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Sustainability in concrete: The use of fiber-reinforced polymer reinforcing bars and low-carbon magnesia-based binders

NOURAN ELMESALAMI

6 December, 2022

UAE CHAPTER

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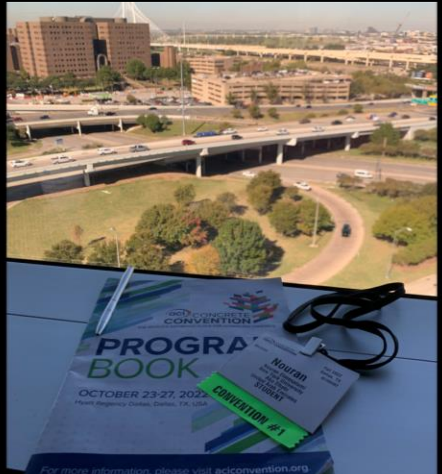
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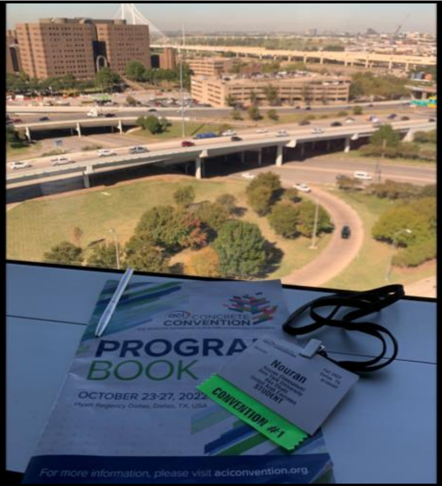
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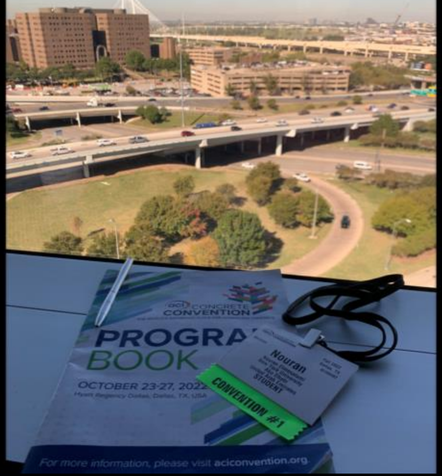
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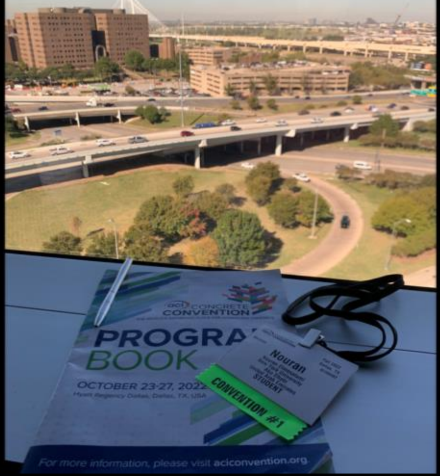
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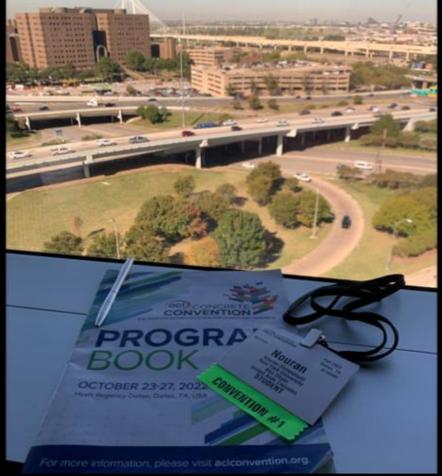
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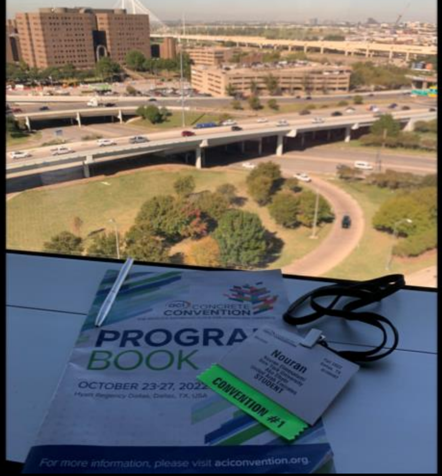
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Benefits:

- $5,000 - $15,000 USD educational stipend;
- Appropriate recognition in Concrete International magazine and on the Foundation website;
- Paid travel expenses and attendance fees to two ACI conventions; and
- Assistance in finding an industry mentor.

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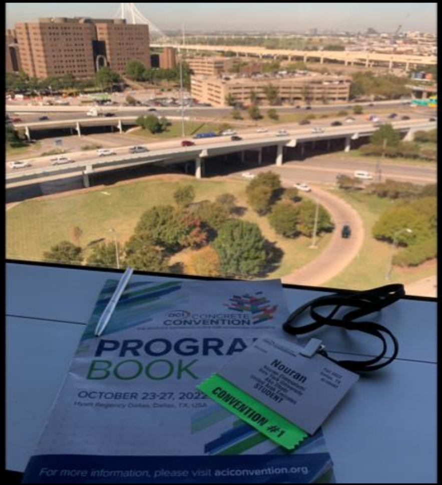

