ICRI 2014 Fall Convention,
Kansas City, MO

University of Missouri Health Care Parking Garage Structural Repairs, Columbia, MO

Richard McGuire, P.E.,
Structural Engineering Associates Inc.
Liao Haixue, P.E.,
Vector Corrosion Technologies Ltd.

Introduction

- The parking garage is a cast-in-place, post-tensioned beam and slab concrete structure that was completed in 1986. There are three (3) elevated decks and one slab-on-grade level, providing a total of some 450 hospital parking spaces.
- Recent tendon eruptions triggered three phases of corrosion investigation: an initial or pilot investigation, then a more extensive sampling at each garage level, followed by a complete investigation of all slab tendons for breaks and moisture content
- As a result of the condition surveys testing and findings, repair strategies were developed for all the slab tendons and other distressed structural elements throughout the garage.

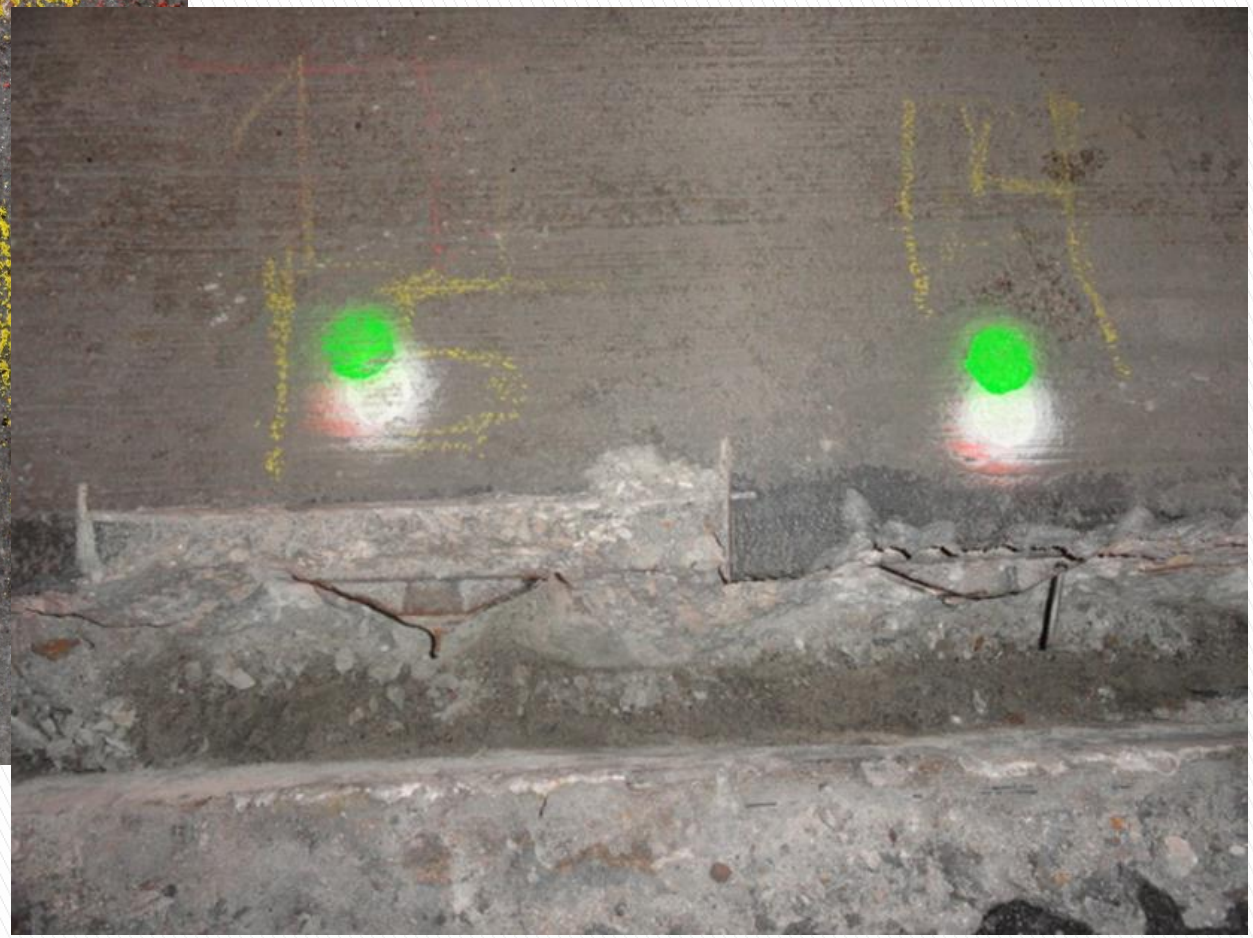
Strand eruption triggered initial investigation

Summary of Forensics Testing – I

- Investigate Level 1 North p/t slab tendons where ruptured tendon at underside soffit occurred
  - Invasive exploratory to expose and assess live stressing anchorages at expansion joint, also to examine and perform screwdriver penetration tests (SPT) at the tendons' mid-span low drape position
  - Out of 39 flexural slab tendons, 17 (43%) found to be broken
  - Most of the live anchors exhibited moderate to severe corrosion due to adjacent leaking expansion joint and partly encapsulated anchors
  - Due to L1-N bay findings, structural repairs documents prepared to replace all live anchors and repair all broken tendons in this bay
  - Additional testing was recommended to obtain a good sample of anchor conditions at all five expansion joint locations, and perform additional testing of slab tendons and corrosion backgrounds

Visual Inspection of Live Anchors at P/T Slab Expansion Joints

Invasive Exploratory at Live Anchors



Summary of Forensics Testing – II

- Investigated sample of 40 live anchor locations at 4 remaining slab expansion joints in garage, expanded structural analysis and testing protocol of p/t slab tendons
  - Performed structural analysis of Level 1 p/t slab using IBC 2012 criteria (LL = 40 psf)
  - Invasive exploratory to expose and assess (partly encapsulated) live stressing anchorages at all expansion joints and stairway slab edges
  - Performed visual condition and elevated slabs chain-dragging surveys of garage
  - Approx. 80% of exposed live anchors exhibited moderate to severe corrosion damage
  - Chlorides levels in the elevated slabs, most > 400 ppm at 1” depth
  - Half-cell potential tests at all exposed anchorages, results indicated approx. 30% had active corrosion values < 350 mV
  - 64 tendons exposed for screwdriver penetration tests, visual examination of strands for corrosion damage, moisture levels and grease. Almost all tendons had excessive moisture

Concrete excavation and visual inspections

Summary of Forensics Testing – III

- Expanded testing to include SPT's to all remaining p/t slab tendons in the garage, total of 24 tendons were found to be broken and were later repaired
- Increased moisture (humidity) testing sample to 105 tendons, over 98% were "Wet"
- Prepared summary of recommendations and cost estimates, including open and closed garage options, temporary shoring approaches, and life cycle cost analysis for 20 years
- MU Hospitals and Clinics management decided to repair the garage, then dry out all of the p/t slab tendons and regrease under a separate construction contract.

