Third International Interactive Symposium On Ultra-High Performance Concrete (UHPC)

Impact of flexural loading induced cracks on chloride penetration of UHPC

Presenter: Qian Zhang, Ph.D., Assistant Professor, Florida State University

Co-author: Kyle Riding, Ph.D., P.E., Professor, University of Florida

Peizhi Wang, Ph.D Candidate, Florida State University

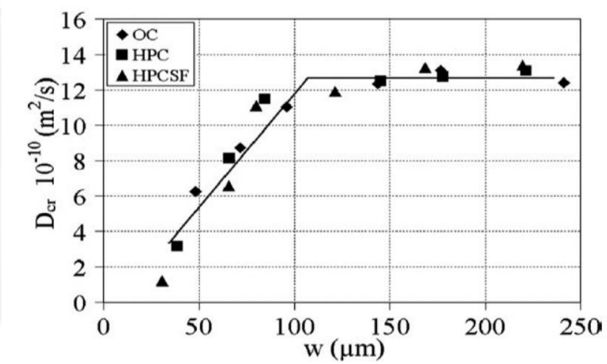
Outline

- Introduction
- Review of existing literature
  - Durability of UHPC
  - Influence of cracks on the transport properties of UHPC
  - Influence of cracks on the corrosion resistance of UHPC
- Ongoing research on chloride penetration of cracked UHPC
  - Experimental plan
  - Expected results
- Summary

Introduction

- There is an exponential growth of UHPC construction in highway infrastructures
- UHPC shows extremely low transport properties and high corrosion resistance when uncracked
- The presence of cracks may significantly increase the transport properties and reduce the corrosion resistance.

UHPC bridge distribution in U.S. (Source: FHWA)



Effect of crack width on chloride diffusion coefficient through crack (Djerbi, 2008)

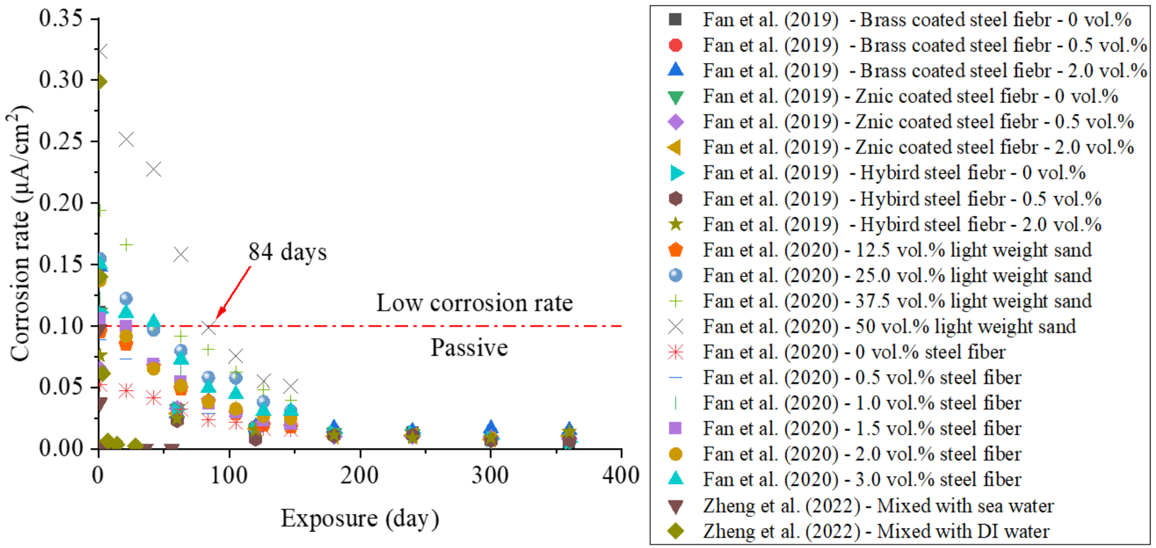
Low Transport Properties of UHPC

- UHPC has extremely low transport properties compared to normal concrete
  - Refined pore structure/Fiber addition