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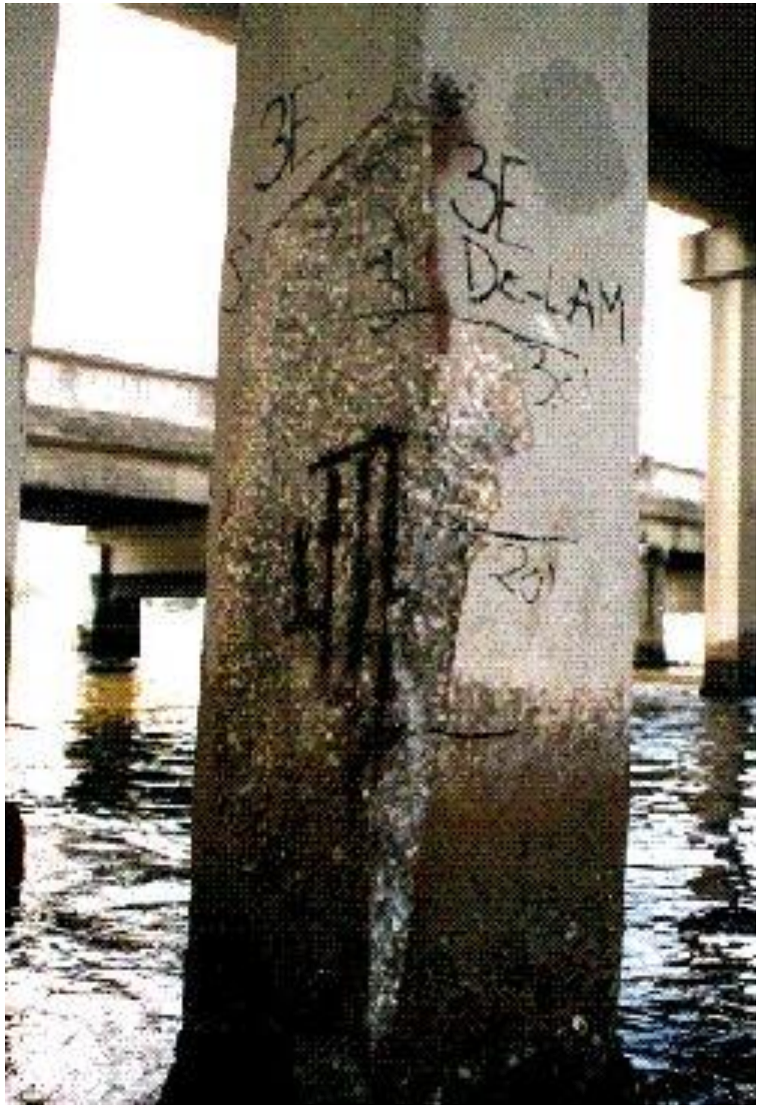
Part II

Fiber-Reinforced Polymer Bars as Compression Reinforcements

Fiber-Reinforced Polymer Rebars

- Results
- Experiments
- Properties
- Motive



Some solutions

- Epoxy coated rebars
- Galvanized rebars
- Powder resin coatings
- Polymer-impregnated concrete
- Alloyed steel bars

Hartt, W. H., Powers, R. G., Lysogorski, D. K., Liroux, V., Virmani, Y. P. (2007). *Corrosion Resistant Alloys for Reinforced Concrete* (Report no. FHWA-HRT-07-039). U.S. Department of Transportation – Federal Highway Administration. https://www.fhwa.dot.gov/publications/research/infrastructure/bridge/07039/index.cfm#toc

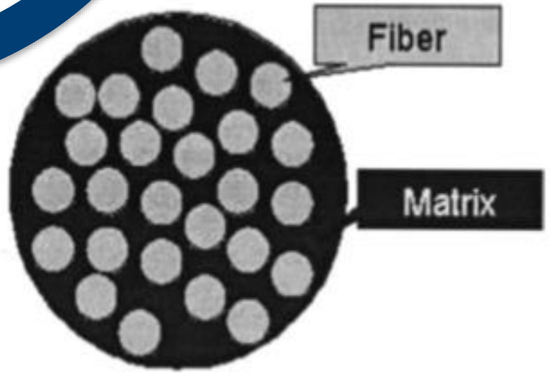
Broomfield, J. P. (2020). *The Corrosion of Steel in Concrete – Basic Understanding, Monitoring and Corrosion Control Methods: Guides to Good Practice in Corrosion Control No. 9.* National Physical Laboratory. https://www.npl.co.uk/getattachment/research/electrochemistry/corrosion-guides/corrosion-of-steel-in-concrete-gpg-9.pdf.aspx?lang=en-GB

Hollaway, L. C. (2003). The evolution of and the way forward for advanced polymer composites in the civil infrastructure. *Construction and Building Materials*, *17*(6-7), 365-378.

American Concrete Institute. Committee 440. (2015). Guide for the Design and Construction of Concrete Reinforced with FRP Bars: ACI 440.1 R-15. American Concrete Institute.

First considered as concrete reinforcements in the 1960s

Consist of high strength fibers embedded in a polymer resin



Hollaway, L. C. (2003). The evolution of and the way forward for advanced polymer composites in the civil infrastructure. *Construction and Building Materials*, *17*(6-7), 365-378.

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Nasvik, J., 2016. *Basalt Fiber Reinforced Rebar*. [online] For Construction Pros. Available at: <https://www.forconstructionpros.com/concrete/equipment-products/article/12184173/basalt-fiber-reinforced-rebar> [Accessed 30 April 2021].

Uomoto, T., Mutsuyoshi, H., Katsuki, F., & Misra, S. (2002). Use of fiber reinforced polymer composites as reinforcing material for concrete. *Journal of materials in civil engineering*, *14*(3), 191-209.

Some Properties of FRP Bars

- Non-corrosive
- Lighter in weight than steel bars
- Lower modulus of elasticity than steel bars
- Low compressive strength
- Higher tensile strength than steel bars
- Brittle (linear stress-strain to failure)
- Anisotropic

Hollaway, L. C. (2003). The evolution of and the way forward for advanced polymer composites in the civil infrastructure. *Construction and Building Materials*, *17*(6-7), 365-378.

American Concrete Institute. Committee 440. (2015). Guide for the Design and Construction of Concrete Reinforced with FRP Bars: ACI 440.1 R-15. American Concrete Institute.

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Review

Fiber-reinforced polymers bars for compression reinforcement: A promising alternative to steel bars

Check for updates

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[c] Department of Civil Engineering, American University of Sharjah, University City, PO Box 26666, Sharjah, United Arab Emirates

HIGHLIGHTS

- Previous studies on compression members reinforced with FRP bars are critically reviewed.
- Factors affecting the performance of FRP-reinforced columns are highlighted.
- Research gaps are identified.
- Directions for future research are outlined.