P/T Live Anchorage Half-cell Corrosion Potential Evaluation

ASTM C876-09 Half-Cell Corrosion Potential

Reading ($Cu/CuSO_4$ Half-cell)	Corrosion Condition
>-200 mV	Low (<5% probability of corrosion)
-200 to -350 mV	Uncertain (50% probability of corrosion)
<-350 mV	High (>95% probability of corrosion)

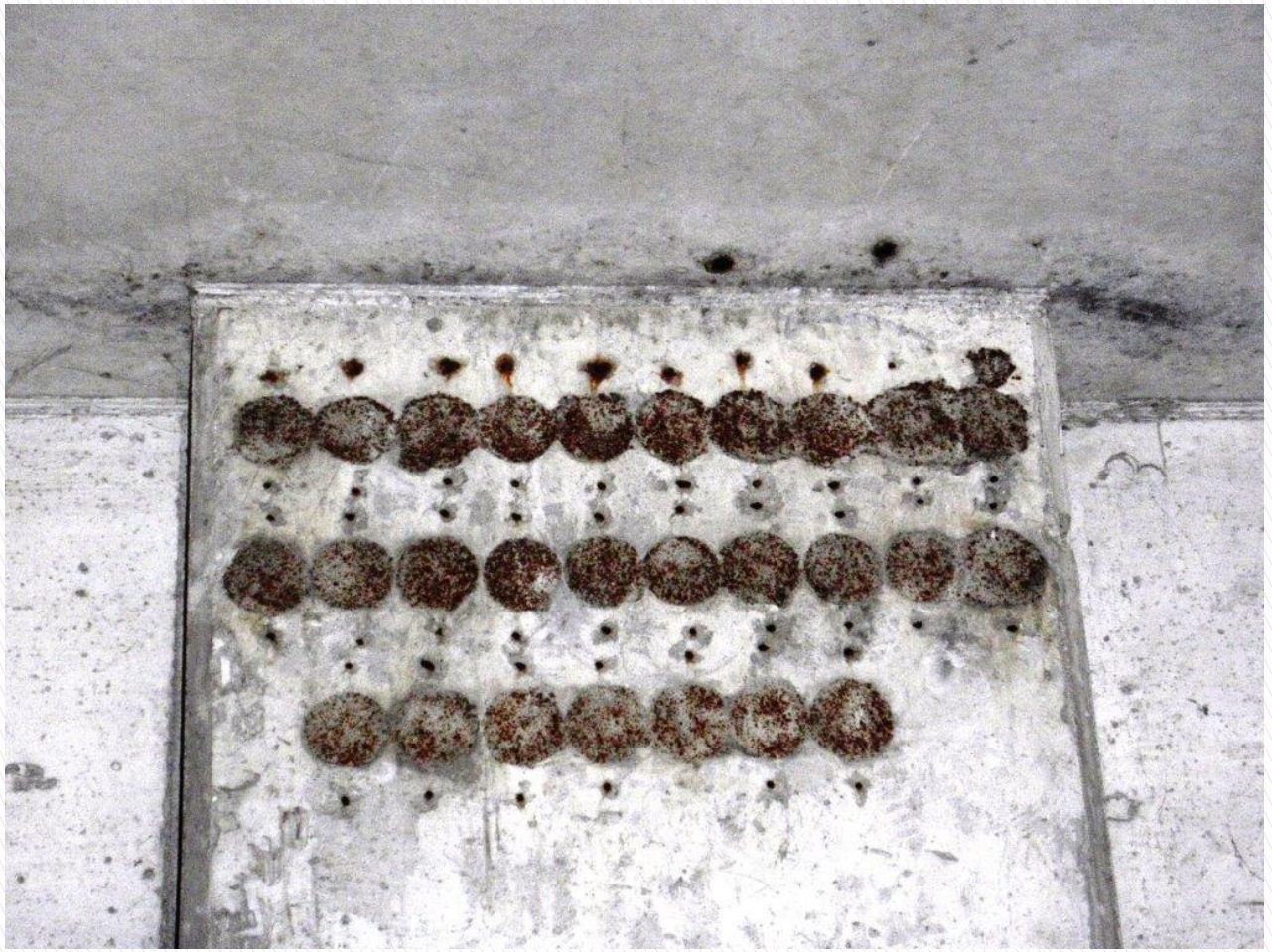
Source: National Association of Corrosion Engineers (NACE)

Chlorides contamination testing of p/t slabs

Screwdriver Penetration Tests of Tendons

Exposed P/T Tendon for Screwdriver Penetration Testing, Corrosion and Grease Condition Grading

Visual Inspections of Anchor Grout Pockets at P/T Beams and Slab Edges



Unbonded Post-Tensioned Cable Corrosion

- The Problem – Corrosion Damage, Wet Tendons, Leaking Joints
- The Cause – Moisture and Oxygen (and Contamination?)
- The Evaluation – Moisture / Humidity Levels (Wet, Moist, or Dry)
- Possible Solution Option is Cable Drying of Original Tendons
- Additional Protection –
  - Installation of Galvanic Anodes at Exp. Joint and Beam Anchorages
  - Traffic Membranes on both Vehicular and Pedestrian Surfaces
  - Grease Injection (Regreasing) following Dehumidification of Slab Tendons

