Additive Construction of Low Embodied Carbon Concrete: Geopolymer Concrete

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Presenter: **Anthony Mackin**
Toronto, ON, Canada, April 2025

Agenda

American Concrete Institute

- Problem statement.
- Introduction
  - What's Geopolymer concrete?
  - 3D Printing + Geopolymer concrete.
- Additive Construction of Geopolymer Concrete Processes.
  - Preparing Geopolymer concrete material.
  - Introduction to additive construction.
  - Preparing the desired 3D-printed shape for printing.
  - Printing the desired shape.
  - Showcases for successful printing processes.
- Observation and Results
  - Activator Temperature effect.
  - Printing time.
  - Mechanical properties.
- Conclusion.

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Construction industry over the last decades

Comparison of construction techniques between 1950s (left) and 21st century (right).

Problem Statement

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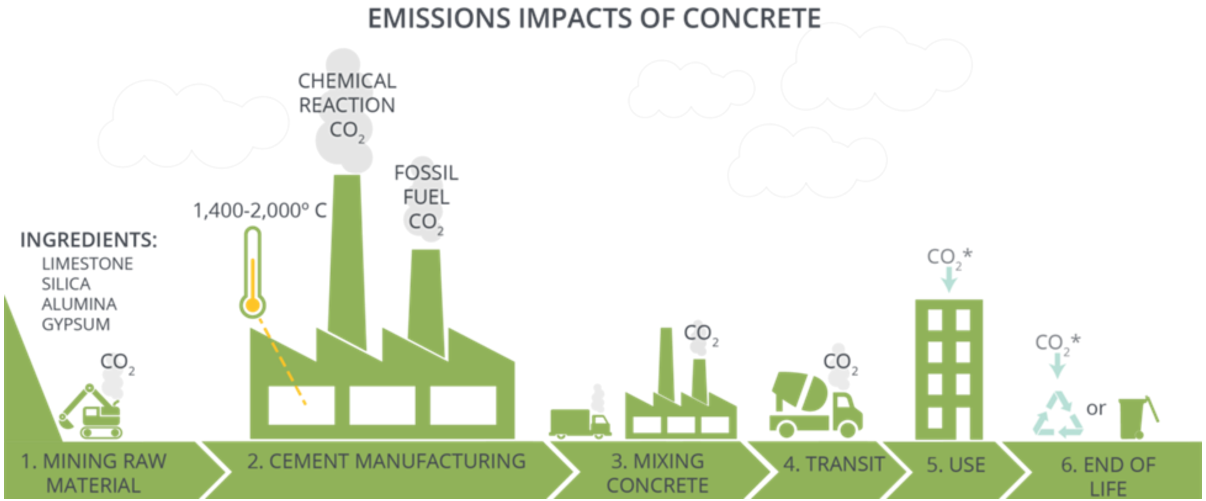

CEMENT AND CONCRETE BY THE NUMBERS

~30 billion metric tons:
Amount of concrete manufactured globally annually.

~8%:
Portion of global anthropogenic CO2 attributed to cement manufacturing.

1,450 ° - 1550 ° C:
Temperature of kilns used to process cement.

25–50%:
Projected global increase in demand for concrete by 2050

Source: International Energy Agency; Nat. Mater. 2017, DOI: 10.1038/nmat4930.

To reduce the Concrete's Carbon Footprint:

Decreasing Carbon Emission

Increasing Carbon Sequestration

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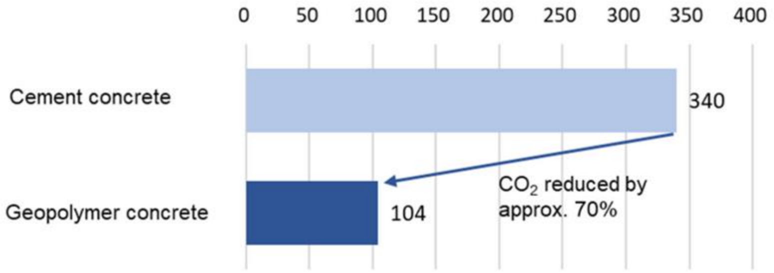
To reduce the Concrete's Carbon Footprint:

Geopolymer Concrete

Comparison of CO_2 emission estimates for cement concrete and geopolymer concrete



Source: Compiled by MGSSI based on Nishimatsu Construction Technical Report VOL 39, “Properties and construction case of geopolymer” [in Japanese]

Decreasing Carbon Emission

Increasing Carbon Sequestration

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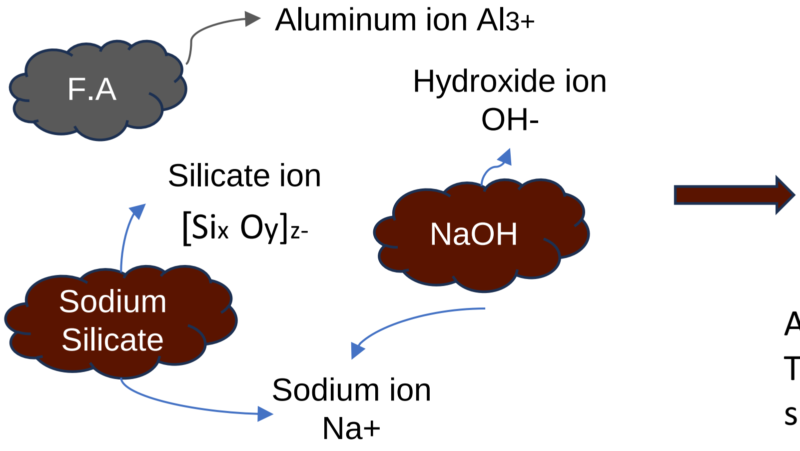
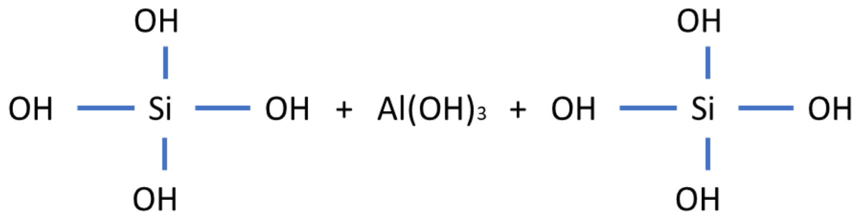
What is Geopolymer Concrete?

Cementless Concrete, formed by **alkali activation** of industrial aluminosilicate **waste materials** “Fly ash (FA), Ground granulated blast furnace slag (GGBS), and Silica Fume (SF)”.





Alkaline activation releases **aluminum** and **silicon** from F.A and S.S. The released aluminum and silicon react with **Hydroxide ions (OH-)** separated from sodium hydroxide, **creating a bond** between aluminum and silicon. This bond is **a Geopolymer**.

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This Research aims to combine ……..

Conventional Construction Method

Geopolymer Concrete

- Overcome the drawbacks of Cement Prod.
- Eco-Friendly construction material.
- Enhance the mechanical prop. of GC.

Portland Cement Manufacturing

+

Additive Manufacturing (3D Printing)

- Reduction in Construction Time.
- Saving in Construction Costs.
- Reduction of Material Utilization.
- Reducing Labor Costs.
- Design freedom and Innovation.

Outline of the research….