ARTICLE INFO

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Columns
Compression
Ductility
Load-carrying capacity
Buckling

ABSTRACT

Fiber-reinforced polymers (FRP) have been introduced as alternative reinforcement for concrete members since decades. Nevertheless, current design codes prohibit the use of FRP bars as main reinforcement in compression members such as columns. Recently, several studies came into sight focusing on evaluating the compressive response of FRP-reinforced concrete (RC) columns. While many of these studies have praised the performance of FRP bars in RC columns, others conservatively neglected their contribution to the columns' capacities. The objective of this study is to present a comprehensive literature review on FRP-reinforced columns in order to better understand their performance under various loading conditions. To do so, the authors collected and analyzed the results of more than 300 tests published in 43 different experimental and analytical studies in the scientific literature. The collected columns were classified according to their slenderness, loading regime, cross sections, concrete type, and reinforcement. The design equations proposed by several authors to predict the load-carrying capacities of the tested columns were collected and assessed. The work presents a critical review of the existing research on

- For the same longitudinal reinforcement ratio, compared to steel-RC columns, FRP-RC columns:
  - Show 1.5% to 20% lower capacities under concentric loads
  - Show almost equal capacities at large load eccentricities

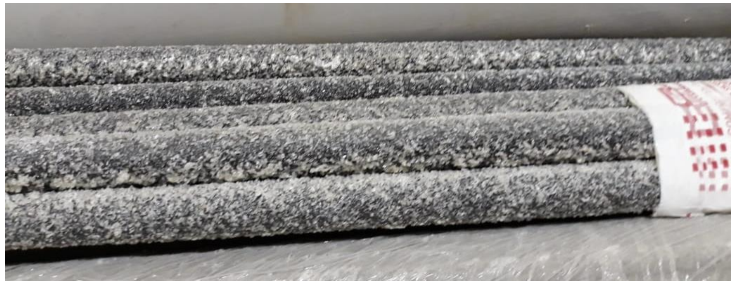
- Contribution of FRP bars to capacity of concentrically loaded columns:
  - **3% to 14%** for glass-FRP (GFRP) bars
  - **6% to 19%** for carbon-FRP (CFRP) bars

  compared to **12%–16%** for steel bars

- For eccentrically-loaded columns, some studies reported that FRP contribution should be neglected, while other studies reported otherwise

1

Reinforcement



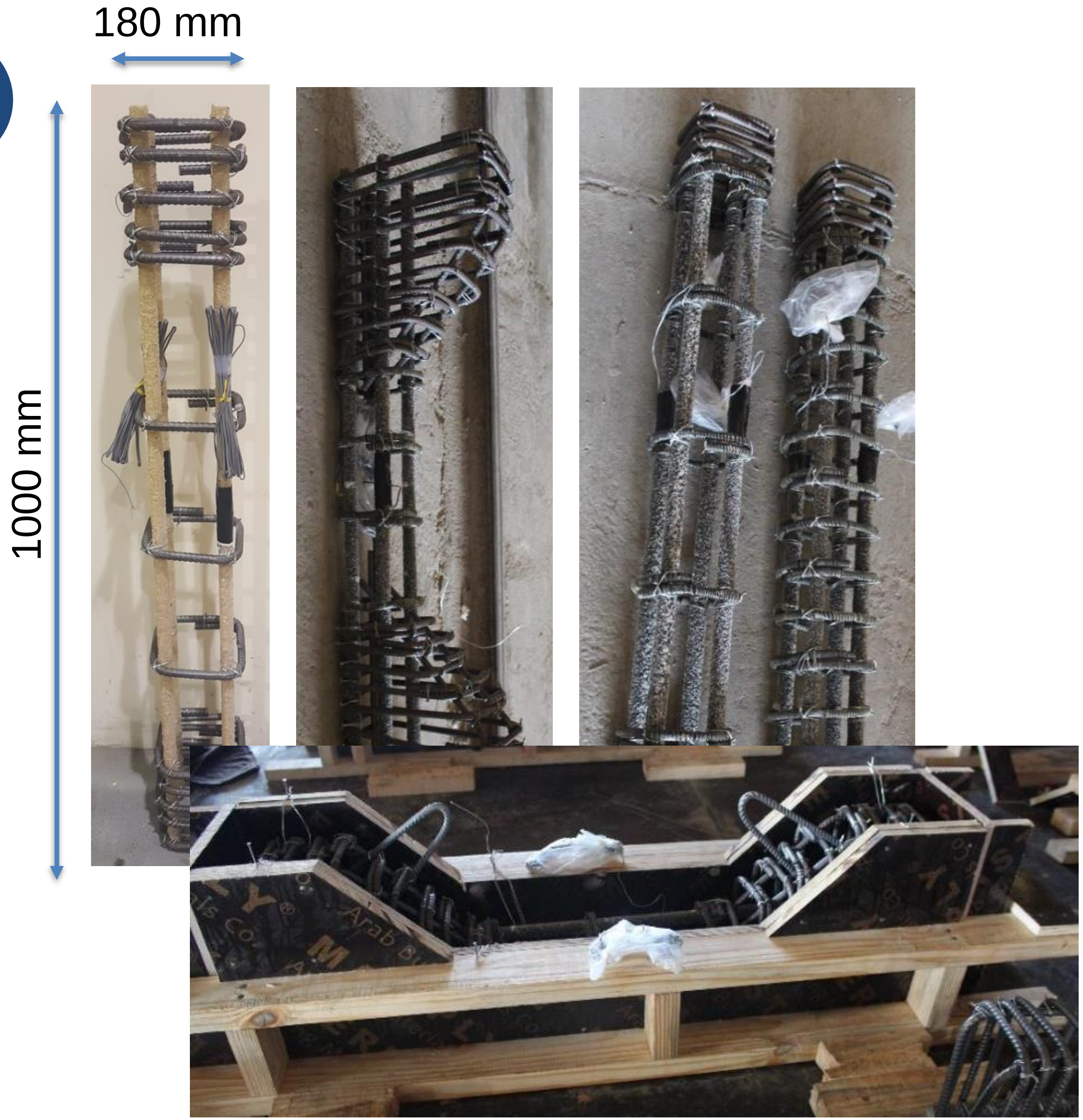
Basalt FRP (Φ=16 and 20 mm)

Glass FRP (Φ=16 mm)