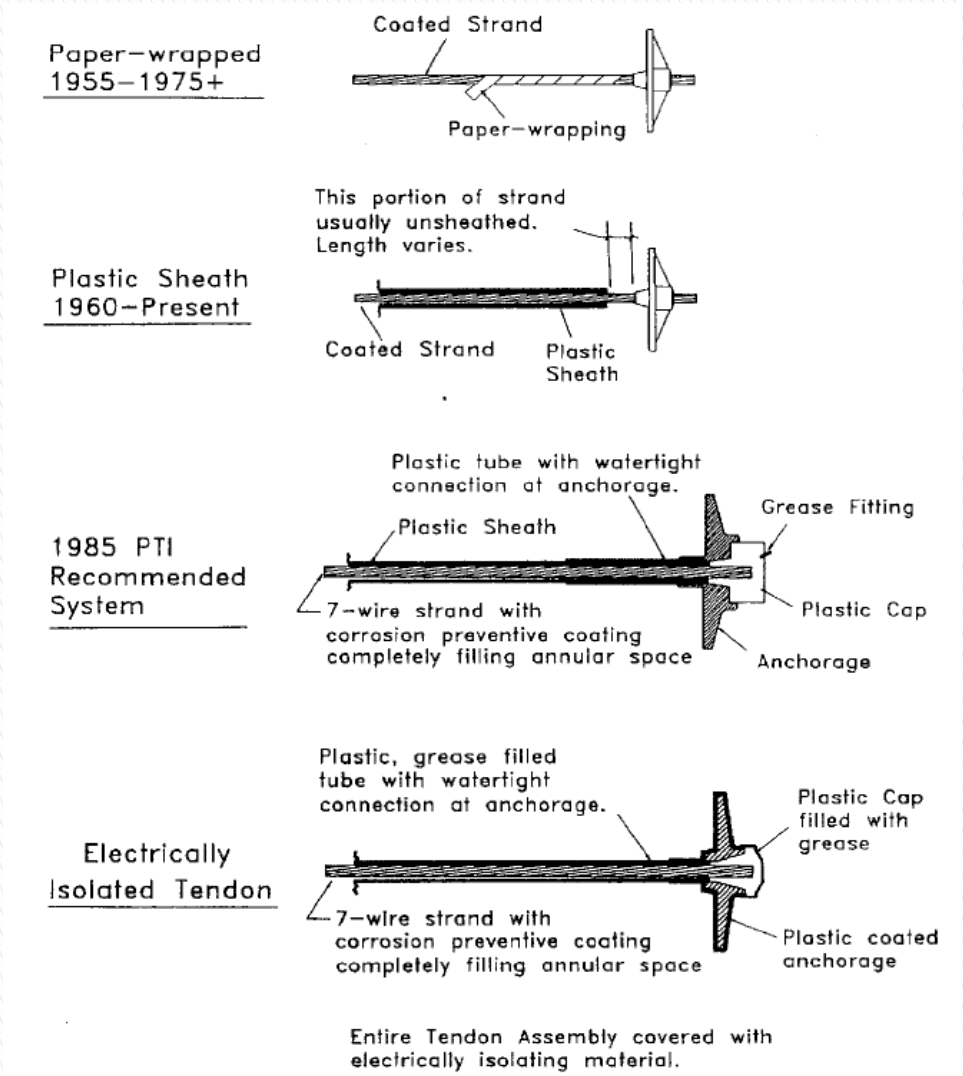
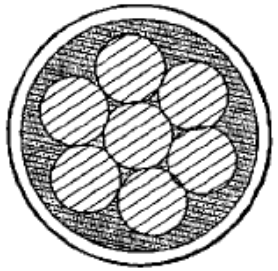
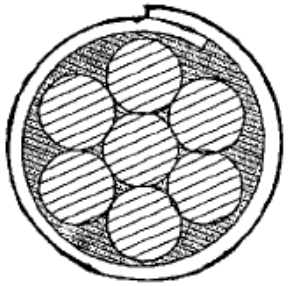


Fig. 3.2—Evolution of corrosion protection for unbonded single strand tendons for buildings (reprinted from Reference 2).



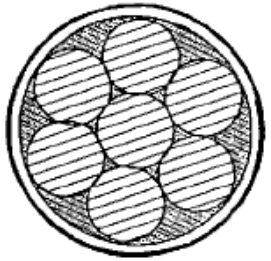
PUSH-THROUGH PREFORMED TUBE

STRAND PUSHED THROUGH AS GREASE IS APPLIED.



HEAT-SEALED

FORMED FROM FLAT STRIP AS GREASE IS APPLIED.



