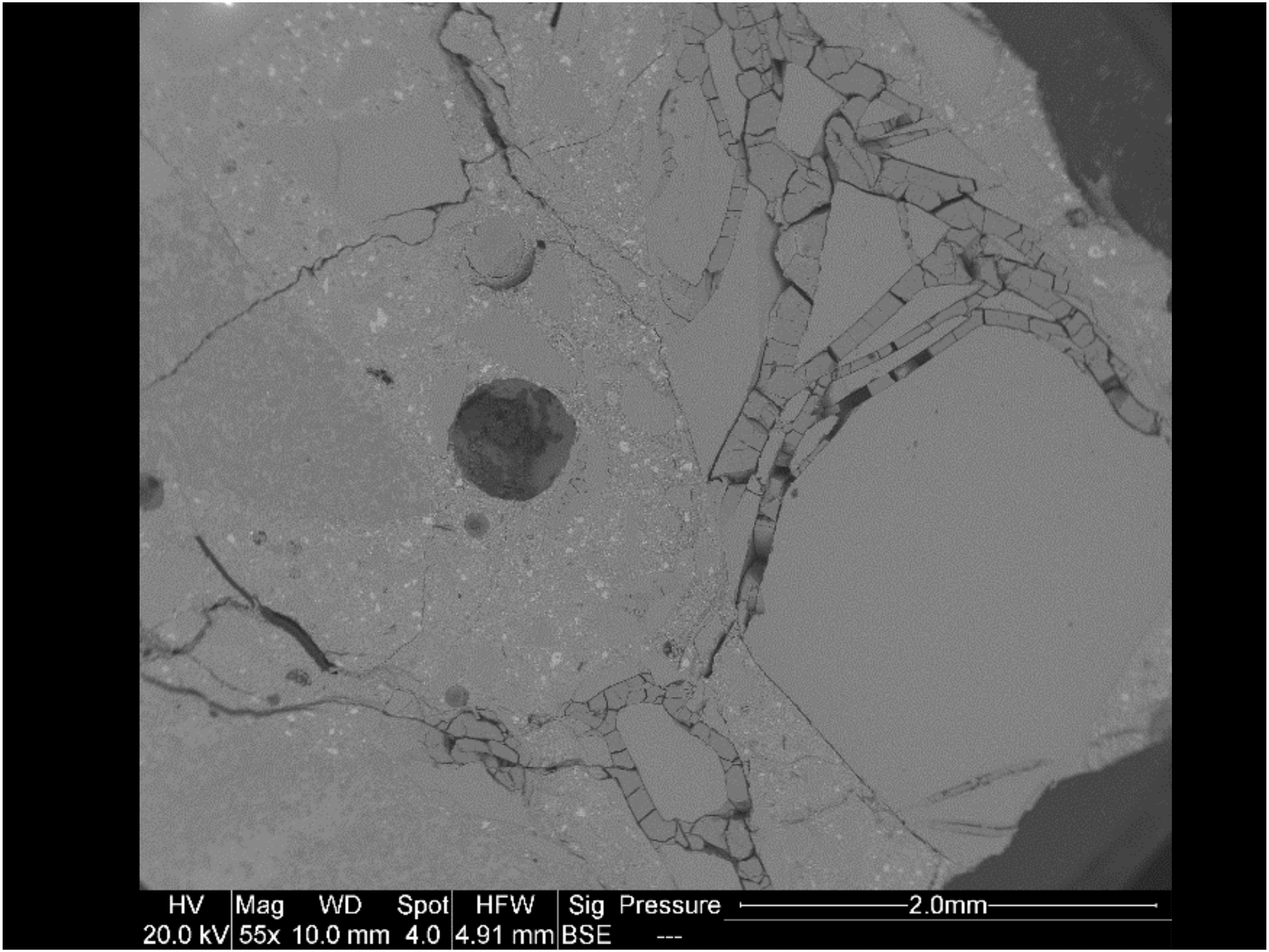
Four-Prongs of ASR promotion

Sufficient Moisture

Calcium Hydroxide

Alkali Silica Reaction (ASR)

- Signs of ASR
  - Expansion and cracking
  - Loss of strength
  - Pop-outs and exudation of viscous alkali-silicate fluid
- Where?
  - Humid environments (dams, bridge piers, sea walls)
  - Exposed environments (roads, building exteriors)


HV 20.0 kV
Mag 55x
WD 10.0 mm
Spot 4.0
HFW 4.91 mm
Sig BSE
Pressure ---
2.0mm

Methods to Prevent ASR

Alkalis + Reactive Silica + Moisture ⇨ ASR Gel

- Limit alkali presence
  - Low alkali cement
  - Limit other sources:
    - salt-contaminated aggregates
    - penetration of seawater
    - penetration of deicing solution
  - Cement content of the concrete
- Limit reactive aggregate
  - amount, size, reactivity
- Limit available moisture
  - RH of 75% required for reaction
  - Repair cracks, joints

Methods to Prevent ASR

- Use slag or pozzolanic admixtures
  - Insoluble alkalis
  - Blast furnace slag, volcanic glass, fly ash, silica fume
  - Iceland uses CFS (Condensed Silica Fume) in all cement
- Air entrainment may help
  - Provides pores; allows gel room to expand harmlessly
- Structural Design
  - Limit access to water
  - Avoid de-icing salt accumulation
  - Adequate compaction
  - Good finished surfaces

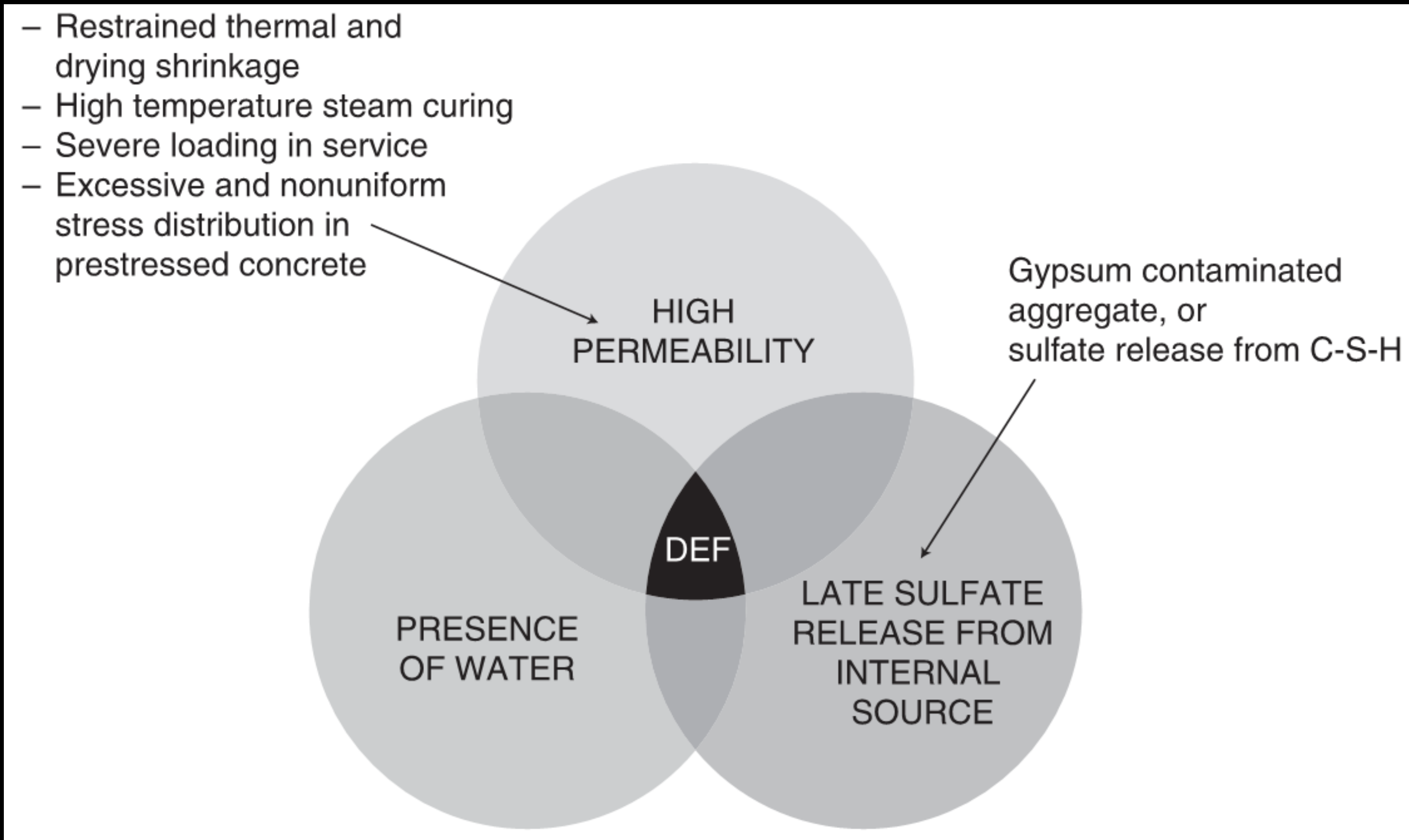
ASTM C1260 - 14

Standard Test Method for Potential Alkali Reactivity of Aggregates (Mortar-Bar Method)

Active Standard ASTM C1260 | Developed by Subcommittee: C09.26

Book of Standards Volume: 04.02

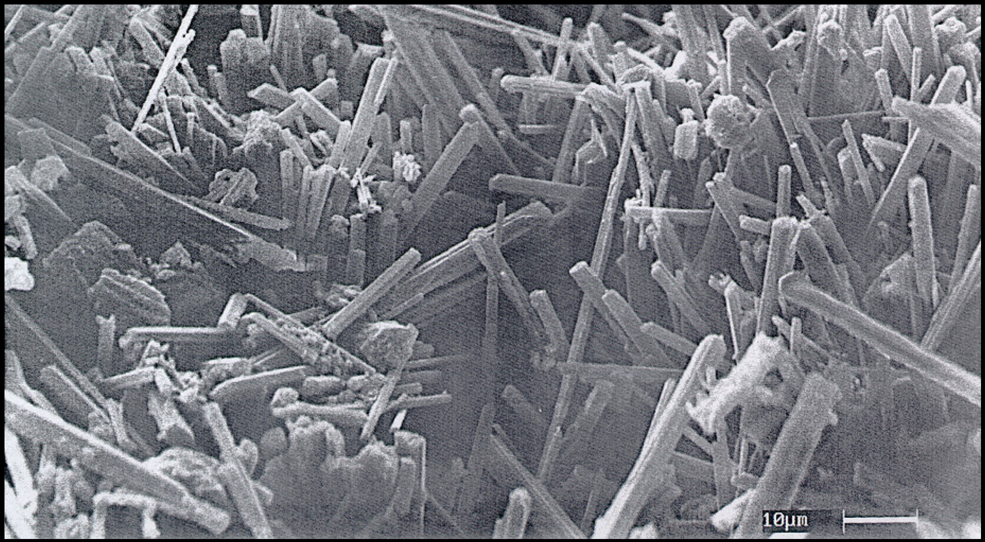
Delayed Ettringite Formation (DEF)



Delayed Ettringite Formation (DEF)

- Ettringite is the mineral name for calcium sulfoaluminate ($3CaO{\bullet}Al_2O_3{\bullet}3CaSO_4{\bullet}32H_2O$), which is normally found in portland cement concretes, as a hydration product with a long, well-crystalized

Ettringite



Delayed Ettringite Formation (DEF)

- DEF is a case of chemical sulfate attack when the source of sulfate ions happens to be internal (within the concrete) rather than external.
- The phenomenon is known to occur when either a gypsum-contaminated aggregate or a cement containing unusually high sulfate content has been used in the concrete

