Environmentally Friendly Pervious Concrete for Treating Deicer-Laden Stormwater (Phase I)

Final Report

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Problem Statement

- Stormwater control is a national priority since non-point sources continue to rank as leading causes of water pollution. Deicer stormwater is a new challenge.
- Pervious concrete is considered a successful Low Impact Development (LID) technology and has been increasingly used as a stormwater BMP for parking lots, sidewalks, and other applications.
- The production of Portland cement (the most common binder in concrete) is an energy-intensive process that accounts for a significant portion of global CO_2 emissions and other greenhouse gases.

Background

- Pervious concrete pavements reduce the quantity of stormwater runoff and improve its water quality by reducing total suspended solids, total phosphorous, total nitrogen, and metals.
- Previous studies show the possibilities of using fly ash as the sole cementitious binder to make concrete that has moderate strength.
- The utilization of nanotechnology to enable expanded use of waste and recycled materials is an unexplored area with great potential.

Project Objective

- Expand the use of industrial waste and recycled materials (such as fly ash and recycled glass) in pervious concrete (Phase I)

- Explore the potential of such "greener" pervious concrete for the treatment of deicer-laden stormwater under a variety of contaminant loading scenarios (Phase II)

Identify “Green” Constituents of Pervious Concrete

- ***Locally available fly ashes***

  serve as alternative binders

- ***Recycled glasses***

  serve as alternative fine aggregates

- ***Local black liquor from pulp plants***

  serve as alternative mixing water

Identify "Green" Constituents - Fly ash

Four types of locally available fly ashes were identified as:

- **WA "C" & "F" fly ash**

Centralia Coal Plant, Washington

- **OR "C" fly ash**

Boardman Coal Plant, Oregon

- **MT "C" fly ash (control group)**

Identify "Green" Constituents - Recycled Glass & Black Liquor

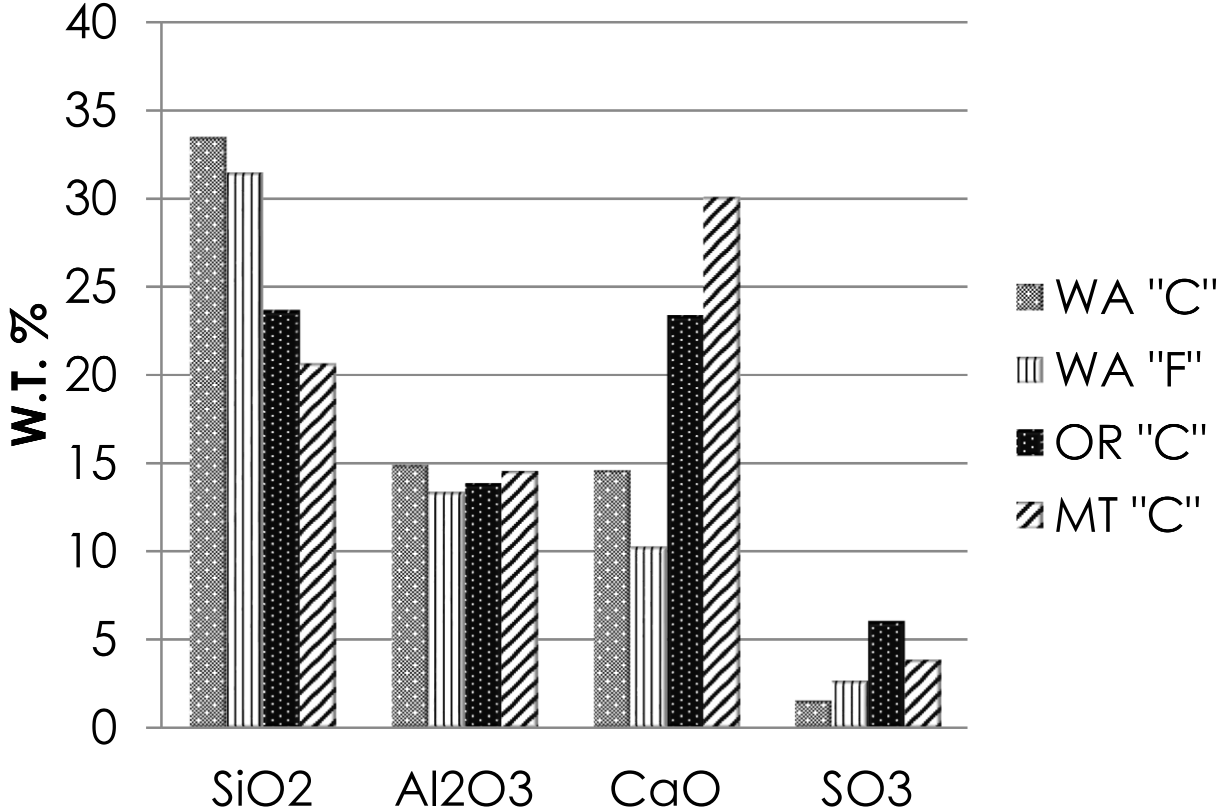
- **Recycled glass**

One commercially available glass powder

- **Black liquors from pulp plants**

Clearwater pulp plant at Lewiston, ID

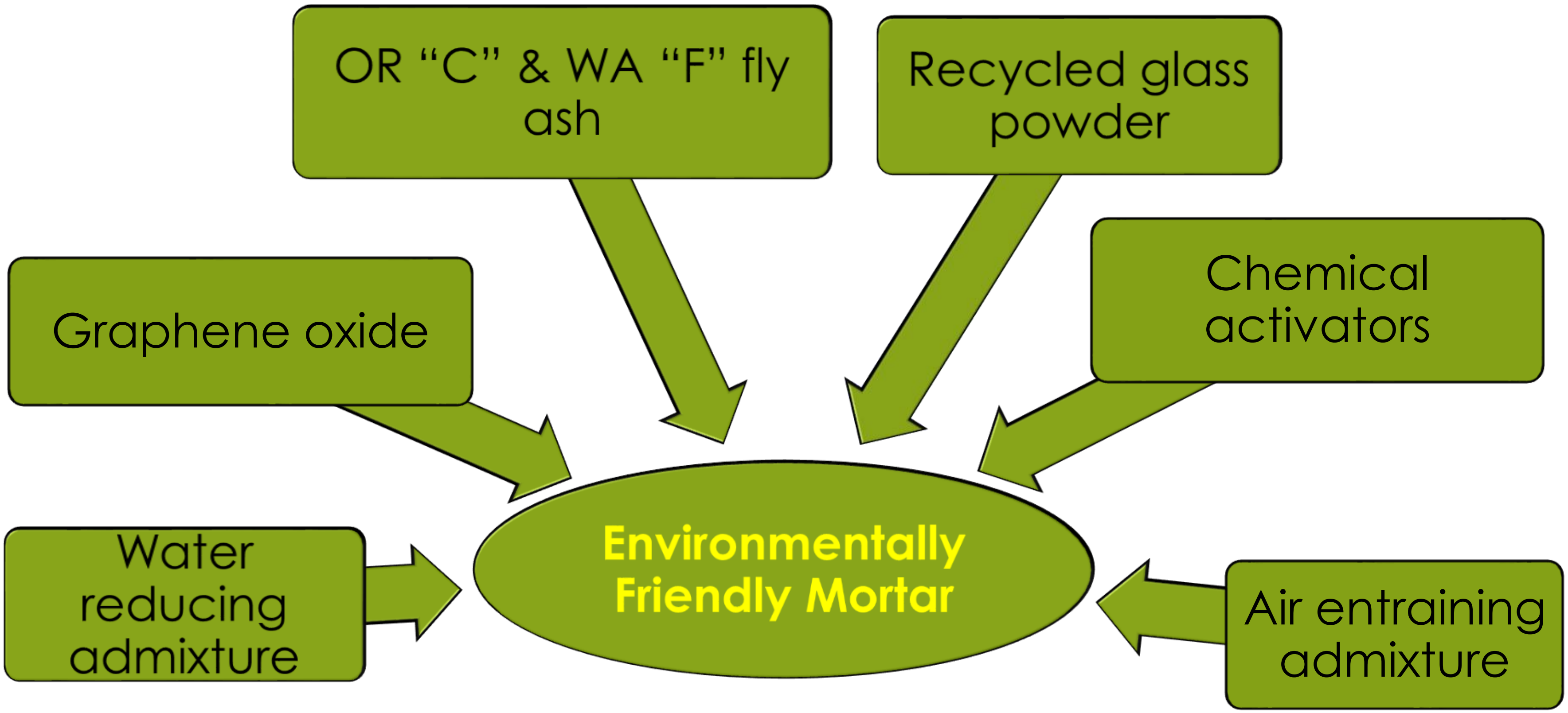
Evaluate "Green" Constituents - Fly ash



Comparison of key contents in fly ash

Pervious Concrete Constituents

- **Evaluate the identified fly ashes as cementitious binder**



Evaluate "Green" Constituents

❑ **Experiment by using uniform design scheme**

5 Factors at 3 Levels

- Na_2SiO_3 to Class "C" fly ash ratio (X_1)
  - 1%
  - 3%
  - 7%
- Lime to Class "C" fly ash ratio (X_2)
  - 2%
  - 5%
  - 10%
- $CaCl_2$ to Class "C" fly ash ratio (X_3)
  - 0.5%
  - 1%
  - 2%
- Na_2SO_4 to Class "C" fly ash ratio (X_4)
  - 1%
  - 2%
  - 3%
- Water to Binder Ratio (X_5)
  - 0.28
  - 0.30
  - 0.32

Fabrication of “Green” Mortar

- ❑ **Sample (2”x4” cylinders) fabrication & testing**

Experimental Design (1)

- **Experiment results (total 27 groups; 324 samples)**

Table.2 28-day Compressive Strength of Mortars with Different Factor Levels

Run No.	Factor 1 (X_1)	Factor 2 (X_2)	Factor 3 (X_3)	Factor 4 (X_4)	Factor 5 (X_5)	f_c(psi) 28-day
1	Lev. 2	Lev. 2	Lev. 3	Lev. 2	Lev. 1	2787
2	Lev. 2	Lev. 2	Lev. 2	Lev. 2	Lev. 2	2988
…..	…..	…..	…..	…..	…..	
26	Lev. 3	Lev. 1	Lev. 3	Lev. 2	Lev. 3	2987
27	Lev. 3	Lev. 1	Lev. 2	Lev. 3	Lev. 2	3277

Experimental Results

❑ **Compression test results (total 27 groups; 324 samples)**

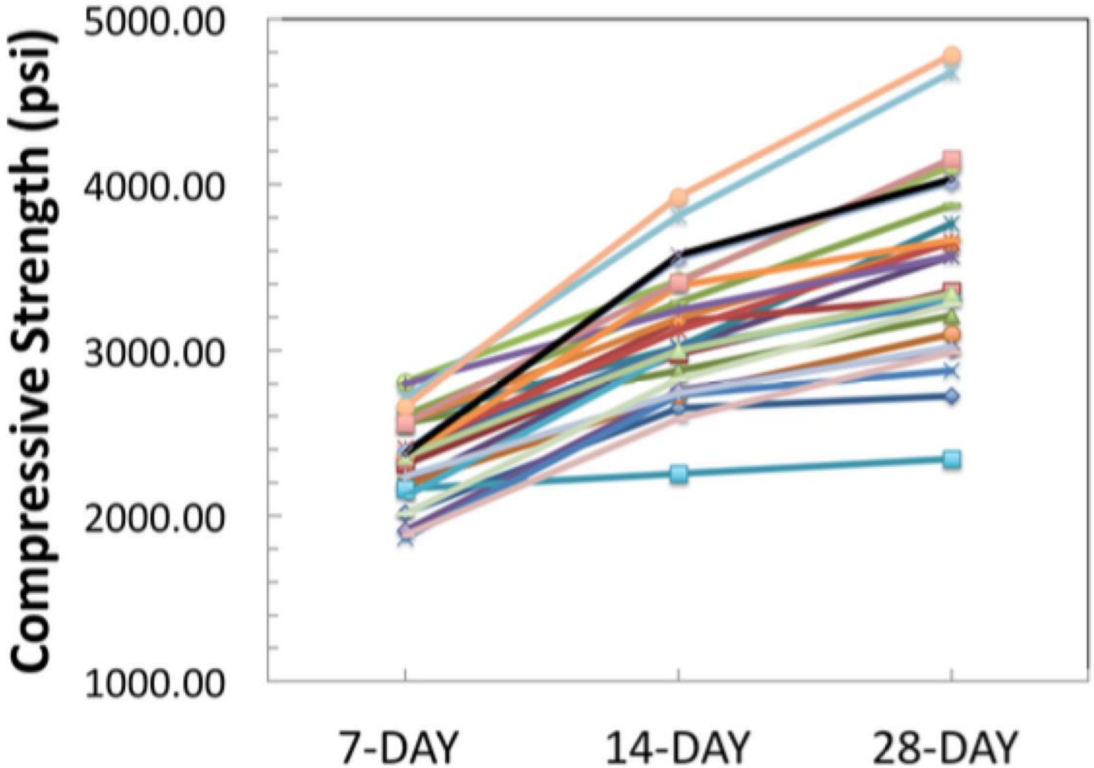


Figure.1 Compressive Strength of Mortars with Different Factor Levels

Experimental Results

- **Experiment results analysis by**
  ANOVA and regression techniques

7-day f_c (psi) = $2343 - 182.5 * X_1 + 108.2 * X_1X_2 + 230.5 * X_3X_5 + 308 * X_1X_2X_3$

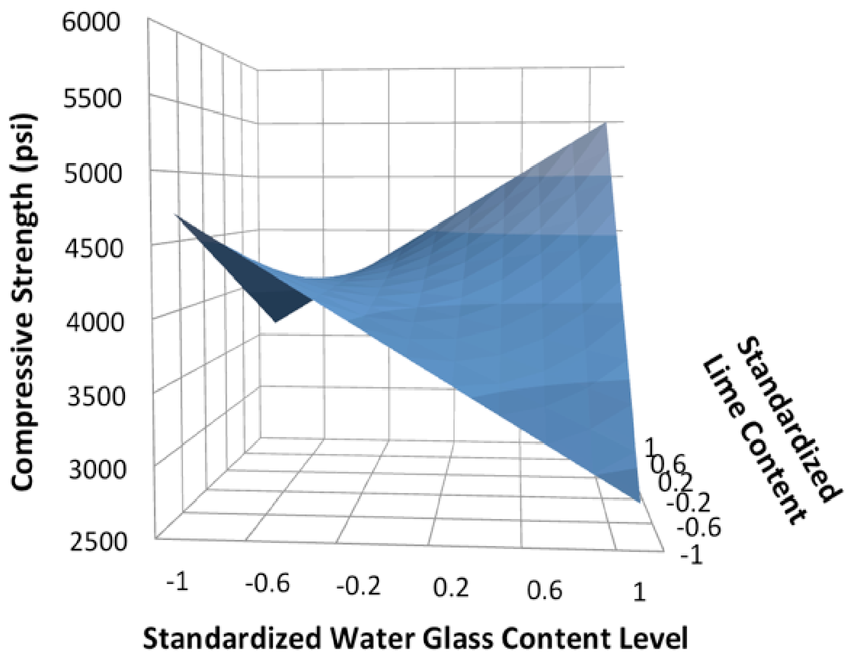
14-day f_c (psi) = $3068 + 227 * X_1X_2 + 344.6 * X_3X_5 + 626.7 * X_1X_2X_3 - 457.6 * X_2X_3X_4$