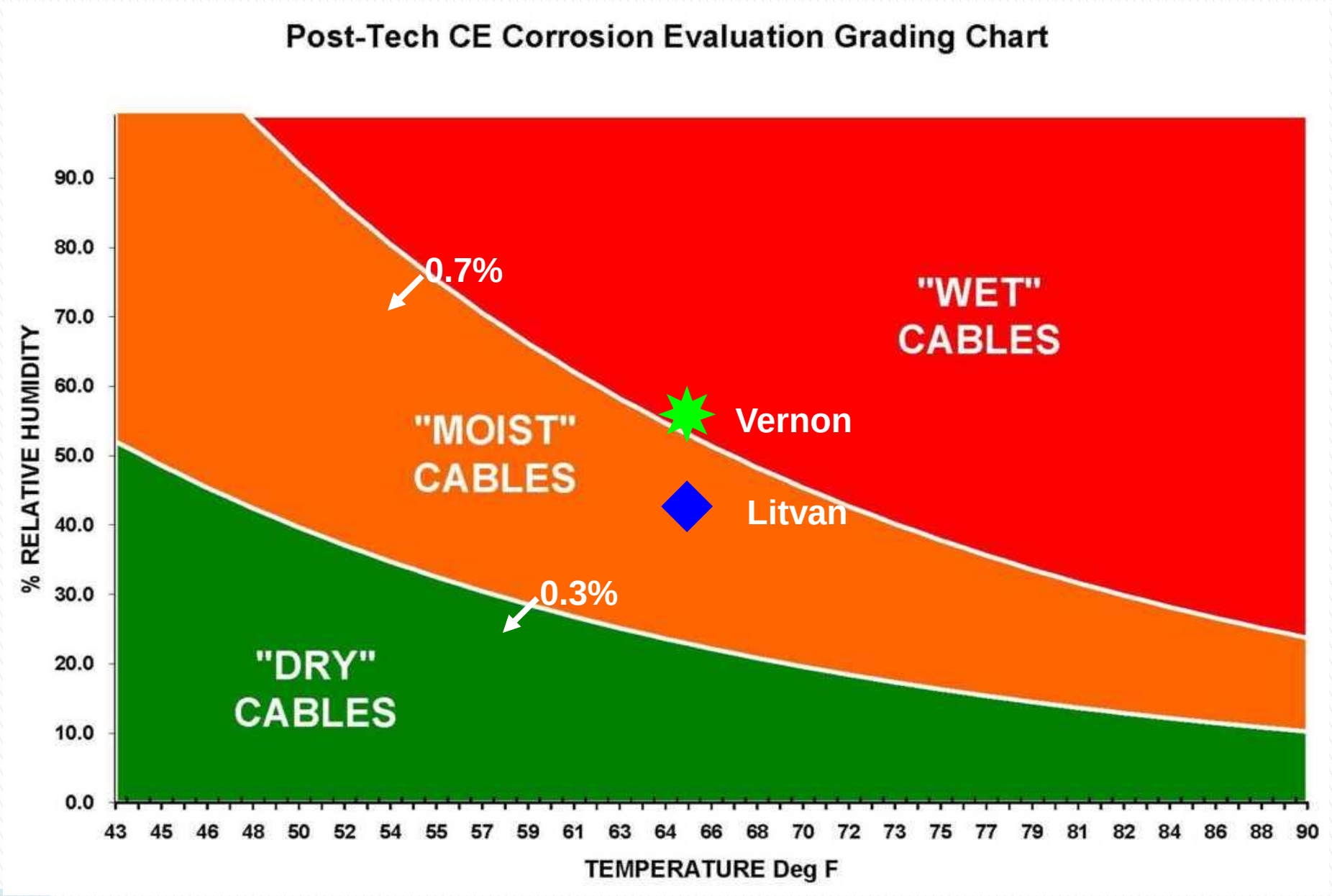
EXTRUDED

FORMED BY EXTRUDING OVER STRAND AS GREASE IS APPLIED.

ACI 423-4r98

Moisture & Corrosion Relationship

- W Vernon was the first to realize the importance of moisture to the rate at which metals corrode in the early 1900's
- Vernon first discovered that a critical relative humidity, (CRH), exists below which the rate of corrosion is negligible at 60% to 70%
- Dr. G.G. Litvan, then Principal Research Officer with the National Research Council (NRC) in Ottawa, that under normal conditions corrosion of steel is negligible below 45% RH


Post-Tech CE Corrosion Evaluation Grading Chart
% RELATIVE HUMIDITY
90.0
80.0
70.0
60.0
50.0
40.0
30.0
20.0
10.0
0.0
43 45 46 48 50 52 54 55 57 59 61 63 64 66 68 70 72 73 75 77 79 81 82 84 86 88 90
TEMPERATURE Deg F
"WET" CABLES
"MOIST" CABLES
"DRY" CABLES
0.7%
0.3%
Vernon
Litvan

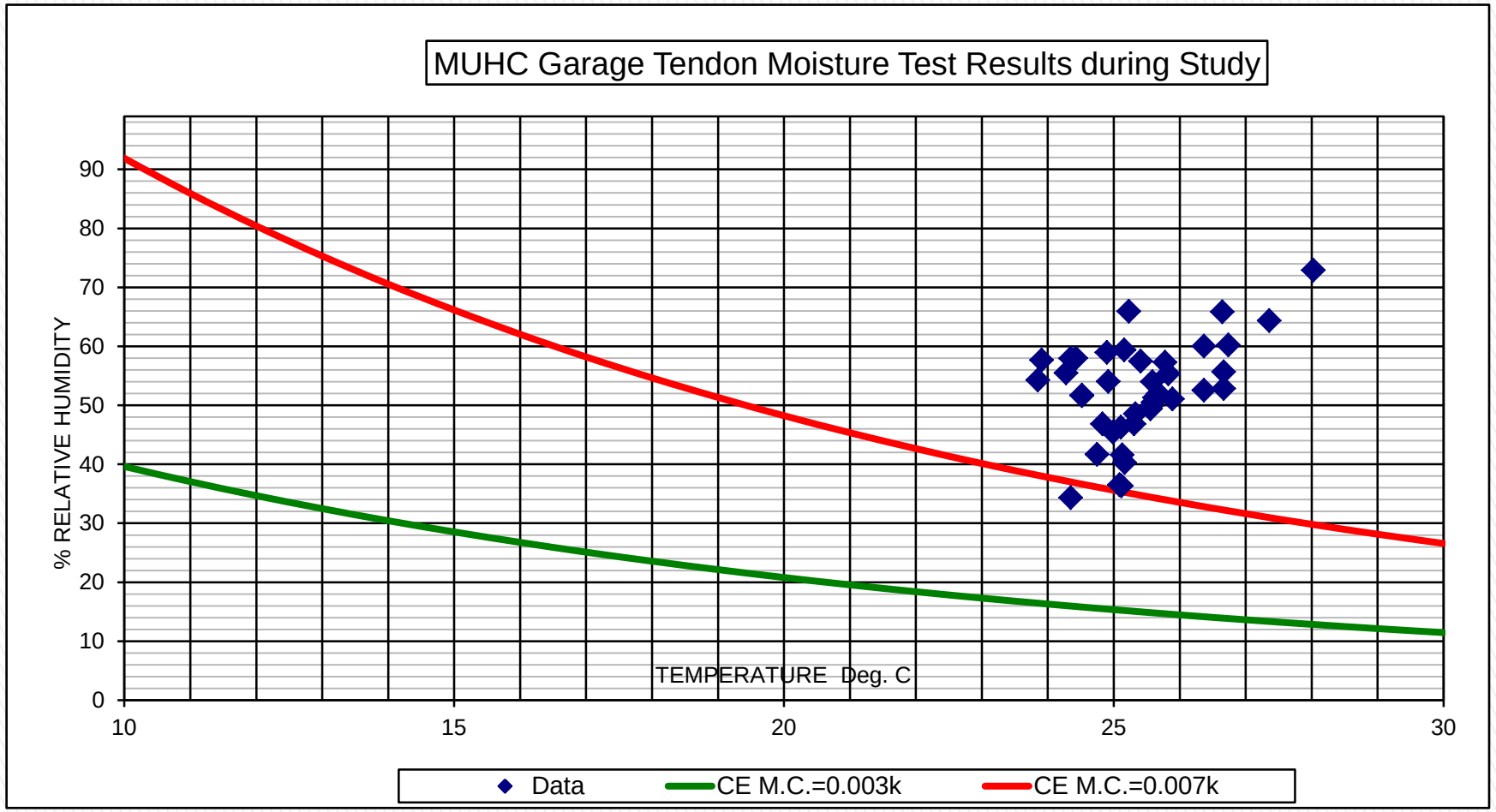
Corrosion Evaluation and Testing of P/T Slab Tendons

