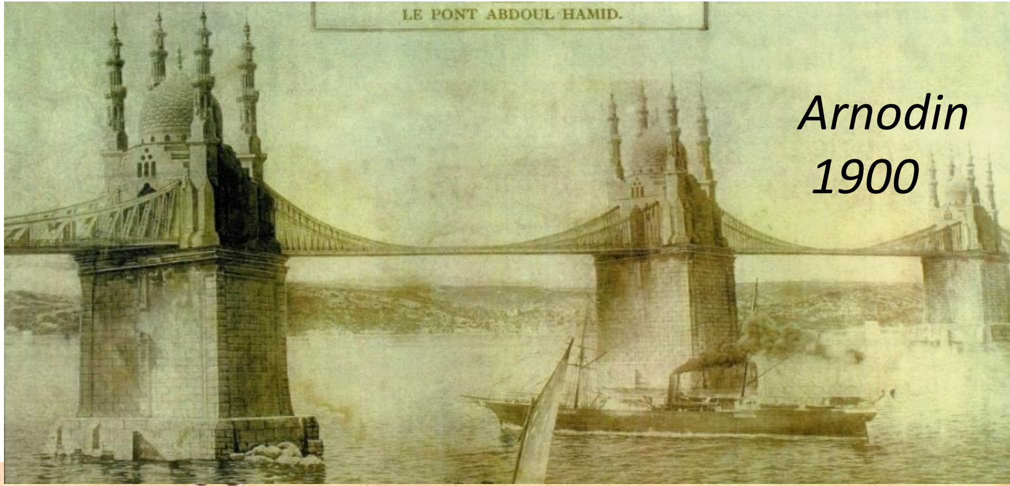
Crossing the Bosphorus: Bridges, Tunnels and a lot of concrete

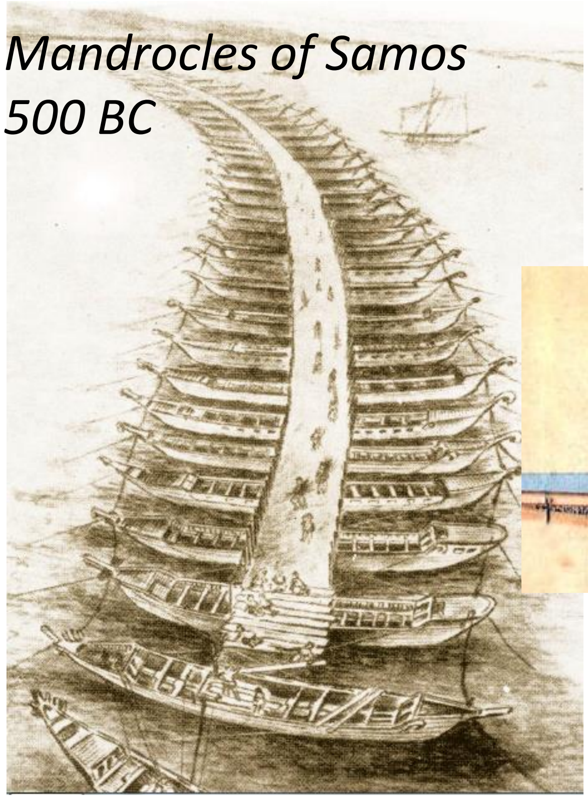
Building a Sustainable Infrastructure for a Modern Silkroad

YILMAZ AKKAYA
Istanbul Technical University

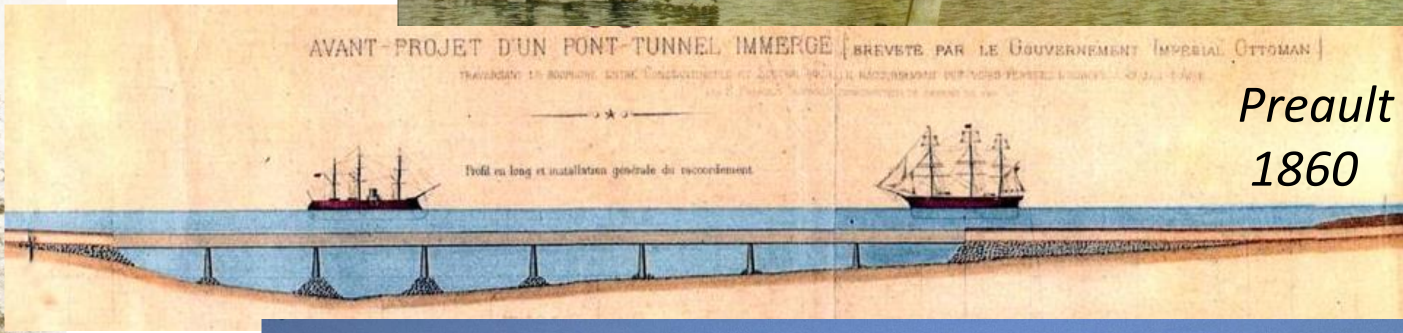
BOSPHORUS
CONNECTING CIVILIZATIONS



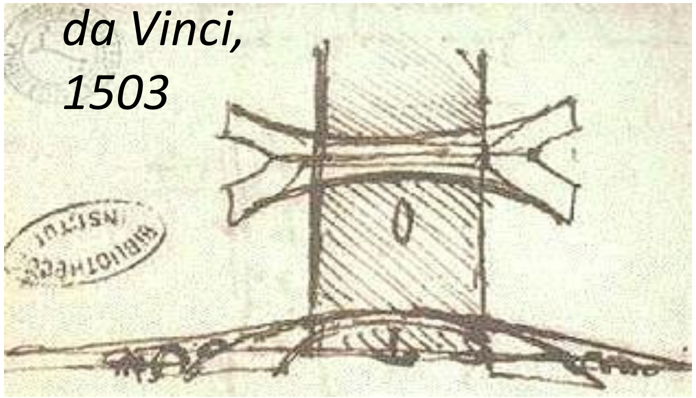
Arnodin 1900



Mandrocles of Samos 500 BC



Preault 1860



da Vinci, 1503

Tom Tom Traffic Index

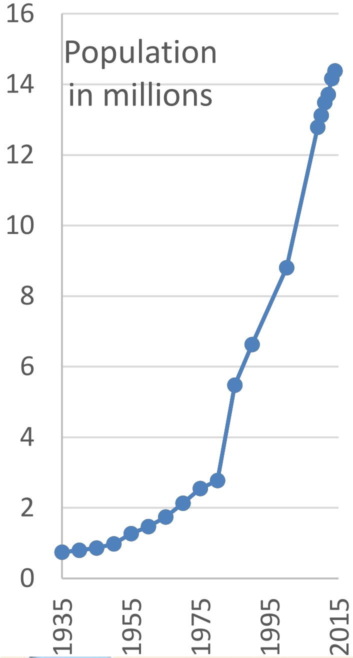
World rank	City	Congestion
1	Istanbul	58%
2	Mexico City	55%
3	Rio de Janeiro	51%
4	Moscow	50%
5	Salvador	46%
6	Recife	45%
7	Saint Petersburg	44%
8	Bucharest	41%
9	Warsaw	40%

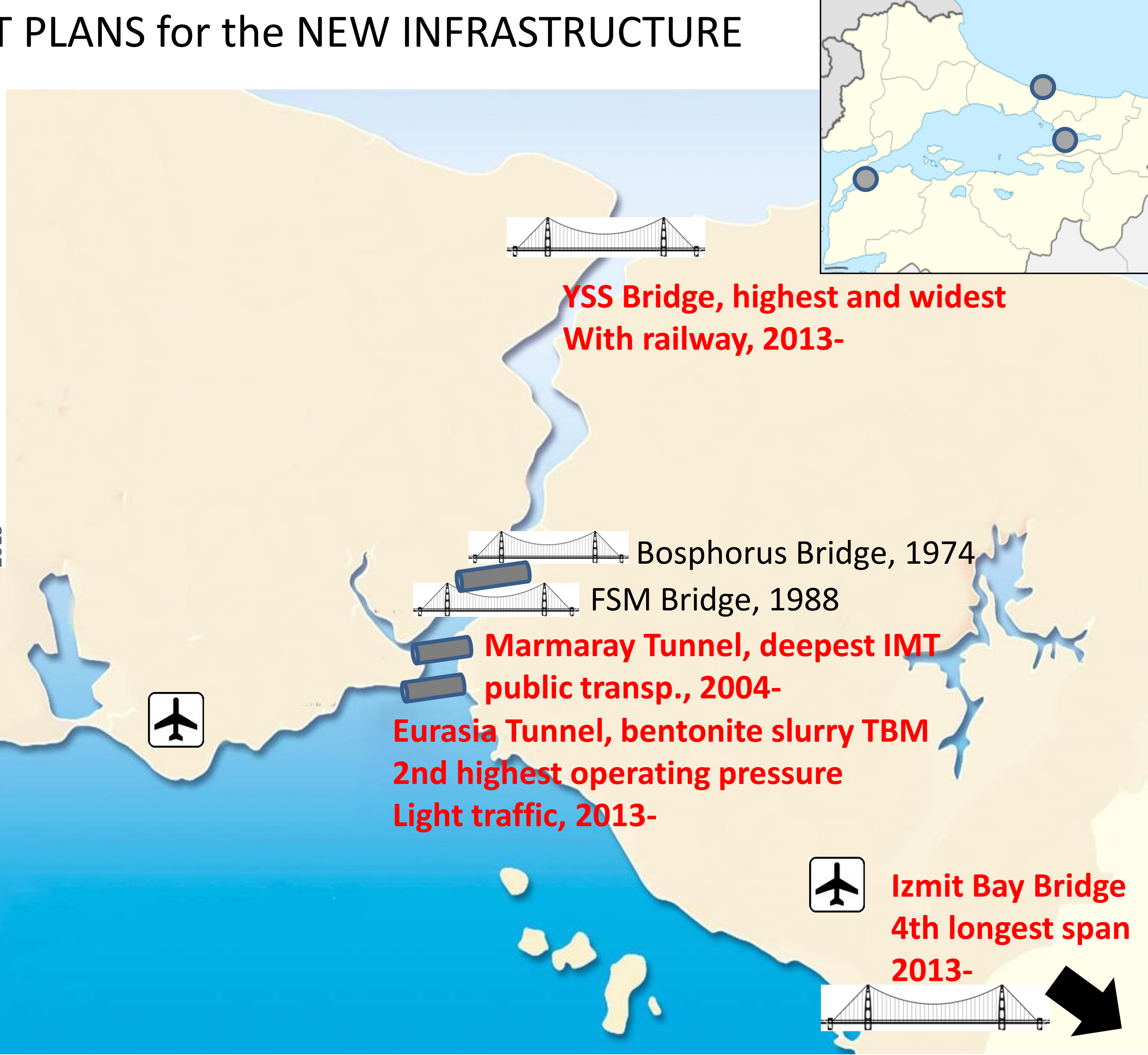
Castrol Magnatec Stop-start Index

1	Istanbul	31200
2	Mexico City	30480
3	Moscow	29520
4	Beijing	28200
5	Jakarta	28080
6	Rome	28080
7	Saint Petersburg	28080
8	Bangkok	26040
9	Shanghai	24960
10	Surabaya	24360

transit ships, dangerous goods

INVESTMENT PLANS for the NEW INFRASTRUCTURE

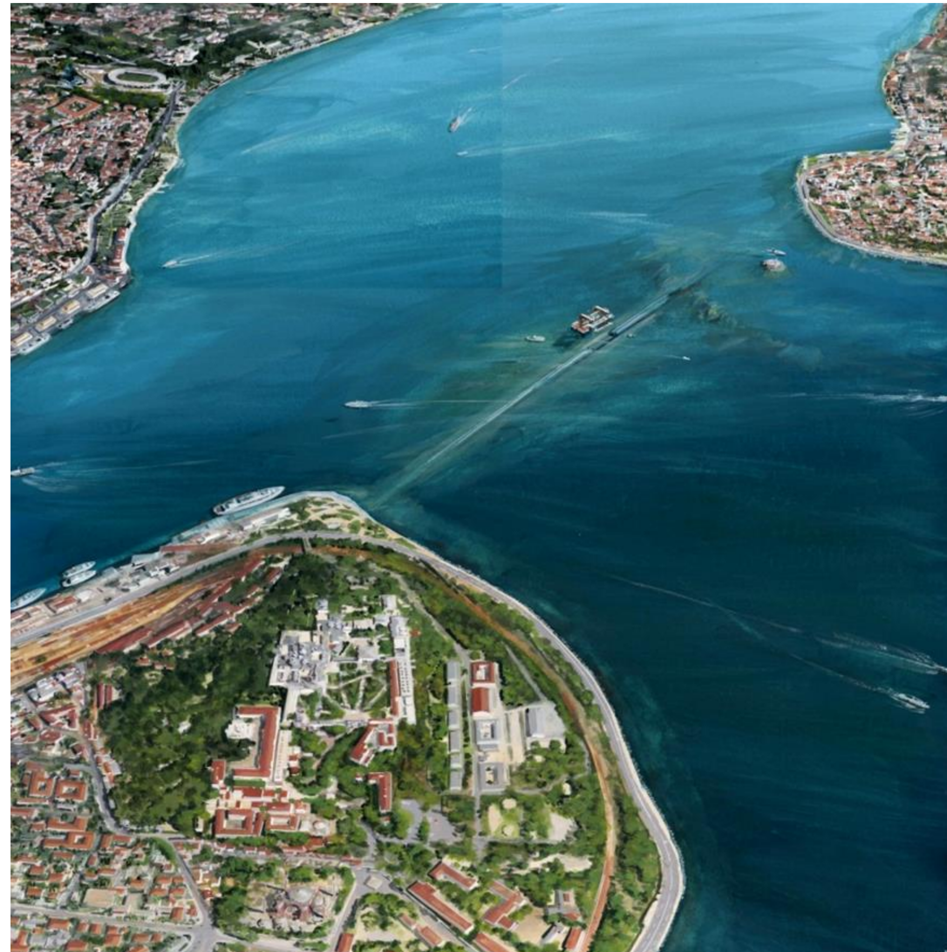


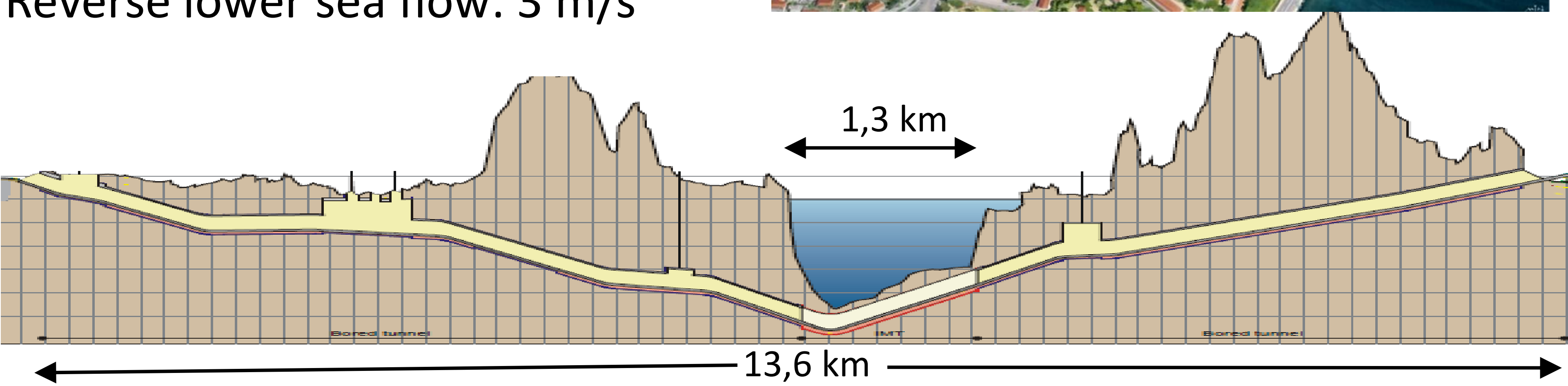


MARMARAY PROJECT

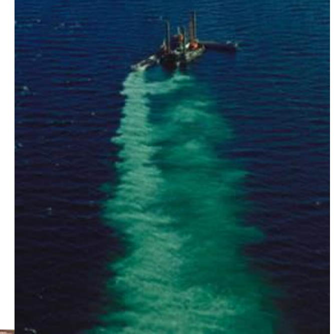
Deepest IMT depth: 58 m,
EPC, Design and Build Project
Started in 2004
$3.3 billion
1,3 million m^3 concrete
150.000 psngrs/hr