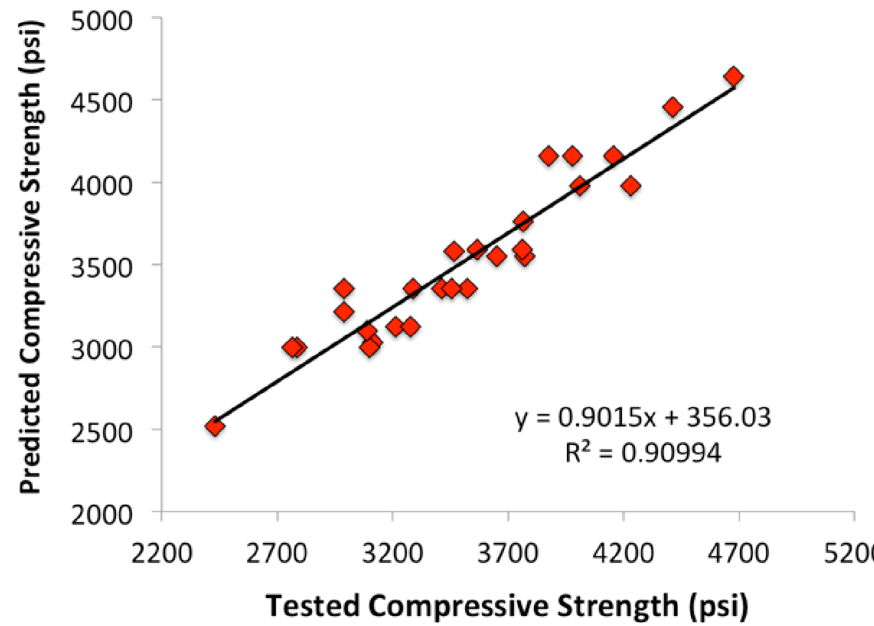
28-day f_c (psi) = $3356 + 223 * X_2^2 + 233.6 * X_1X_2 + 581.3 * X_3X_5 + 713.9 * X_1X_2X_3 - 397.1 * X_2X_3X_4$

compressive strength models

Experimental Results

❑ Model Visualization & Verification

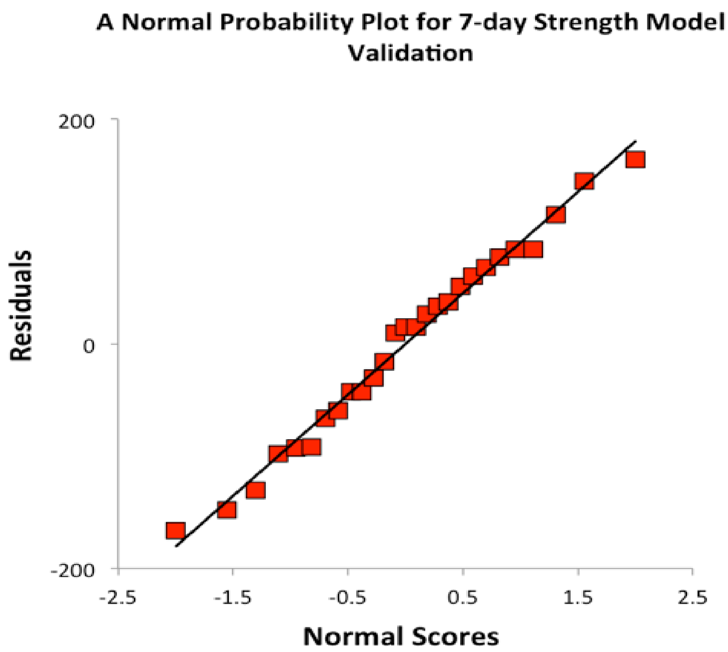




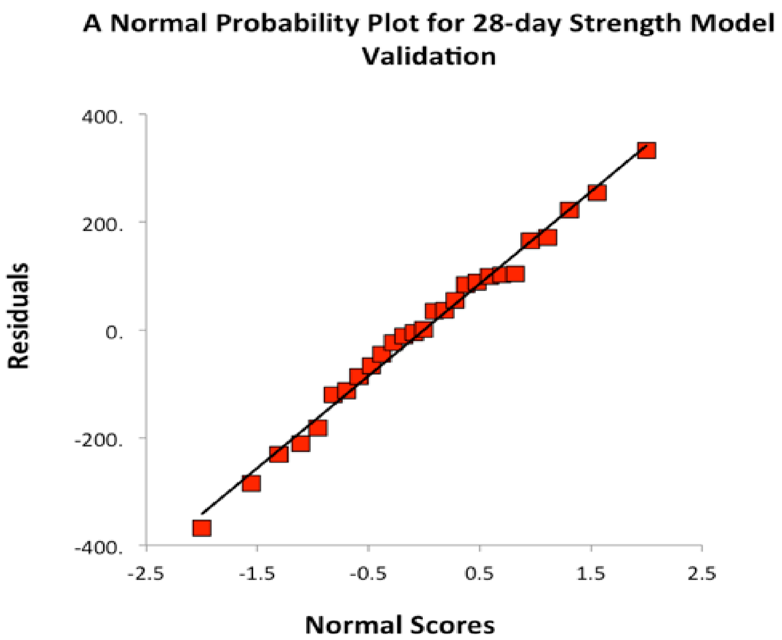
3D contour diagram of 28-day compressive strength model and model prediction vs. actual data

Experimental Results

❑ Model Errors



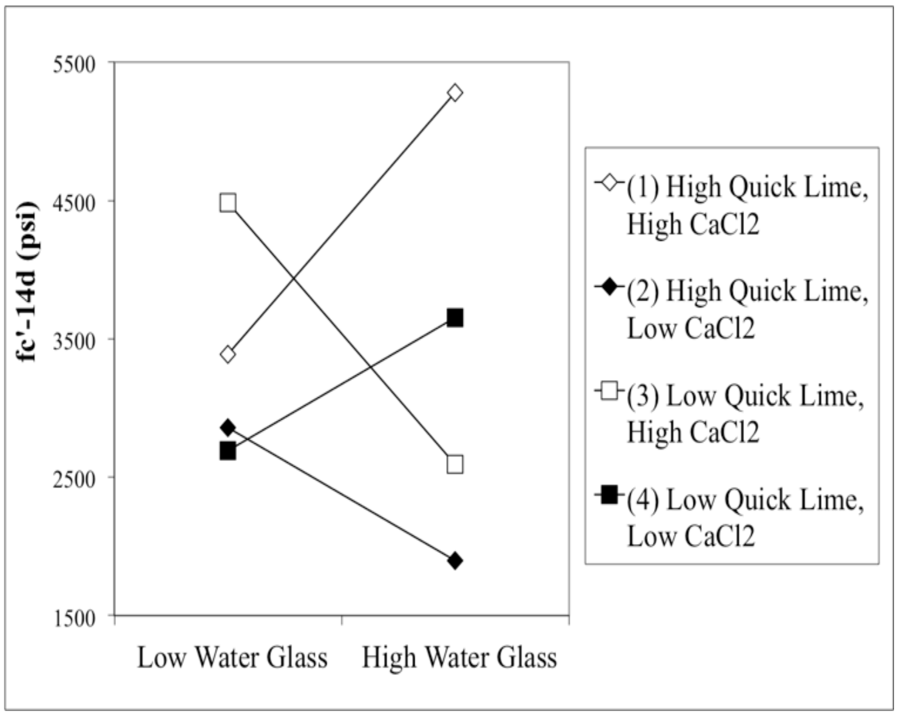
Normal probability plot for 7-day f'_c model