Corrosion Evaluation Testing Classification:

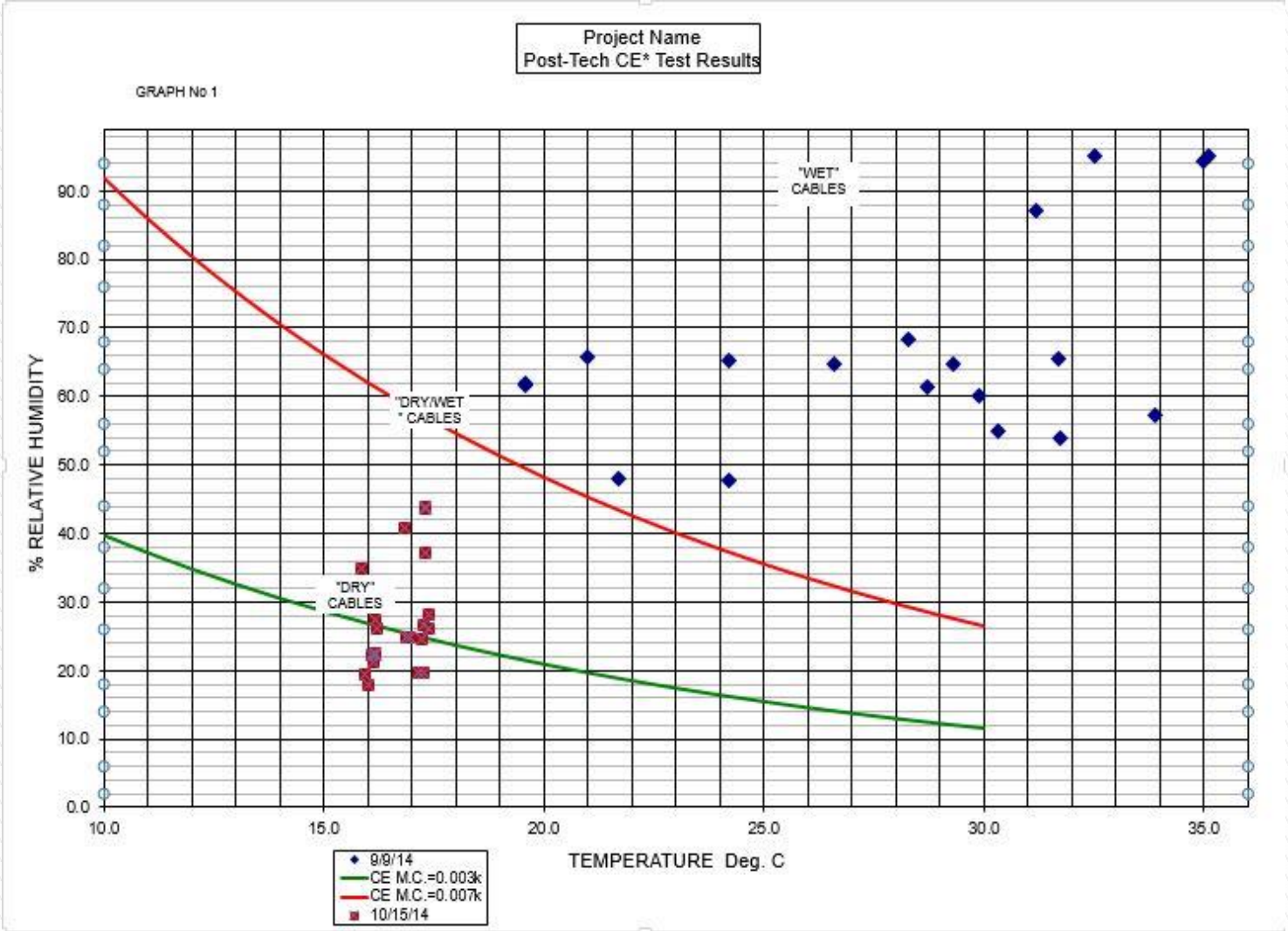
	Classification Code	Potential for Corrosion	Moisture Content
	1	Low (Dry)	< 0.3%
Dry	2	Moderate (Moist)	0.3% to 0.7%
Wet	3	High (Wet)	> 0.7%