- Materials
- Mixtures Designs
- Printable Material preparation process
- Mechanical Properties

Geopolymer Concrete

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Additive Manufacturing (3D Printing)

- ARC Lab Add. Construction System.
- 3D Printing Process
- Successful prints.
- Printability discussion

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Additive Construction of Geopolymer Concrete Processes

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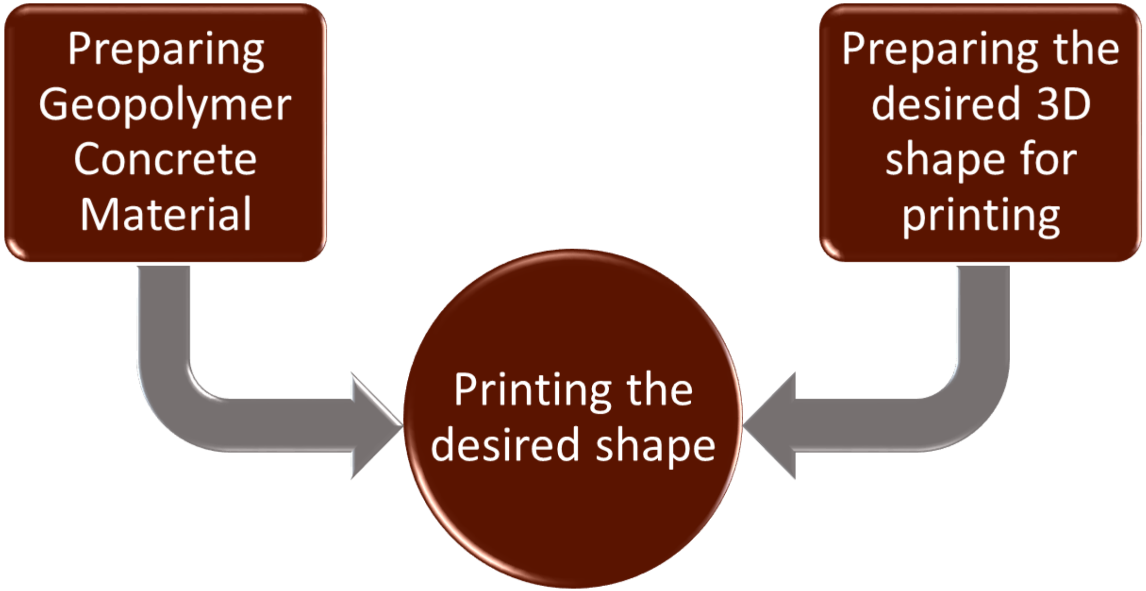
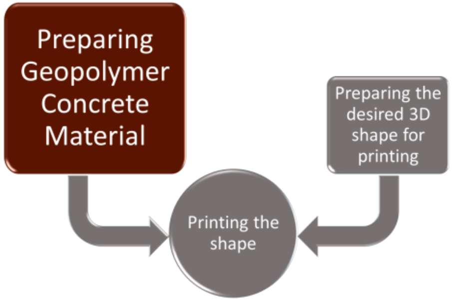


Preparing Geopolymer Concrete Material:

1- Design the in-house printable mixtures.

	Mix	M1	M2	M3	M4	M5
% of Total weight of Binder	**Slag**	0 %	20 %	30 %	40 %	50 %
	Fly Ash (C)	80 %	70 %	60 %	50 %	40 %
	Silica Fume	20 %	10 %	10 %	10 %	10 %
Aggregates	**Sand (Type 1)**	Aggregates to binder ratio is **2:1**, consists of different particle sizes with ratios of **50%, and 50% by weight**				
	Sand (Type 2)					
alkaline activator	**NaOH**	The alkaline activator has a modulus **(MS) of 0.80** (where MS = SiO_2 / Na_2O, Na_2O = 13 %)				
	Sodium Silicate					
Water	**H_2O**	W:B ratio is **0.45**				



Preparing Geopolymer Concrete Material

Preparing the desired 3D shape for printing

Printing the shape

Preparing Geopolymer Concrete Material:

1- Design the in-house printable mixtures.

2- Mixing process.