Concrete

Normal strength OPC

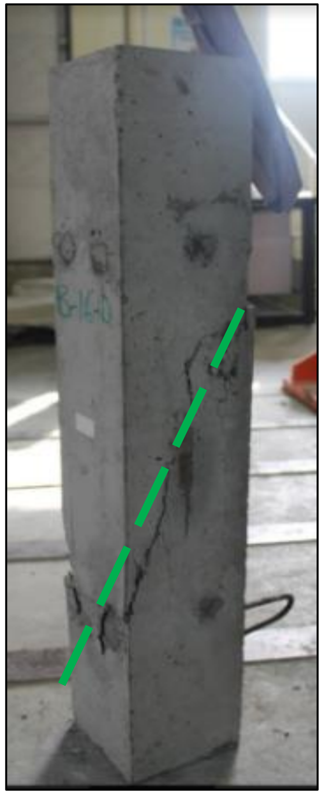
2

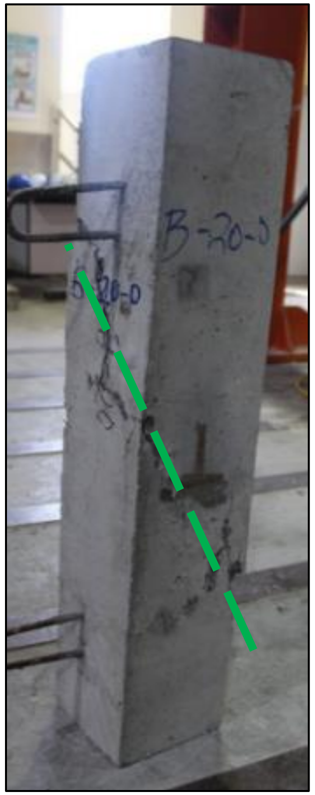


3

Concentrically-Loaded Columns

Column Reinforcement	Ultimate load capacity, P_u (kN)	Force carried by bars, P_{bars} (kN)	P_{bars} / P_u (%)
Steel	1305	409	**31.4**
Basalt FRP	1077	117	**10.9**
Glass FRP	1046	110	**10.5**
Basalt FRP (higher reinf. ratio)	1080	192	**17.8**





ANALYTICAL STUDY | Design Equations

For steel-RC columns under concentric load:

Concrete contribution — Steel contribution

$$P_o = 0.85f_c'(A_g - A_{st}) + f_y A_{st}$$

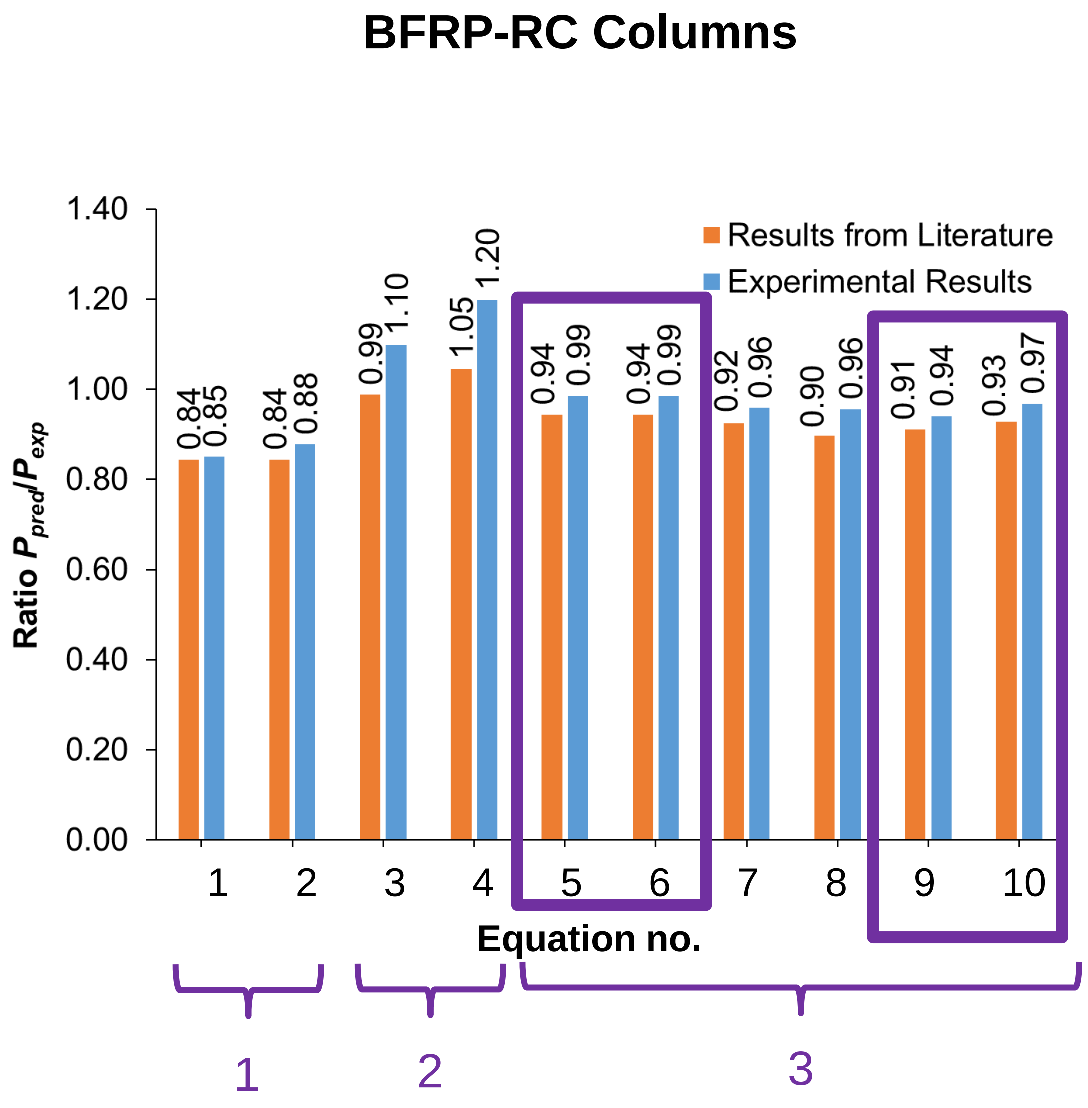
1. Neglect FRP contribution (Eq. 1–2)