PT Corrosion Potential Evaluation

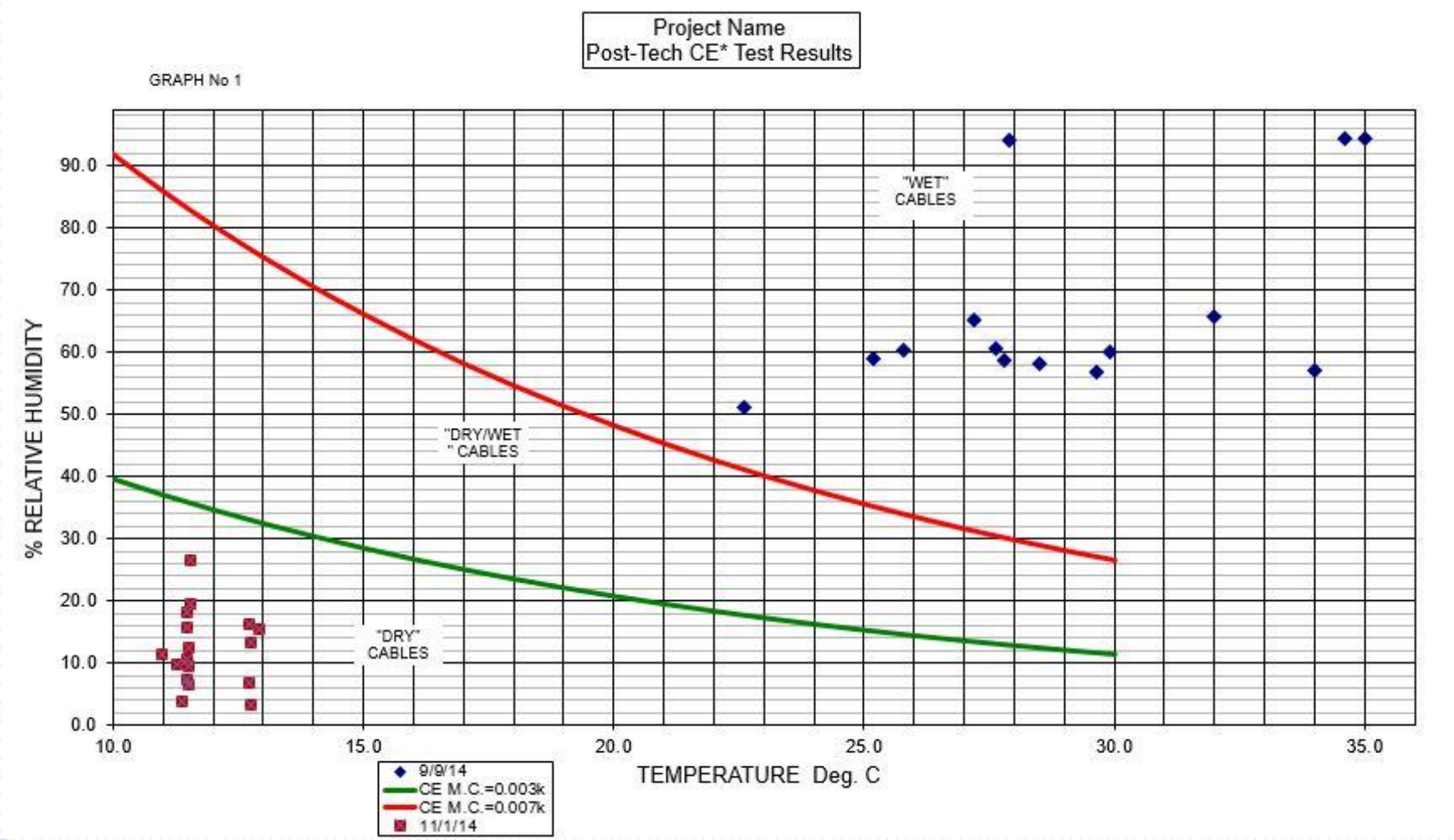
MUHC Garage - PT Corrosion Potential Evaluation



MUHC Garage PT Corrosion Potential Evaluation



MUHC Garage PT Corrosion Potential Evaluation



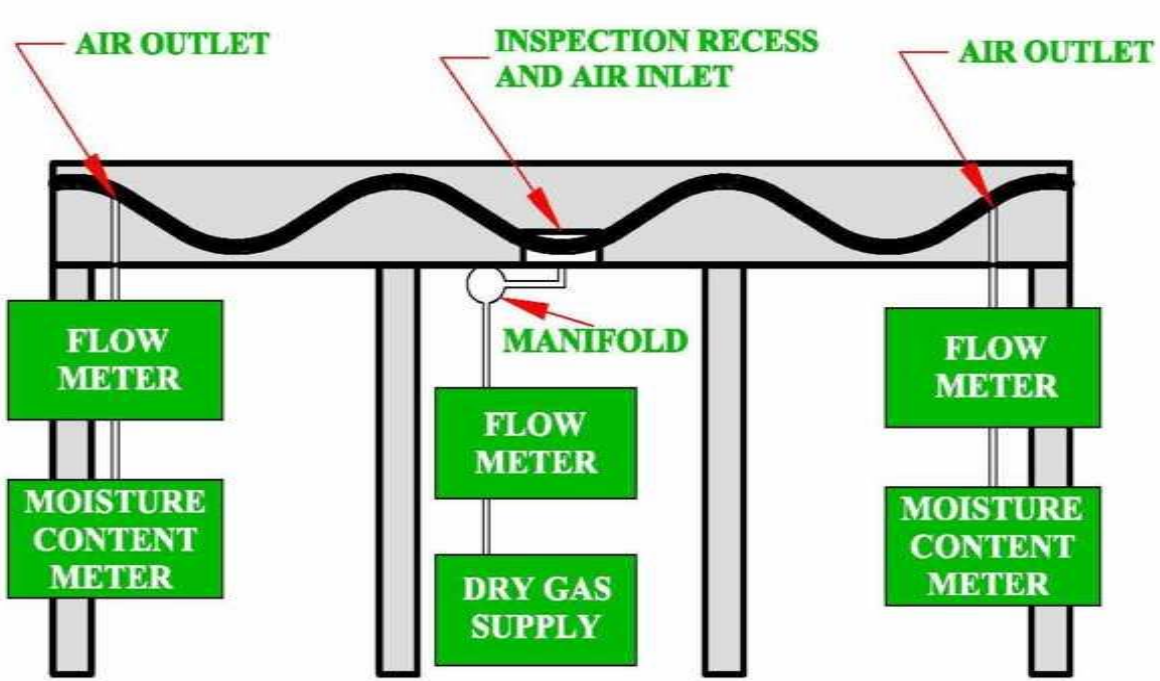
Investigation results

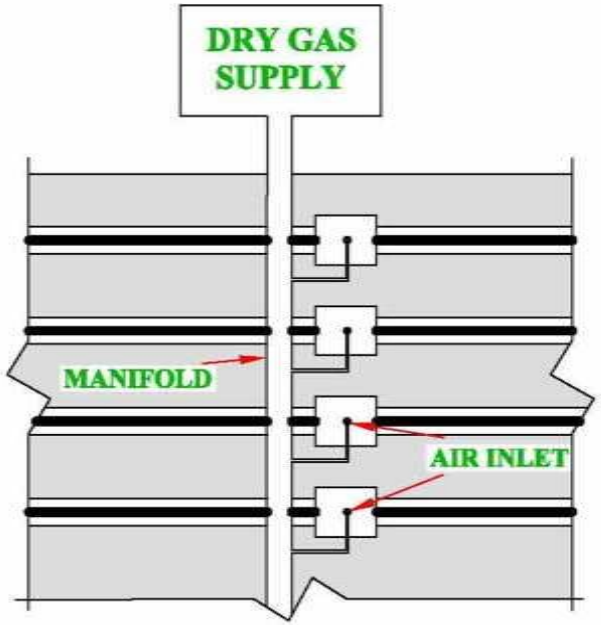
- The tendons were made from stuffed cables, in which voids between the sheath and the strands are present.
- 25 out of 497 strands that were exposed are broken, and in addition two sheaths with no strands at the location of drilling were detected in Phase II. 5 out of 6 breaks are in Level 1.
- 65%exposed strands are in good to fair conditions.
- 62% exposed cables have either no grease or deteriorated grease.
- 100% of the Level 1 tested cables have excessive moisture in the tendon sheath, 39 out of 40 Level 2 and 3 tested cables have excessive moisture, while cables in Levels 2 and 3 are drier than those in Level 1.
- 30% of the 41 half cell potential readings are in the active corrosion category while only 25% of the tendons have no active corrosion