Dry Mixing (5 Mins)

Cooling Activator (11°-13°C)

Dry mix + Activator (3 Mins)

Figure 1. Raw Dry Materials

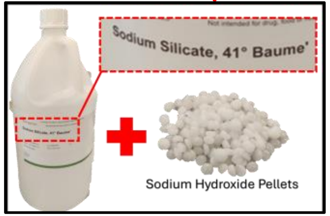
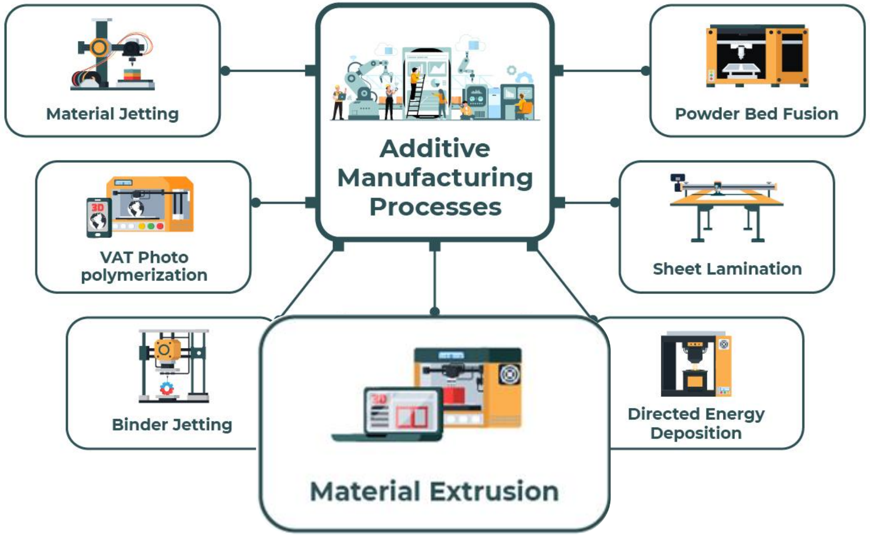


Figure 2. Alkali Activator

Figure 3. the mixer

According to ISO / ASTM 52900:2021

Open System using Auger



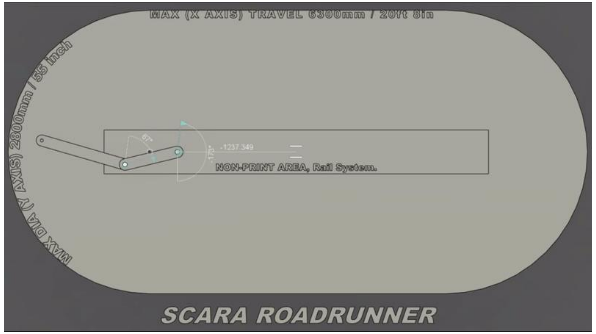
Layer by Layer deposition of the material

Closed System using Tube

Intorduction to Additive Construction

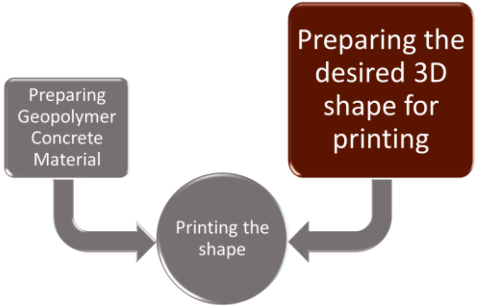
The ARC Lab at Rowan University hosts an additive construction systems including:
The Scara Elite Roadrunner 3D printer.