Total length: 76 km
Surface flow: 3 m/s
Reverse lower sea flow: 3 m/s



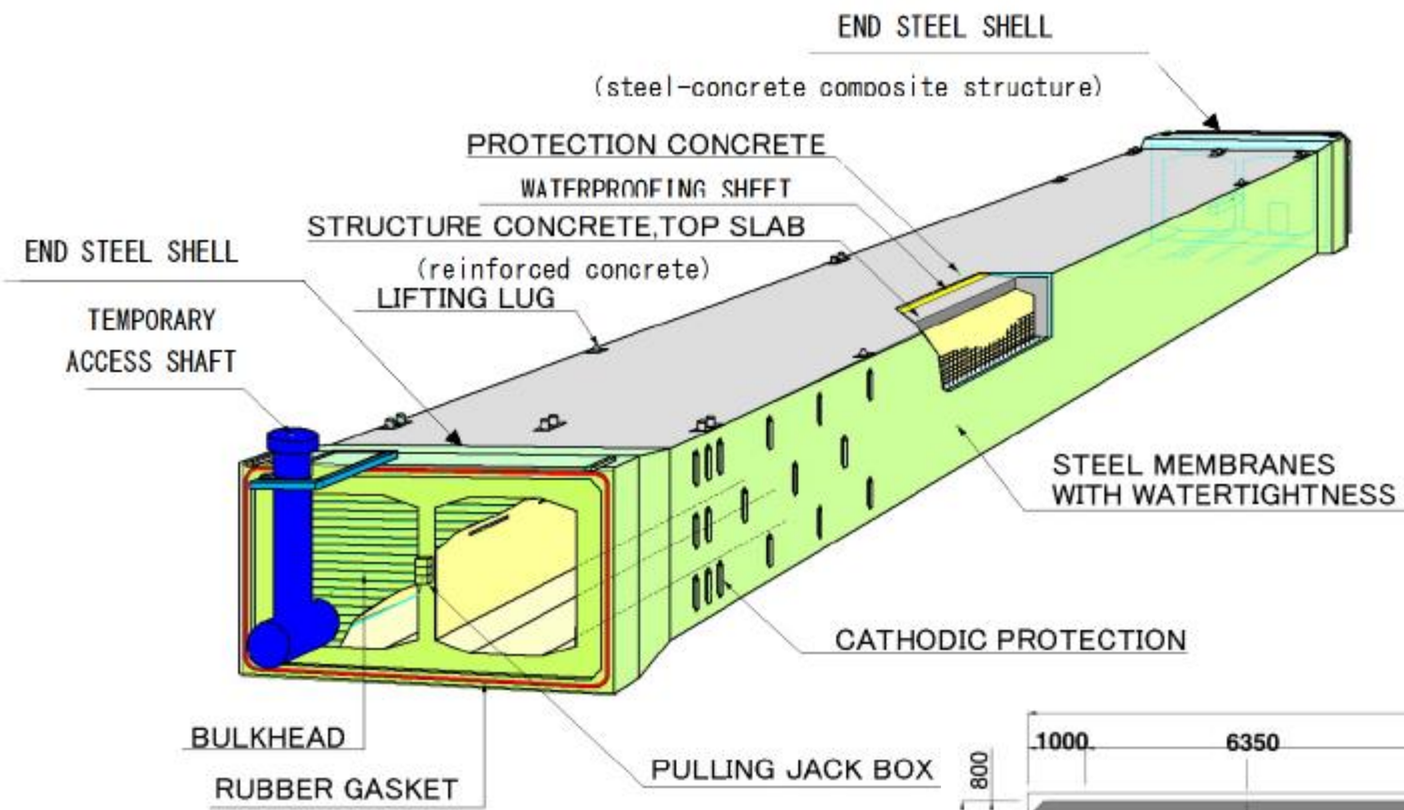


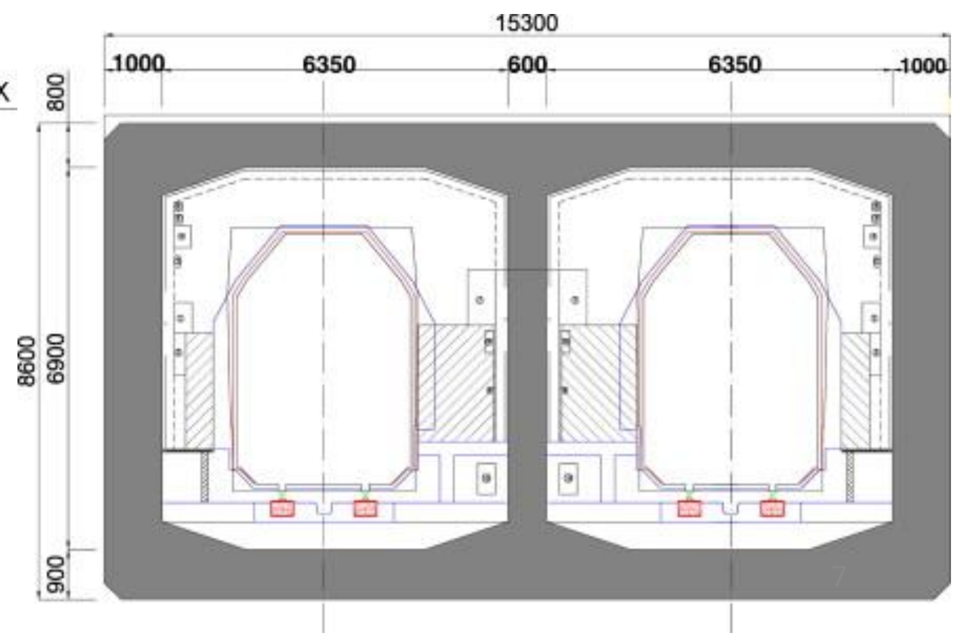
Challenges for sustainability: Nature, history and society



Immersed Tube Design

11 unique tubes
L= 98.5 - 135 m
different curvatures



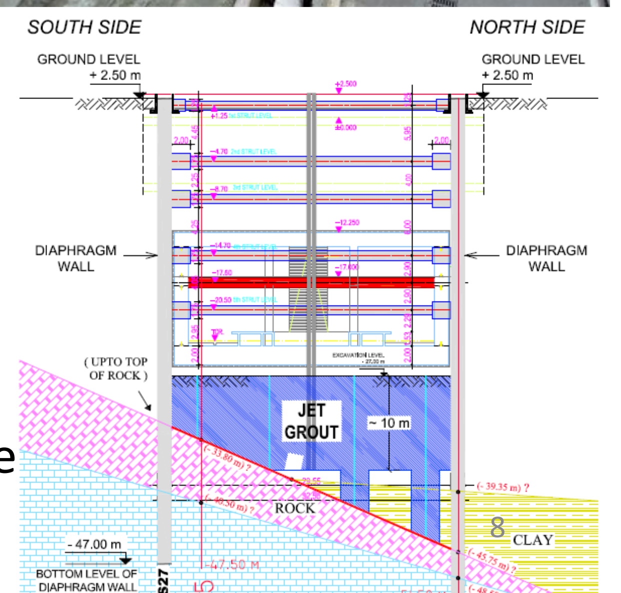


Designed for loads from train, hydrostatic effects, earthquake, impacts from sinking ships, ship anchorages, train derailment, differential settlements, currents, explosion, fire…

Uskudar Station

Construction in buoyancy

41 500 pssngrs/hr
L: 278m, W:32m, D: 30m



Watertight concrete: early-age crack and frost resistance

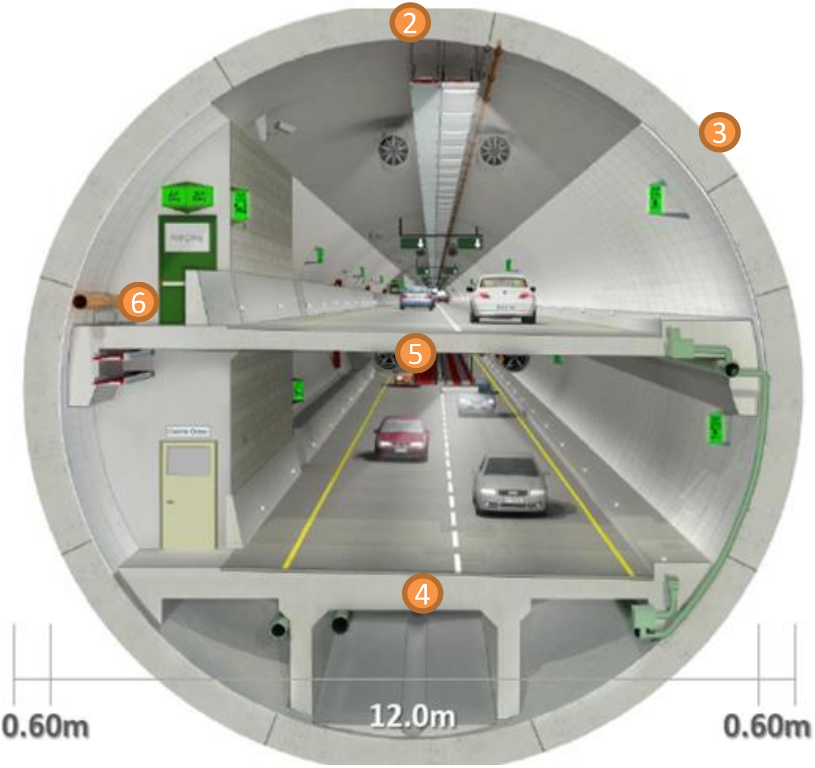
EURASIA TUNNEL Bentonite composite slurry TBM,

World’s 2. with 11 bars operating pressure & 6. with 13.7 m excavation D.

Started in 2013, BOT, 30.5 y Contract Period

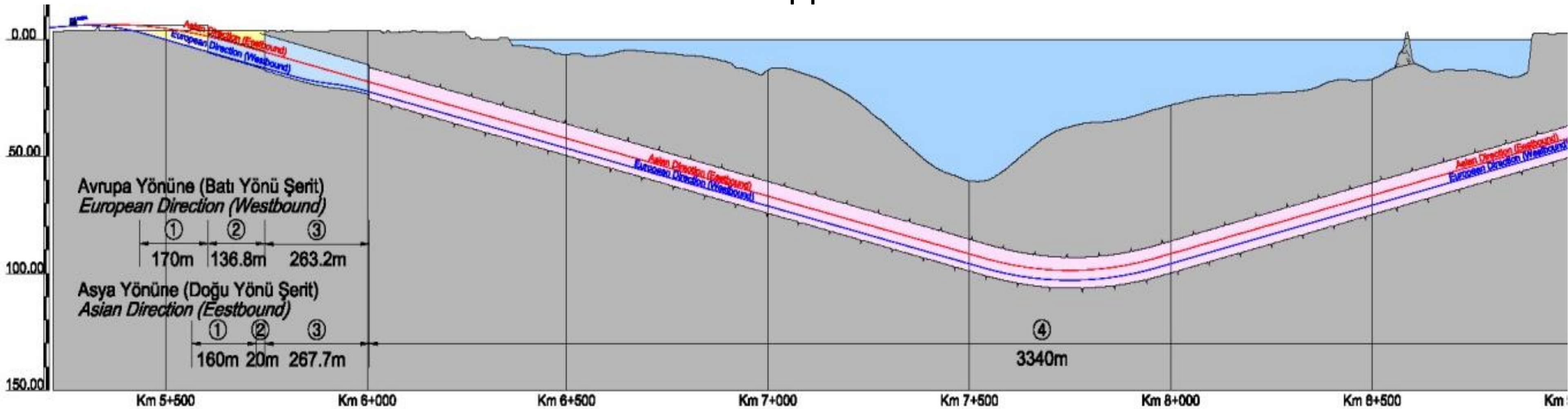
90.000 Annual av. daily traffic, $1.2 Billion

Tunnel Plan & Profile



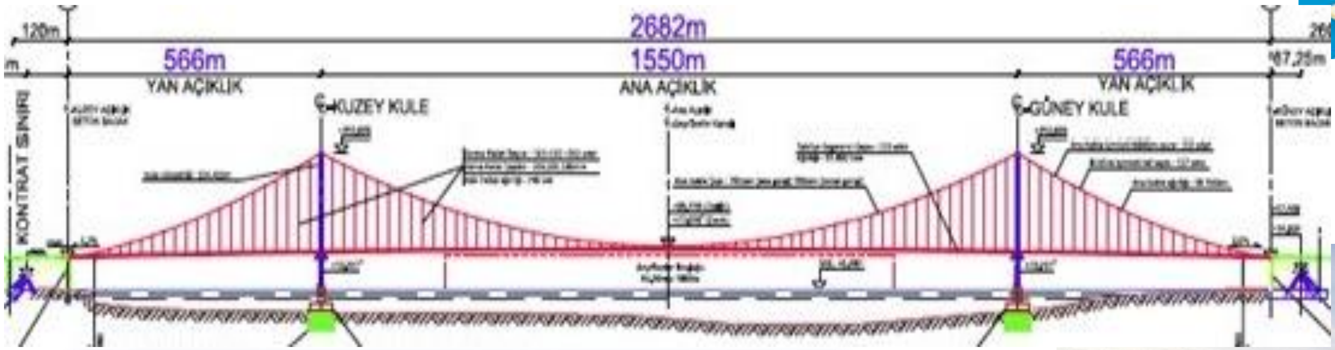
1. TBM Excavation
2. Segment Lining
3. Backfill Grouting
4. Bottom Deck Construction
5. Upper Deck Construction
6. Emergency Exit Structure