P/T Repair Strategies for MUHC Garage

- Replace all the p/t slab expansion joints in garage
- Replace all the live stressing anchorages at the expansion joints and approx. 20’ adjacent sections of strands near expansion joints
- Install galvanic anodes at expansion joints, beams and slab edges (stairway) anchorages for corrosion protection.
- Repair approx. 24 broken tendons and replace 3000’ of monostrand
- Repair all unsound structural concrete surfaces in garage
- Apply heavy duty vehicular traffic membrane to all levels and stairway
- Dry /Dehumidify and re-grease all the tendons to remove the moisture sources of the corrosion.

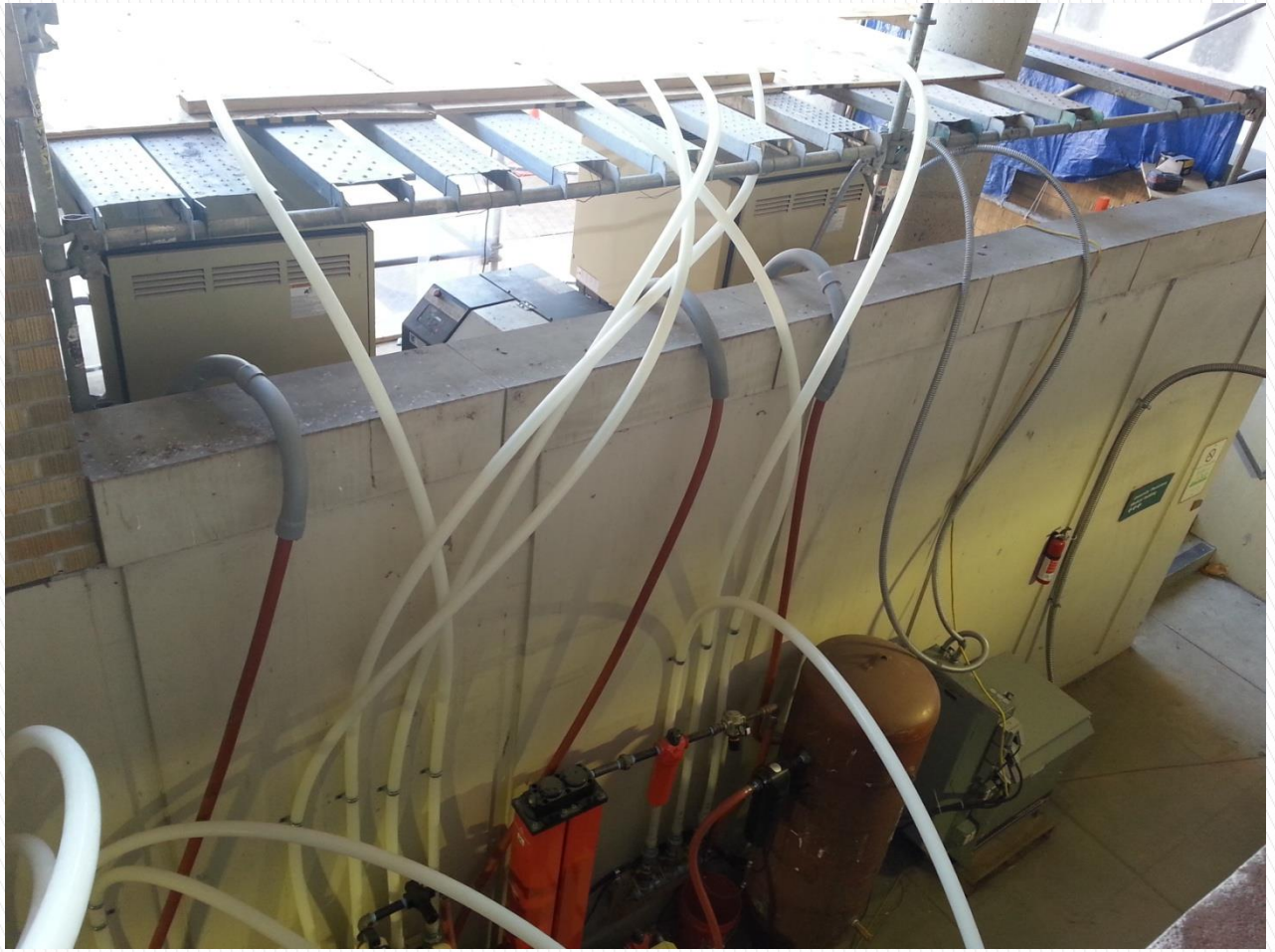
Cable Drying Process Diagram





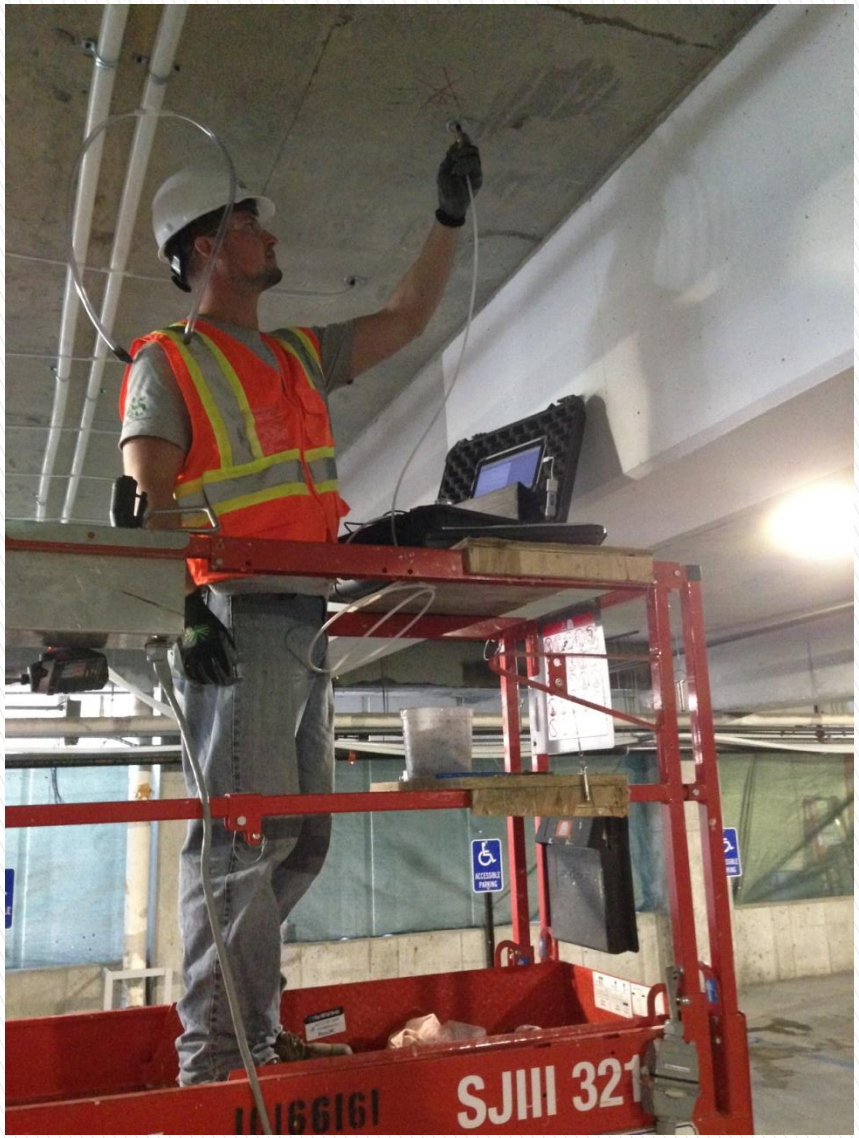
Tendon Drying Equipment Area

Drying Piping Distribution from Plant



P/T Drying Piping to Slab Tendons

Monitoring Drying Data and Performance



FILE: Post-Tech CE* TEST & GRADING

PRJCT: Project: MUHC PARKING GARAGE

SURVEYED BY: TYLER BROWN, CHARLES WHITE

AREA: LEVEL 2

DATE: 9/9/2014

CPE RDGS Initial __X__ Progress _____ Final _____

AMBIENT COND. % RH Deg. C

LINE READING

INPUT DATA

WET/DRY BOUNDARY MC = 0.007 Kg/Kg Dry Air

CABLE Set	CABLE No.	Cable Reading Deg C	%RH	Pws	MC "W"	CE	Max M.C	Wet or Dry	DRY/WET GRADE	Flow
2N1										
	0	NA								
	1	26.8	95.8	3.46	0.0210	3	0.0210	WET	30	
	2	NT								
	3	28.4	64.2	3.78	0.0153	3	0.0153	WET	30	
	4	28.4	66.2	3.78	0.0157	3	0.0157	WET	30	
	5	28.4	65.7	3.78	0.0156	3	0.0156	WET	30	
	6	NT								
	7	28.4	63.9	3.78	0.0152	3	0.0152	WET	30	
	8	28.4	62.1	3.78	0.0148	3	0.0148	WET	30	
	9	28.4	60.7	3.78	0.0144	3	0.0144	WET	30	
	10	NT								
	11	28.5	61.9	3.78	0.0147	3	0.0147	WET	30	