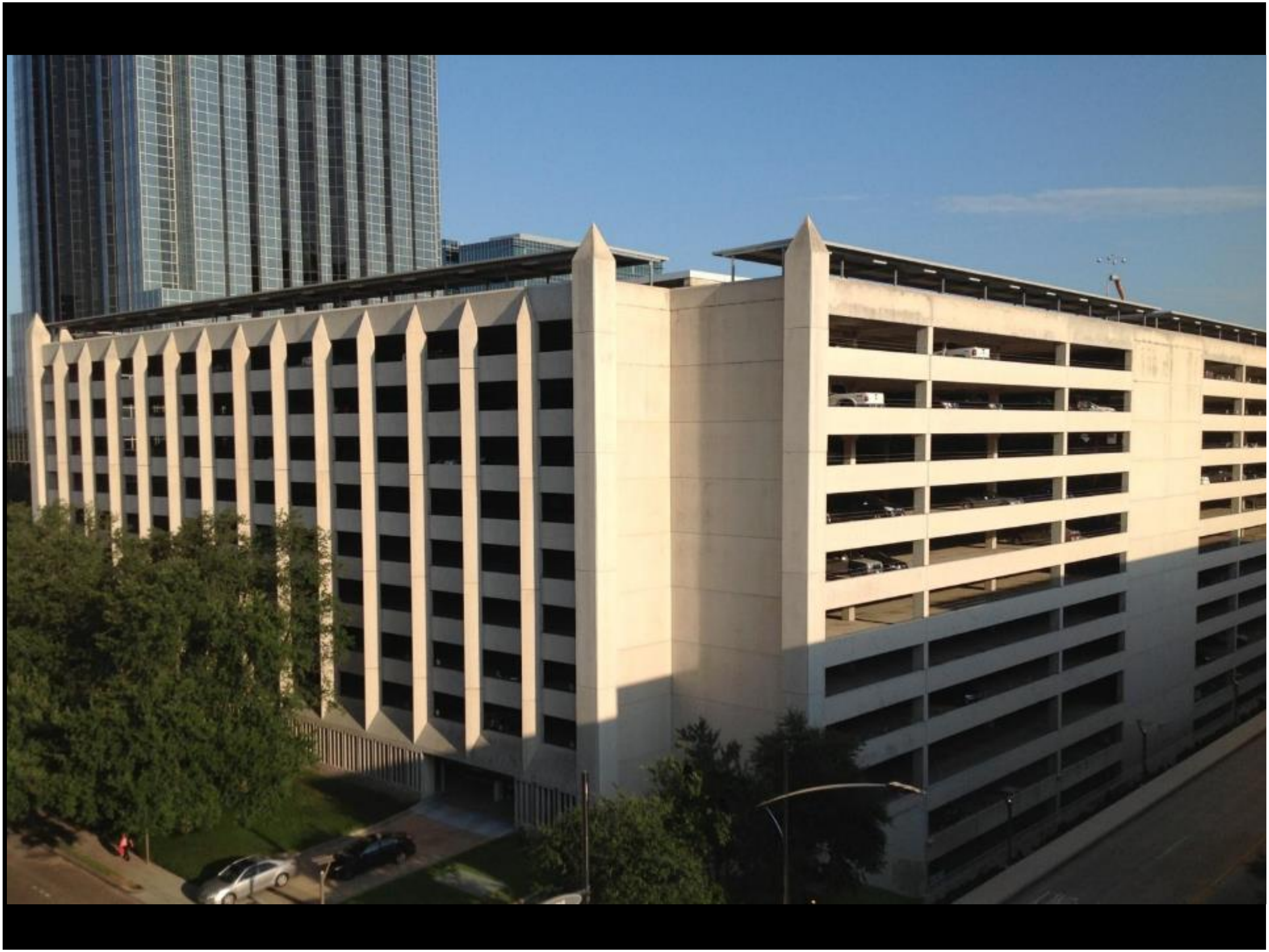
Delayed Ettringite Formation (DEF)

- Cases of delayed ettringite formation have been reported with steam-cured concrete products.
- Ettringite is not a stable phase above 65°C, it decomposes to form the monosulfate hydrate if steam-curing temperatures higher than 65°C; are used in the manufacturing process.

Delayed Ettringite Formation (DEF)

- The sulfate ions released by the decomposition of ettringite are adsorbed by calcium-silicate hydrate.
- Later, during the service, when sulfate ions are desorbed, the re-formation of ettringite causes expansion and cracking.

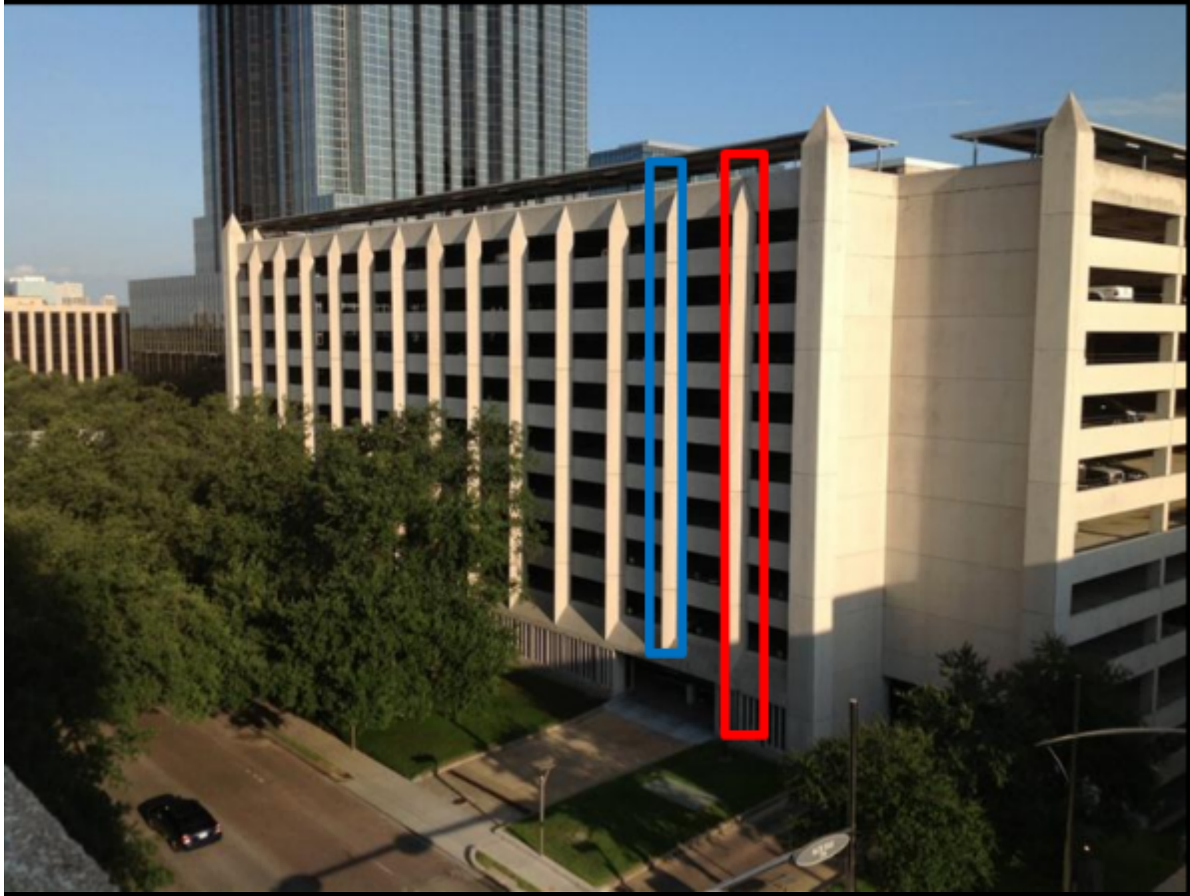
Case Study

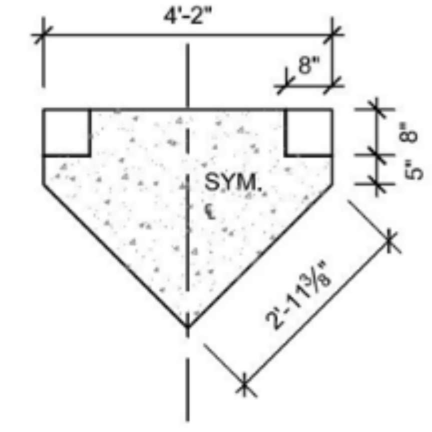


Project Information

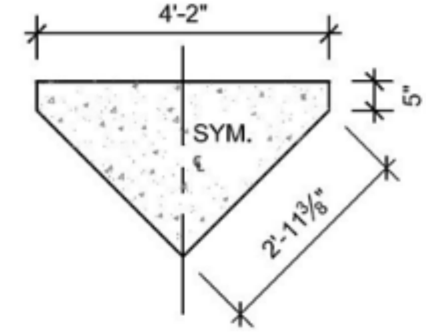
- 12-Story (2 below ground)
- Footprint: ~ 364ft x 271ft
- Built in 1983
- Precast concrete DTs with CIP topping
  - 10 ft wide and 28 in deep
  - 47 to 59 ft span (6 bays)