Open System using Auger



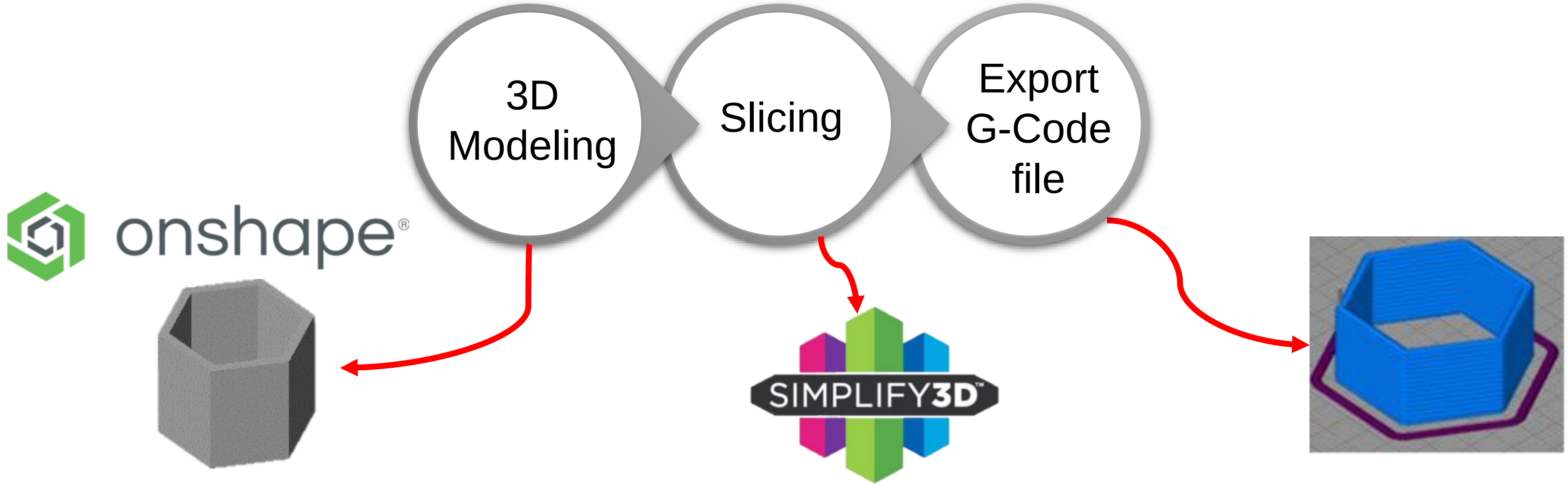
Printing specifications	
Length	20 ft
Width	14 ft
Height	7 ft
Prints 1”- 4” per second.	
Prints 360° with continuous rotation	


Closed System using Tube



Preparing the desired 3D shape for printing:

1- 3D shapes were designed and modelled in CAD software.
2- 3D models were sliced for printing using slicing software.
3- Exporting the G-Code file to the printer.



Printing the desired shape:

1- The Geopolymer Concrete materials were manually loaded into **a closed printing tube system.**

2- The closed printing tube system employs **a plunger and motor to extrude concrete mixtures through various nozzle sizes** ranging from 1 to 8 millimeters.

3- The printing path and process parameters were **remotely controlled** for printing **Layer-by-Layer**.

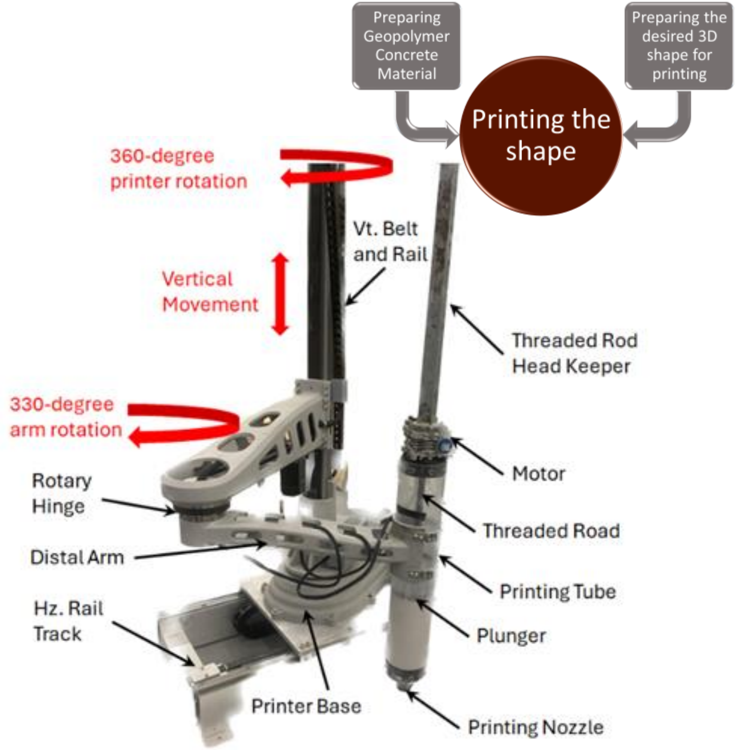
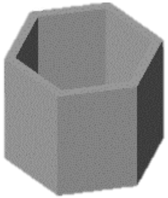