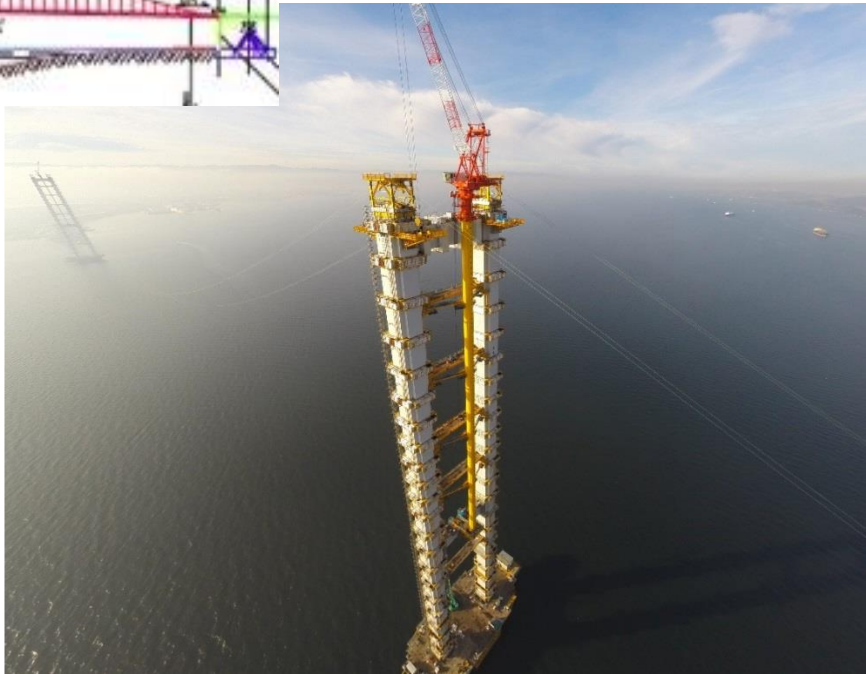
Tunnel Depth	106m
Lining	60cm precast concrete
Upper Deck	Cast insitu concrete



IZMIT BAY BRIDGE

World's 4. longest suspension bridge, started in 2013
$3,8 Billion, BOT, 22 years
Width: 35m, Steel towers h: 234m
175 000 m^3 concrete for anchorages and caissons (at 40 m depth)





Designing with Concrete

Some limits are **prescribed** to ensure the quality,
some degree of freedom in the mixture design for **performance**.

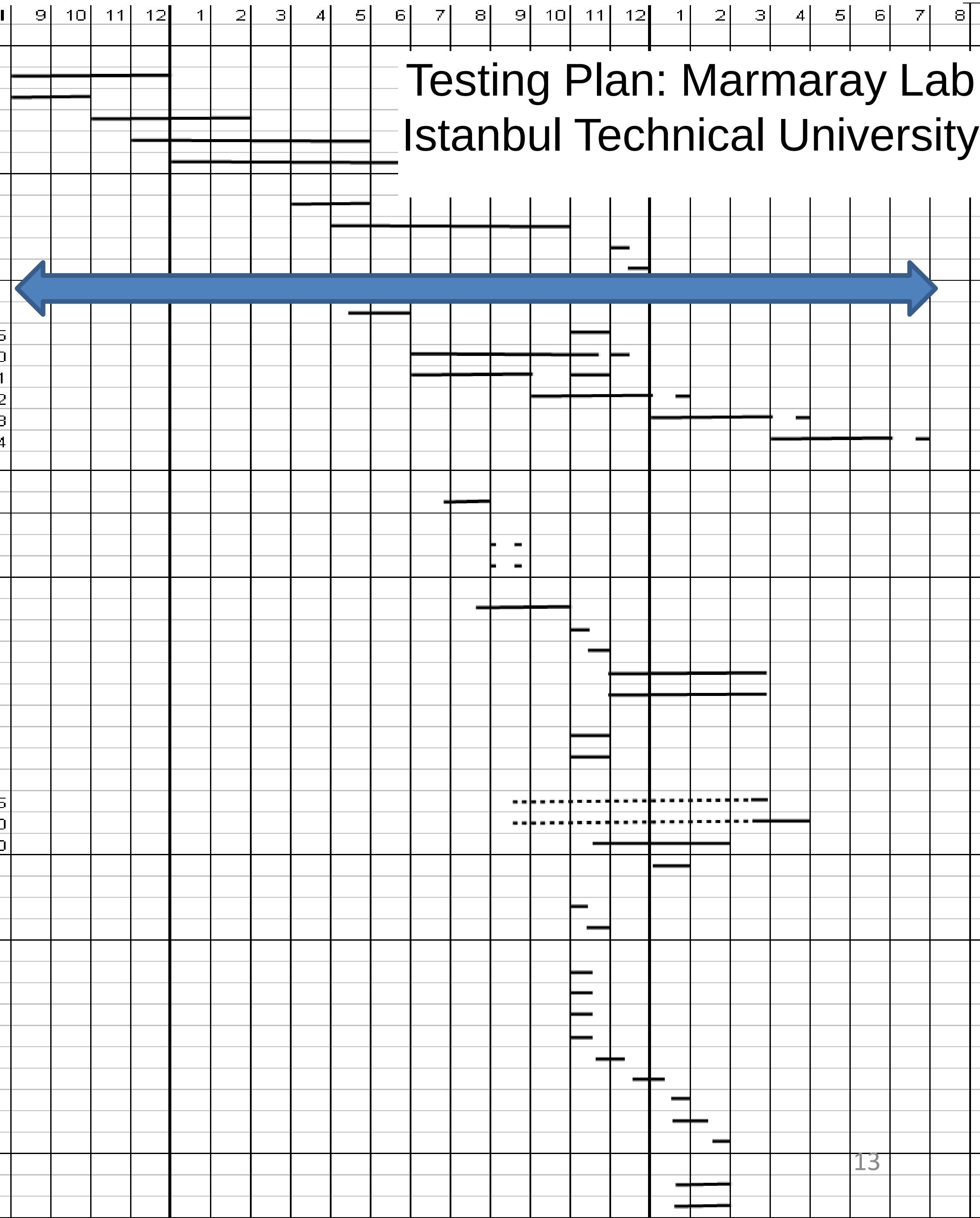
Min. 100 Years of service life:

• Quality management: designer + experts + construction team
Identification of durability parameters
• Pretesting**:** Accelerated & long term (more reliable) material tests
Declaration of limit values
• FSTC and simulation: Workmanship, methods, curing, early C_R
Planning of casting, curing and monitoring
• Production: Traceability and quality control tests
Inspection sections of materials and in-situ quality

Early age properties: cracking risk, temperature monitoring
Long term durability: permeability, microstructure on cores

Testing Plan: Marmaray Lab
Istanbul Technical University

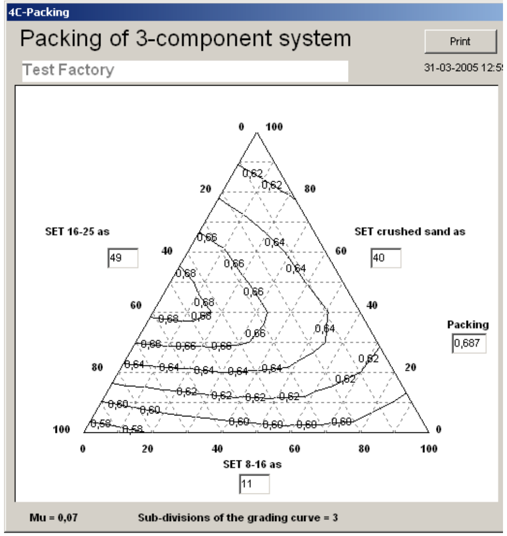
Act ID	ERQ No	Activity Description	Testing Period Mat. day	Test. day	Total day
		Preliminary Works			
0010		Planning all concrete works			
0020		Initial procurement, Subcontractors			
0030		Constituent materials, investigation			
0035		Preliminary testing			
0040		Lab preparations			
	4.2.3.	**Constituent Materials**			
0045		Sampling			
0050		Pretesting			
0060		Reporting-Constituents			
0061		ER review			
		Aggregates Alkali Reaction			
	4.2.3.7/8	Petrographic Analysis			
		Short Test ASTM C1260	0	15	15
	4.2.3.7	FA-Mortar Bar Test+Reporting	0	140	140
0070	4.2.3.8	CA-CAN Test-Phase A+Reporting	0	91	91
0080	4.2.3.8	CA-CAN Test-Phase B+Reporting	91	91	182
0090	4.2.3.8	CA-CAN Test-Phase C+Reporting	182	91	273
0100	4.2.3.8	CA-CAN Test-Phase D+Reporting	273	91	364
	4.2.4.2	**Concrete Mix Design**			
0110		Laboratory Pre-Testing			
0140		**Concrete Mix Design**			
0150		Production testing- 1 m3 Trial Pours			
	4.2.4.4	Fresh Concrete Tests			
	4.2.4.5	**Hardening Concrete Tests**			
0120		Pre-Testing			
0130		Reporting-Mix and Hardening Conc			
0131		ER review			
		Comp.Str.test (cured at Max Temp.)			
		ASTM C 1202 (cured at Max Temp.)			
	4.2.4.5	**Hardened Concrete Tests**			
0137		Pre-Testing (comp, density, air)			
0138		Petrographic Testing			
0136		**Chloride Diffusion**			
		Chloride Diffusion on 1 m3	180	5	185
		Chloride Diffusion on 1 m3	180	40	220
		Chloride Diffusion on FSTC	35	5	40
0160		Reporting-Mix and Hardened Conc			
	3.8.2	**Simulation and Controls**			
0170		Simulation Report			
0180		Review and Comment			
		Full Scale Trial Casting (FSTC)			
0190		Full program			
0181	4.2.5/6	Pre-Tests for operations			
0200		ER review of full program			
0210		CIQP for curing and simulation			
0220		ER review of CIQP for curing			
0230		Full scale trial casting			
0240		Reporting on FSTC			
0250		Additional FSTC incl. curing			
0260		Reporting on additional FSTC			
		Pre-Testing Completion			
0290		Adjustments and Conclusion			
		Full Pre-Testing Report			



Materials

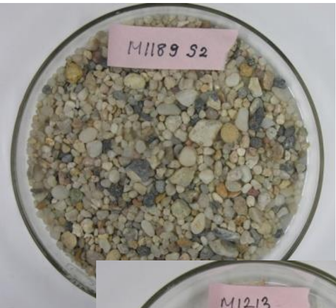
Special CEM I 42.5 N, CEM IIIB 42,5
$C_3A < 2\%$ $C_3S < 45\%$
Fly ash, micro silica

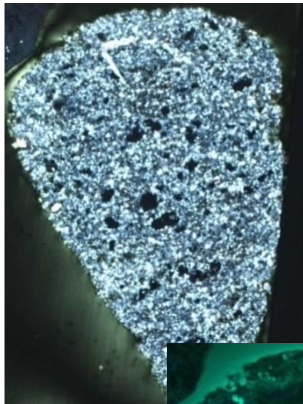
Special production/storage of Aggregates
Coarse limestone
4-16 & 16-22 mm
limestone & natural sand
0-4 & 0-2

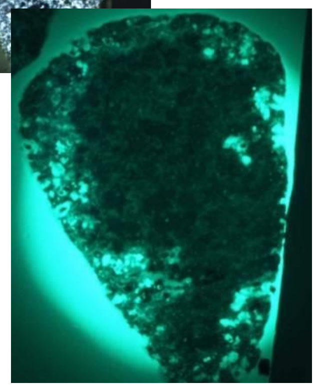


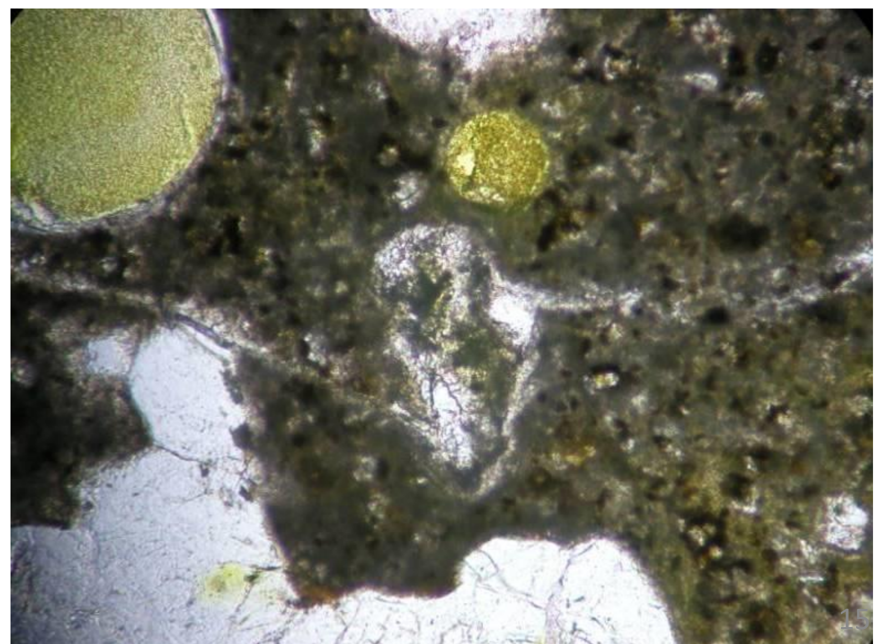
Special Chemical Admixtures for compatibility with Cement, fine sand: robustness, pumpability and slump life
PC and AEA

Alkali Aggregate Reactions









Design of Concrete Mixtures
Marmaray Project

C40/50 strength class, w/c= 0.38
Max Cl = 0.1% of total powder
Max. eq. Na_2O = 3.0 kg/m^3

Slump = 210 ± 30 mm
Entrained air = 4.5 ± 2%

Mix 1: low hydration heat
Mix 2: high early strength

	Mix 1 Kg	Mix 2 Kg
CEM I 42,5 N	-	275
CEM III B	375	-
Fly Ash	-	50
Micro Silica	-	30
Water	143	129
0-2 mm	462	640
0-4 mm	366	280
4-16 mm	445	473
16-22 mm	557	475

SCC mix for IMT end shells
Highly flowable mix for IMT joints
High early strength mix for TBM segments

Hardening Concrete

0.5, 1, 2, 3, 7, 14, 28. days

Compression, Split tension, E modulus

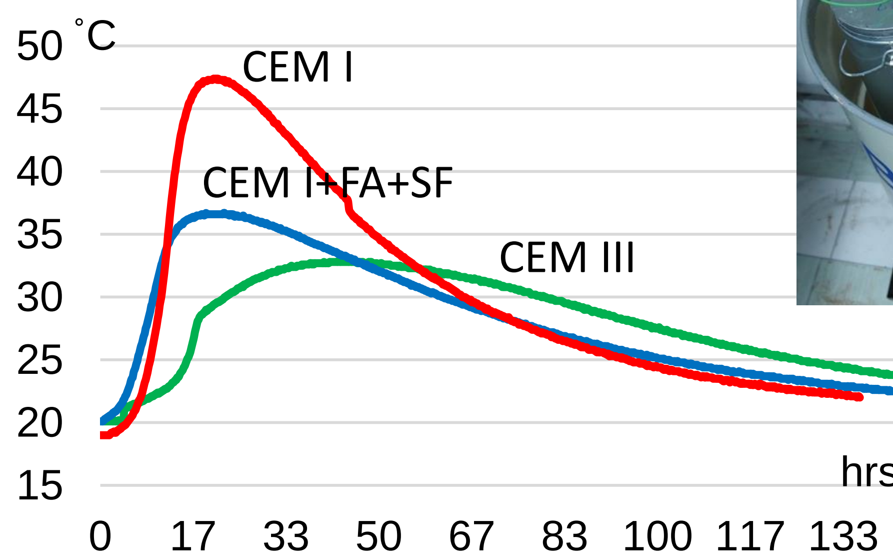
Activation energy

Thermal exp. coeff.