Evaluation – Project Information

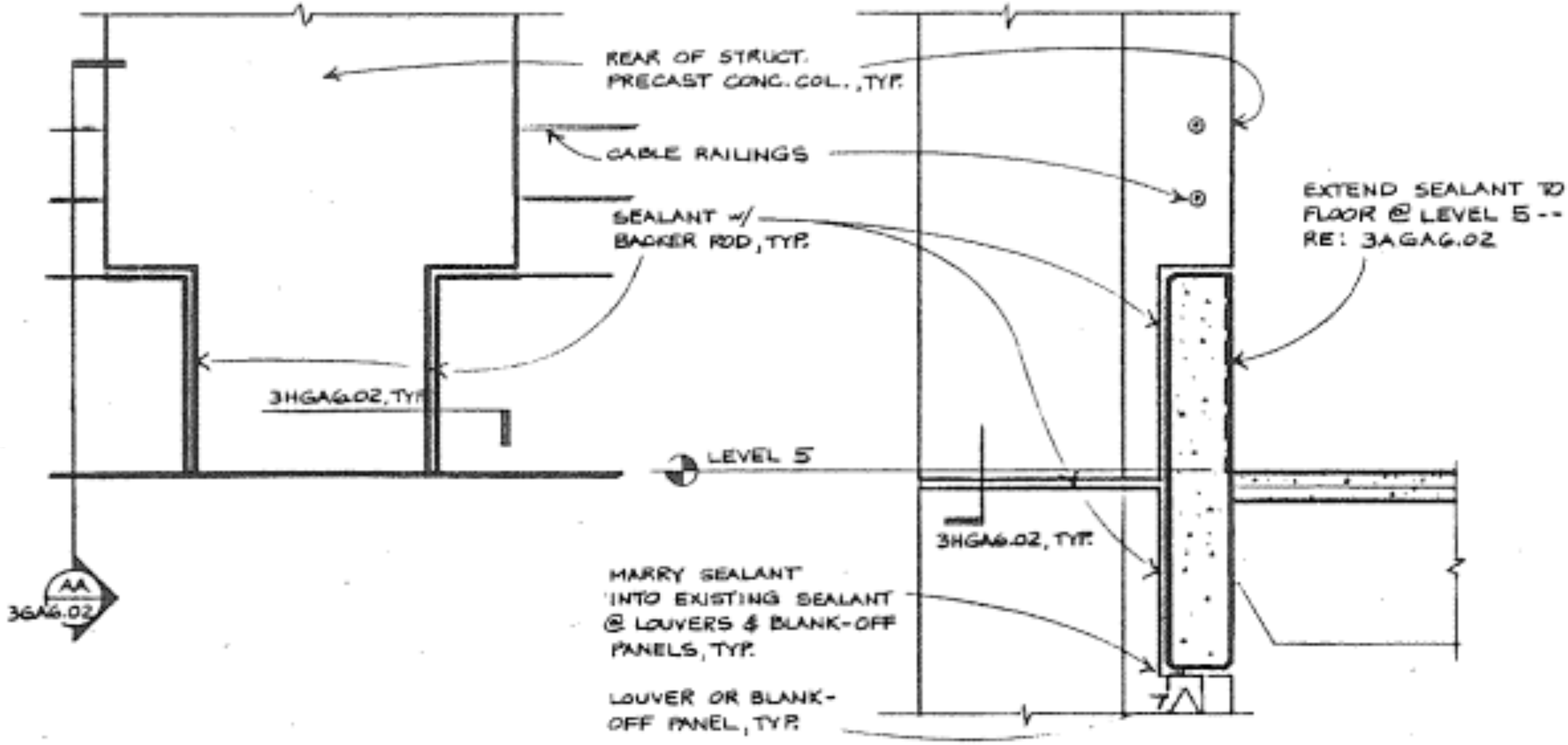




LOAD BEARING COLUMN

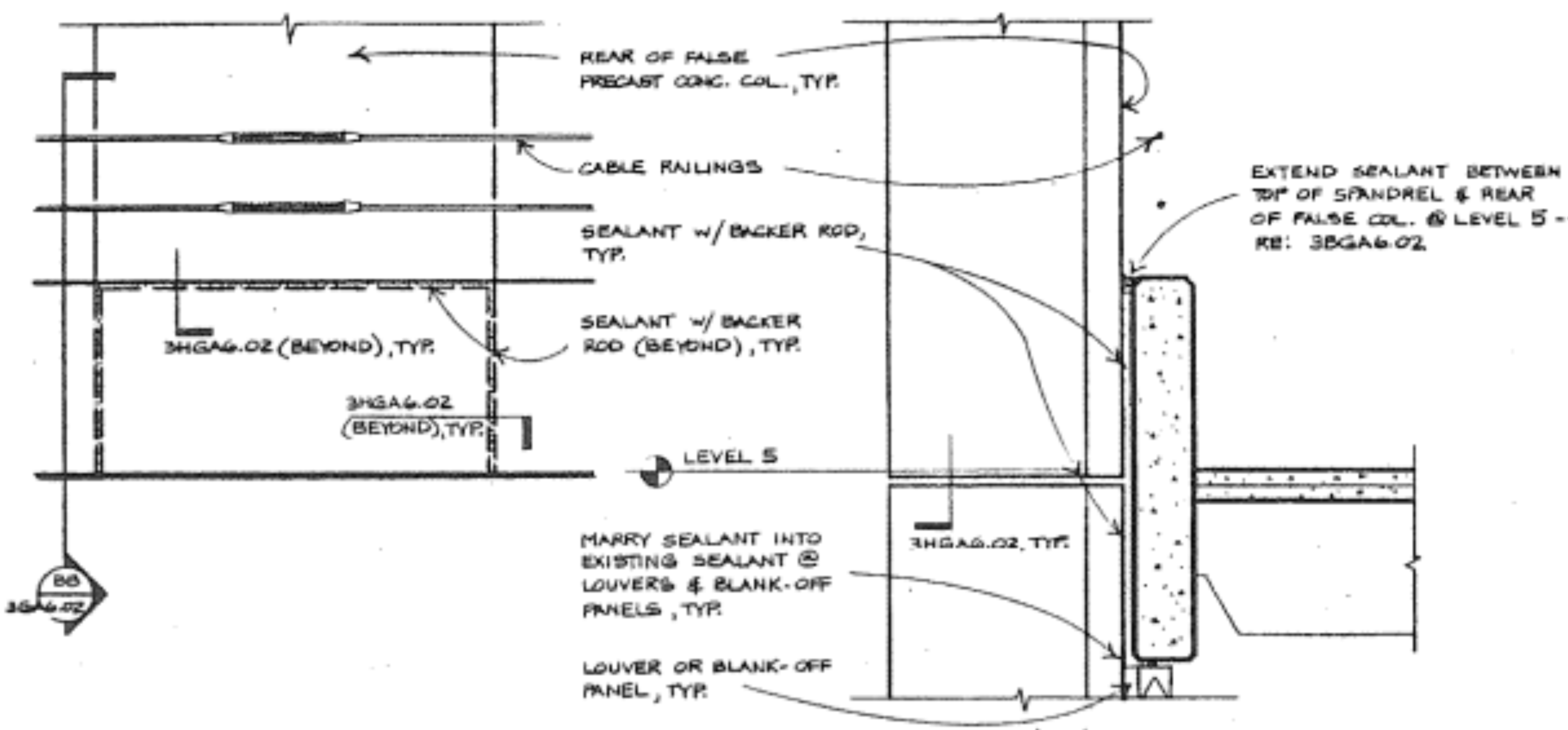


NON LOAD BEARING COLUMN



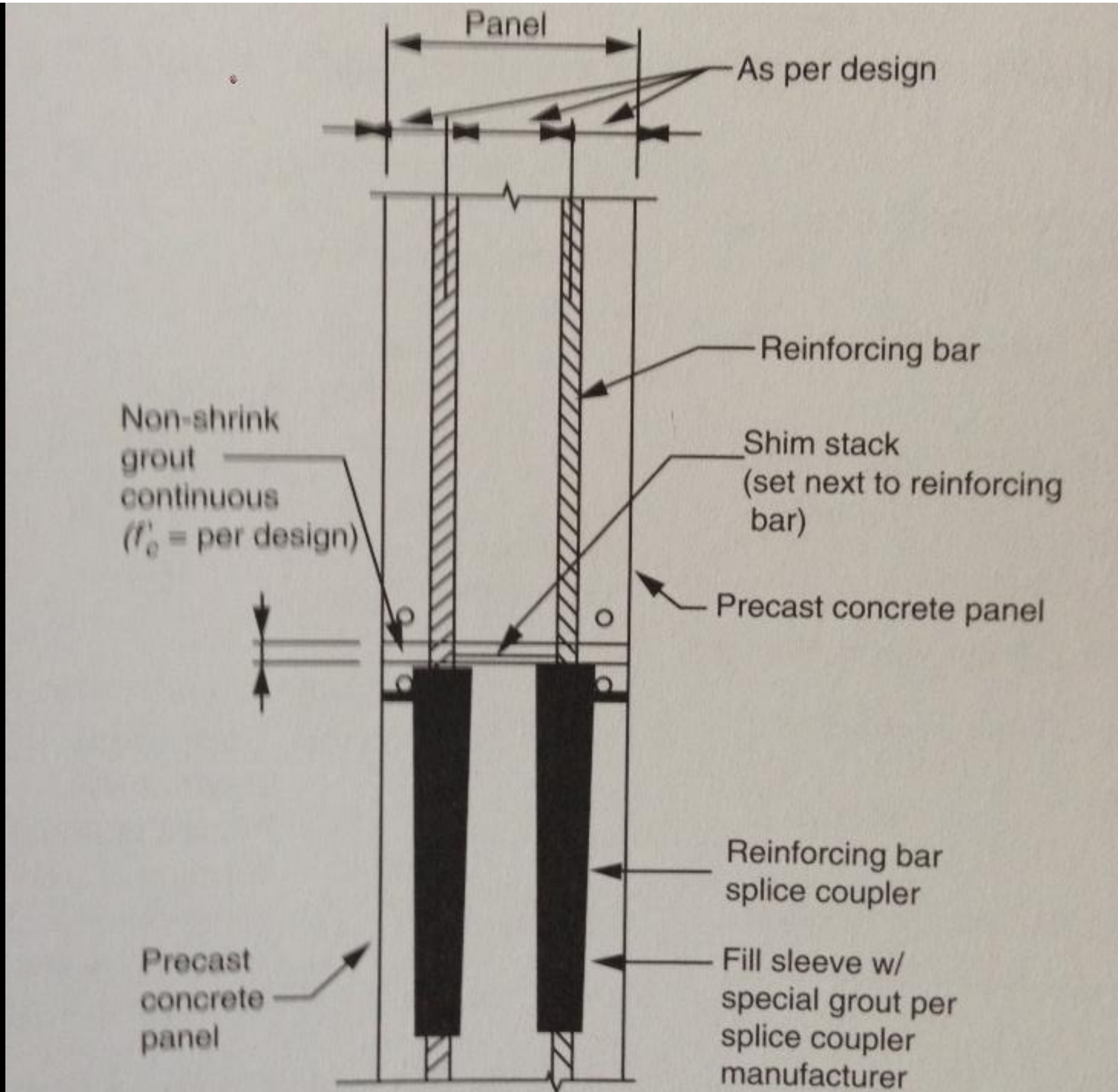
"A" - REAR VIEW OF STRUCT. PRECAST CONC. COL.

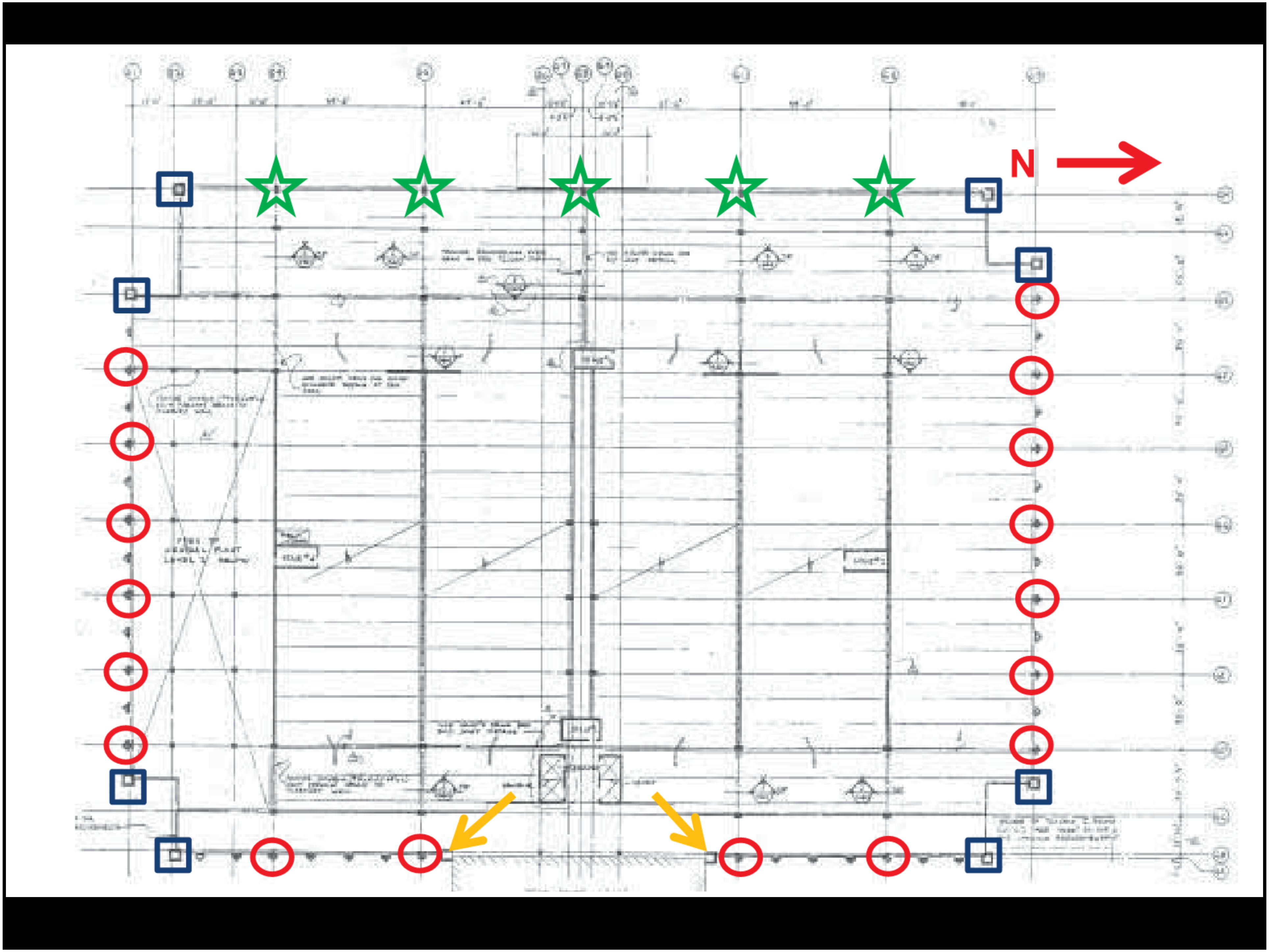
SECTION "AA"



'B' - REAR VIEW OF FALSE PRECAST CONC. COL.

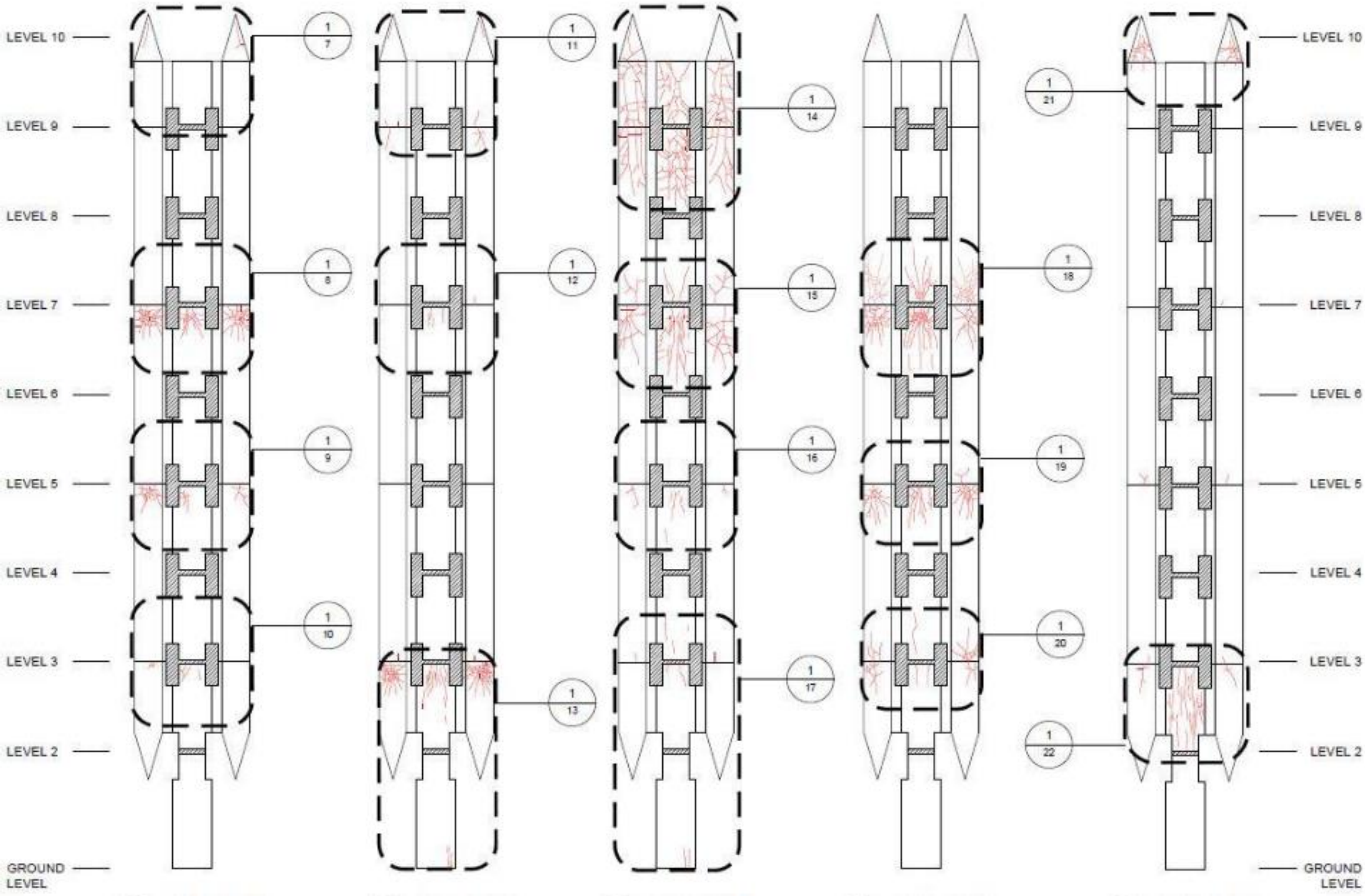
SECTION 'BB'



Panel
As per design
Reinforcing bar
Non-shrink grout continuous (f'_c = per design)
Shim stack (set next to reinforcing bar)
Precast concrete panel
Reinforcing bar splice coupler
Fill sleeve w/ special grout per splice coupler manufacturer
Precast concrete panel