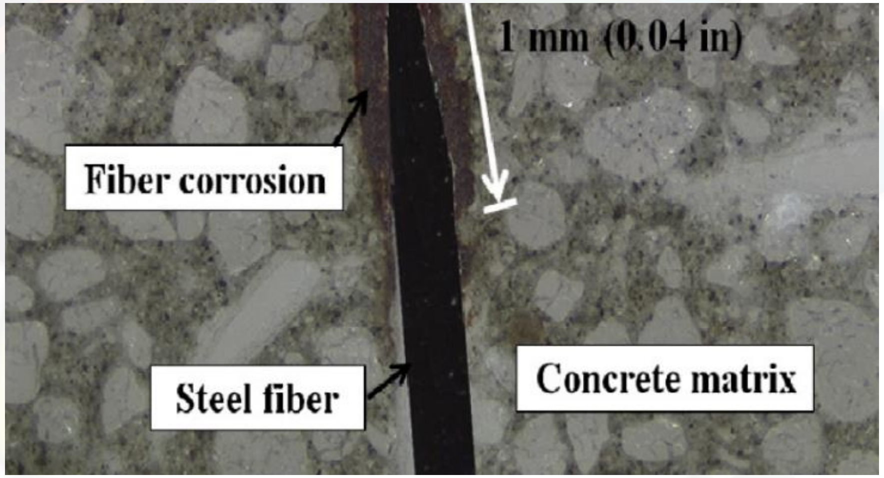
Transport properties	Indicator	UHPC	Normal strength concrete
Porosity	Porosity	2.29 to 7.52%	9 to 10%
Sorptivity	Water absorption coefficient	0.178 to 1.56 e-1 kg/m^2 h$^{0.5}$	3 to 7.8 e-1 kg/m^2 h$^{0.5}$
Water permeability	Water permeability coefficient	0.5 to 6.712 e-3 mm^2/s bar	6.679 to 7.857 e-3 mm^2/s bar
Gas permeability	Gas permeability coefficient	0.3 to 2.54 e-19 m^2	5 e-18 to e-16 m^2
Chloride penetration	Charges passed by	18 to 360 Coulombs	2290 to 5445 Coulombs
	Non-steady chloride migration coefficient	0.051 to 6.63 e-12 m^2/s	5.2 to 19.1 e-12 m^2/s
	Chloride content	0 to 5.5 e-2 kg/m^3	6 e-1 kg/m^3 for steel corrosion
	Chloride diffusion coefficient	0.06 to 5.9 e-13 m^2/s	0.20 to 7.97 e-12 m^2/s

Excellent Corrosion Resistance of UHPC

- Corrosion of steel rebar
  - Almost no corrosion found in steel rebar embed in UHPC
- Corrosion of steel fiber
  - Only surface fiber corroded
  - Mechanical properties strengthened with moderate corrosion



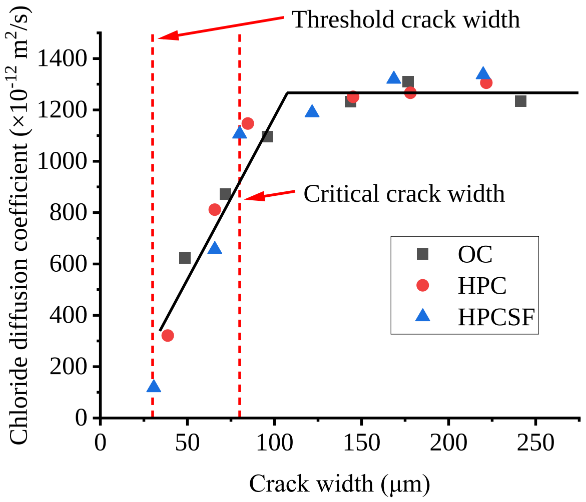
Corrosion rate of steel reinforcement in UHPC