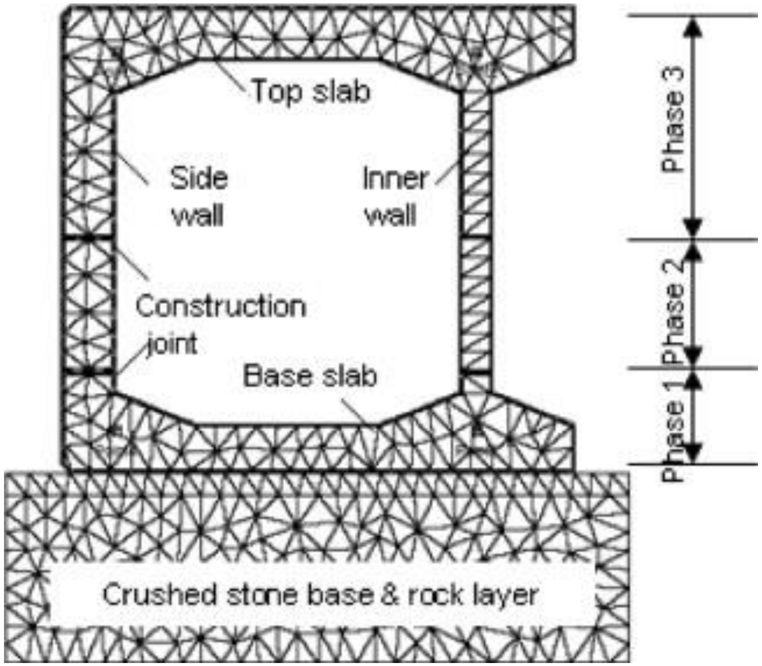
Shrinkage

Creep

Semi-adiabatic testing

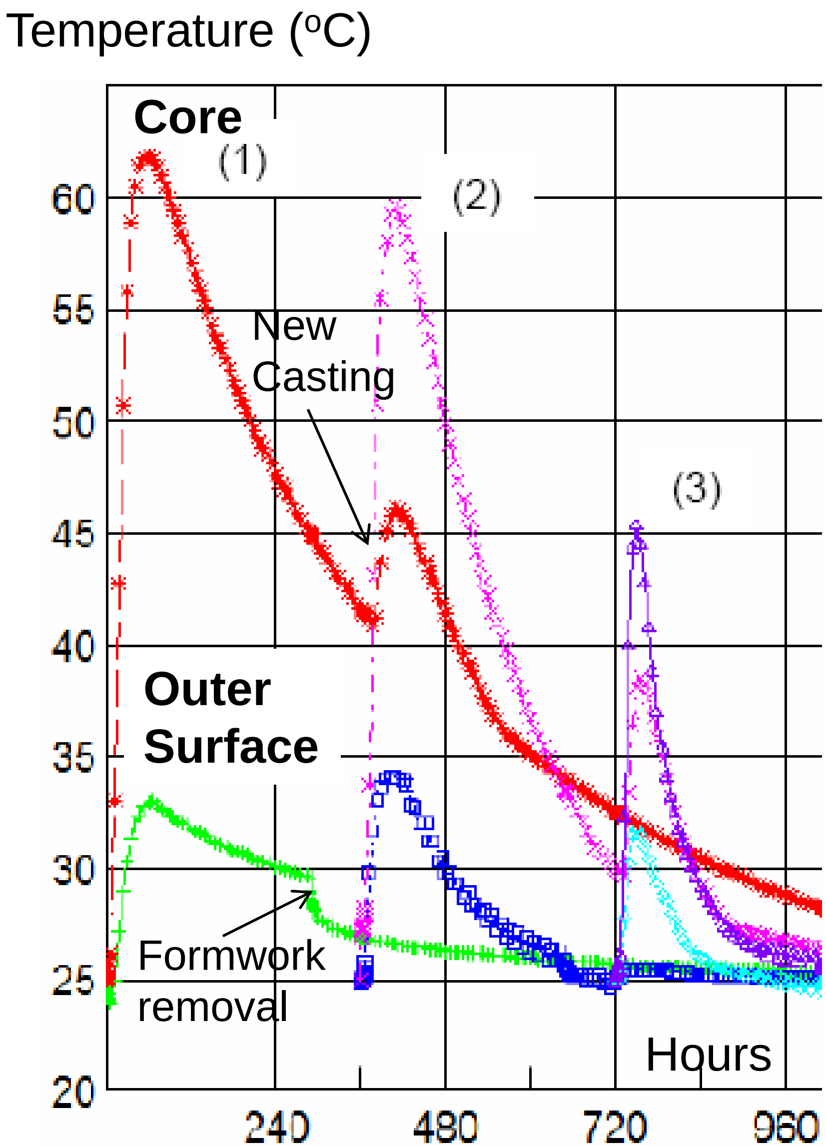


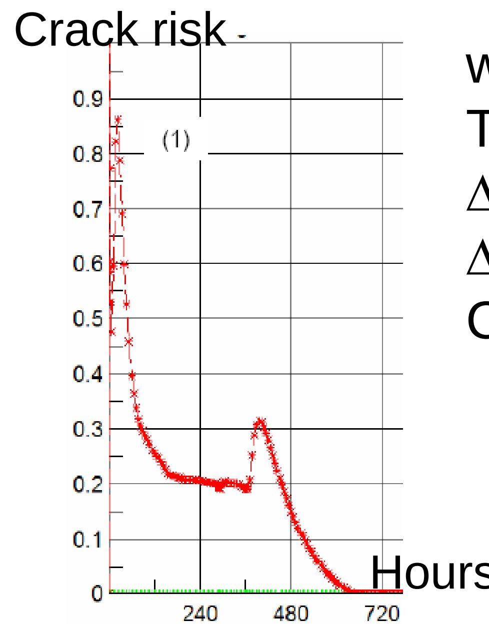
Simulation for Early Age Crack Risk



Early Age Concrete Properties
- E modulus, tensile strength development
- Thermal expansion coefficient
- Poisson's ratio
- Shrinkage and creep
- Adiabatic heat development
- Specific heat capacity, heat conductivity

Contractor's Variables
- Ground spec. heat capacity, heat conduct.
- Structural boundary conditions
- Environmental temp., humidity
- Casting days and sequence
- Removal day of formwork/ insulation
- Formwork/Insulation thickness, heat conduct.
- Fresh concrete temp.
- Cooling/heating





water retaining str.:

$T_{max} < 50^oC$

$\Delta T_{int} < 15^oC$

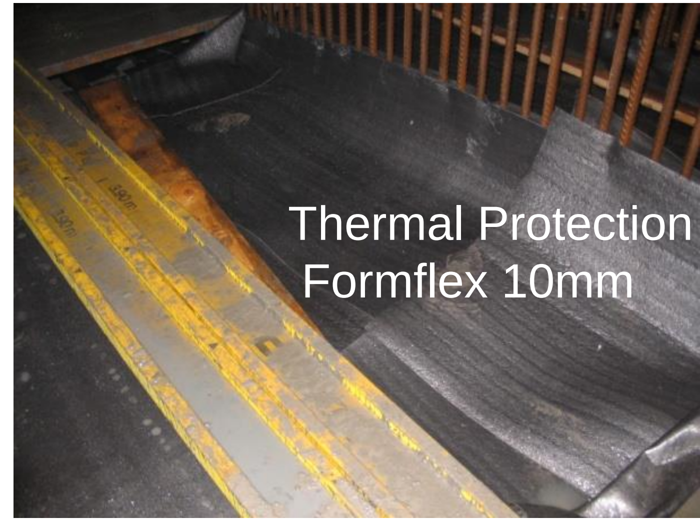
$\Delta T_{ext} < 15^oC$

$C_R < 0,7$

Prediction of maturity and strength development for site planning of:

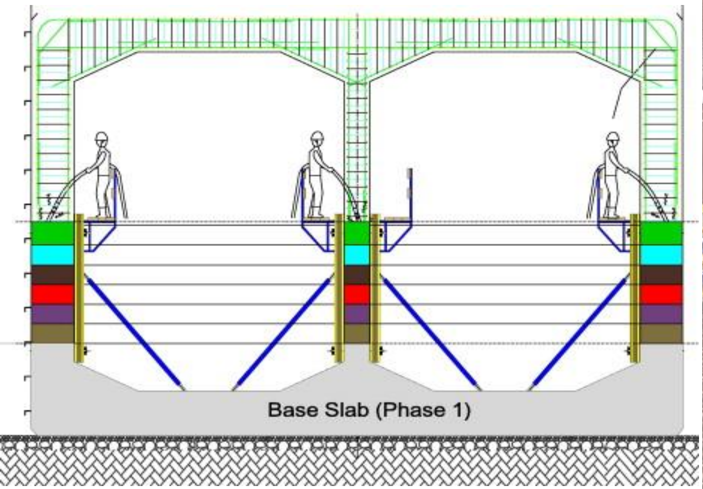
- Casting sequence
- Use of cooling/insulation
- Type/duration of curing
- Stripping time of the formwork

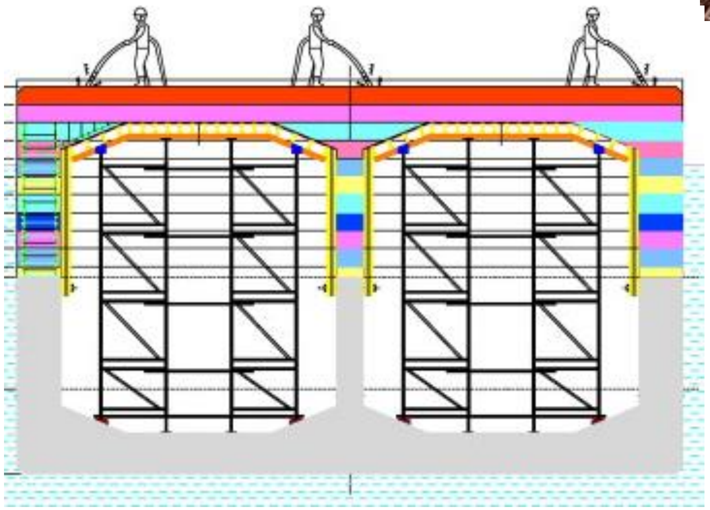
Post cooling and curing operations

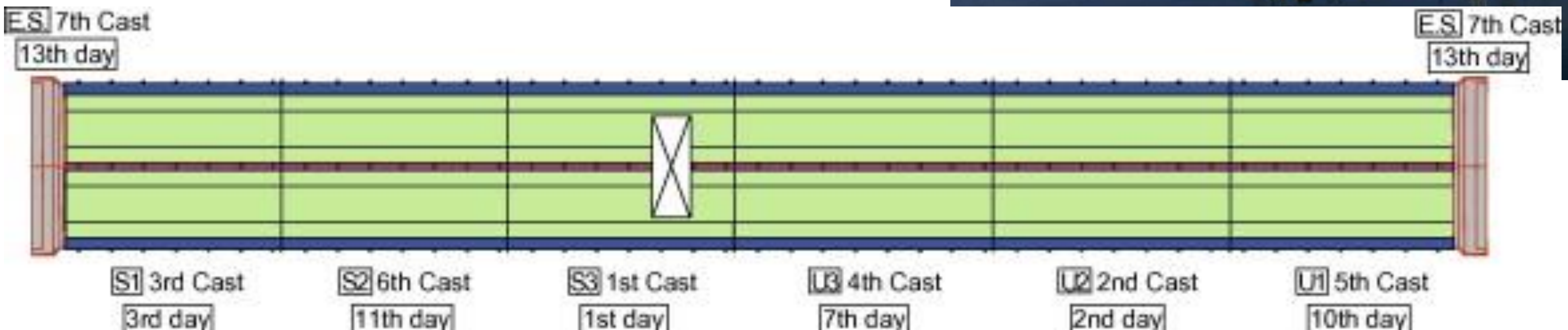


°C		T_{fresh}	T_{max}	D_{int}	C_R
Criteria			≤ 65	≤ 15	**≤ 0.7**
Simulation Summer		30	54	4.5	0.66
Monitoring	Max	30	51	14	
	Min	18	41	3	
	Avg	25	45	10	

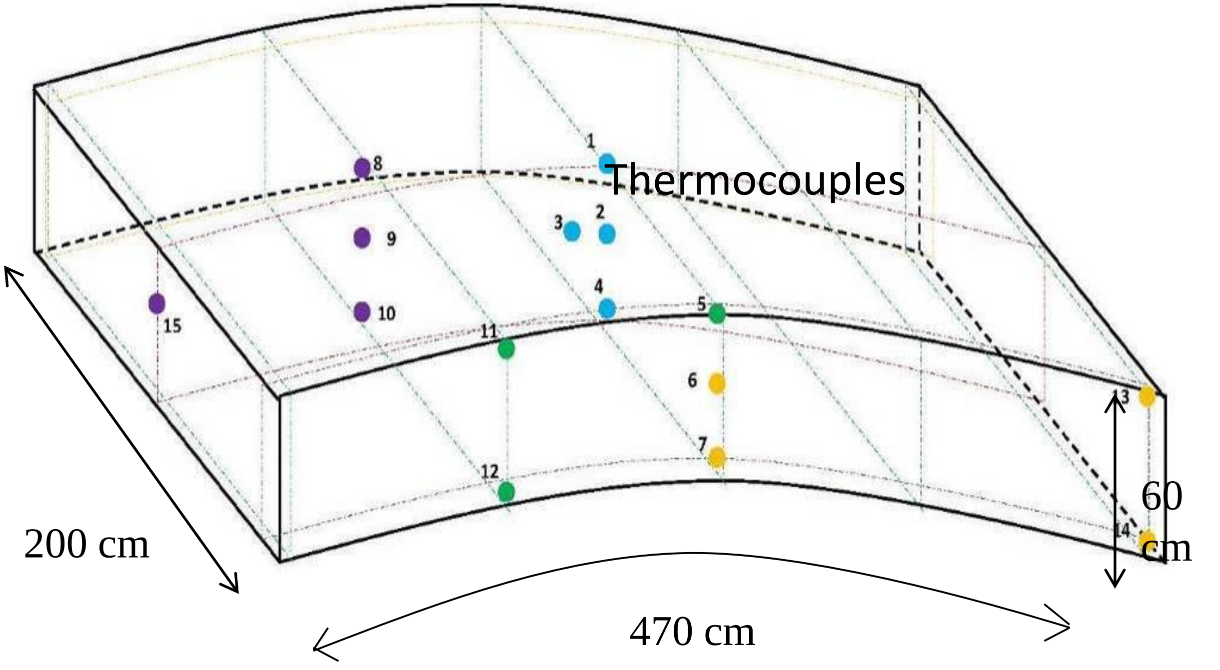
Casting Sequence







Transfer time



Scenario	Curing	Formwork removal (hrs)	PE cover application (hrs)	Transfer to stock (hrs)	Simulation TMax/time (°C)/(hrs)	Measured TMax/time (°C)/(hrs)	Cracking Risk Factor
A	4 hrs/35°C	20	44	120	57/29	55/21	0,60
B	Ambient	20	44	120	55/29	51/21	0,50
C	Ambient	20	44	72	55/29	-	0,50
D	Ambient	15	44	72	55/29	-	0,50
E	Ambient	20	44	48	55/29	-	0,93
F	Ambient	15	44	48	55/29	-	0,93