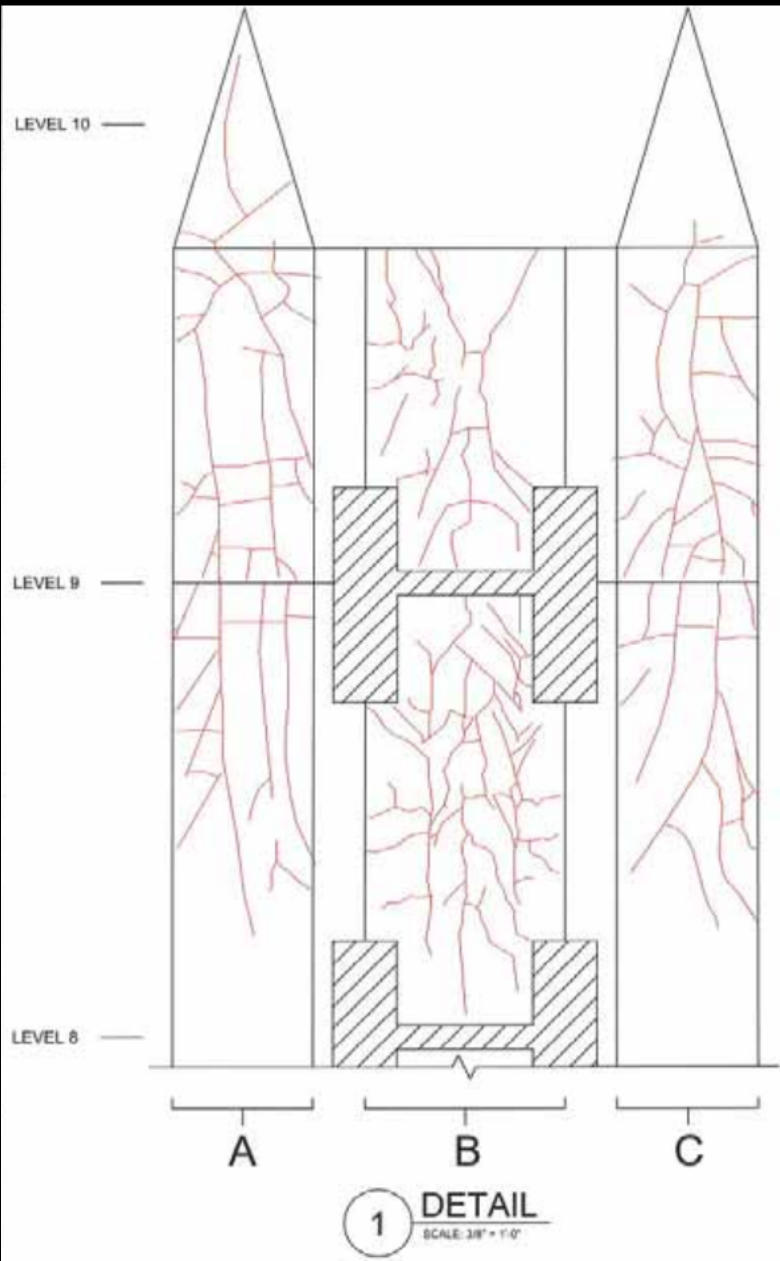

N

Up-close Survey

Crack Mapping



Crack Mapping



COLUMN KEY PLAN
B
C A
LEGEND
= COLUMN CRACK
= PORTION OF COLUMN NOT VISIBLE

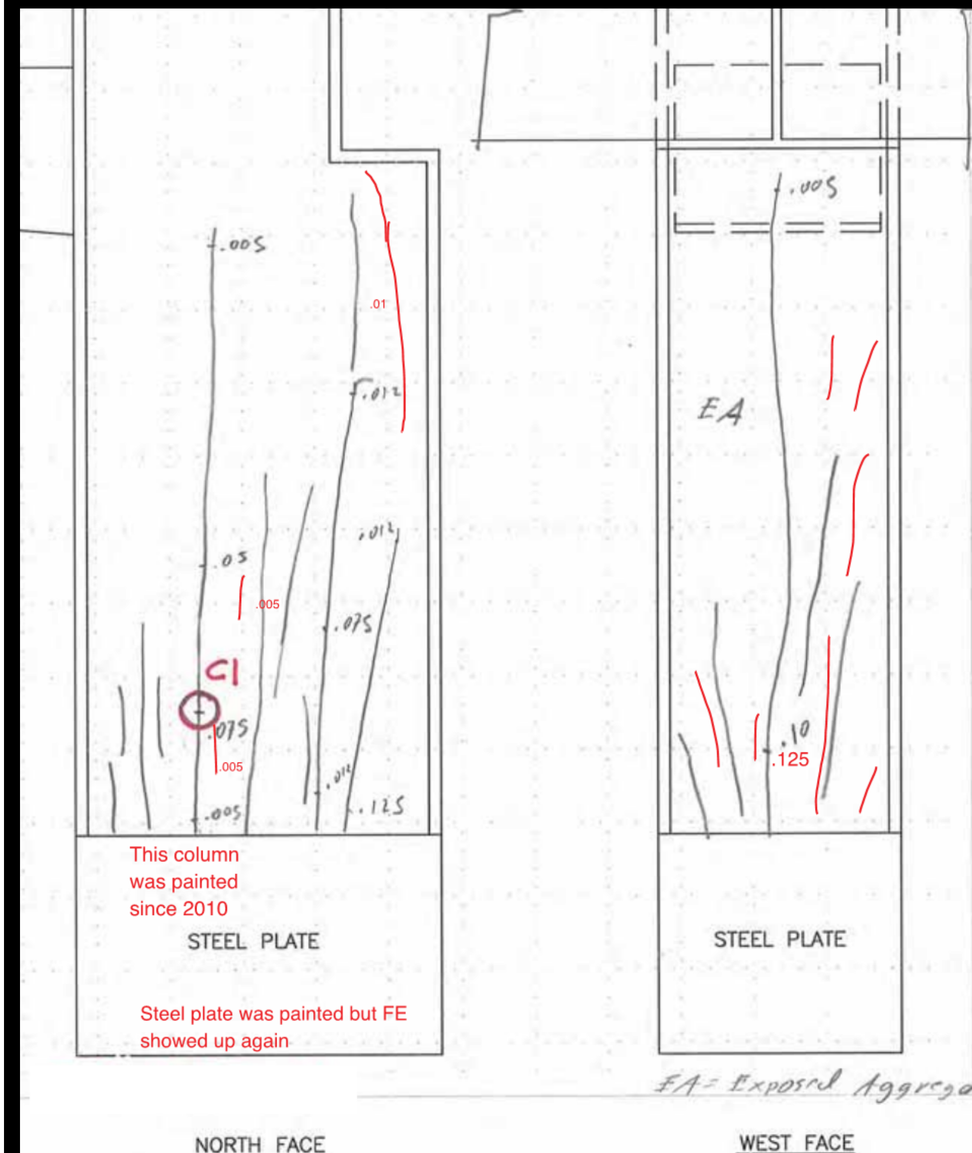
SOUTH FACE

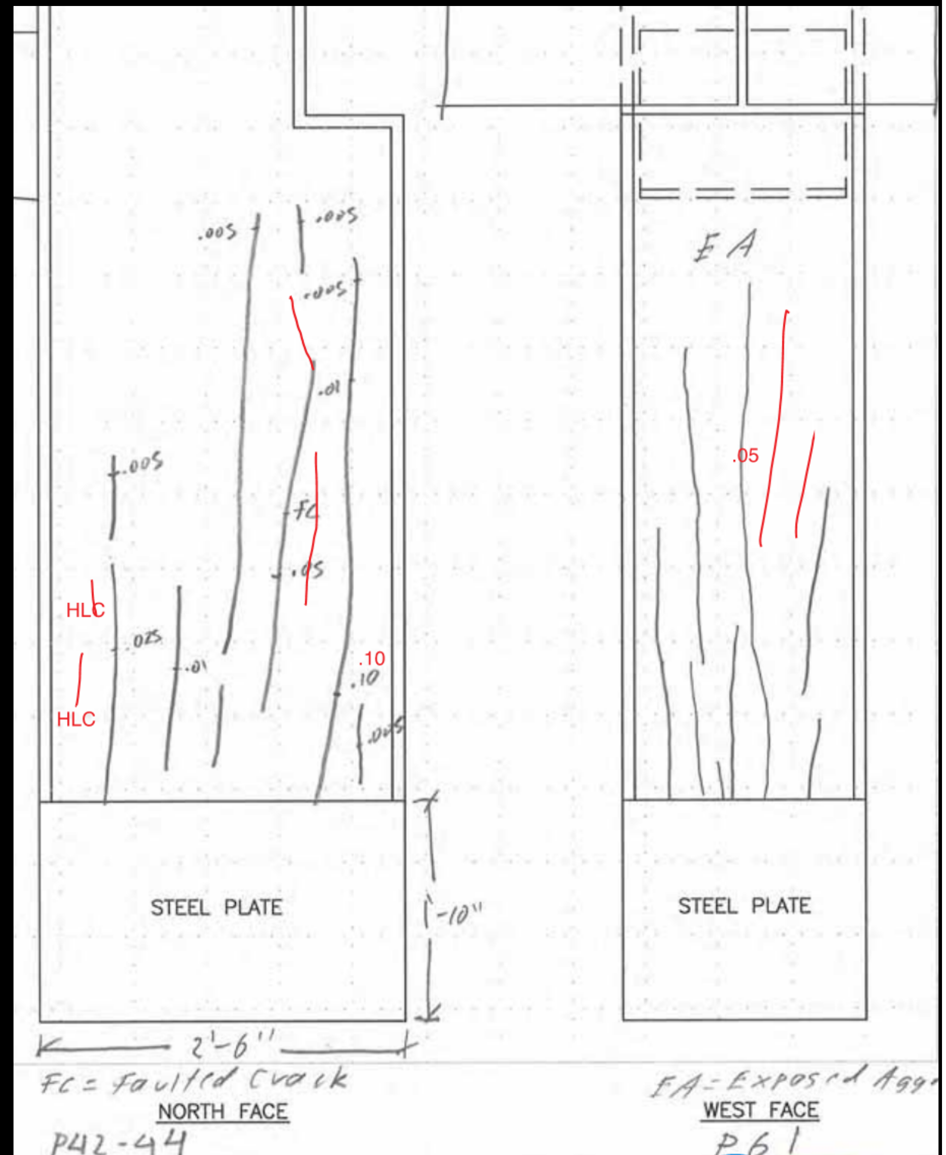
EAST FACE

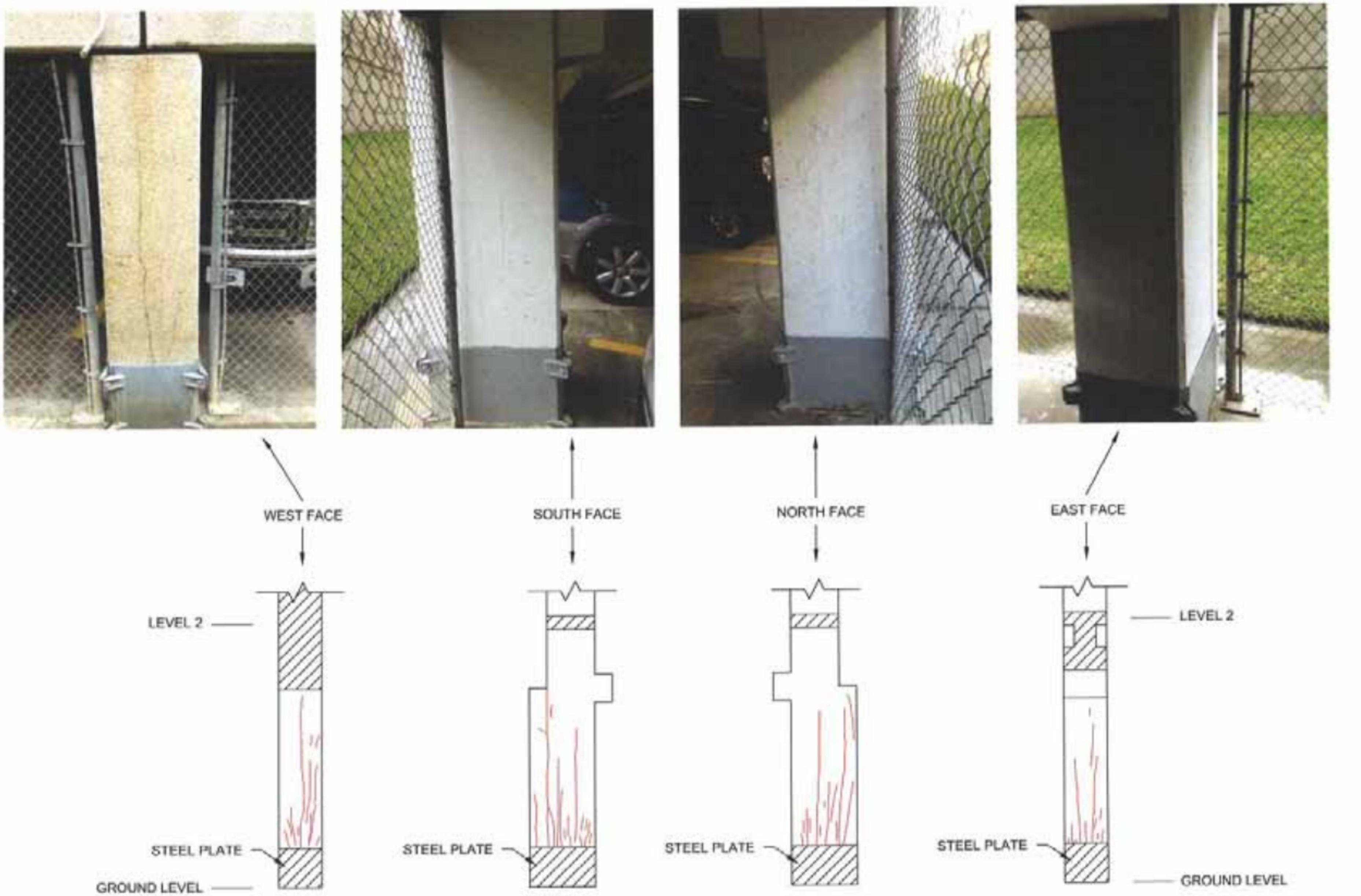
NORTH FACE

WEST FACE

Crack Mapping







1 DETAIL
SCALE: 1/4" = 1'-0"

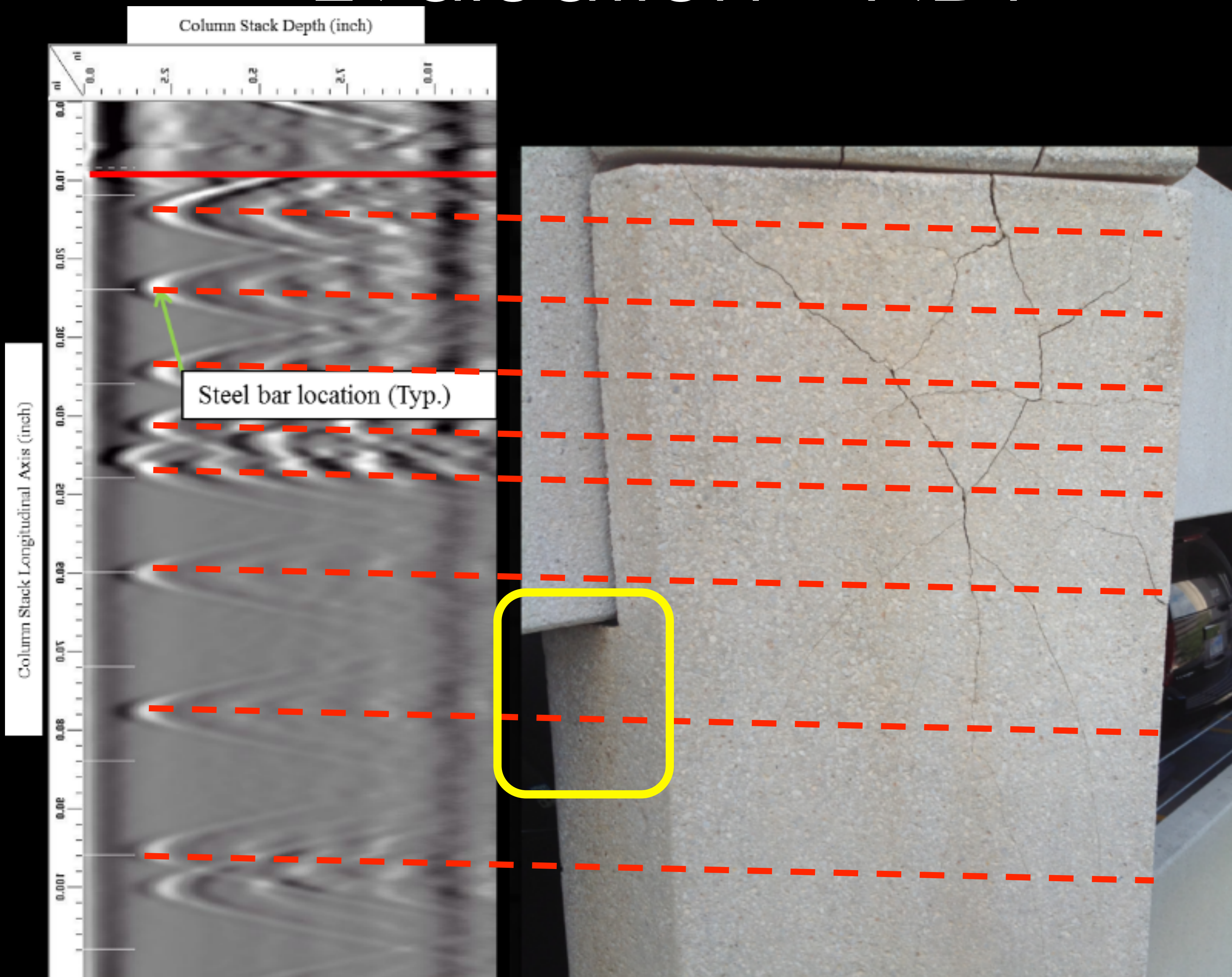
LEGEND
= COLUMN CRACK
= PORTION OF COLUMN NOT VISIBLE

Table 1. Column Crack Survey Summary

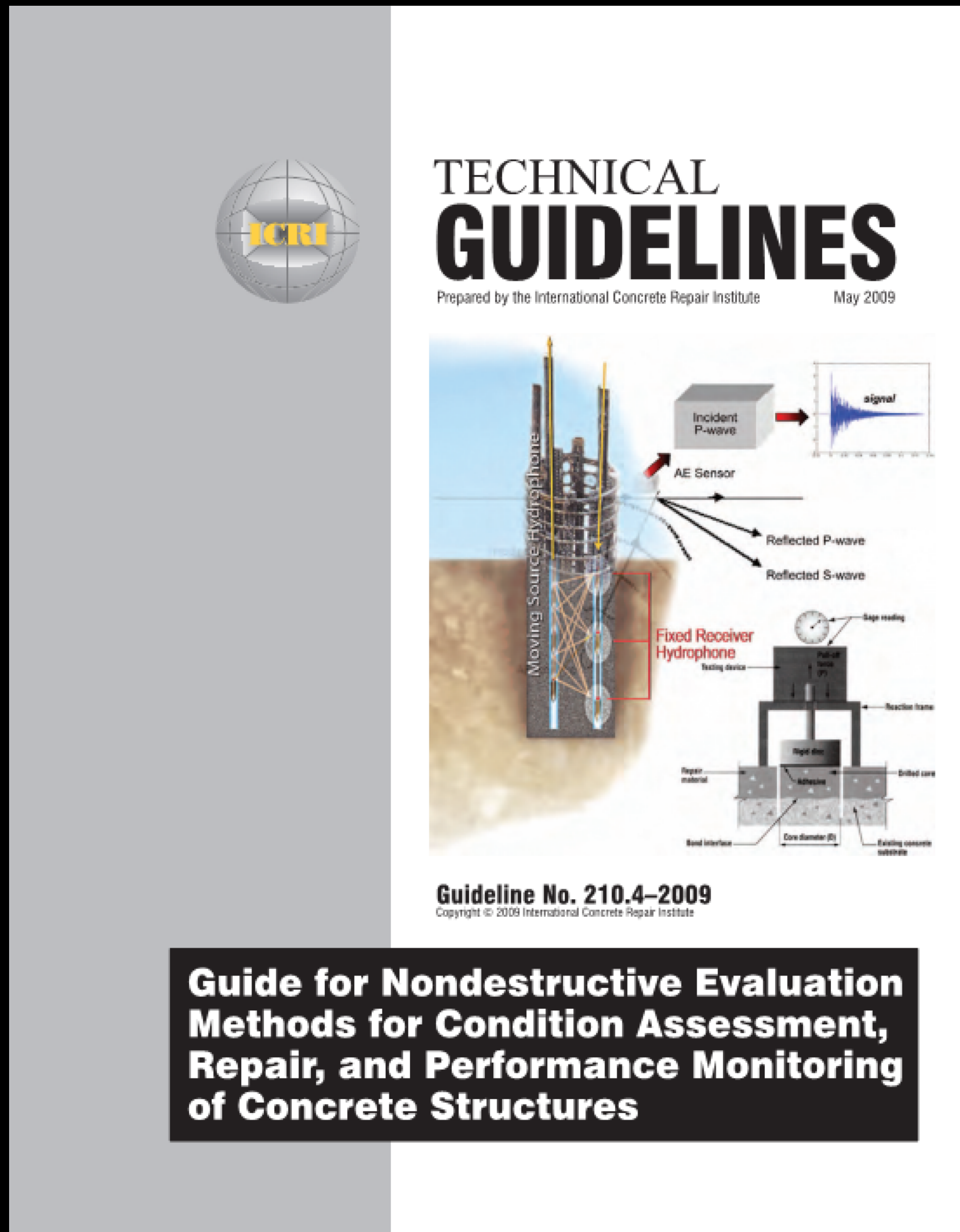
Column No.	Column Faces								Totals	
	South		East		North		West			
	Crack Length (LF)	Crack Density (lf/sf)	Crack Length (LF)	Crack Density (lf/sf)	Crack Length (LF)	Crack Density (lf/sf)	Crack Length (LF)	Crack Density (lf/sf)	Crack Length (LF)	Crack Density (lf/sf)
1	21.4	1.9	9.8	1.5	15.8	1.4	9.5	1.4	56.5	1.6
2	14.4	1.3	6.2	0.9	14.0	1.2	11.6	1.7	46.2	1.3
3	17.4	1.6	3.8	0.6	6.1	0.5	2.5	0.6	29.8	0.9

Core ID's	**Locations**	**Description**
C1	Level 9, inside face of Column GF	Core at longitudinal crack
C2	Level 2, outside face of Column GE; below grade	Control sample - no cracks
C3	Level 8, outside of Column GF	Core at wide longitudinal and narrow transverse crack
C4	Level 7, outside face of Column GF	Core at transverse and diagonal cracks

Evaluation – NDT



ICRI Guideline Tables


TECHNICAL
GUIDELINES

Prepared by the International Concrete Repair Institute May 2009