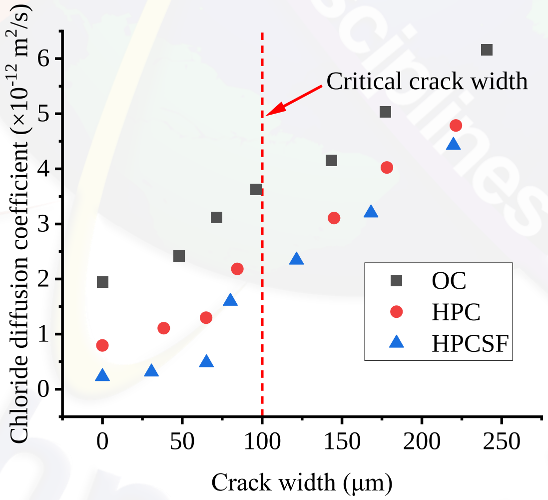
Corrosion of steel fiber in UHPC (Abbas, 2014)

Influence of Cracks in Normal Concrete

- Chloride penetration
  - Increases by one order of magnitude for overall cracked specimens with crack width up to 392 μm in terms of normal and high strength concrete
  - Increases with crack depth and density
  - Threshold crack width: 30 to 100 μm
  - Critical crack width: 80 to 400 μm



Chloride diffusion coefficient through cracks (Djerbi, 2008)



Chloride diffusion coefficient for overall cracked concrete (Djerbi, 2008)

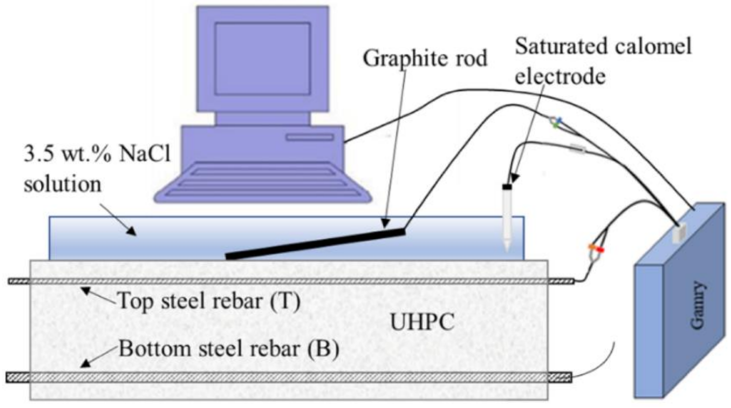
Influence of Cracks in UHPC

- Cracks are also shown to increase the chloride penetration in UHPC
  - Increases dramatically after cracking
  - Still comparable to that of uncracked concrete