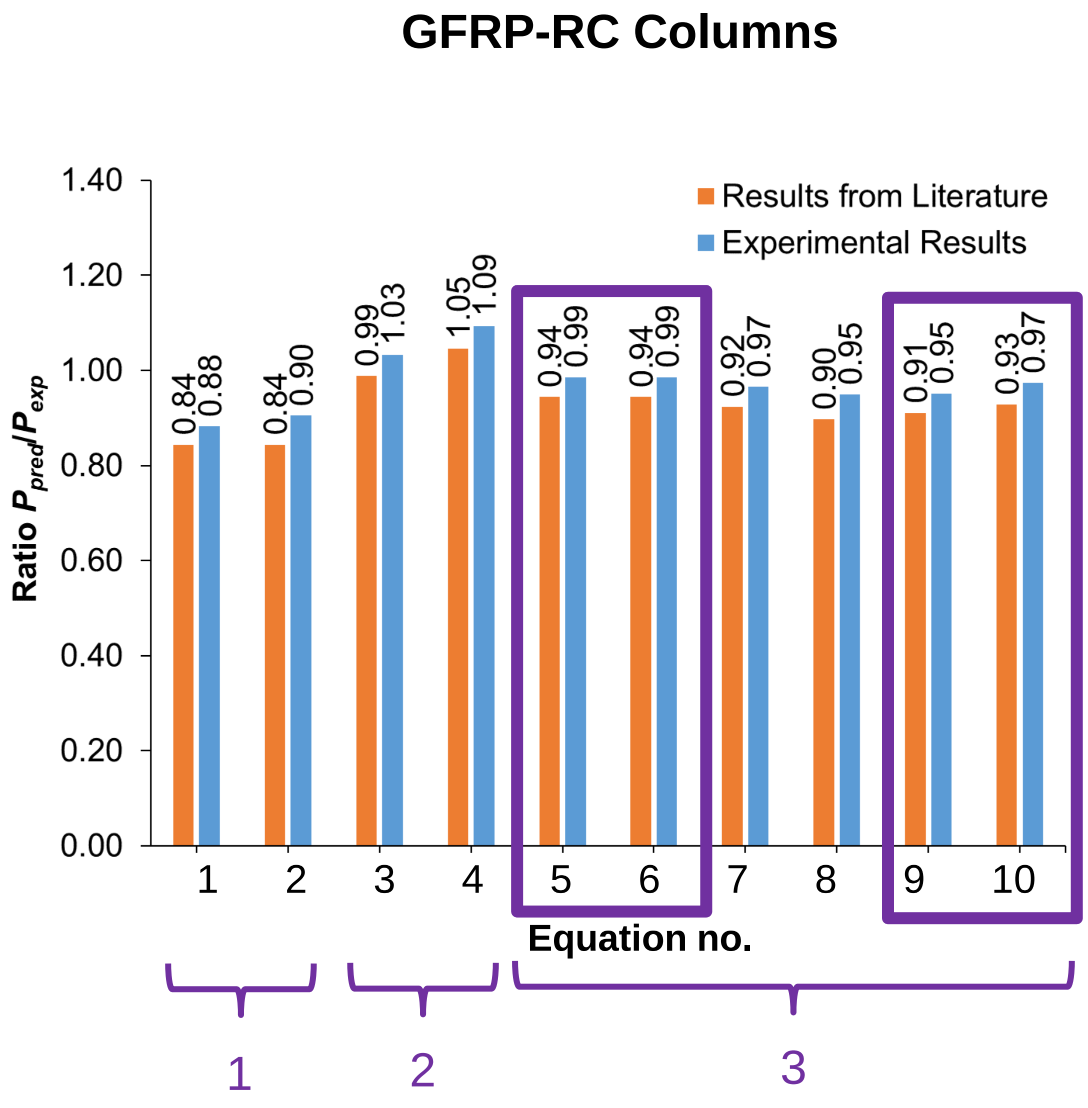
2. Reduced FRP contribution (Eq. 3–4)

3. Limit maximum compressive strain in FRP bars to concrete crushing strain (Eq. 5–10)

FRP-RC Columns Proposed Design Equations	Eq. no.
$P_{pred} = 0.85f_c'(A_g - A_f)$	1
$P_{pred} = 0.85f_c'A_g$	2
$P_{pred} = 0.85f_c'(A_g - A_f) + \mathbf{0.25f_{fu}A_f}$	3
$P_{pred} = 0.85f_c'(A_g - A_f) + \mathbf{0.35f_{fu}A_f}$	4
$P_{pred} = 0.85f_c'(A_g - A_f) + \boldsymbol{\varepsilon_c E_f A_f}$	5
$P_{pred} = 0.85f_c'(A_g - A_f) + \mathbf{0.003E_fA_f}$	6
$P_{pred} = 0.85f_c'(A_g - A_f) + \mathbf{0.0024E_fA_f}$	7
$P_{pred} = 0.85f_c'(A_g - A_f) + \mathbf{0.0035E_fA_f}$ $(\alpha_1 = 0.85 - 0.0015f_c' \geq 0.67)$	8
$P_{pred} = 0.85f_c'(A_g - A_f) + \mathbf{0.002E_fA_f}$	9
$P_{pred} = 0.85f_c'(A_g) + \mathbf{0.002E_fA_f}$	10