Guideline No. 210.4–2009

Guide for Nondestructive Evaluation Methods for Condition Assessment, Repair, and Performance Monitoring of Concrete Structures

ICRI Guideline Tables

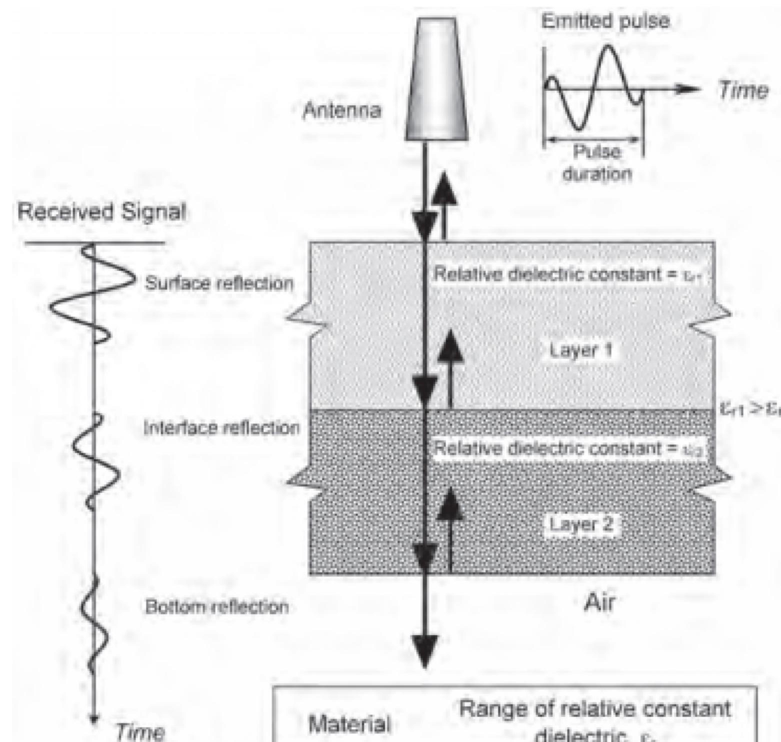
Table 7.4: NDE Methods for Reinforcement/Metal Location, Cover Depth, Sizing, and Corrosion Condition Assessment

NDE methods	**Visual methods**	**Acoustic sounding**	**Impact echo**	**Ground-penetrating radar**	**Radiography**
References Standards/guidelines	ACI 201.1R, 207.3R, 224.1R, 362R, 228.2R, SEI/ASCE 11-99	ASTM D4580	ASTM C1338	ASTM D6087	—
Appendix section	A.2.26	A.2.1	A.2.10	A.2.8	A.2.20
Property/condition					
Reinforcing bar/strand Location/cover Thickness/mapping	—	—	—	X	X
Reinforcing bar/strand size	—	—	—	—	X
Corrosion activity	X	—	—	—	—
Corrosion rate	—	—	—	—	—
PT duct grouting	—	—	X	X	—

ICRI Guideline Tables

A.2.8 Ground Penetrating Radar (GPR) (ASTM D6087)

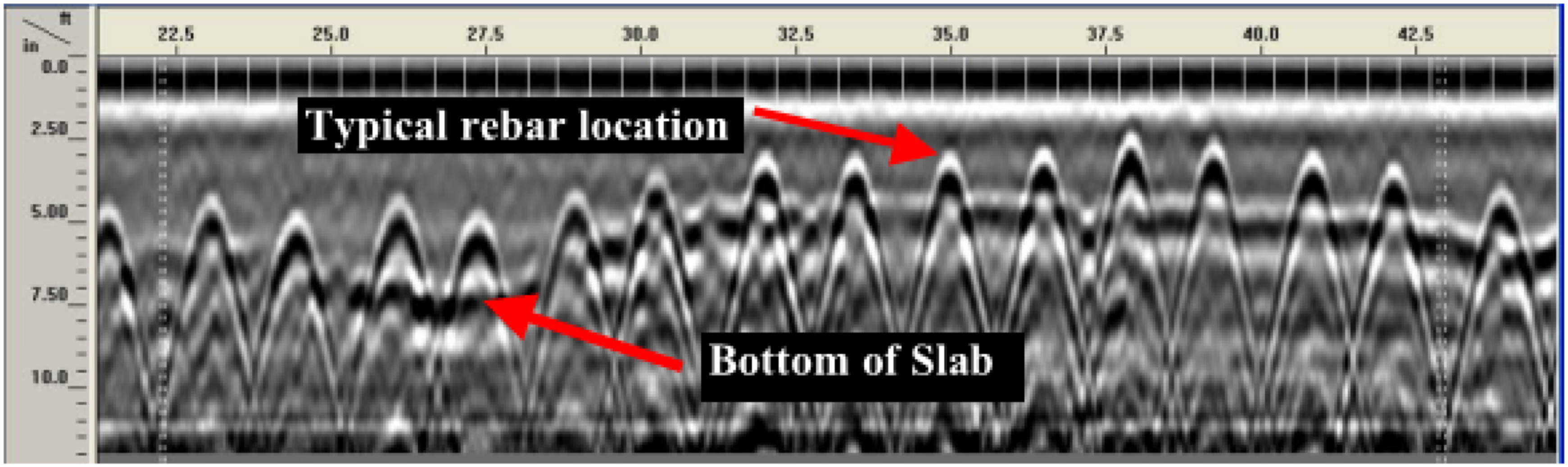
The GPR testing method uses an antenna that is either dragged across the surface or attached to a survey vehicle to transmit short pulses of electromagnetic energy that penetrate into the surveyed material and are then reflected back from anomalies and interfaces, as shown in Fig. 15. The common uses of this technique are to locate metallic objects (for example, reinforcement), identify layer thicknesses, identify areas of changes in moisture and density, and locate voids. Further details can be found in ACI 228.2R.