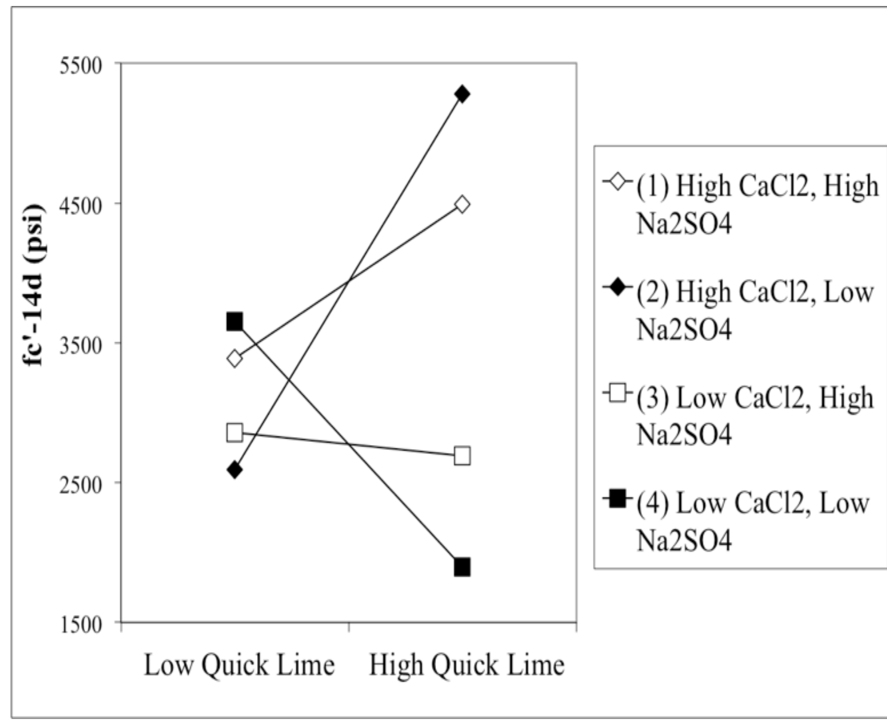
Normal probability plot for 28-day f'_c model

Experimental Results

❑ Synergetic effects of activators



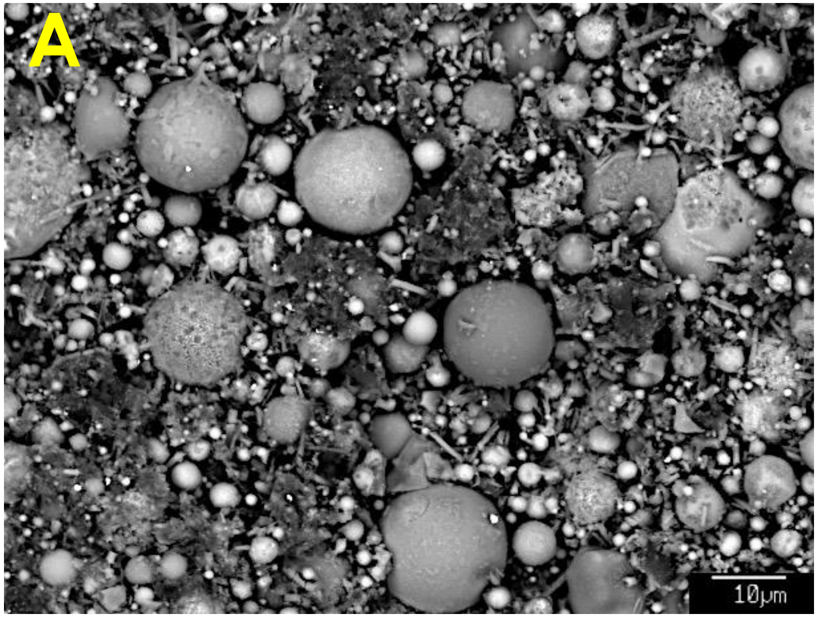
Synergetic effect of lime, $CaCl_2$ and water glass in 14-day *fc'* model