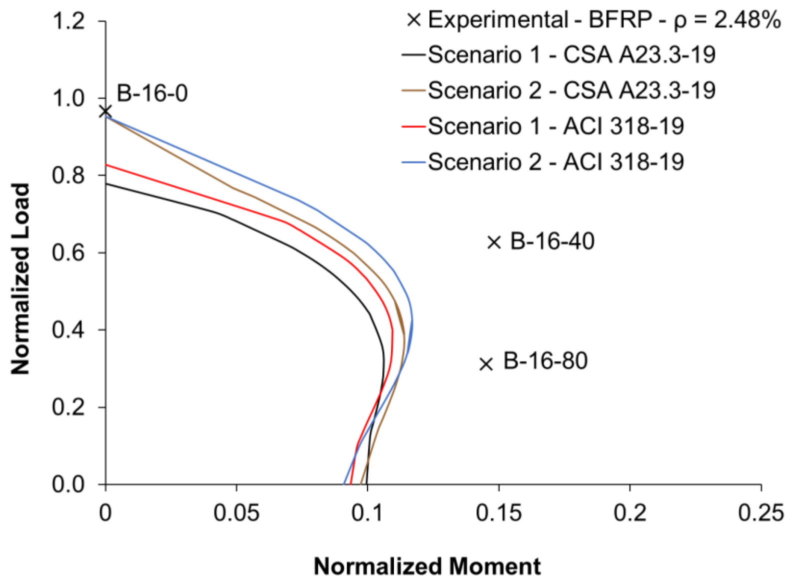
ANALYTICAL STUDY | Design Equations



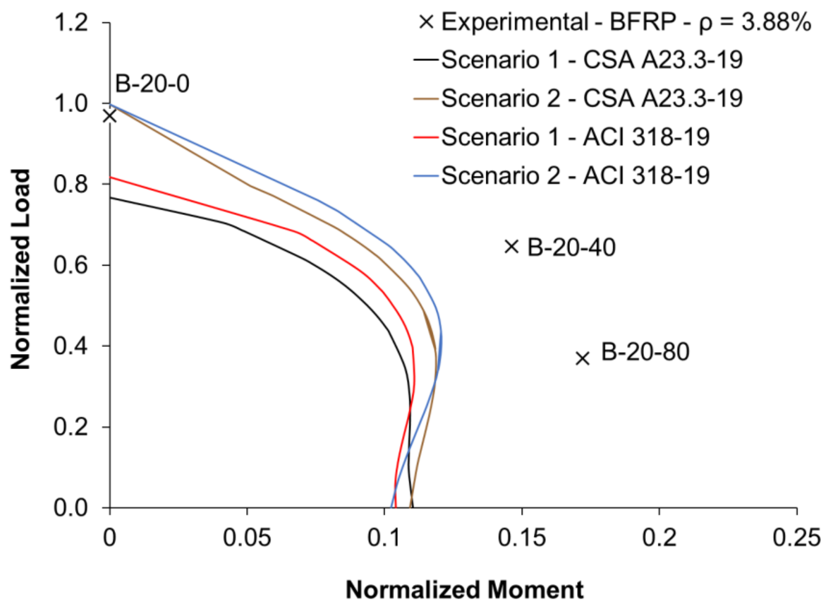


ANALYTICAL STUDY | Load-Moment Interaction Diagrams

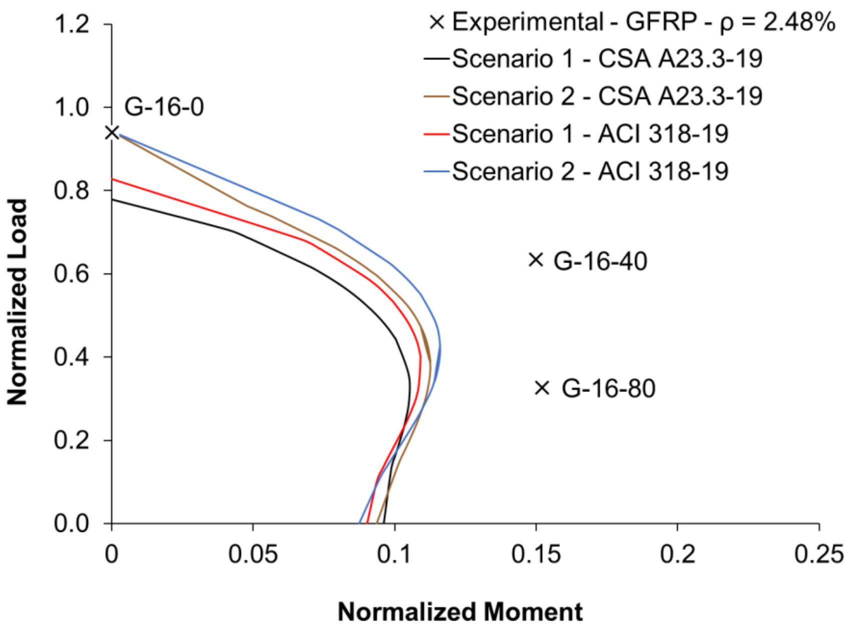
Scenario 1: ignores FRP bars contribution
Scenario 2: considers FRP bars contribution



BFRP-RC, ρ = 2.48%
(Group B)



BFRP-RC, ρ = 3.88%
(Group D)



GFRP-RC, ρ = 2.48%
(Group C)

Conclusions

Check for updates

ASCE

Concrete Columns Reinforced with GFRP and BFRP Bars under Concentric and Eccentric Loads: Experimental Testing and Analytical Investigation

Nouran Elmesalami[1]; Farid Abed, F.ASCE[2]; and Ahmed El Refai[3]

Abstract: Twelve concrete columns reinforced longitudinally with fiber-reinforced polymer (FRP) bars were tested under both concentric and eccentric loadings. The investigated parameters were the type of the FRP bar, the longitudinal reinforcement ratio, and the load eccentricity-to-width ratio. The test results showed that the columns reinforced with basalt-FRP (BFRP) and glass-FRP (GFRP) experienced similar load-carrying capacity with a difference of less than 5%. Both types of columns attained lower ultimate capacity than their steel-reinforced counterparts. The contribution of the GFRP and BFRP bars to the ultimate capacity of the columns was similar, approximately 11% of the capacity, as compared to 31% for the steel bars. The effect of increasing the reinforcement ratio on the capacity was more pronounced in the eccentric FRP-reinforced concrete (FRP-RC) columns than the concentric ones. The analytical investigation showed that ignoring the strength contribution of the FRP bars, as recommended by most of the current codes and design guidelines, would result in conservative predictions. It also showed that current Canadian design code recommendation limiting the strains in FRP bars in compression to 2,000 με yielded reasonable predictions of the column capacity. **DOI:** 10.1061/(ASCE)CC.1943-5614.0001115.

Author keywords: Concrete columns; Concentric loading; Eccentric loading; Fiber-reinforced polymer; Basalt; BFRP; GFRP; Interaction diagrams.