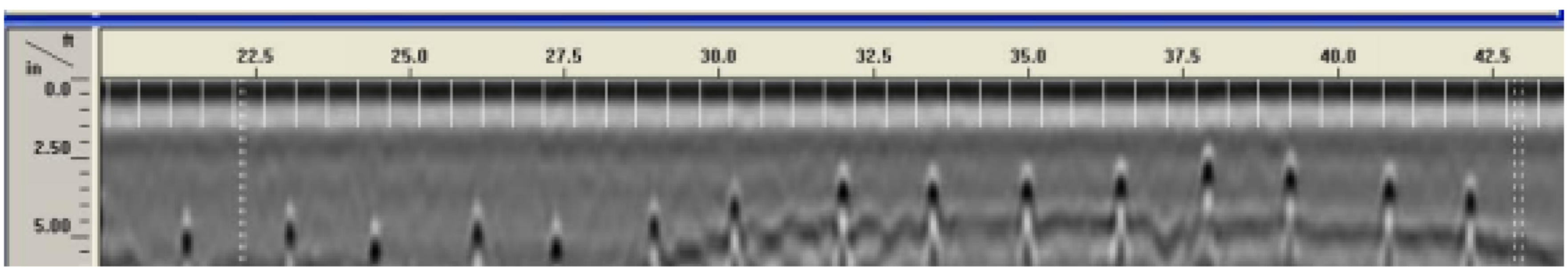
Material	Range of relative constant dielectric, ε_r
Air	1
Portland cement concrete*	6 to 11
Bituminous concrete*	3 to 5
Gravel *	5 to 9
Sand*	2 to 6
Rock*	6 to 12
Water	80

* ASTM D4748

Fig. 15: Reflections of electromagnetic radiation pulses at interfaces between materials with different dielectric constants



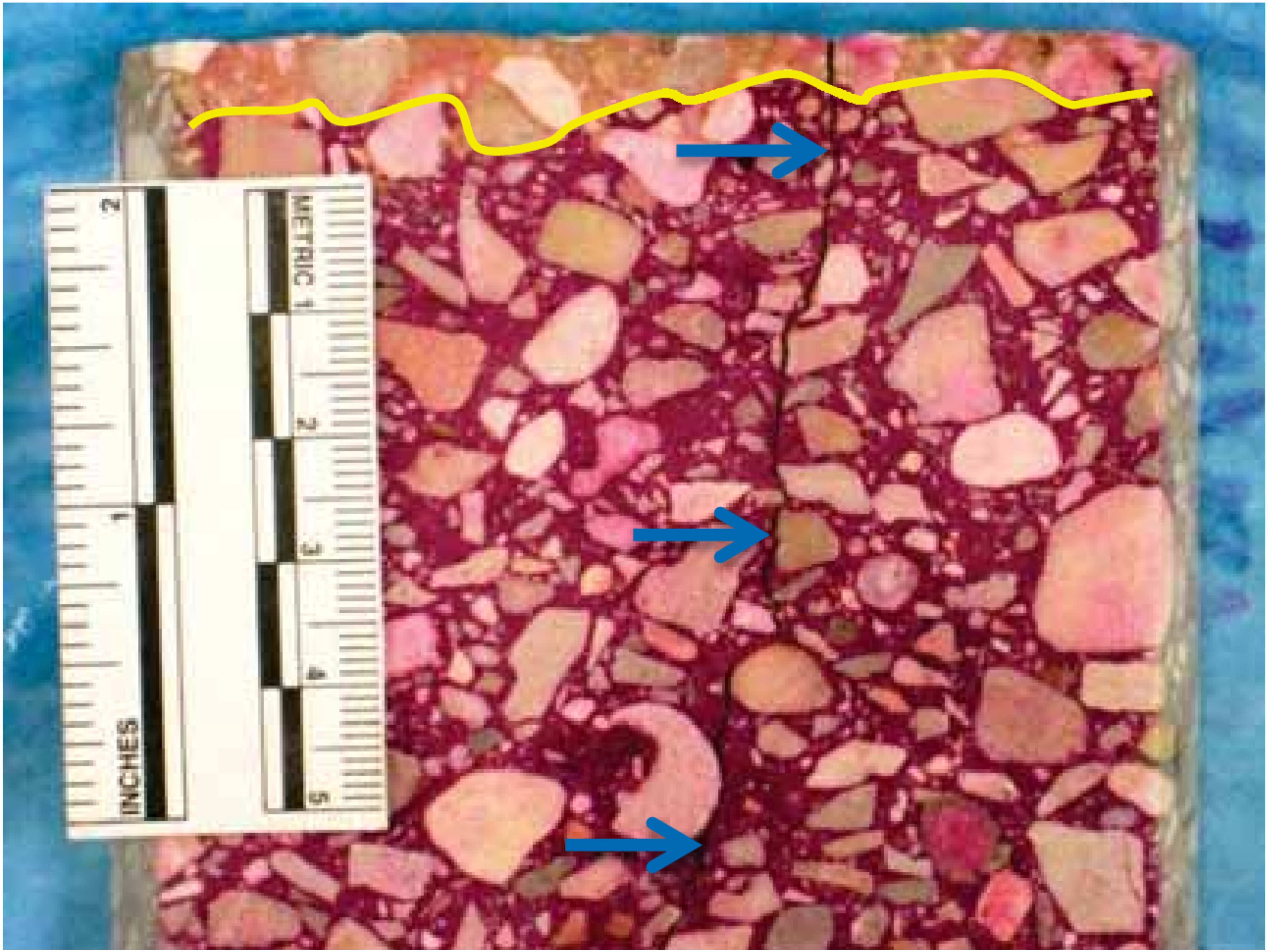
(a) Raw data



(b) Post-processed data

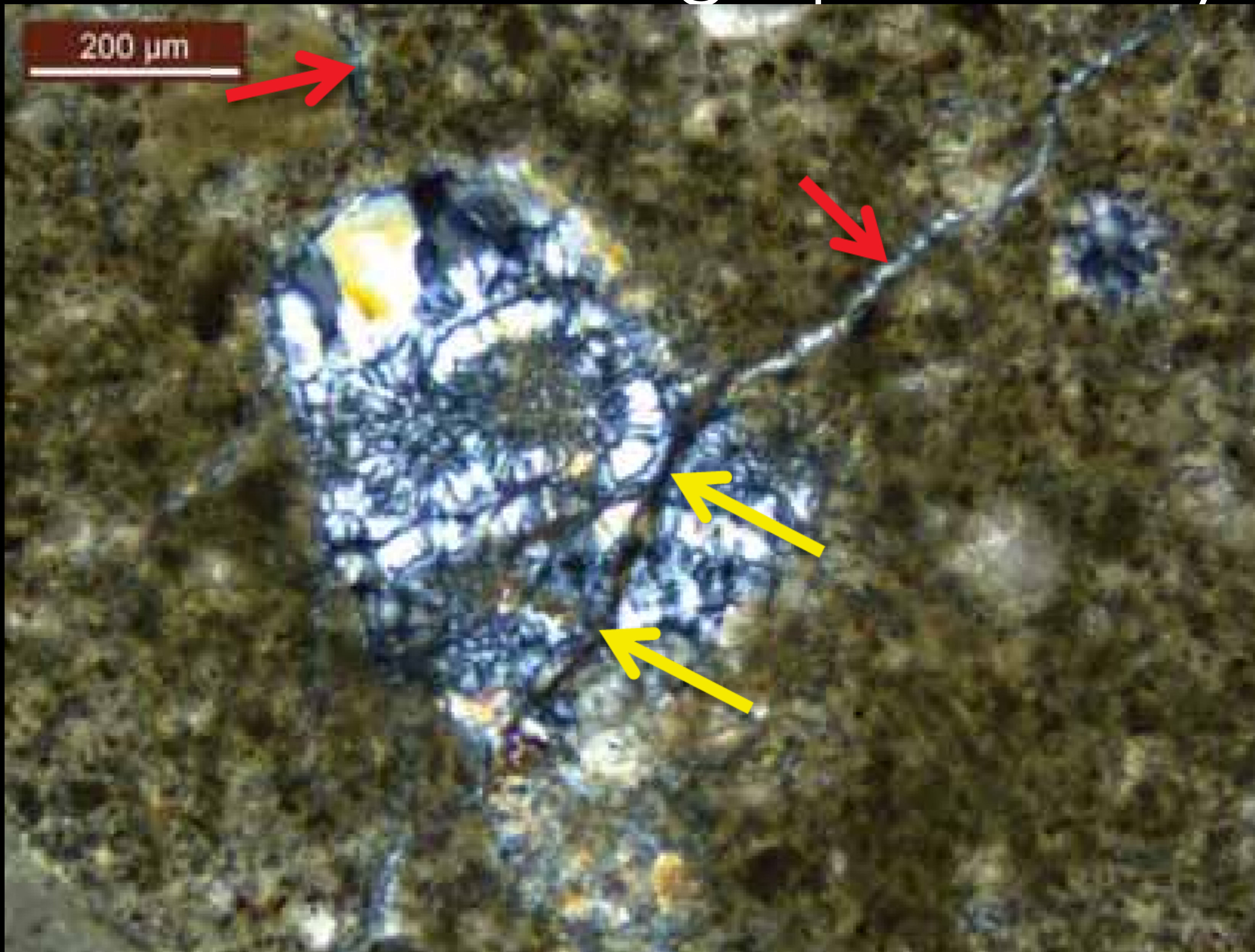
Core Sample at Crack

Control Sample


METRIC
INCHES

Evaluation – Petrographic Analysis

Evaluation – Petrographic Analysis

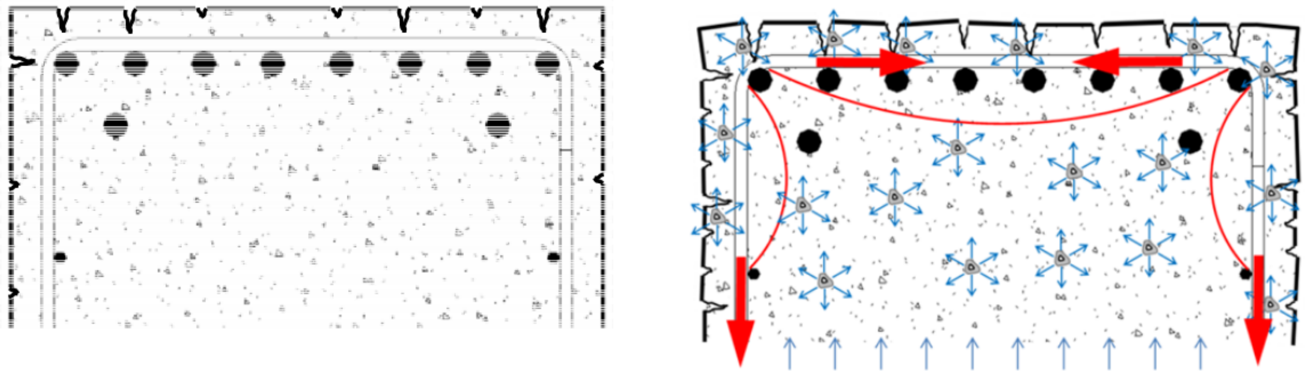


ASTM C-856

Sample Type	Precast concrete column.
Dimensions	Core diameter = 94 mm (3.7 inches); Core length = 200 mm (7.9 inches); partial column depth.
General condition	A surface perpendicular crack extends to a depth of 110 mm (4.3 inches).
Surfaces	Exposed surface exhibits a major crack and a minor crack. The minor crack intercepts the major one. Bottom surface is an irregular, fracture surface that passes both around and through aggregate particles.
Consolidation	Well consolidated
Embedded Items	None observed.
Macro-Cracks	The major crack is approximately 2.5-mm (0.10 inch) in width at exposed surface and tapers off at the depth of 110 mm (4.3 inches). The other crack is 0.4 mm (0.02 inch) wide at exposed surface, tapers off at a depth of 40 mm (1.6 inches). The cracks extend both around and through aggregate particles.
Distribution	Uniform distribution of aggregates, paste and air voids.
Aggregate Gradation and Top Size	Fairly well graded to an observed top size of 12 mm (0.5 inch).
Aggregate Types Coarse (CA)	Crushed carbonate rocks and/or gravel including mainly limestone, dolomitic limestone, dolomite and minor to trace amounts of chert, cherty dolomite and possibly opaline material.
Fine (FA)	Similar to the coarse aggregate in lithology.
Aggregate Condition	Many aggregate particles, both coarse and fine, exhibit microcracks and less frequently meso-scale cracks that often extend into or from surrounding paste. Both coarse and fine aggregates are angular to subrounded and mainly equant to bladed.
Paste-Aggregate Bond	Moderately tight to moderately weak.
Interfacial Zone	Frequently lined with ettringite; occurrence of such features increases with increasing depth.
Paste Color, Hardness, Luster	Light gray, moderately hard, and dull to subvitreous.
Paste Constituents	Residual portland cement estimated at 4 to 6 percent, finely ground; Abundant ground carbonate rocks, estimated greater than 10 percent was observed. Portlandite was not estimated due to interference of the carbonates fines.
Water-cementitious materials ratio (w/cm)	Estimated at moderate 0.50 +/- 0.02.
Carbonation Depth	1 mm (0.04 inch) from the existing exposed surface.
Air-Void System	Air content estimated at 1 to 2 percent. Concrete is not air-entrained.
Secondary Deposits	Ettringite frequently lines around aggregate particles, microcracks and voids; Alkali silica reaction (ASR) gel was observed in a few voids and microcracks in a few aggregate particles and the microcracks extending into surrounding paste.
Meso-scale and micro-scale crack	Abundant microcracks were observed in the paste and aggregate. Many of the microcracks intercept aggregate particles. Microcracks are frequently filled with ettringite, ASR gel or both.