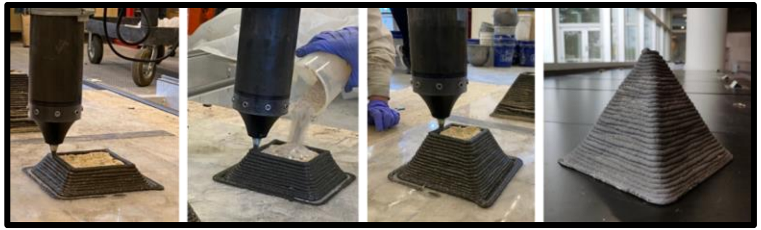
Figure 4. 3D Printer, ARC Lab, Rowan University.

Showcases for Successful Printing Processes



Height	6 in
Width	5.12 in
No. of layers	30

Height	12 in
Diameter	5.12 in
No. of layers	50



Height	7.8 in
Width	7.8 in
No. of layers	30

Successful Extrusion and Buildability (Geopolymer Concrete)

Showcases for Successful Printing Processes

Height	10 in
Diameter	3 to 6 in
No. of layers	42

Successful Extrusion and Buildability (Geopolymer Concrete)

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Observation and Results

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Activator Temperature effect:

1. The main challenge is to **control the setting time** and extend the open time of the material.
2. The main observation was that **the temperature of the activator liquid controls the setting time** of the Geopolymer concrete.
3. The temperature of the alkaline activator reaches 85° c at the same moment of fully dissolving the NaOH pellets in the Sodium silicate solution, 22° c after cooling down for (3-4 hours) in a room temperature, and temperatures range of (18° to 7° c) after cooling down in an appropriate refrigerator.
4. The temperature of **(11° to 13° c)** gives the best printability properties.

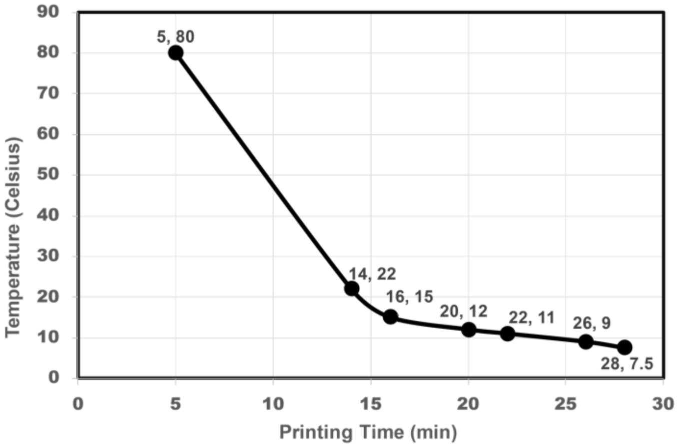

Chart 1. Temperature – Setting time Curve.

Printing time:

1. Geopolymer Concrete mixtures require a **specific idle time before initiating the 3D printing process** to achieve optimal texture and flowability for consistent printing.
2. The slag percentage is **directly proportional** to both idle time and open time in the mixtures.
3. Increasing the percentage of **Slag to 50 %,** increase the idle time from **6 to 15 mins** and the open time from **8 to 12 mins**.
4. This effect results from **different geo-polymerization reaction rates** in Fly Ash-based and slag-replaced GC.