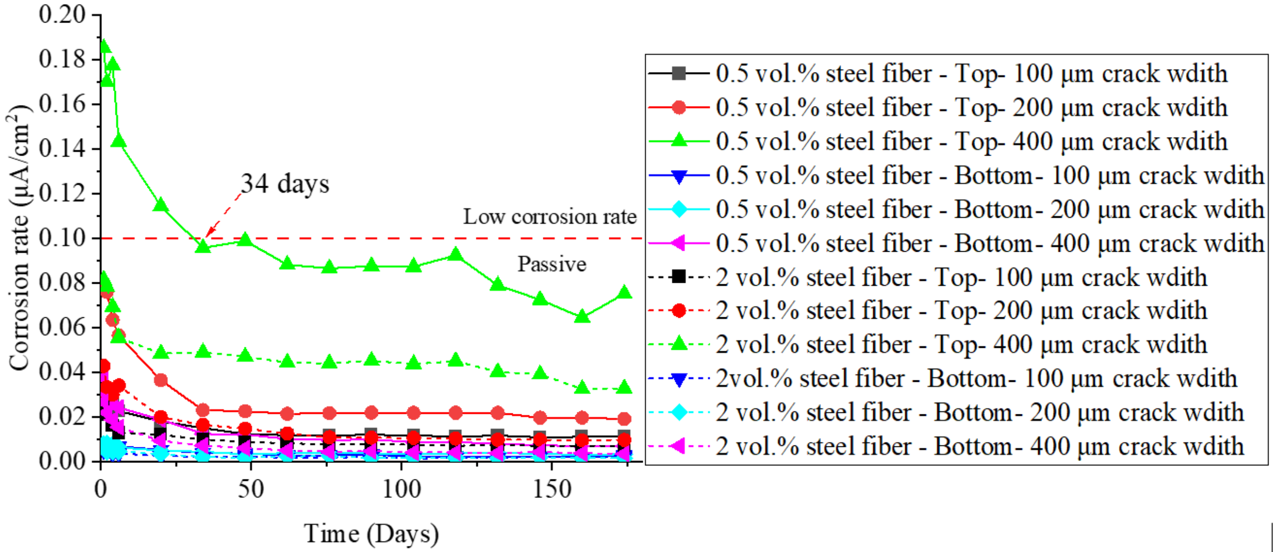
<table>
<tr><th>Measured transport properties</th><th>Crack pattern</th><th colspan="2">Crack width</th><th>Cracked UHPC</th><th>Uncracked normal strength concrete</th></tr>
<tr><td>Chloride diffusion coefficient</td><td>Multiple cracks</td><td colspan="2">0 to 80% of ultimate strength (compression/tension)</td><td>1.5×10^{-12} to 14×10^{-12} m^2/s (Ma, 2016)</td><td>0.20 to7.97 $\times 10^{-12}$ m^2/s (Bertolini, 2014)</td></tr>
<tr><td rowspan="3">Chloride content (Max.)</td><td rowspan="3">Multiple cracks</td><td colspan="2">0 to 80% of ultimate strength (compression/tension)</td><td>0.143 to 0.502 wt. % of concrete (Ma, 2016)</td><td rowspan="3">0.1 to 0.5 wt.% by cement (threshold value) (Ann, 2007)</td></tr>
<tr><td rowspan="2">0 to 30 μm</td><td>Salt water</td><td>0.015 to 0.037 wt.% (by cement) (Lv, 2021)</td></tr>
<tr><td>Marine</td><td>0.149 to 0.155 wt.% (by cement) (Lv, 2021)</td></tr>
</table>

Corrosion of steel rebar in cracked UHPC

- Corrosion rate and risk of embedded steel reinforcement increases with crack width



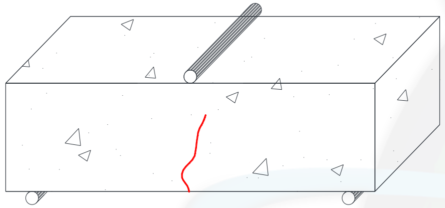
Measurement of corrosion rate of steel rebars inside cracked UHPC subjected to salt ponding

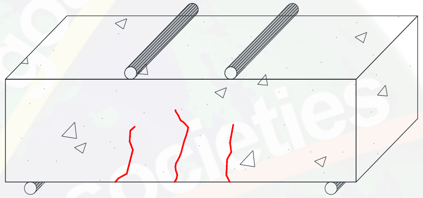


Higher corrosion rate caused by wider major crack, however, all steel rebars were back into passive after 34 days exposure due to insufficient oxygen supply (Fan, 2021)

