Graphene Oxide Modified Pervious Concrete with Fly Ash as Sole Binder

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Background

- Pervious concrete is considered as 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 CO₂ emissions and other greenhouse gases.
Project Objective

- Expand the use of industrial waste and recycled materials (such as fly ash and recycled glass) in pervious concrete
- Explore the potential of such “greener” pervious concrete for the treatment of storm water under a variety of contaminant loading scenarios
- Expand the use of nanotechnology to improve cementitious material performance
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
Pervious Concrete Constituents

- Evaluate the identified fly ashes as cementitious binder

Diagram:

- Fly Ash
- Recycled glass powder
- Graphene oxide
- Chemical activators
- Water reducing admixture
- Air entraining admixture

Central: Environmentally Friendly Binder
Evaluate “Green” Constituents

Experiment by using uniform design scheme

5 Factors at 3 Levels

- \( \text{Na}_2\text{SiO}_3 \) 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\(_2\)SO\(_4\) 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” x 4” 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

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

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

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

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

compressive strength models
Experimental Results

Model Visualization & Verification

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

- Back-Scattered Electron (BSE) Analysis

A) BSE 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)

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

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

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 Ca²⁺ 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.
Fabrication of Pervious Concrete Samples

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
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

Samples after the 3rd cycle during test

Weight loss during salt scaling test

Cement + GO

Fly ash + GO

| Sample Type | 3rd Cycle (after dry) | 5th Cycle (after dry) | 6th Cycle (after dry) |
|-------------|-----------------------|-----------------------|-----------------------|
| C           | -1.57%                | -1.90%                | -2.26%                |
| Cg          | -5.35%                | -2.06%                | -15.80%               |
| F           | -100%                 | -100%                 | -100%                 |
| Fg          | -100%                 | -100%                 | -100%                 |

- Wet weight
- 3rd cycle (after dry)
- 5th cycle (after dry)
- 6th cycle (after dry)
Tests – Degradation Resistance

Sample before and after test

Degradation test results at 90-day
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 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 500 in./hr to 2000 in./hr. Portland cement pervious concrete had a higher infiltration rate than fly ash groups.
Questions ?