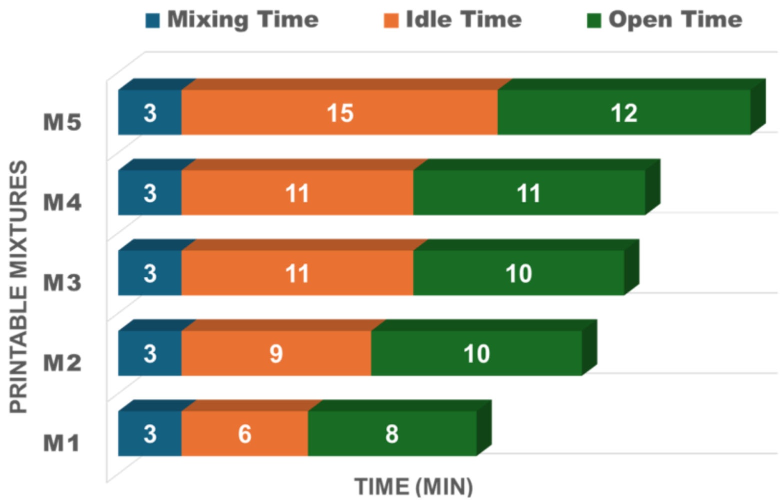

Chart 2. Total printing time of GC mixtures

Mechanical properties:

1. Geopolymer concrete mixtures achieved compressive strengths ranging from **3.5 to 5.5 ksi.**

2. Compressive strength values **improved with increasing the percentages of slag** replacing the total binder weight in printable Fly Ash-based GC.

3. The Geopolymer concrete's compressive strength increased by **175% when 50% of the binder weight was replaced by slag**, compared to the mixture without slag.

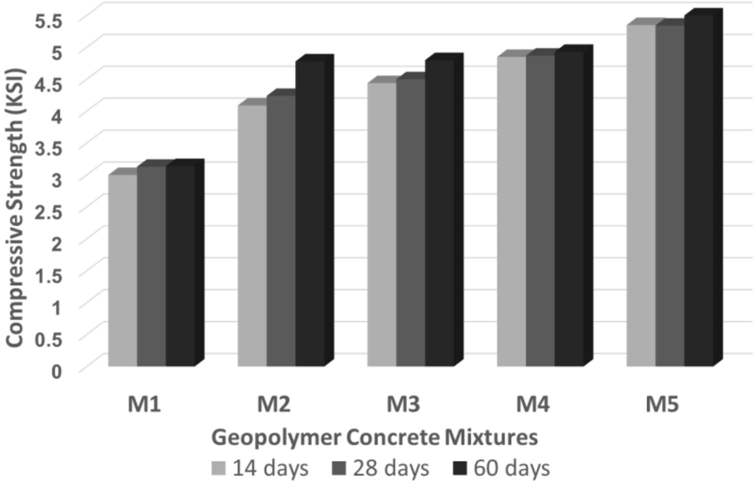

Chart 3. Compressive Strength Results.

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Conclusion

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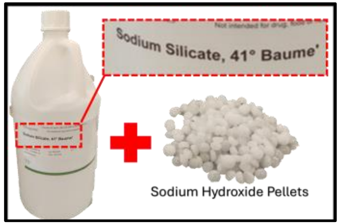
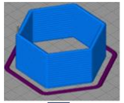


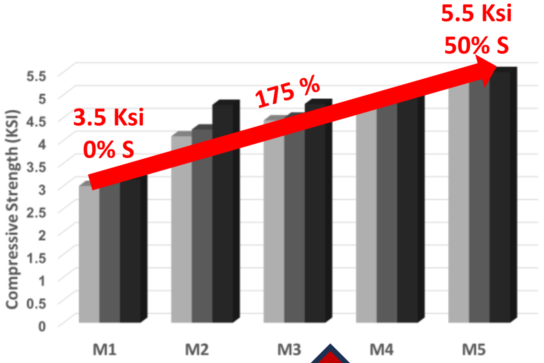
Cooling down (11°-13°C)

5 in-house printable GC Mixtures

onshape

SIMPLIFY3D





Printing Time

Buildability

Extrudability

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ARC Lab Team, Rowan University.

Thank you.

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