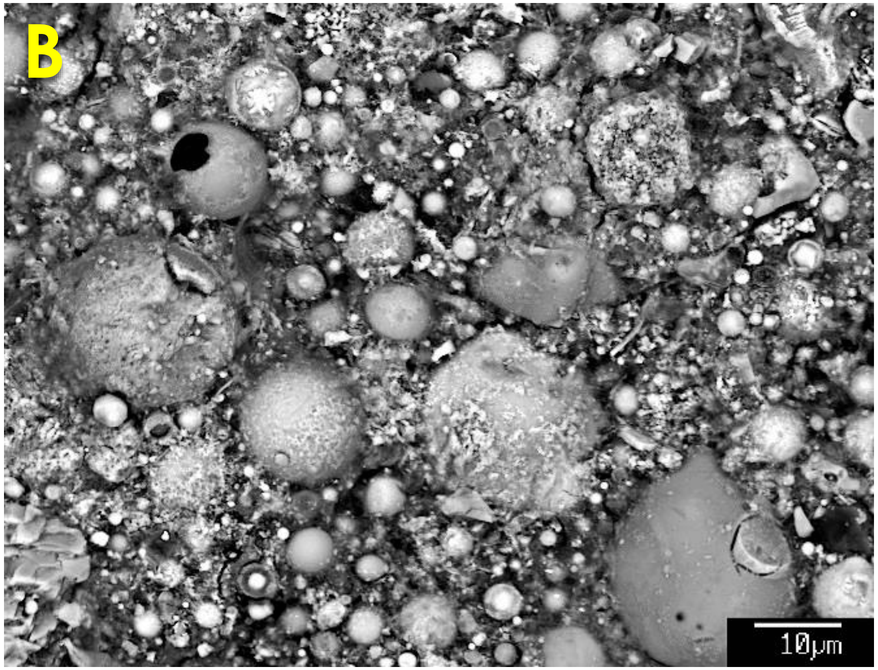


Synergetic effect of lime, $CaCl_2$ and Na_2SO_4 in 14-day *fc'* model

Microscopic Investigation

❑ Back-Scattered Electron (BSE) Analysis

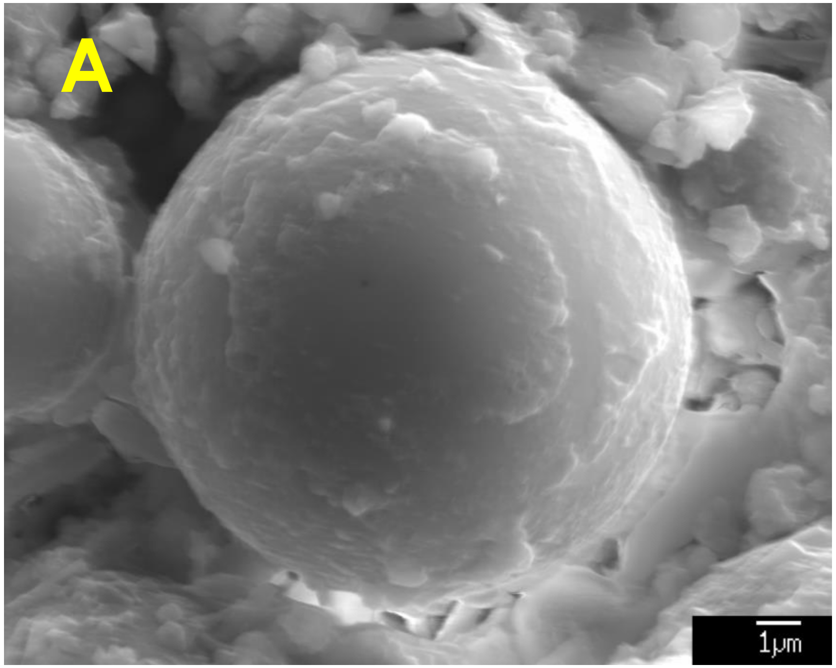


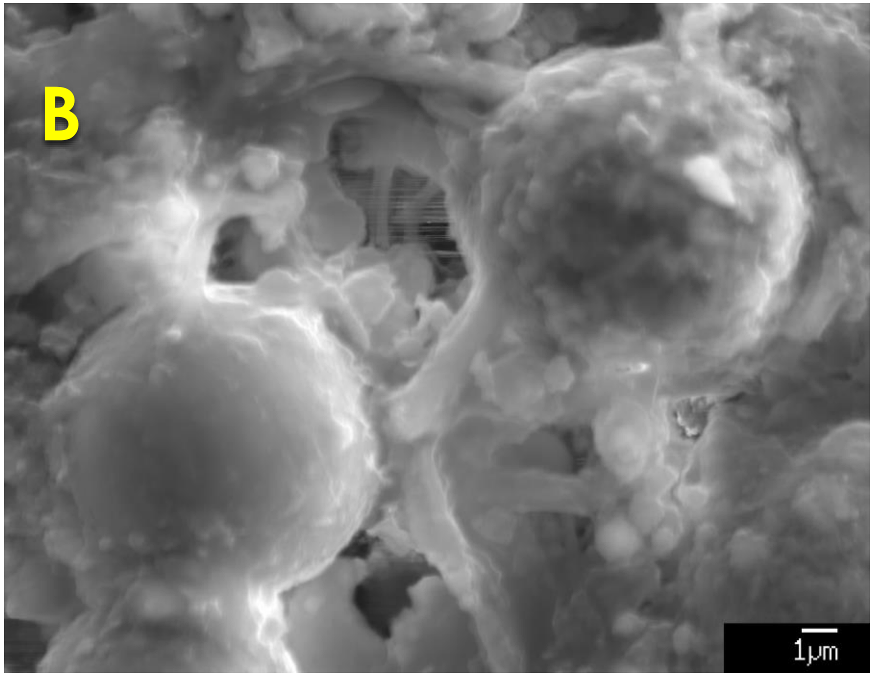


BSE micrograph of mortar surface cured for 28 days.
A) Mortar without activators.
B) Mortar with activators.

Microscopic Investigation

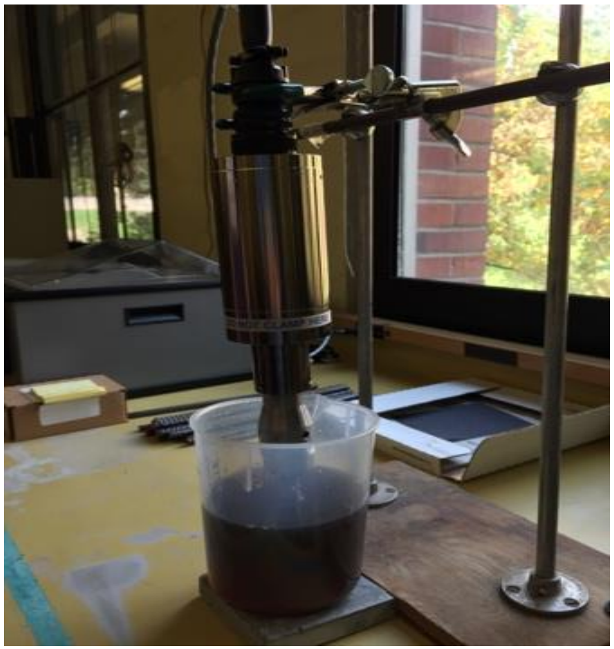
❑ Secondary Electron Imaging (SEI) Analysis



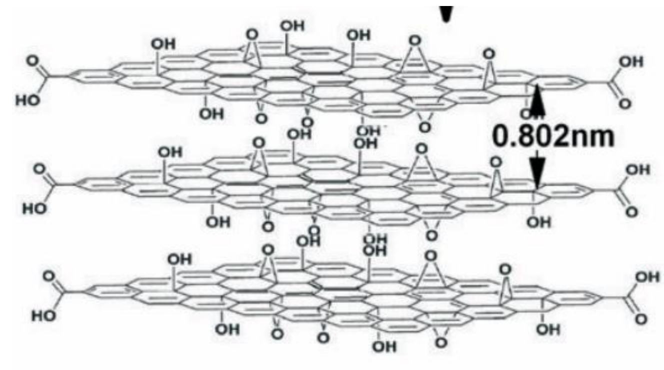


SEI micrograph of mortar surface cured for 28 days.
A) Mortar without activators.
B) Mortar with activators.

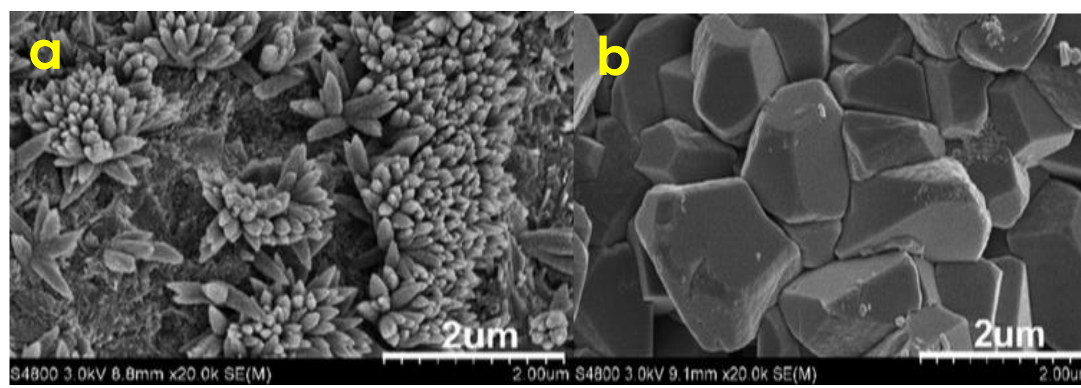
Graphene Oxide (GO) Modified Mortar



Ultrasonification of GO suspension

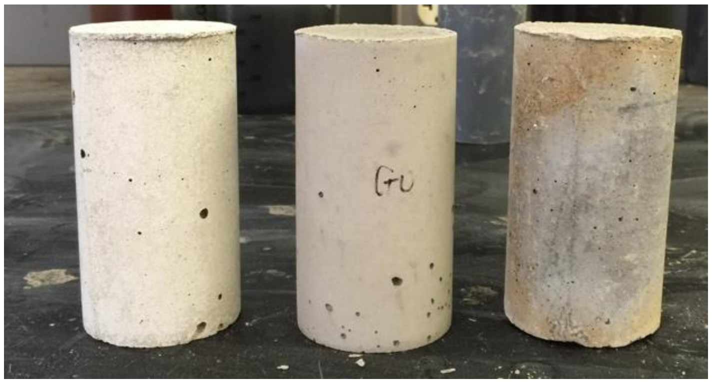


Molecular model of GO (Lv et al. 2014)



SEI image of cement hydrates at 7-days: (a) flower-like shape with 0.01% GO; (b) polyhedron-like shape with 0.05% GO (Lv et al. 2014)

Graphene Oxide (GO) Modified Mortar



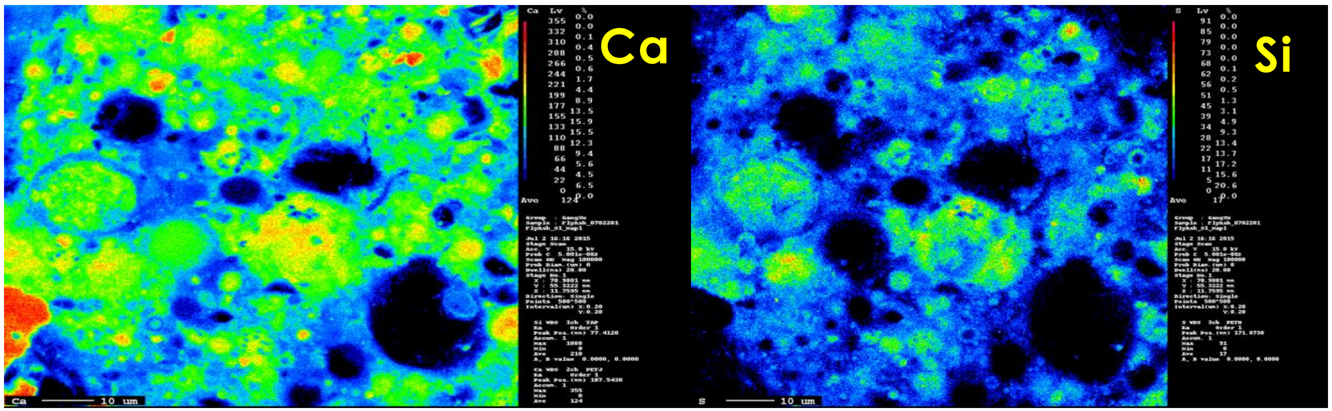
Mortar cylinders, 2 inch × 4 inch in size: cement mortar (left); GO-modified fly ash mortar (middle); fly ash mortar (right)