- Maximum of 5% difference in load-carrying capacities between BFRP-RC and GFRP-RC columns
- Concentrically loaded BFRP-RC and GFRP-RC columns exhibited **17% and 20% less** capacity than steel-RC control columns, respectively
- FRP bars contributed about **11%** to the ultimate capacities of concentrically-loaded columns (lower than steel bars contribution of **31.4%**)
- Ignoring the strength contribution of FRP bars resulted in conservative capacity predictions
- The current Canadian highway design code (CSA S6-19) recommendation on limiting compression strains of FRP bars to **2,000 με** yielded reasonable predictions of FRP-RC columns capacity
- Strength contribution of FRP bars increased as load eccentricity increased, as was confirmed by interaction diagrams for FRP-RC columns

Part III

Reactive Magnesia Cements

Reactive Magnesia Cement

- Background
- Overview
- Ongoing Work

Introduction| Background

- Concrete is one of the most consumed materials on Earth; second only to water
- It is the most widely used construction material
- However, concrete is not environmentally-friendly because of Ordinary Portland Cement (OPC)
- OPC production alone accounts for 7% of global carbon emissions
- Solutions for low-carbon concretes:
  1. Use of alternative fuels to coal for OPC production
  2. Replacement of OPC with industrial by-products (supplementary cementitious materials)
  3. Replacement of OPC with alterative binders

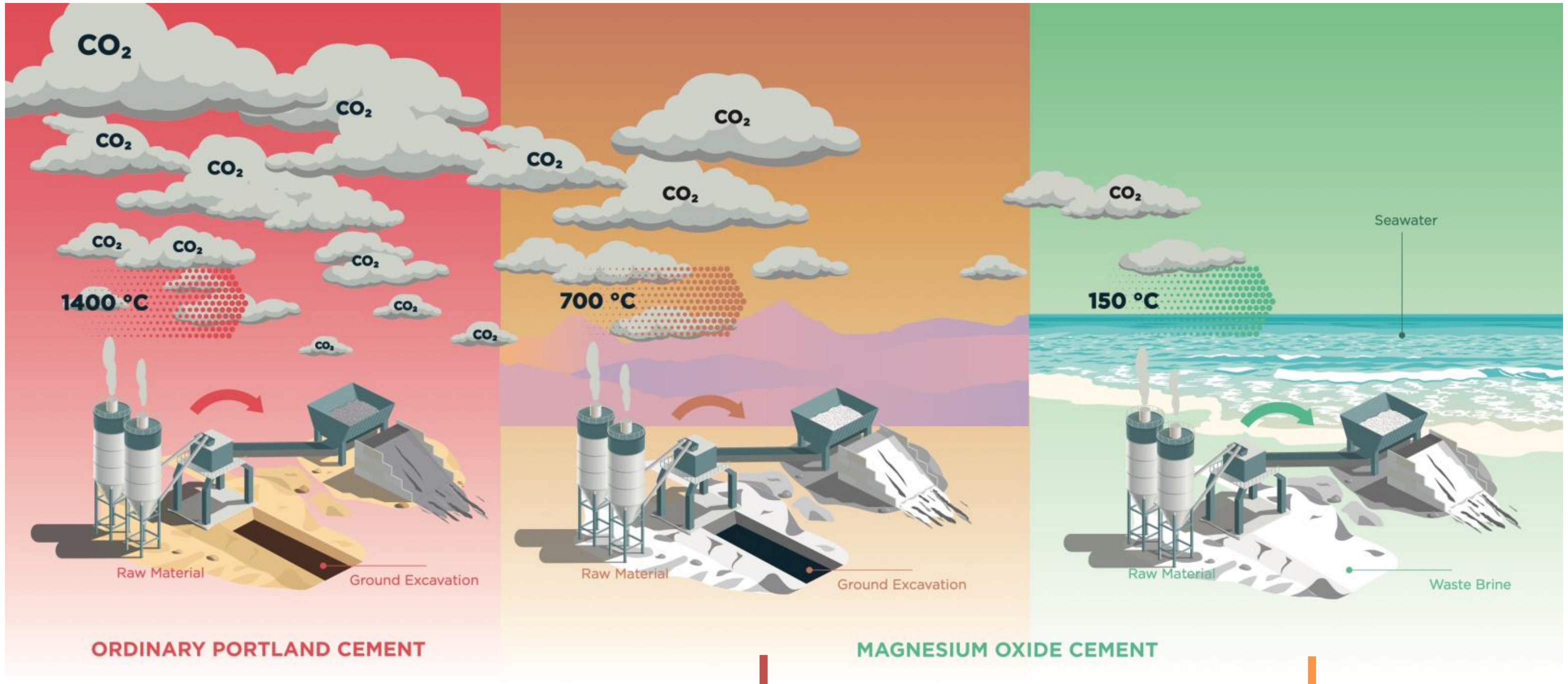
Sakai, K., & Noguchi, T. (2012). The sustainable use of concrete. CRC press.

Mehta, P. K., & Monteiro, P. J. (2014). Concrete: microstructure, properties, and materials. McGraw-Hill Education.

Fransen, T., Lebling, K., Weyl, D., & Kennedy, K. Toward a Tradable Low-Carbon Cement Standard: Policy Design Considerations for the United States.

Overview on Reactive MgO Cement

- ‘Reactive MgO cement’ (RMC) is a promising low or even negative carbon solution
- It is currently being produced by one of two ways:
    1. Calcination of $MgCO_3$
    2. From seawater



Calcination of naturally deposited $MgCO_3$

Processing brackish water from desalination plants

Walling, S. A., & Provis, J. L. (2016). Magnesia-based cements: a journey of 150 years, and cements for the future?. Chemical reviews, 116(7), 4170-4204.

Overview on Reactive MgO Cement

- RMC absorbs CO_2 through its hydration and carbonation processes:

$$MgO + H_2O \rightarrow Mg(OH)_2 \qquad \textbf{Hydration}$$

$$Mg(OH)_2 + CO_2 + 2H_2O \rightarrow MgCO_3.3H_2O \qquad \textbf{Carbonation}$$

- The resulting hydrated magnesium carbonates form cohesive binding agents
- RMC usually has higher water demand and lower compressive strength than OPC

Walling, S. A., & Provis, J. L. (2016). Magnesia-based cements: a journey of 150 years, and cements for the future?. Chemical reviews, 116(7), 4170-4204.