Chloride Penetration of Cracked UHPC

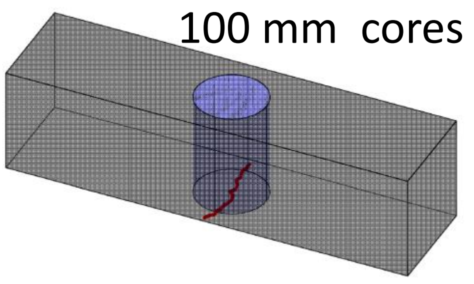
Crack Characterization



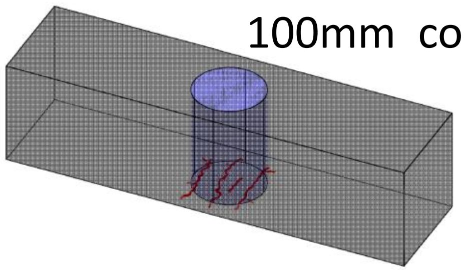


Core extraction

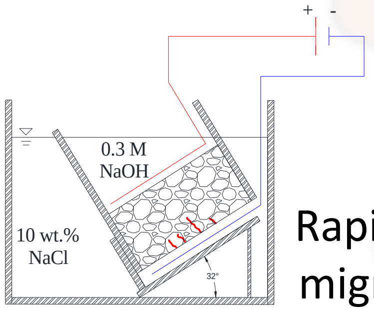
Single crack
100 mm cores



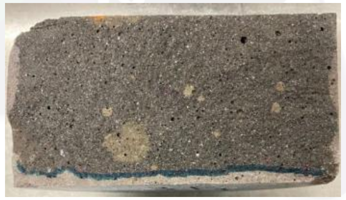
Multiple cracks
100mm cores



Chloride penetration test



Rapid chloride migration test



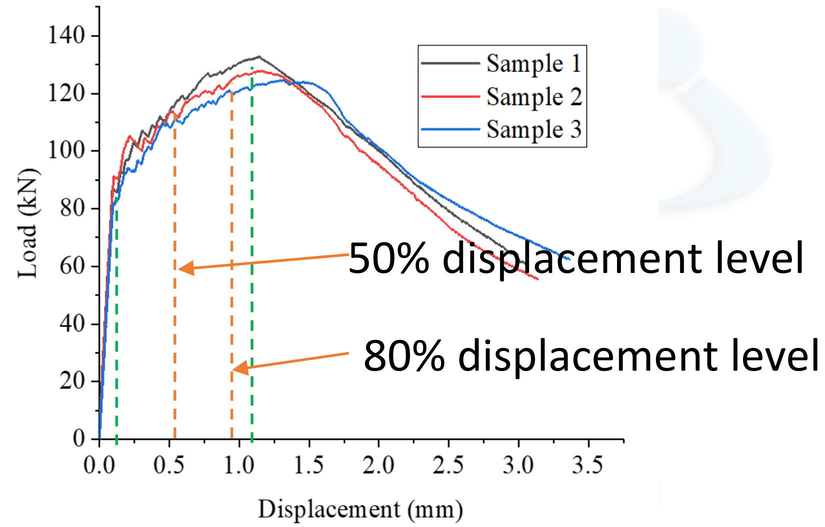
Chloride penetration depth and migration coefficient

Experiment Program

- Three different mixtures
- Single crack pattern
  - Targeted crack width 30~1000 µm
- Multiple crack pattern
  - Varying crack width and density
  - Casting methods/displacement levels

Displacement	Average crack width (µm)	Major crack width (µm)	# of Crack
50%	26.02±12.88	49.18±10.10	14~16
80%	69.63±135.62	542.50 ±172.68	20~21

Casting of UHPC mixture from one end



Crack generation at different displacement levels

Expected Outcome of Ongoing Research

- More comprehensive data on the chloride penetration of cracked UHPC
- Direct correlation between chloride penetration and crack characteristics and crack patterns
- Critical crack characteristics (e.g., threshold and critical crack width or density) that significantly influence the chloride penetration

Summary

- Transport properties and corrosion rate of steel members in uncracked UHPC is extremely low
- Cracks significantly increases the transport properties of UHPC material, nevertheless the transport properties of cracked UHPC is still comparable to that of uncracked normal concrete
- Cracks also increase the risk of steel reinforcement and fiber corrosion within UHPC, although minimal corrosion is observed in limited studies
- An ongoing research project is conducted to systematic study the effect of crack characteristics on the chloride penetration within UHPC

Acknowledgement

- The authors wish to express their gratitude to the Florida Department of Transportation (FDOT) for funding this research through project BED30 977-05.
- The opinions, findings and conclusions expressed in this publication are those of the author(s) and not necessarily those of the Florida Department of Transportation or the U.S. Department of Transportation.

Thank you!

Qian Zhang, Ph.D.
qzhang@eng.famu.fsu.edu