Table: Comparison of compressive strength

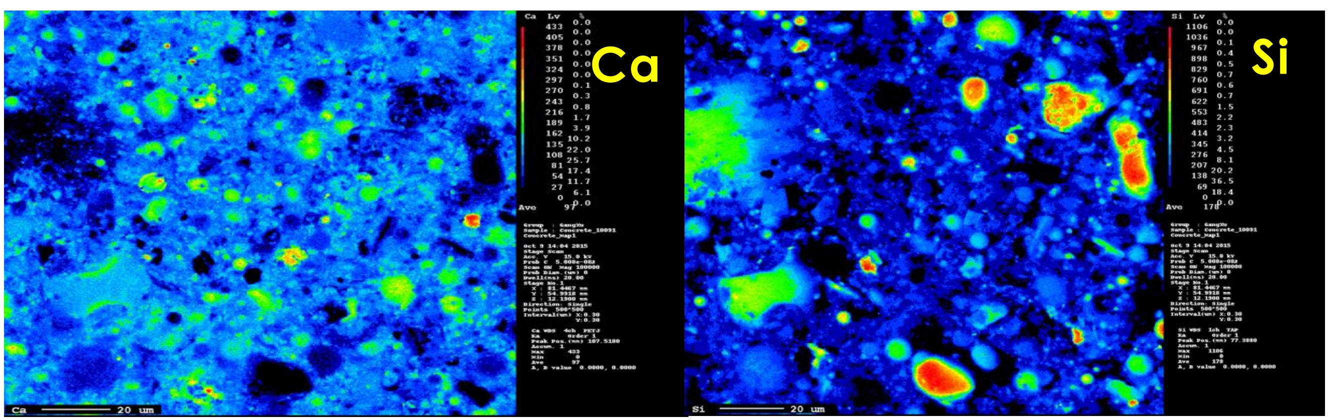
	0.03% GO-modified fly ash mortar	Regular fly ash mortar	Compressive strength increase
7-day f_c' (psi)	3353.2	2705.9	24%
14-day f_c' (psi)	4688.0	3721.1	26%
28-day f_c' (psi)	5998.2	4877.9	23%

Graphene Oxide (GO) Modified Mortar

❑ SEM/WDS Analysis (4)



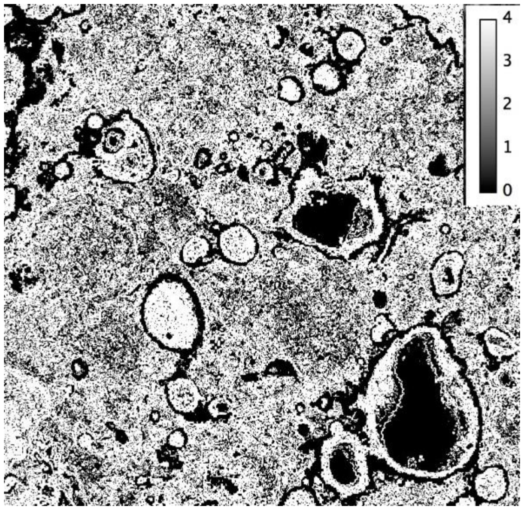
(a)



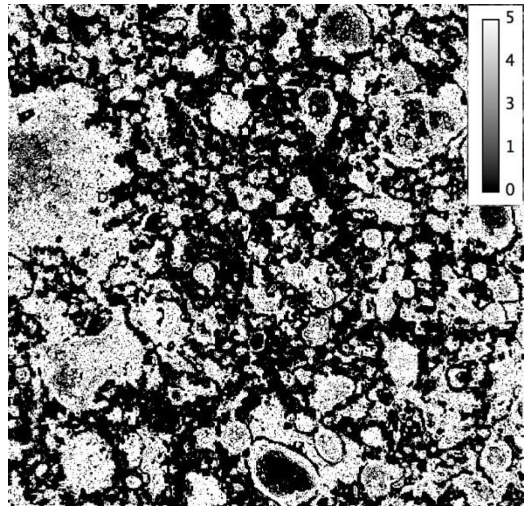
(b)

Element mapping (Ca and Si)
(a) mortar without GO;
(b) GO-modified mortar

Graphene Oxide (GO) Modified Mortar

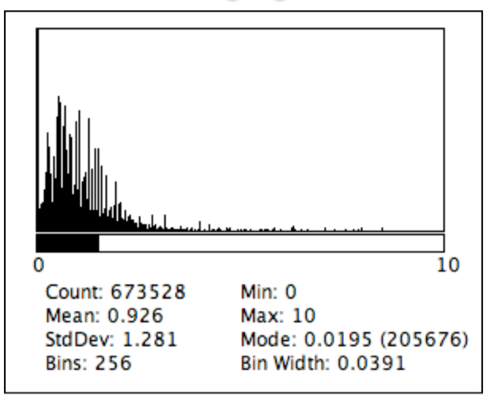


(a)

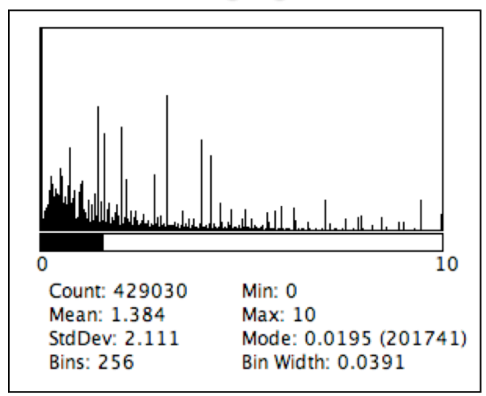


(b)

Ca/Si mole ratio mapping
(a) mortar without GO;
(b) GO-modified mortar



(c)



(d)

Histogram of Ca/Si
mole ratio mapping
(c) mortar without GO;
(d) GO-modified mortar

Function of GO in fly ash mortar

Evaluation Conclusion

- The increased average bulk Ca/Si ratio, from 0.926 to 1.384, by GO indicated that the addition of 0.03% GO could facilitate the leaching of Ca^{2+} from fly ash particles.

- GO nanosheets dispersed in fly ash paste act as growth points to form hydration products with a higher Ca/Si ratio due to GO's higher surface energy and template effect.