Transfer time to stock area is critical due to the ΔT between $T_{environment}$ and $T_{segment}$
=> continue curing at the stock area

Production Issues

Low $T_{concrete}$:

Shades and sprinklers on the stock

Buried cooled/chilled water tanks

T_{Cement}

Fresh concrete consistency:

Temperatures:10-32 ^{o}C

Moisture: up to 16% in washed natural fine sand

Fineness: up to 12% in crushed sand

Batching plant & pumping distances

After pump slump: controlled by initial slump, admixture content, mixing time

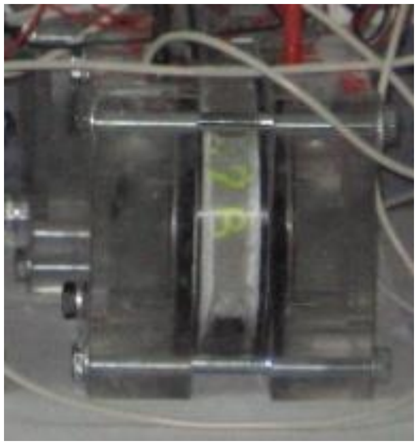
T_{conc} - admixture content relation & lifetime: determine at all expected T

Mixer type effects the correlation between lab and plant, site testing is important

Permeability and Durability

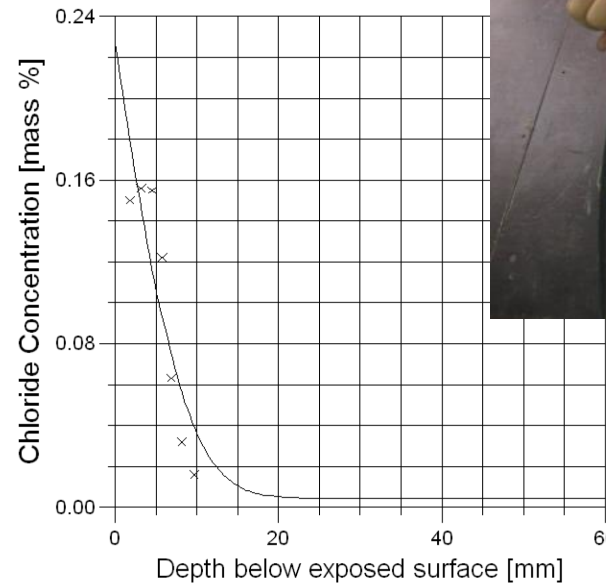
Testing at the lab

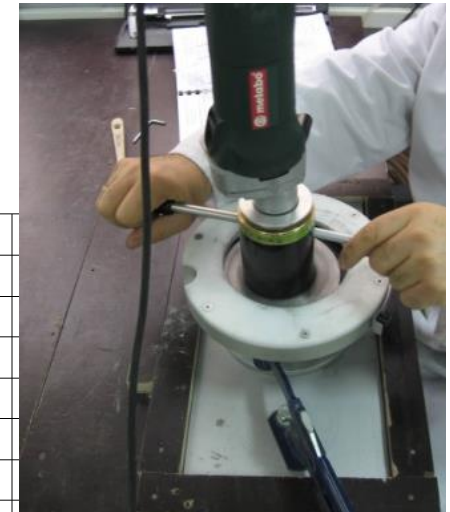
Rapid Chloride Permeability



For on site QC besides strength

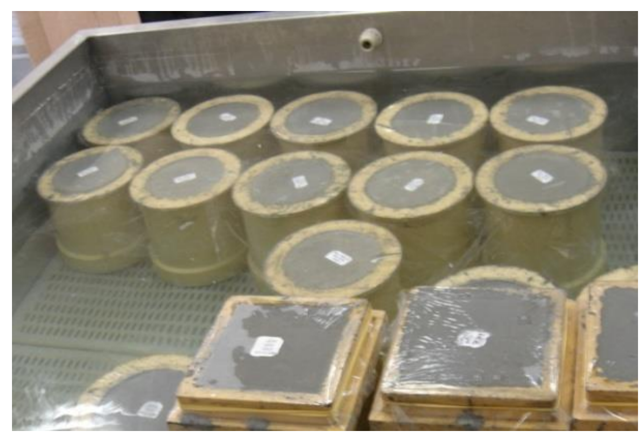
Chloride Diffusion





Salt Scaling Freeze-thaw

DEF

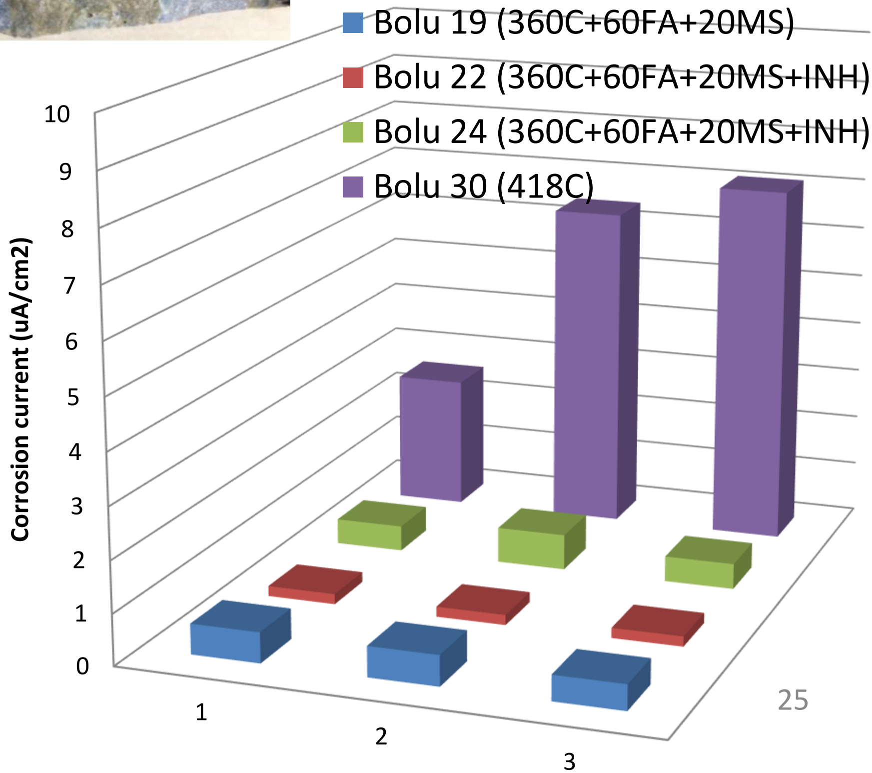


Diffusion Coefficient...from lab to site

Heat development

Compaction

Corrosion inhibitors

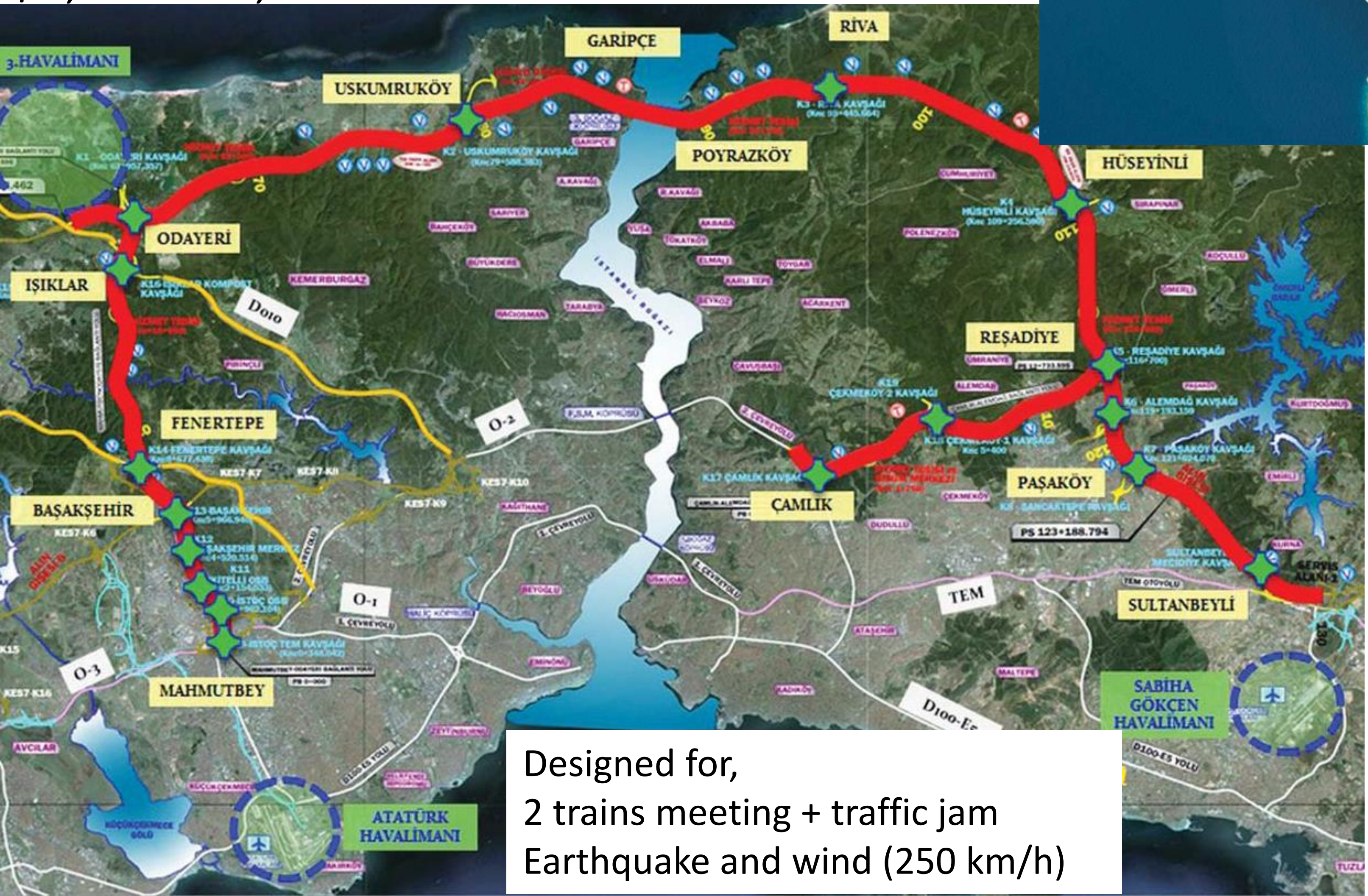


YSS BRIDGE N. Marmara Motorway

Started in 2013, BOT, 10 yrs

36 viaducts, 4 tunnels, 117 bridges

$1,7 Billion, 2 million m^3 concrete



Designed for,
2 trains meeting + traffic jam
Earthquake and wind (250 km/h)

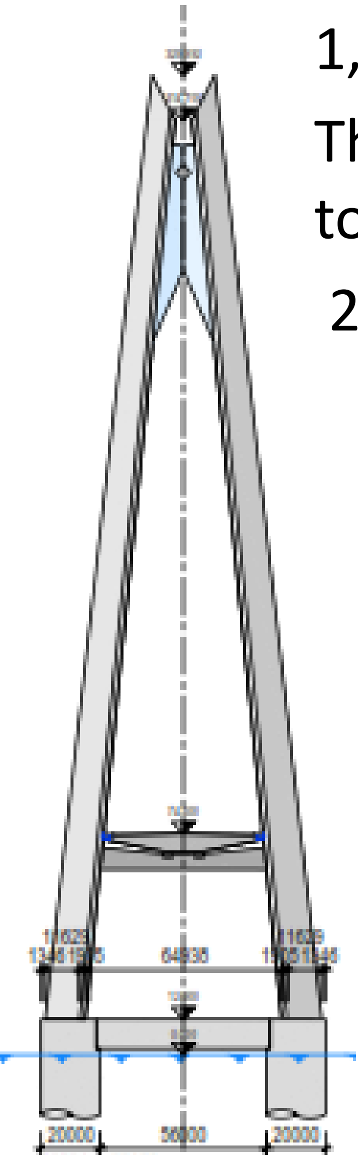
Hybrid system (suspension and cable-stayed)

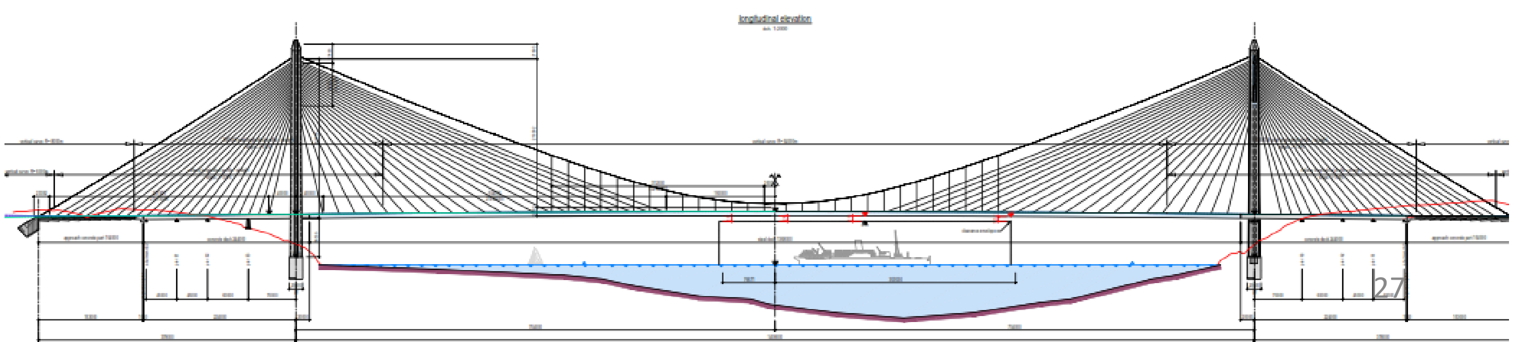
Design: M. Virlogeux, T-Engineering, Sub-contr: Hyundai-SK