Comments:

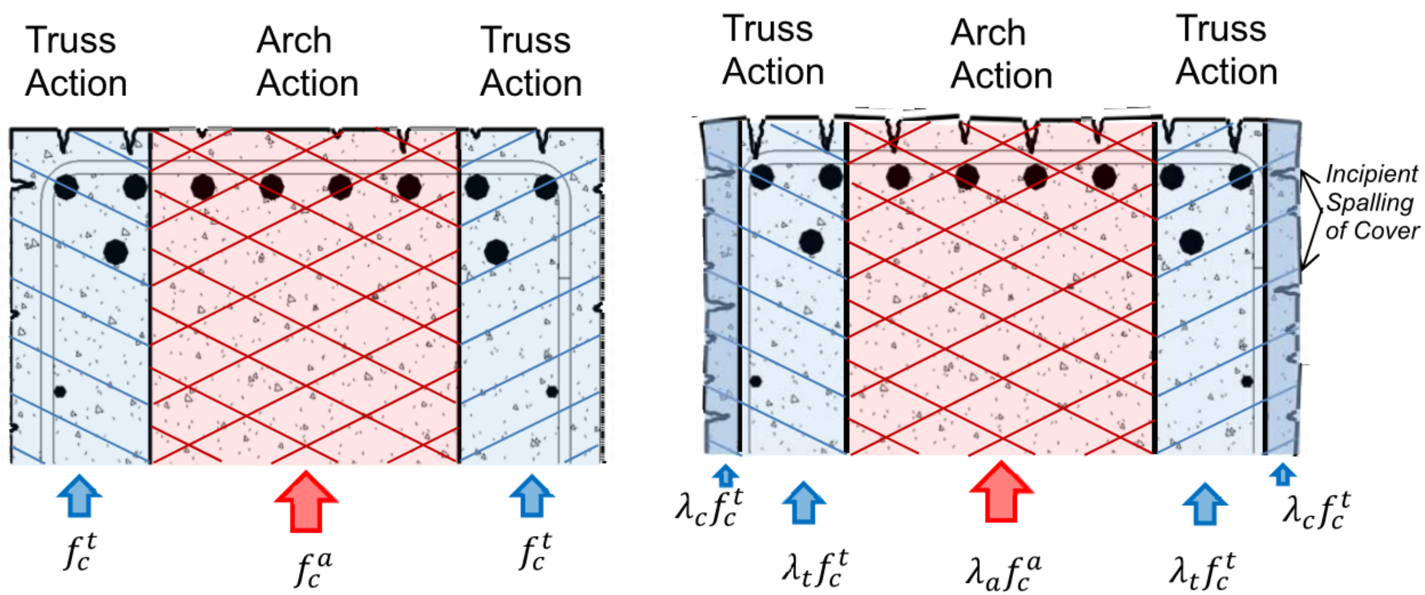
- The exposed surface of concrete exhibits a thin layer of coating material.
- Major crack partially filled with a small amount of sealant-like material.



(a) Structure without ASR/DEF

(b) Partially pre-confined due to ASR/DEF

Figure taken from TXDOT and Texas A&M Report No. FHWA/TX 12/0-5997-1



(c) No confining effect

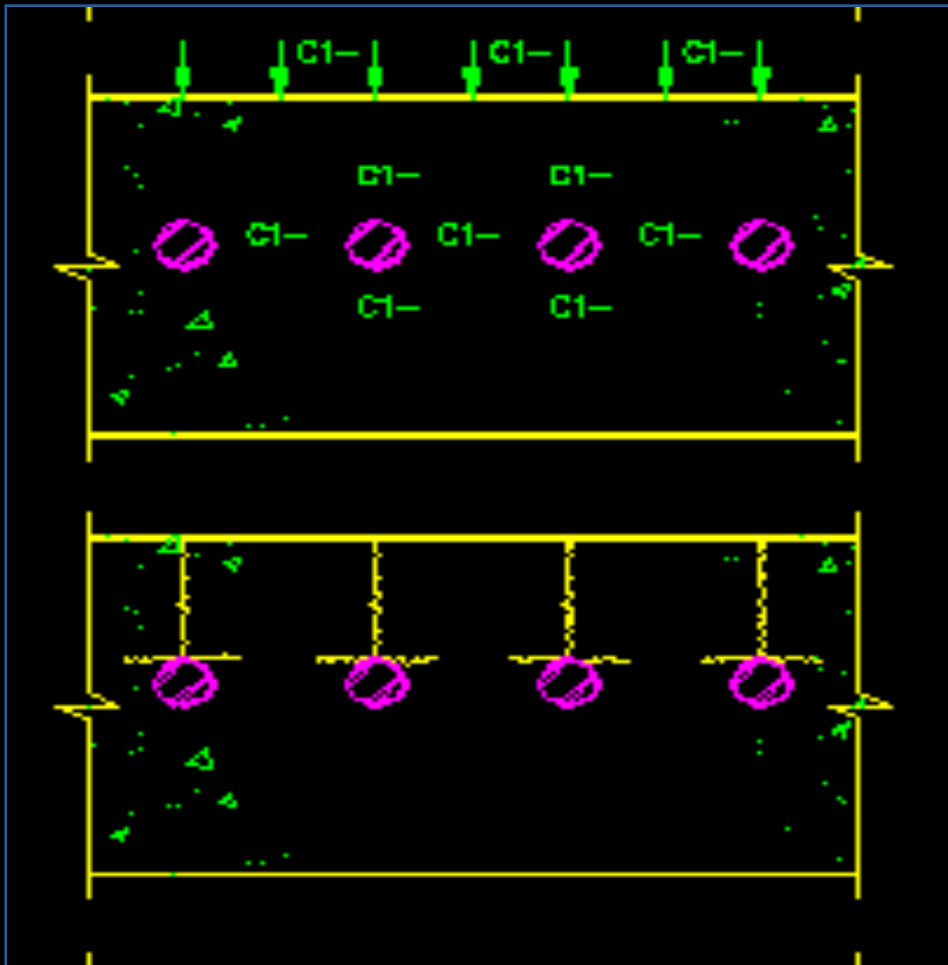
(d) Actively confined due to ASR/DEF effects

Corrosion Deterioration

<u>Stage 1</u>
Chloride ion is limited to surface and slab upper region.

Preventative Maintenance

Corrosion Deterioration

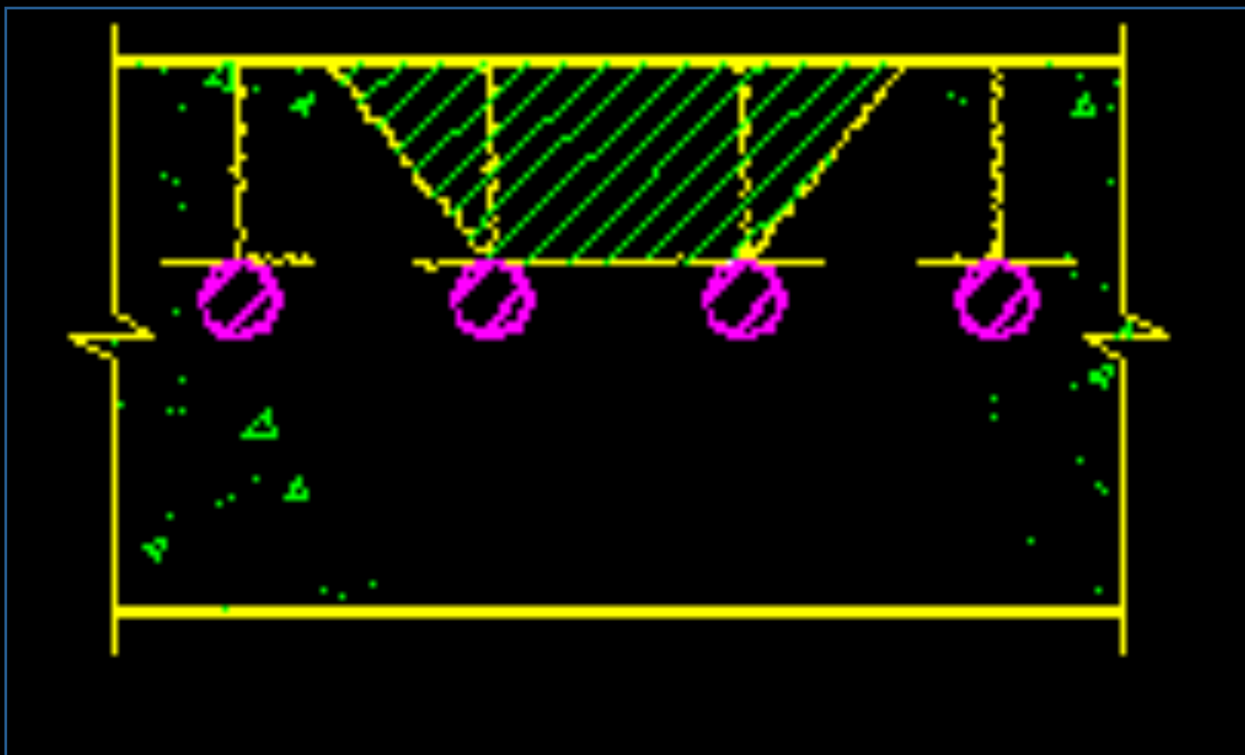


Stage 2
Over time the chloride ions penetrate down to the level of the steal reinforcement and beyond.

Stage 3
Initial stage of corrosion induced concrete deterioration result in formation of horizontal fractures and vertical cracking over the reinforcement.