Develop Pervious Concrete with 100% Fly Ash

Mix Design	Agg. Size (inch)	Agg. (kg/m^3) [a/b]	Cement (kg/m^3)	Fly ash CFA1 (kg/m^3)	Water (kg/m^3) [w/b]	$NaSO_4$ (kg/m^3)	CaO (kg/m^3)	$CaCl_2$ (kg/m^3)	Water Glass (kg/m^3)	GO (g/100kg binder)	TEA (ml/100 kg binder)	HRWR (ml/100 kg binder)	AE (ml/100 kg binder)
Cement	3/8	1425 [4.45]	320	--	80 [0.25]	--	--	--	--	--	40	300	30
Cement + GO	3/8	1425 [4.45]	320	--	80 [0.25]	--	--	--	--	96	40	300	30
Fly ash	3/8	1435 [4.0]	--	358	97 [0.27]	3.6	17.9	3.6	25	--	40	1000	30
Fly ash + GO	3/8	1435 [4.0]	--	358	97 [0.27]	3.6	17.9	3.6	25	108	40	1000	30

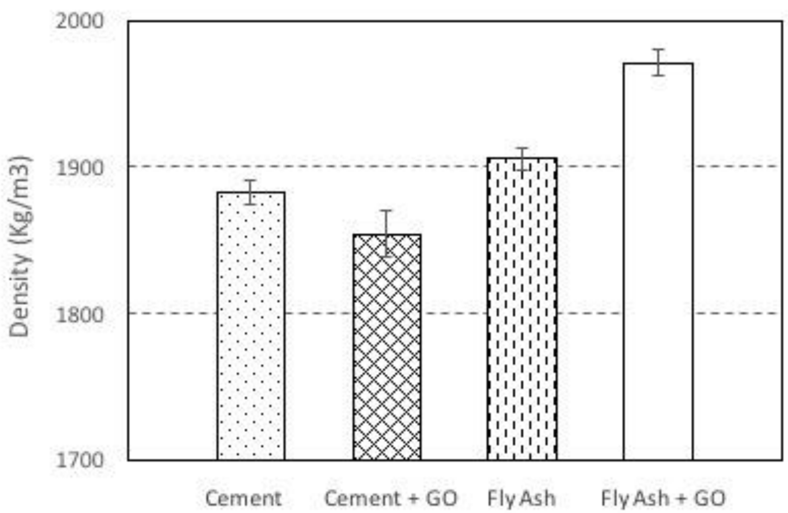
Fabrication of Pervious Concrete Samples

(a)

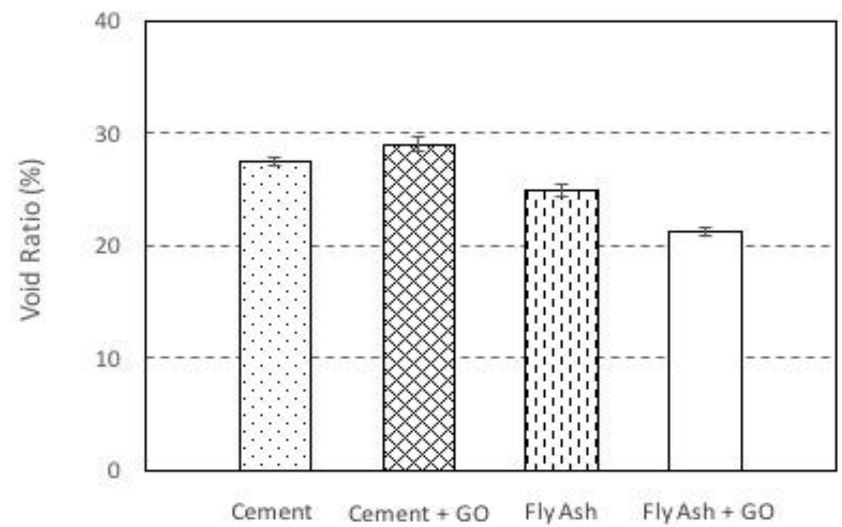
Pervious concrete 4X8 cylinders (left to right) cement, cement + GO, fly ash, fly ash + GO
(a): cylinders with capping
(b): Close-up view of surface

(b)

Tests – Density and Void Ratio

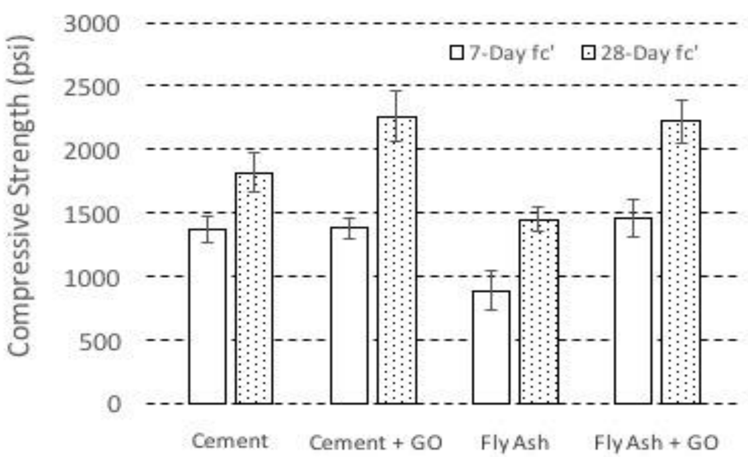


Density of hardened pervious concrete at 28 days

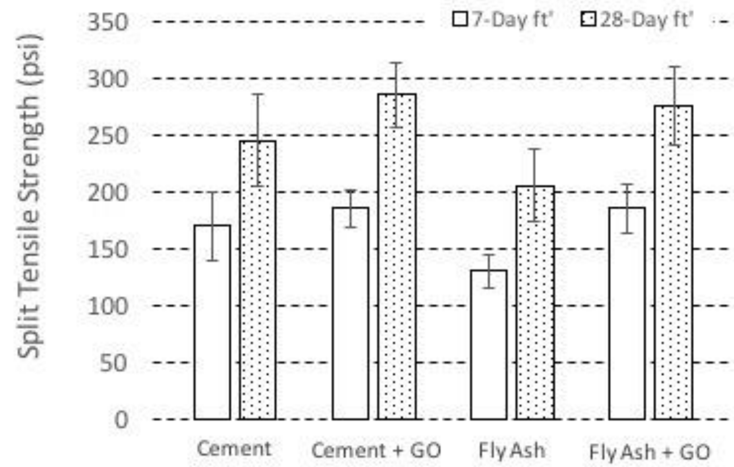


Void ratio of hardened pervious concrete at 28 days

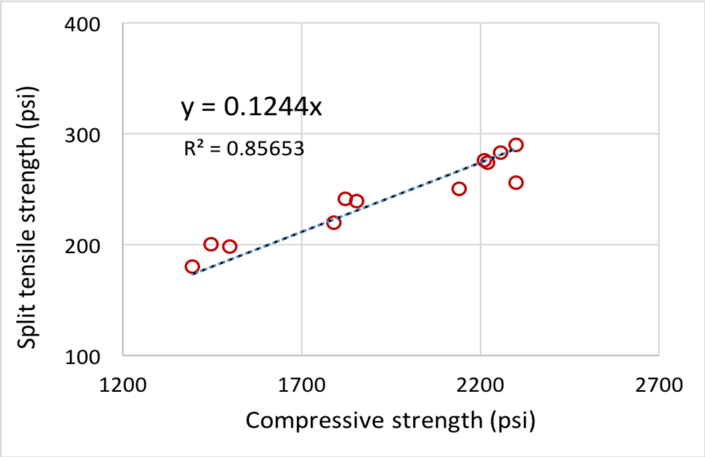
Tests – Compressive and Split Tensile Strength