321m RC tower H, 59m deck W, 5,5m deck H and 2,164 m L, 1,408m main span

The widest, the longest with a railway system, the highest towers and 8th longest suspension bridge

228 000 m^3 concrete

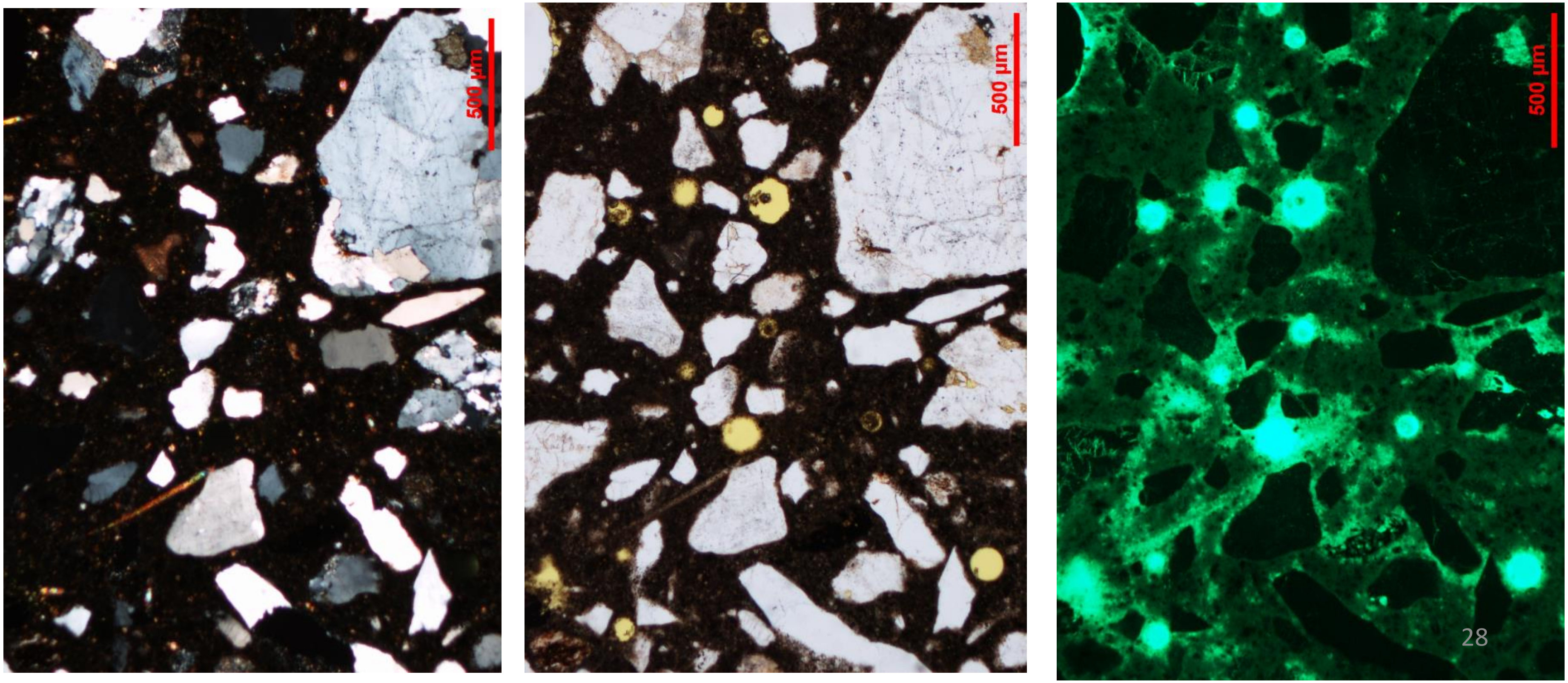


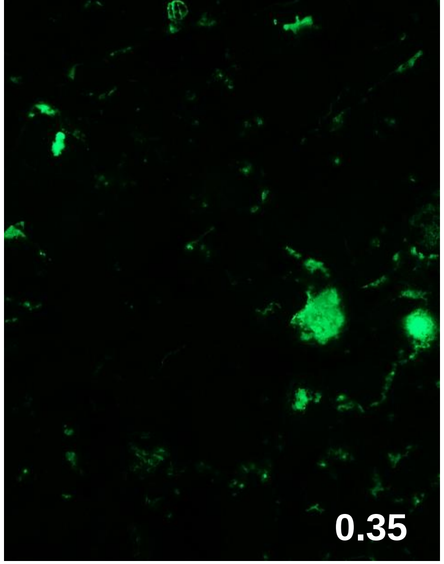


Insitu Quality Pretesting, FSTC, Production: 6 cores/5000 m^3

- 2,5x4 cm^2, Mineralogy
- Cementitious materials

Fluoresence intensity:
- Capillary porosity (w/c)
- Paste homogeneity
- Cracks - interfaces

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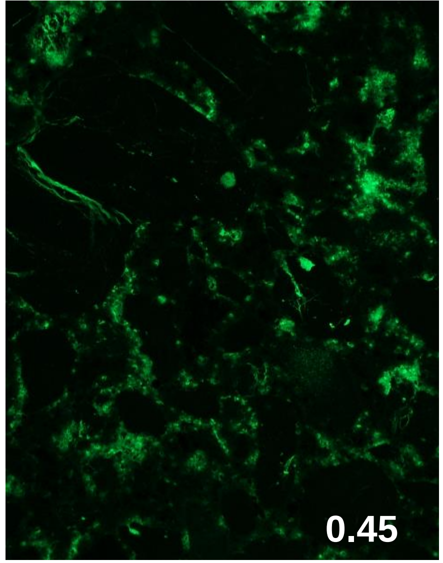
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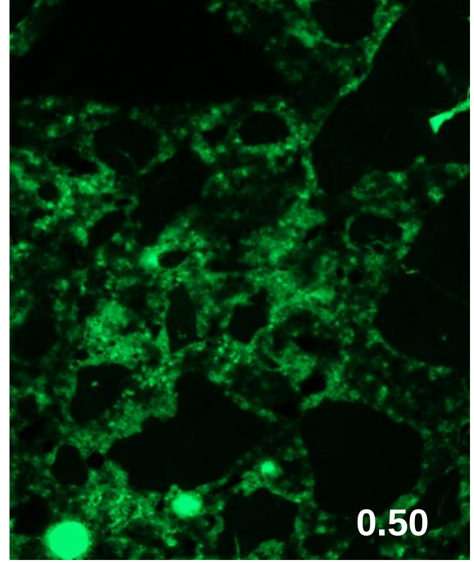
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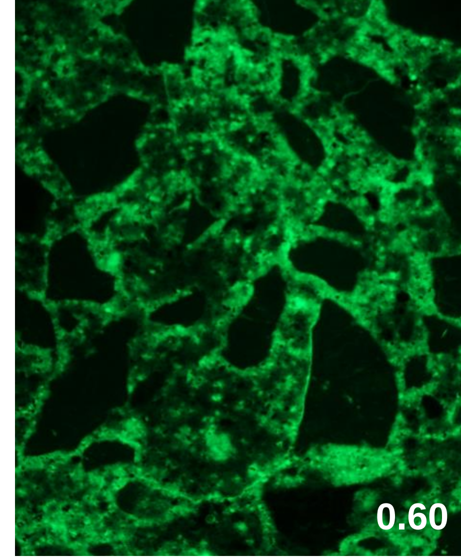
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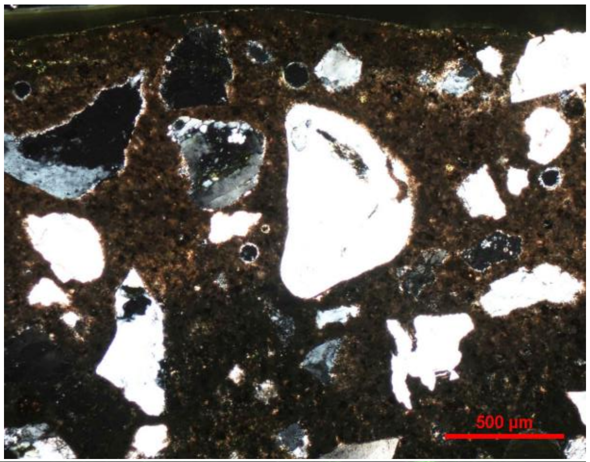
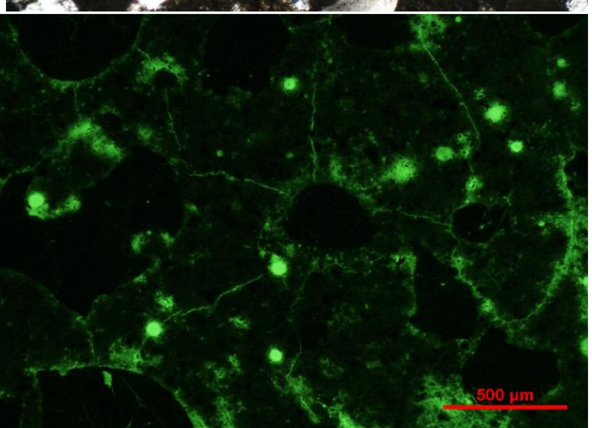
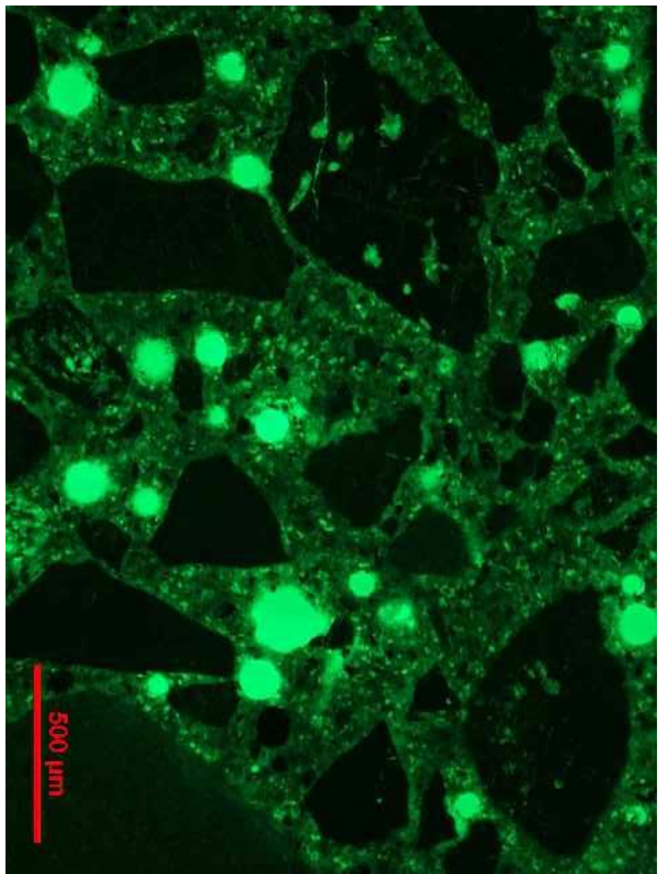
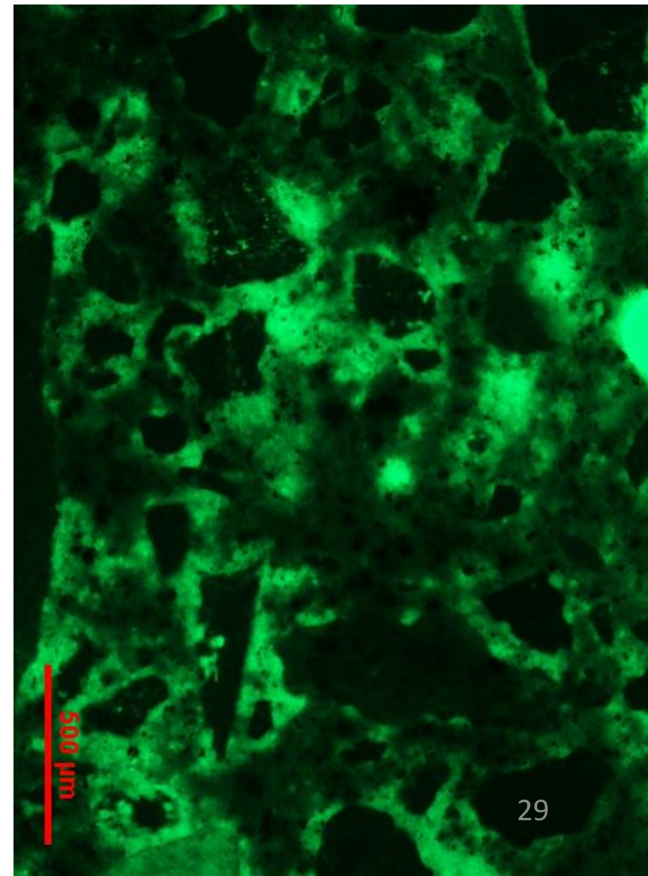
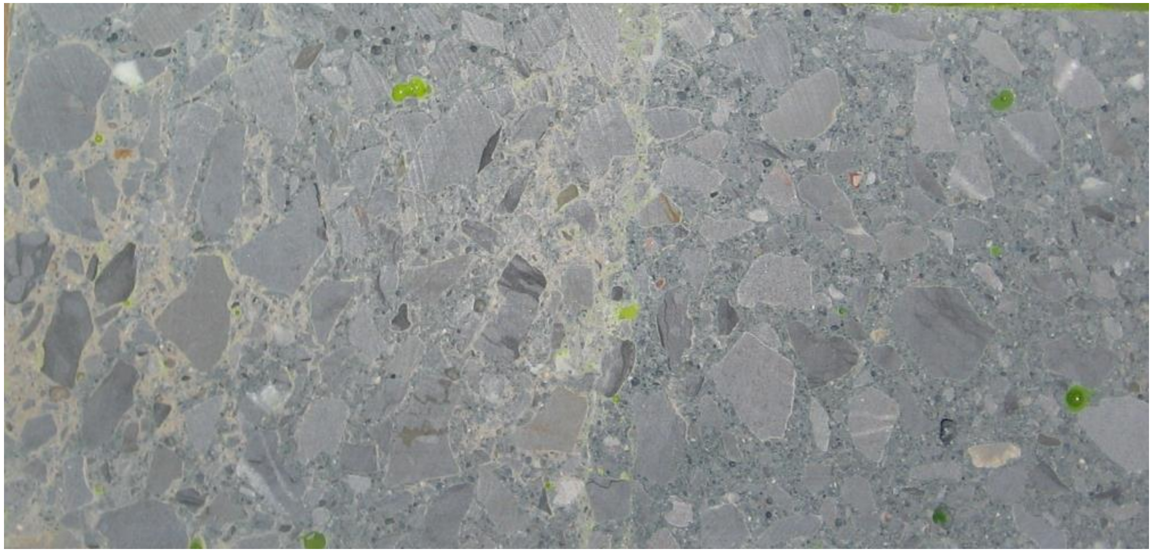