Concrete Repairs & Preventive Coatings

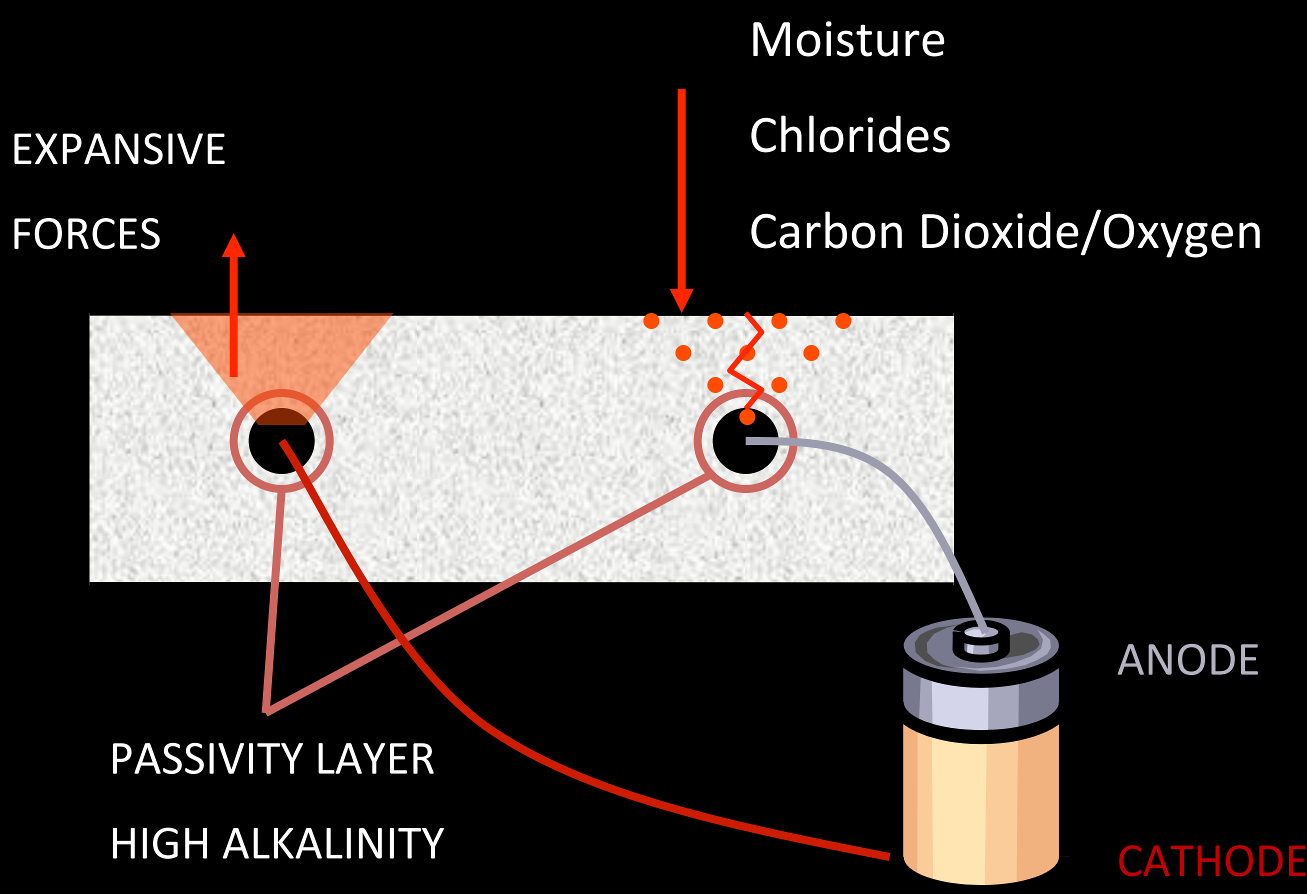
Corrosion Deterioration

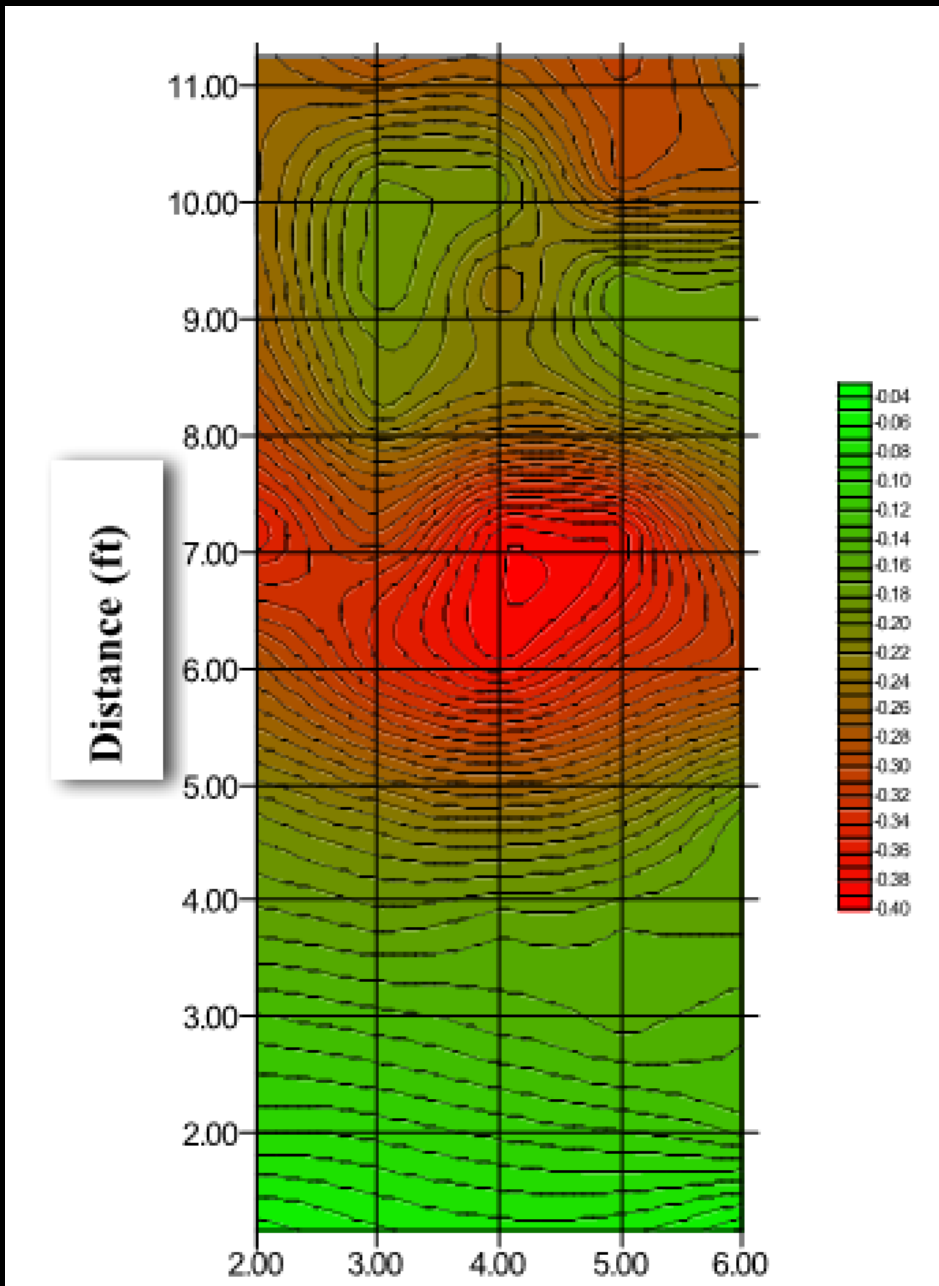


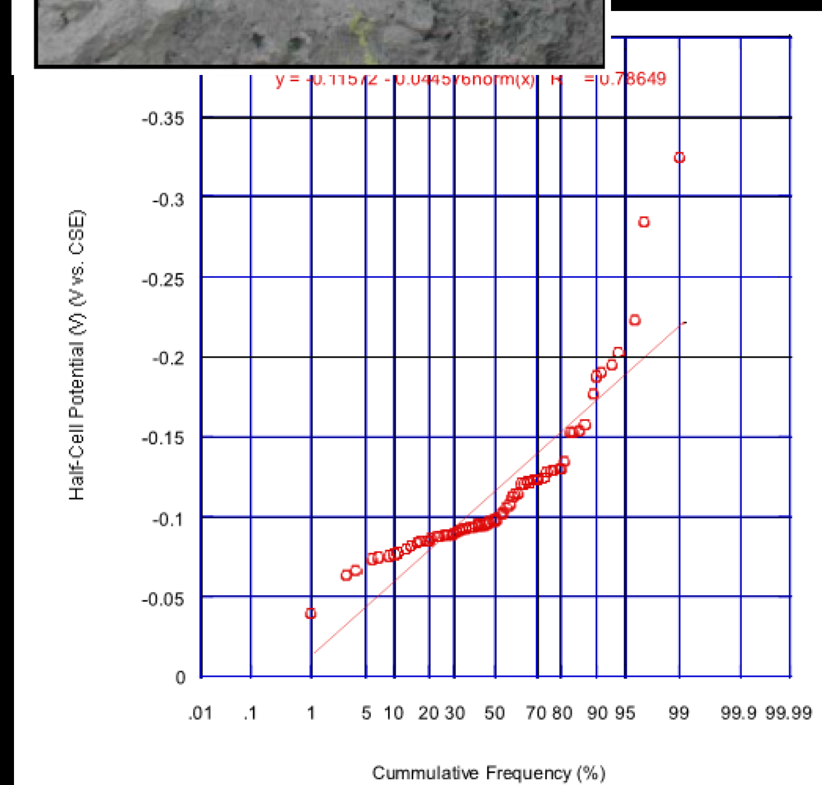
Stage 4
Formation of delaminations and concrete spalling.

Repair & Coat

Corrosion Mechanism




Distance (ft)
11.00
10.00
9.00
8.00
7.00
6.00
5.00
4.00
3.00
2.00
2.00
3.00
4.00
5.00
6.00
-0.04
-0.06
-0.08
-0.10
-0.12
-0.14
-0.16
-0.18
-0.20
-0.22
-0.24
-0.26
-0.28
-0.30
-0.32
-0.34
-0.36
-0.38
-0.40


Half-Cell Potential (V) (V vs. CSE)
-0.35
-0.3
-0.25
-0.2
-0.15
-0.1
-0.05
0
.01
.1
1
5
10
20
30
50
70
80
90
95
99
99.9
99.99
Cummulative Frequency (%)

CONCLUSION

CRACKS DO NOT HAVE A STRUCTURAL SIGNIFICANCE

Repairs

- Clean and prepare concrete surface: Water-assisted blasting.
- Water repellant: Silane 100% solids
- Seal cracks and joints: Flexible sealant
- Flexible surface coating: Elastomeric
- Periodic surveys: Annual

Repairs

- Water Repellant
  - Resistance to water
  - Allow vapor transmission
  - Penetrate to a measurable depth
  - UV resistant
  - Silane – 100% solids
  - Long-term stability in alkaline environment
  - Will not bridge cracks over 0.012 inch

Repairs

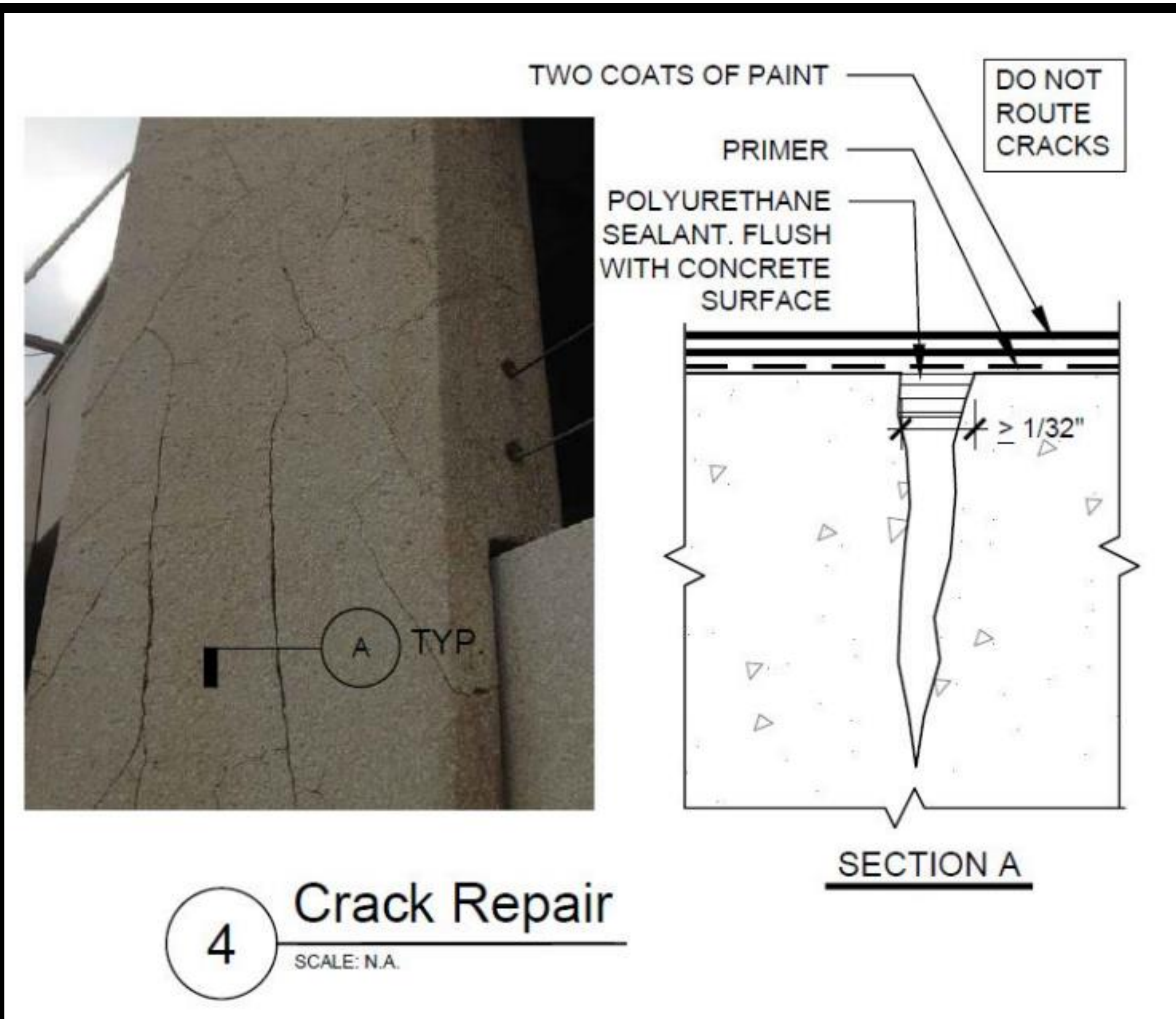
- Seal cracks and Joints
  - Seal surface of cracks over 0.02 inch
  - Seal open joints
  - UV resistant
  - Elongation – 700% per ASTM D412
  - Compatible with water repellant and coating

Repairs

- Flexible Surface Coating
  - Seal surface of cracks up to 0.02 inch
  - Breathable
  - UV resistant
  - Compatible with flexible sealant and water repellant
  - Aesthetic implications

Repairs

- Mock-ups
  - Large scale
    - Performance
    - Aesthetics
- Reapplication
  - Water repellant: 7-10 years
  - Surface coatings: little data
  - Flexible sealants: 5 to 20 years

REPAIR COST – COLUMN REPLACEMENT = $6,000,000

REPAIR COST – WALKER APPROACH= $250,000

QUESTIONS?

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