Compressive strength test results

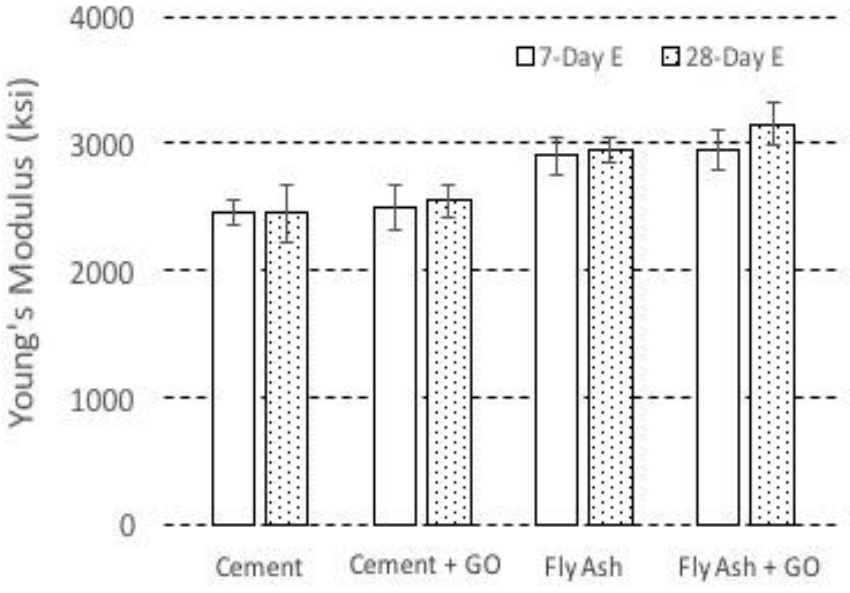


Split tensile strength test results



Relationship between split tensile strength and compressive strength at 28 days

Tests – Young’s Modulus



Young’s modulus of pervious concrete

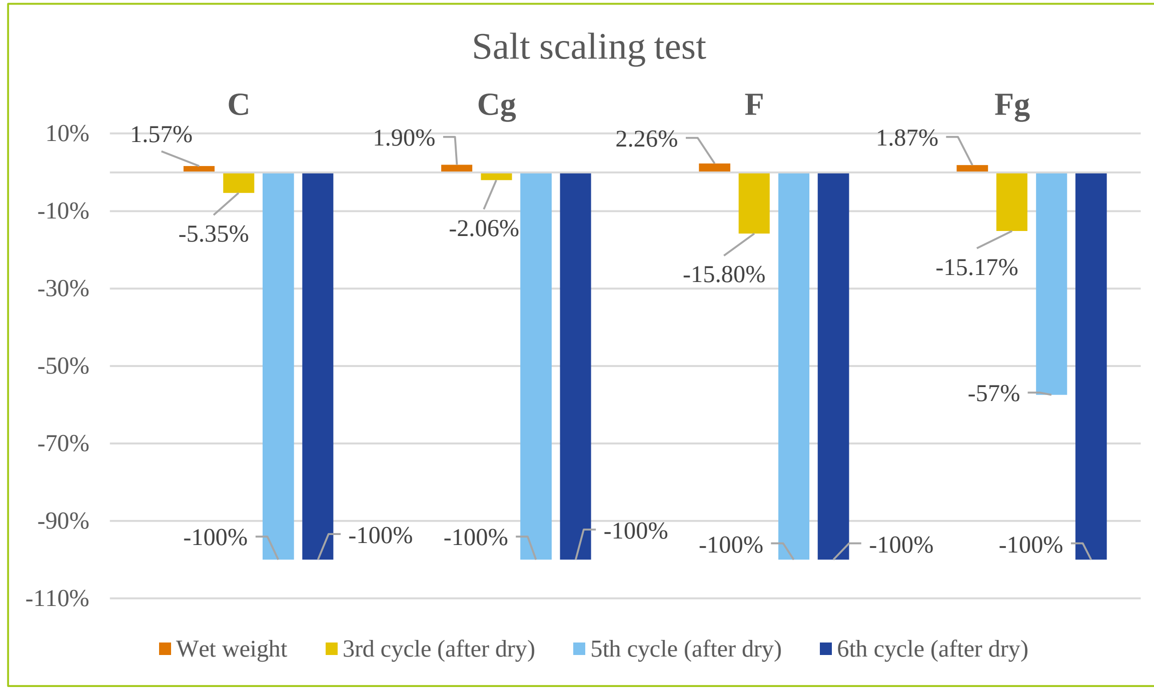
Tests – Freeze-deicer Salt Scaling Resistance Test

Pervious concrete samples before freeze-deicer salt scaling test

Cement + GO

Fly ash + GO

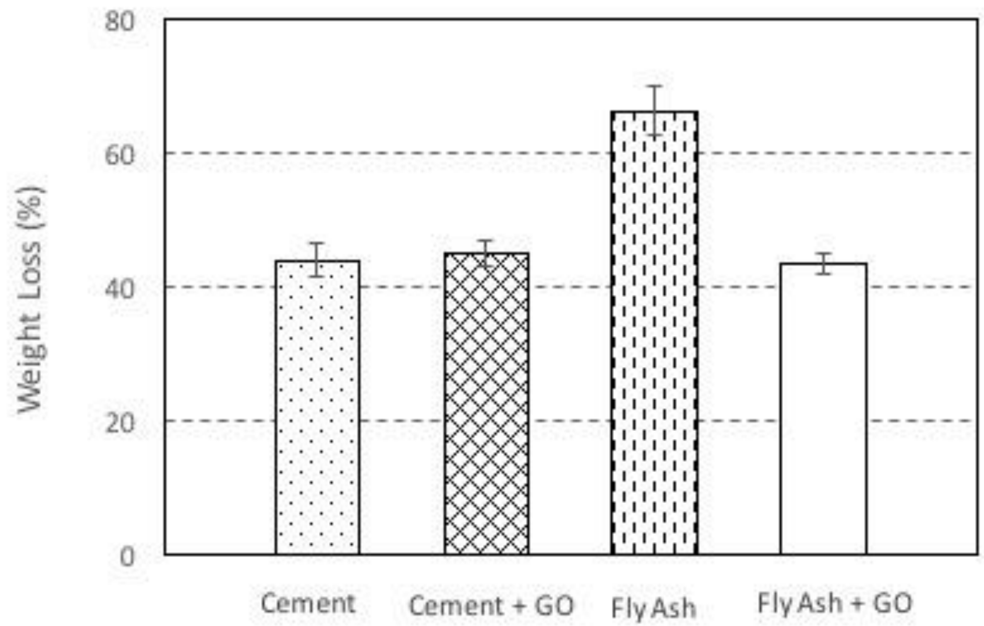
Samples after the 3rd cycle during test



Weight loss during salt scaling test

Tests – Degradation Resistance

Sample before and after test



Degradation test results at 90-day

Summary

- The addition of 0.03% GO increased the 28-day *fc’* of fly ash pervious concrete by more than 50%. It also increased the 28-day *ft’* of fly ash pervious concrete by 37%. The split tensile strength was approximately equal to 12% of the compressive strength for all the pervious concrete mixes at 28 days.

- The incorporation of 0.03% GO increased the *E* of the fly ash pervious concrete by 6.8%.

- The GO-modified fly ash pervious concrete was the only group that survived after the fifth cycle during the salting scaling test.

- For all mixes, the measured infiltration rate ranged from 515 in./hr to 2082 in./hr. Portland cement pervious concrete had a higher infiltration rate than fly ash groups.

Findings

- In addition to being categorized as Class C and Class F, fly ash can be divided into *high-calcium* fly ash (CaO content > 10%) and *low-calcium* fly ash (CaO content < 10%)

- *High-calcium*, *high-reactivity* fly ash is cementitious in nature. *High-calcium*, *low-reactivity* fly ash is both pozzolanic and cementitious in nature, which requires activation for complete hydration. *Low-calcium* fly ash is generally pozzolanic.

- Graphene oxide improved the overall performance of pervious concrete significantly by regulating hydration, providing a crack branching and bridging mechanism, and acting as nanofillers.

Recommendations

- Water treatment tests should be conducted to evaluate the effectiveness of the filtration function provided by fly ash pervious concrete.

- The performance of fly ash at early ages must be improved.

- More studies are needed to characterize fly ash hydration products with GO, such as NMR, FI-IR.

- Some other environmental benefits from fly ash pervious concrete, such as heat-island effects and acoustic absorption effects, need evaluation.

Products and Timeline

- One poster presented at Academic Showcase, WSU, March 27, 2015: “Environmentally Friendly Mortars with Coal Fly Ashes as Cementitious Binder”.

- One poster presented at the TRB annual meeting, January 18, 2016, Washington, D.C.

- Two manuscripts are ready for submission for ACI Material Journal and ASCE Journal of Materials in Civil Engineering .

- Two provisional patents

Acknowledgements

- Thanks for funding from CESTiCC

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Questions ?