Some problems associated with RMC

Problems

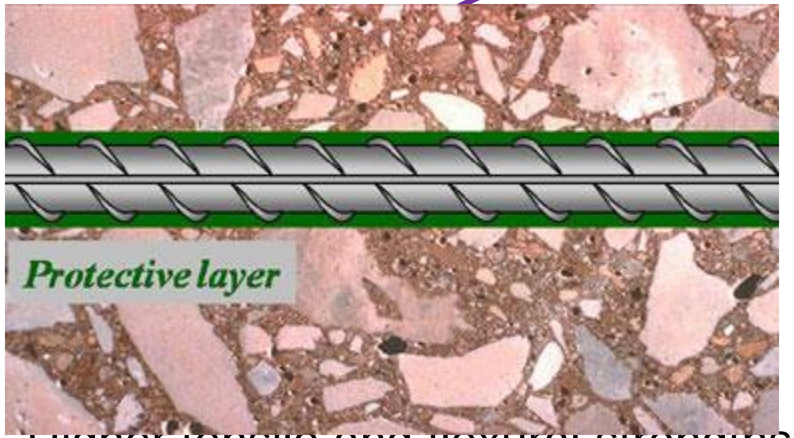
Hydration and carbonation of MgO lead to a larger unit volume

Induces cracking under restraint

low alkaline environment makes steel reinforcement vulnerable to loss of protective oxide layer

high risk of corrosion

Proposed Solutions



Higher tensile and flexural strengths, and crack mitigation

Restrict volume change, limit ingress of moisture and ions, and improve corrosion response

Material at micro level to improve its properties

Walling, S. A., & Provis, J. L. (2016). Magnesia-based cements: a journey of 150 years, and cements for the future?. Chemical reviews, 116(7), 4170-4204.

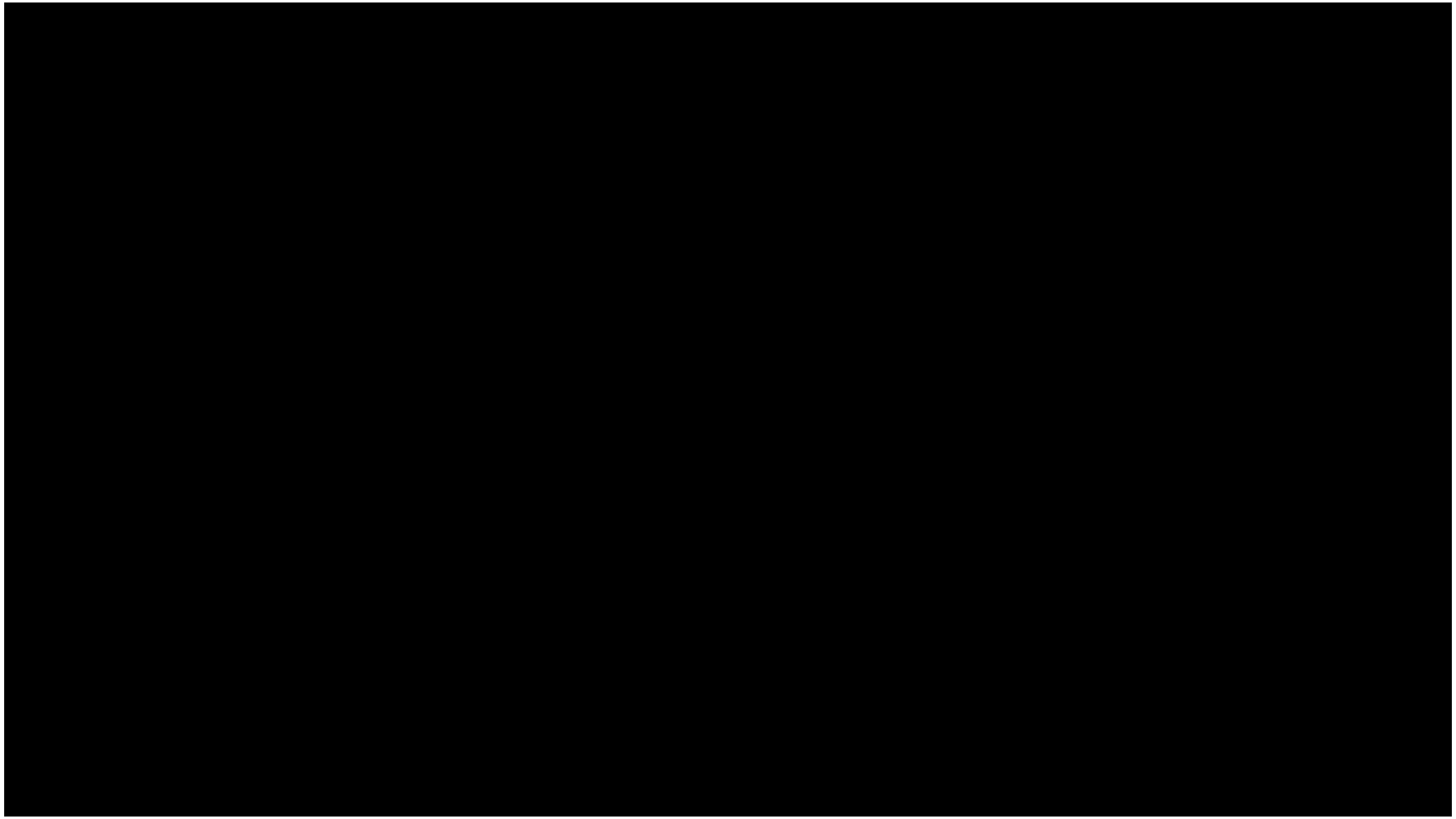
Portland Cement Association. 2021. *Corrosion of Embedded Materials*. [online] Available at: <https://www.cement.org/learn/concrete-technology/durability/corrosion-of-embedded-materials> [Accessed 30 April 2021].

Transmission Electron Microscope (TEM)

X-Ray Diffractometer (XRD)

Atomic Force Microscope (AFM)

TEM | In-situ experiments for hydration and carbonation reactions of RMC



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Talks Solar
Talks Stone Design
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Talks Urban Design & Landscape