	12	28.8	96.0	3.89	0.0238	3	0.0238	WET	30	
	13	27.8	65.8	3.67	0.0152	3	0.0152	WET	30	
	14	28.4	61.0	3.78	0.0145	3	0.0145	WET	30	
	15	NT								
	16	28.6	62.6	3.89	0.0153	3	0.0153	WET	30	
	17	28.6	63.7	3.89	0.0156	3	0.0156	WET	30	
	18	28.7	61.5	3.89	0.0150	3	0.0150	WET	30	
	19	NT								
	20	28.7	64.1	3.89	0.0157	3	0.0157	WET	30	
	21	29.1	95.0	4.01	0.0243	3	0.0243	WET	30	
	22	20.5	68.1	2.34	0.0099	3	0.0099	WET	30	
	23	NT								

CPE GRADE DISTRIBUT'N

BIN	DIST	% TTL	% TESTED
0	0	0.0	N/A
1	0	0.0	0.0
2	0	0.0	0.0
3	275	100.0	100.0
TTL QUANT	275	100.0	
TTL TESTED	275		

DRY/Wet Cable Distribution

	No.		%
10	0	DRY CABLES	0.0
20	0	DRY/WET CABLES	0.0
30	245	WET CABLES	100.0
	245		

DRY/WET Grades

Dry = 10	Dry <	0.003
Dry/Wet = 20	Dry/Wet <	0.007
Wet = 30	Wet ≥	0.007

CPE Grades

0 = No Test
1 = Dry
2 = Moist
3 = Wet

NT=NO TEST
NA=NO ACCESS
NP=NO PORT
NF=NO FLOW

Water bubbling from tendon during Initial drying

Tendons Regreasing Operations Underway

Suggested Parking Structure References:

American Concrete Institute (ACI) 362.1R-12:

Guide for the Design and Construction of Durable Concrete Parking Structures

ACI 362.2R-13:

Guide for Structural Maintenance of Parking Structures

Precast Concrete Institute (PCI):

Maintenance Manual for Precast Parking Structures (2004)

National Parking Association (NPA):

Parking Garage Maintenance Manual

International Concrete Repair Institute (ICRI) 320.6-2012:

Guide for Evaluation and Repair of Unbonded Post-Tensioned Concrete Structures

ACI 546R-14:

Guide to Concrete Repair

ACI/ICRI:

Concrete Repair Manual – 4th Ed.

ICRI Technical Sessions

Thank you for your attendance
and participation!

Questions??