500 µm

500 µm

500 µm

500 µm

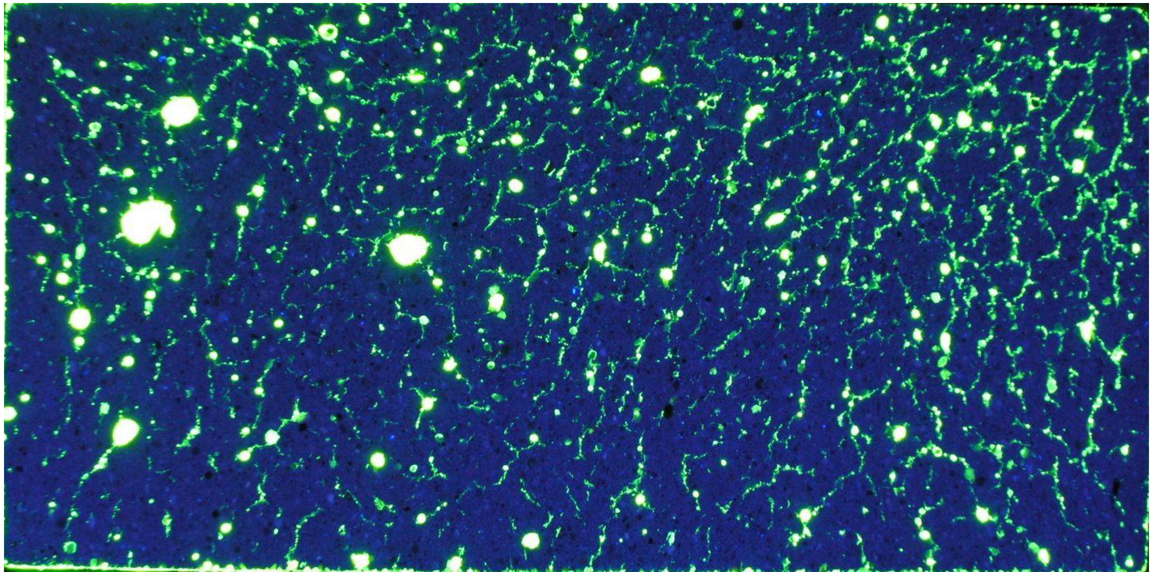
Plane Section Analysis

10x20 cm^2

Aggregate shape, type, content, distribution
Mortar homogeneity, segregation
Workmanship, entrapped air voids, bleeding
Crack connectivity, direction, length, width, location

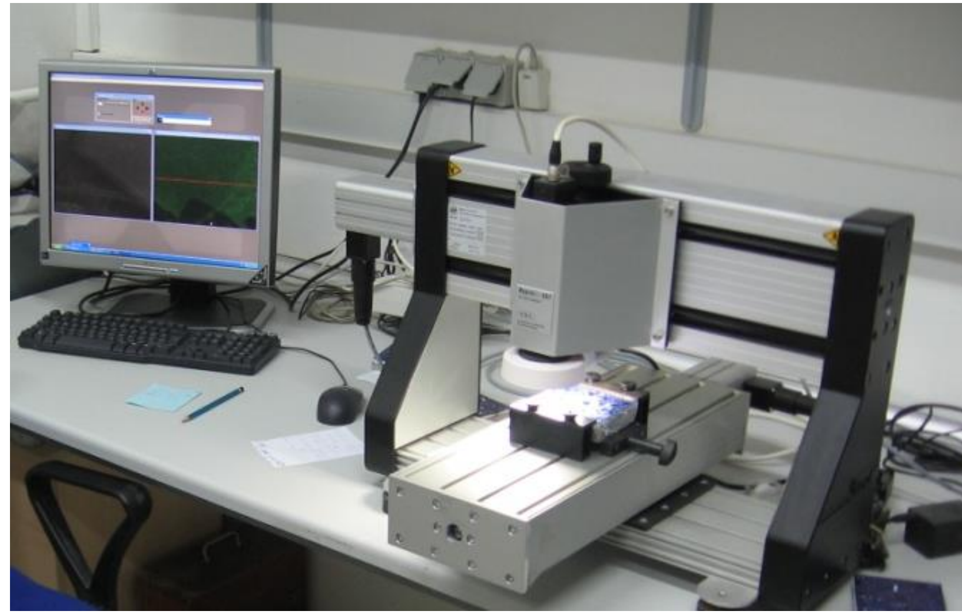


Normal light

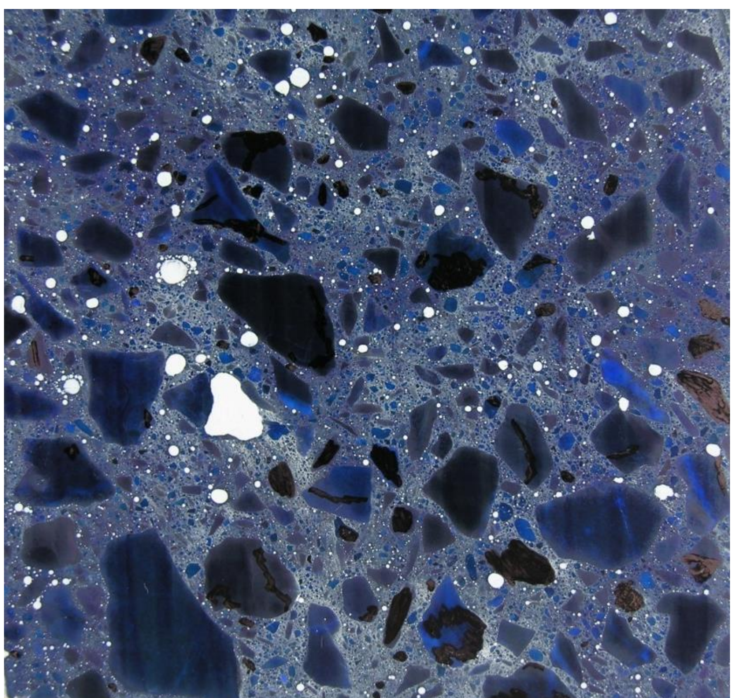


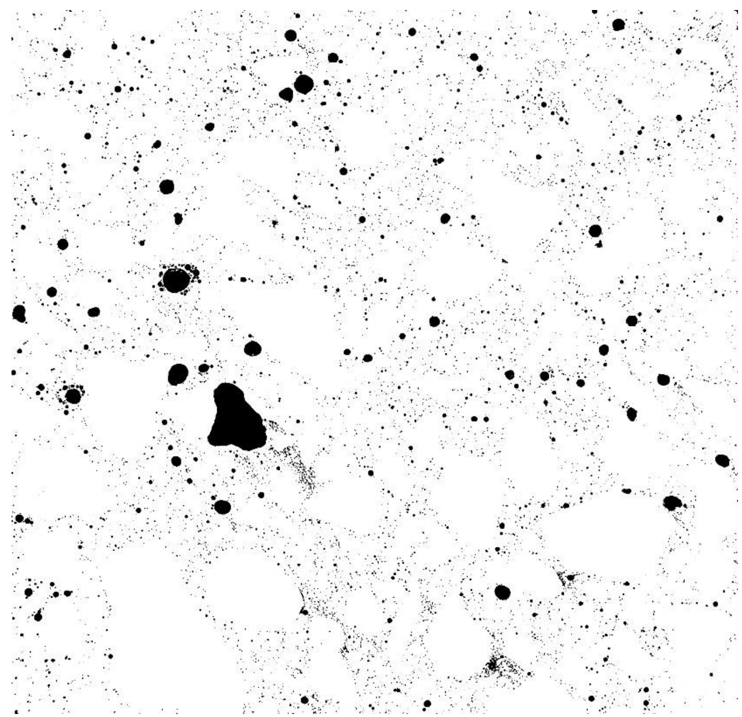
UV light

Air Void Analysis

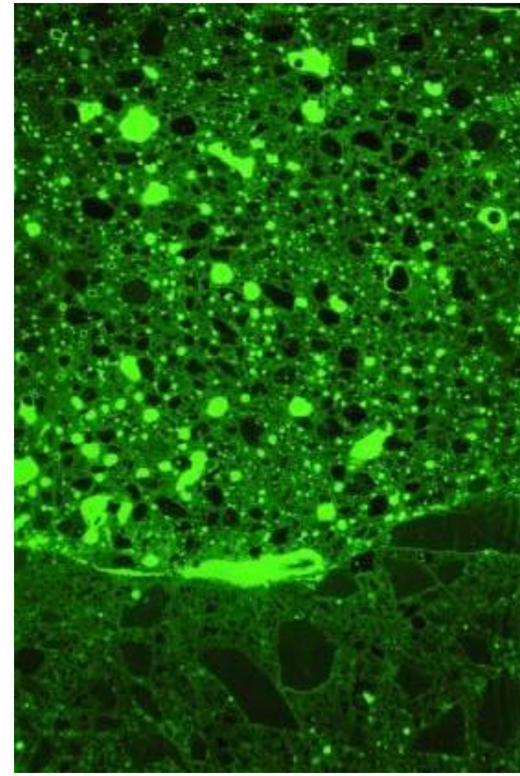


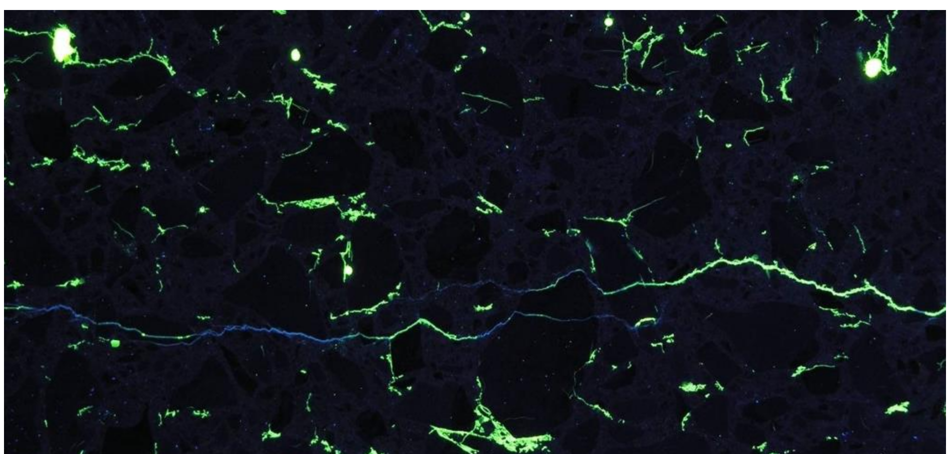
- Air Content
- Specific Surface
- Spacing Factor

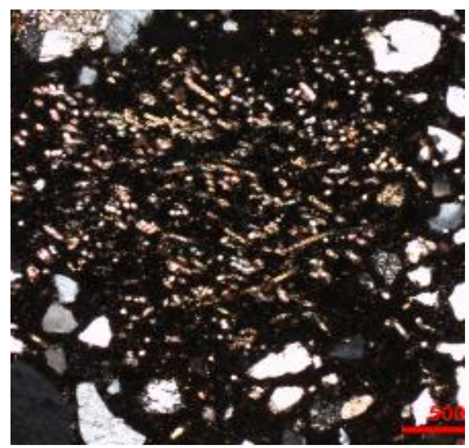




Quality of Repair Works



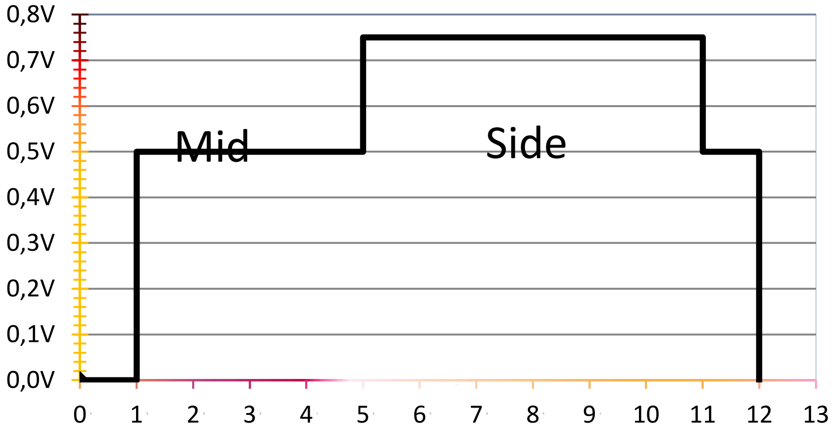


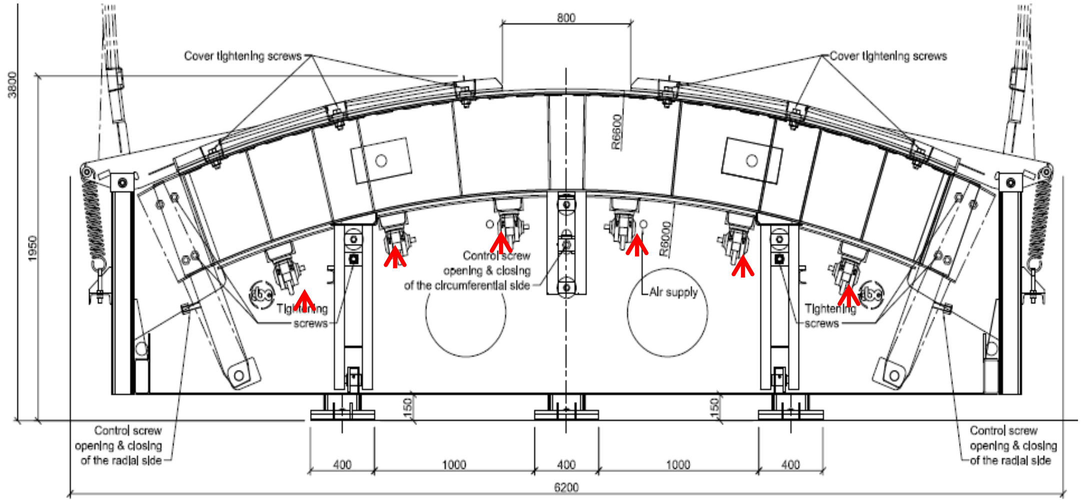


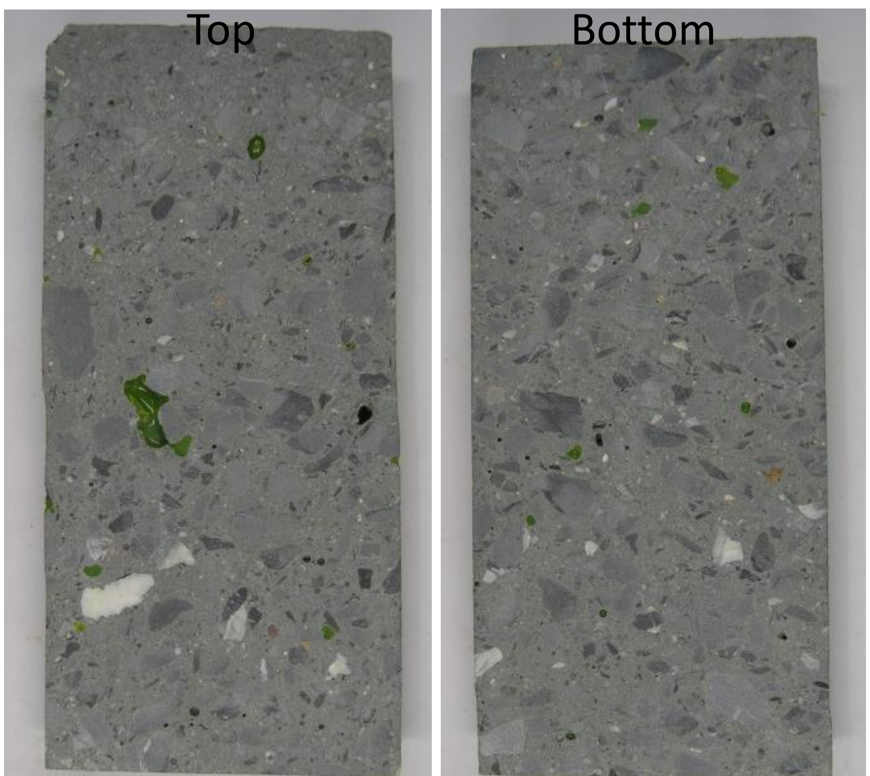
Workmanship, materials and limits defined by trials

Formwork vibrators

RD-3 VİBRATİON SCHEME





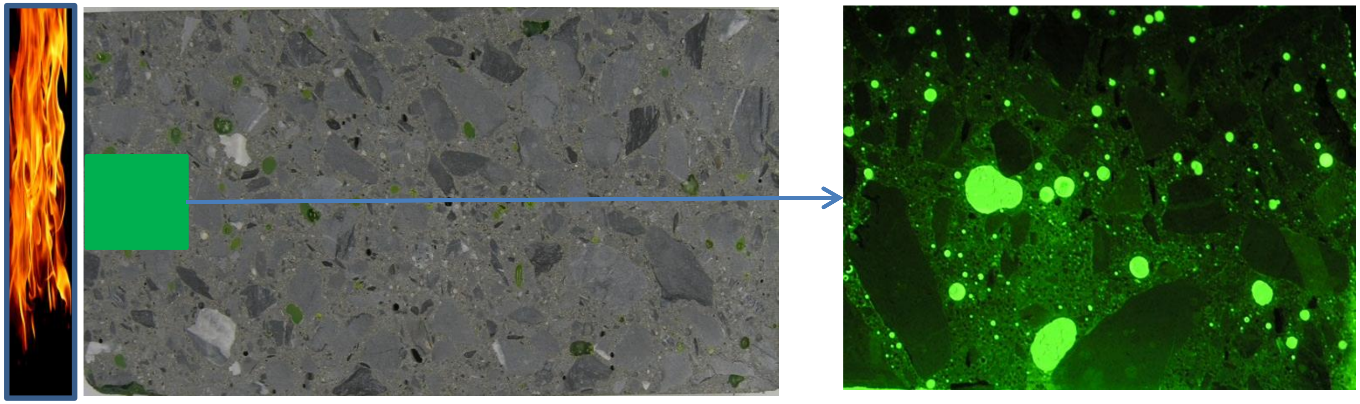


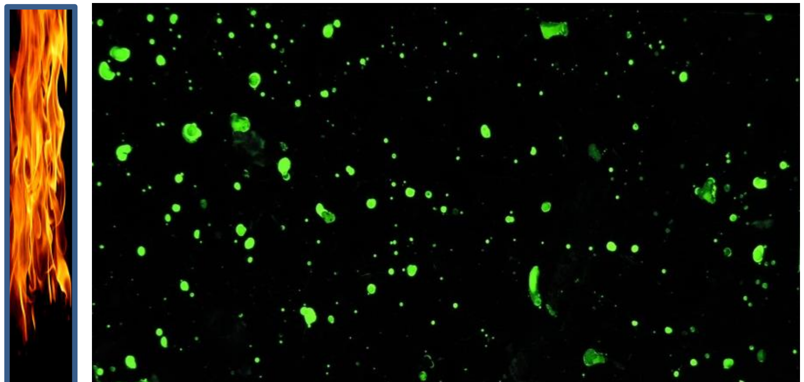
$T_{concrete}$ ° C	Slump cm	S. Flow cm	Flow cm	Vibration	
				min	Scheme
18	22	41	54	11	I
15	19	36	42	11	II
15	20	33	47	8,5	III
12	21	39	51	8	III
13	22	35	49	7	III
12	19	30	43	7,5	II

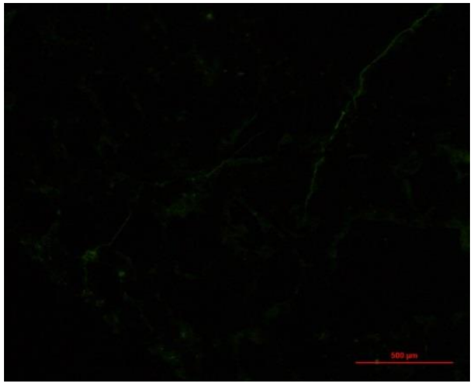
vibration scheme depends on flow

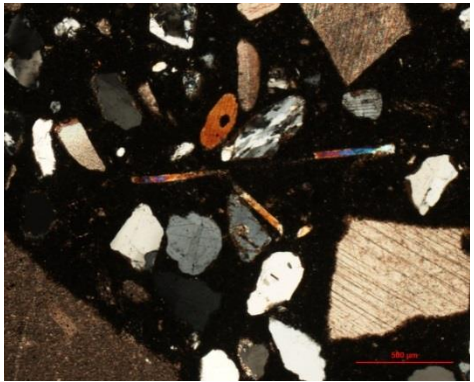
PP FRC Fire Testing

6mm, 64 microns 1,75kg/m3 fibers => workability



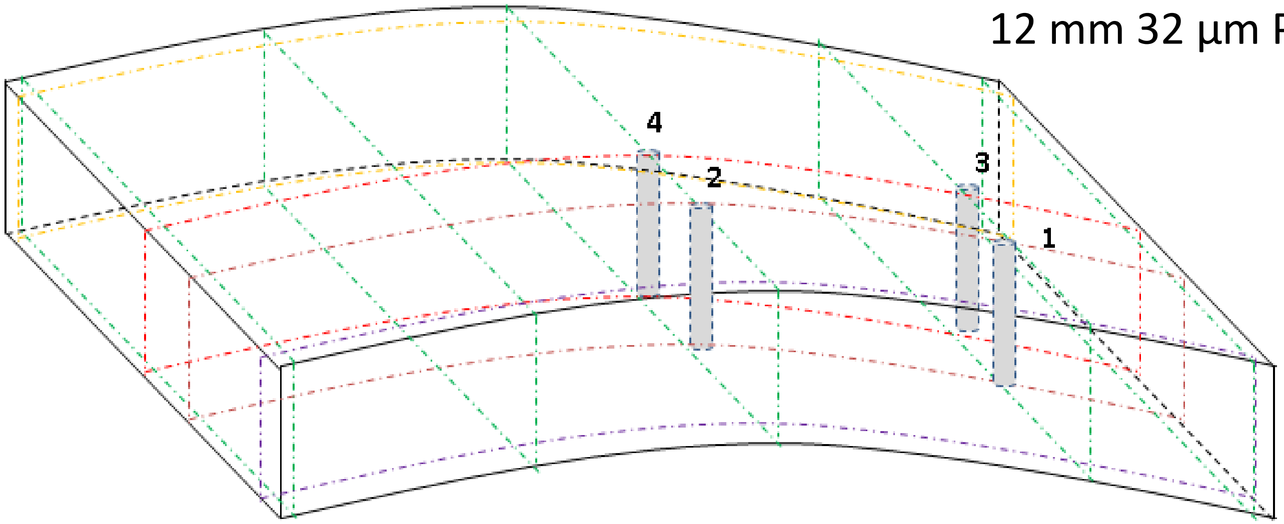


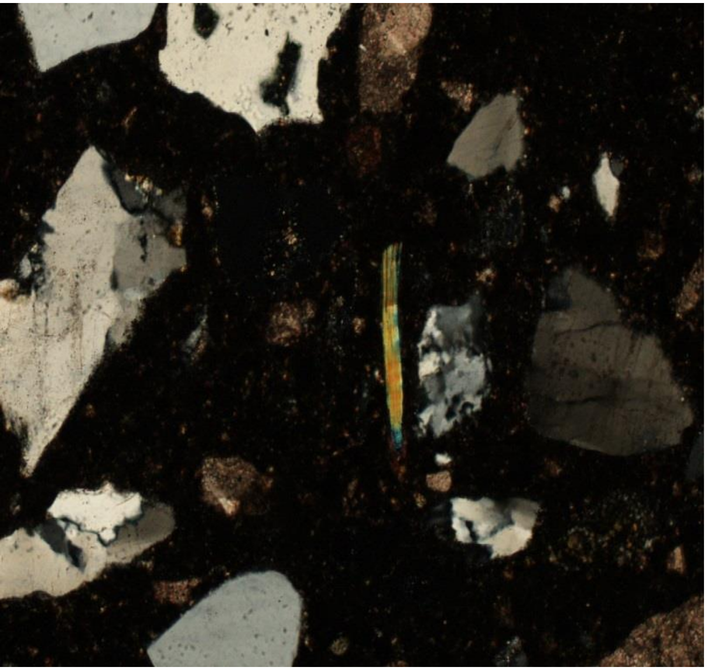




PP FRC to Minimize Cracks in Segments

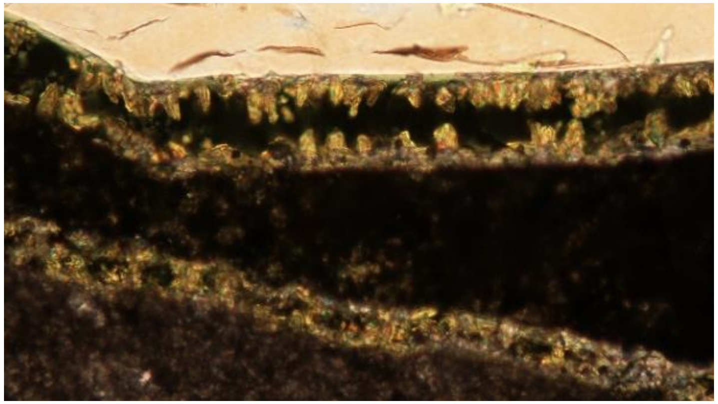
12 mm 32 µm PP fiber 0,9 kg/m3

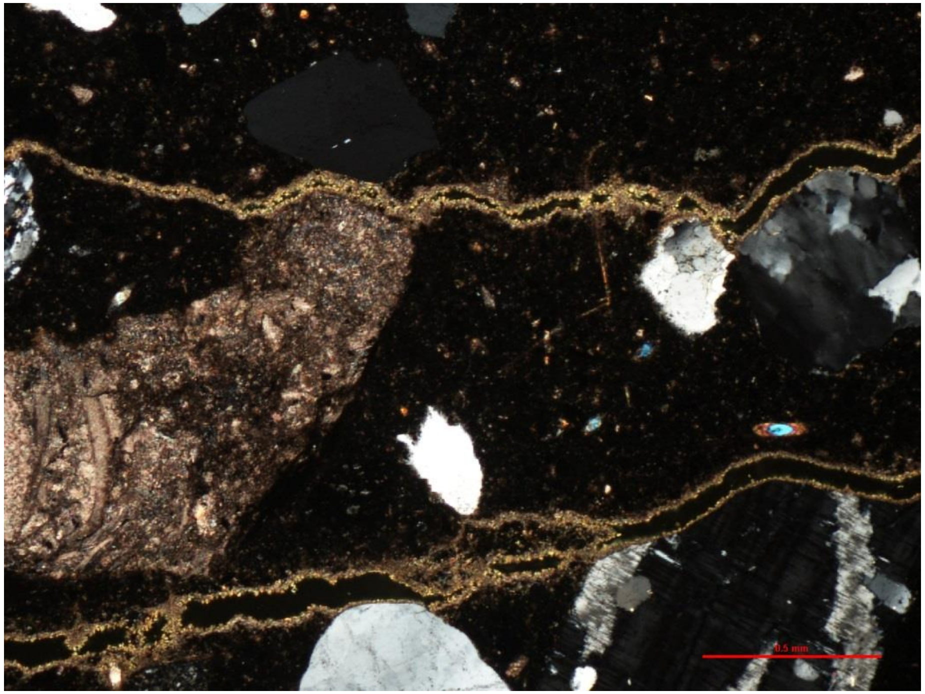




PP clumps => cracking earlier with smaller width

Quality of Crack Repairs with self-healing materials





Pre-concreting: Go/ No Go decisions

Database and inspection checklists

- Material IS Certificates
- Temp & stress analysis for casting section
- Weather forecast
- Variation in adiabatic heat development of concrete
- Maintenance and calibration records
- Organization chart, site layout plan
- Ongoing tests (petrography, Cl diffusion, ASR..)

Account for details, risks, coordination under possible scenarios

Post-Concreting: Logging and monitoring

Curing start/stop time, type (moisture and heat)

$T_{Concrete}$, maturity calculations for stripping of forms

Visual inspection for location, type and patterns of surface defects, cracks

Concrete cover inspection

Repair methods/operators.

Concrete for Sustainable Infrastructure Projects

Design for Durability: Principles & specifications prepared/evaluated by **multidisciplinary** expertise
Comprehensive **test plan** (up to 1 year) and lab facility

Mat'ls & Mix Design: Methods and **correlations** for ASR, F-T, D_e
Additional material resources, mixture designs, RMCs
Inspection sections & storage (C fineness & aggregate temp., moisture..)
Binder composition for C_R, durability, curing

Simulation & FSTC: C_R & durability testing, mix adjustments for **casting & curing plan**
Workmanship, Team organization, **Quality plans** for production & repair works
Interpretation and site adaptation requires knowledge and experience

Concrete works: Mixture design **adjustments** for T, transportation & pumping dist, slip forming..
Monitoring depends on site lab quality
Design vs insitu properties: Higher strengths, up to 90 MPa
Insitu quality with **petrography**
Insitu cover thickness: 20-120 mm

Unique project challenges: Concrete **technology** & **dedicated peopl**e for problem solving.

New standarts with a **holistic approach** (testing, modeling and monitoring) are needed: