CIVIL, CONSTRUCTION & ENVIRONMENTAL ENGINEERING

Early Age Properties of 3D Printed Concrete, Part 1 of 2

3D-Printed Polymer Concrete Mix Design Optimization: Insights from Early-Age Rheological and Mechanical Properties

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Outlines

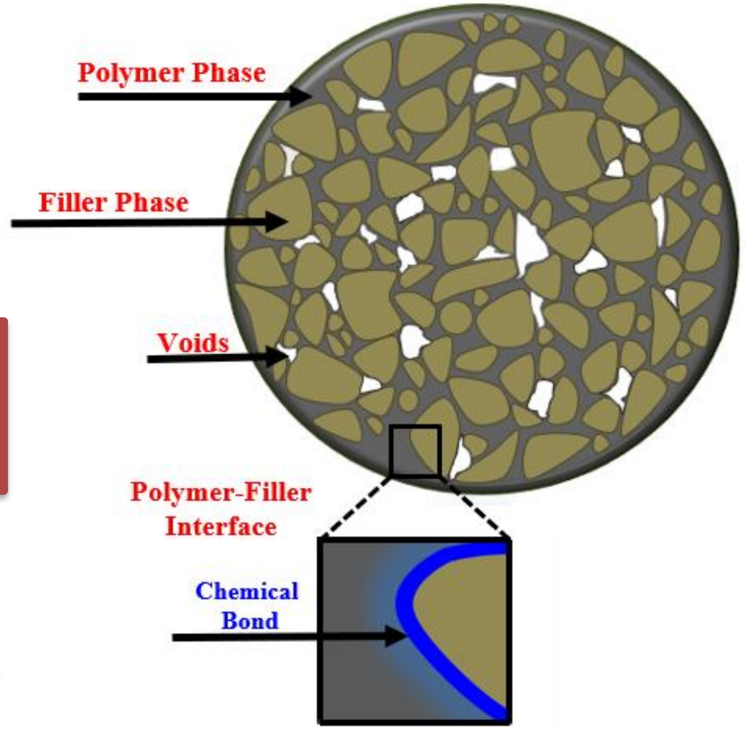
- 3D-Printed Polymer Concrete By-Design
- Preliminary Assessment of Polymer Concrete Mixes
- PC Printing Parameters, Printability Window and Buildability
- Rheological and Early-age Strength Assessment
- Full-Scale 3D-Printing of PC
- Application of 3D-Printed Polymer Concrete

Introduction to Polymer Concrete

- Polymer Concrete (PC) is a flowable concrete where the **polymer fully or partially replaces cement** as a binder.

Types of PC

- **Latex/Polymer Modified Concrete (LMC)**
- **Polymer Impregnated Concrete (PIC)**
- **Polymer Concrete (PC)**

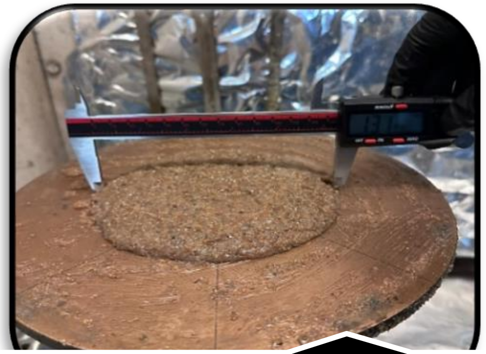


- Several polymers are used to produce PC, including thermosets: epoxy, vinyl ester, polyester, and methyl Methacrylate, among others, and high-temperature thermoplastics, such as Peek and Altium.

3D-Printed Polymer Concrete By-Design

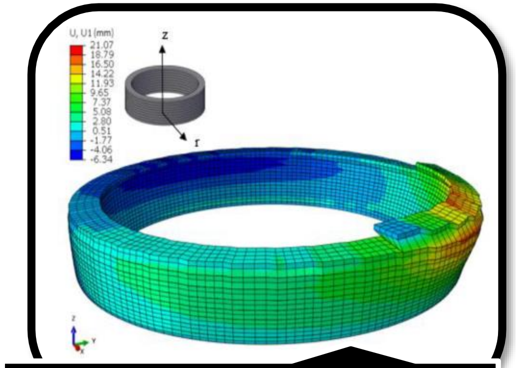
Material	Weight (kg/m³)
Resin & Hardener	393
Aggregate	1699
7-day compressive strength (MPa)	60
7-day modulus of elasticity (GPa)	7.0
Setting time (minutes)	120

PC mix design



Preliminary assessment of 3D-printability

Rheological and Early-age strength Characterization



Design Simulation

3D-Printed Polymer Concrete By Design

3D-Printed PC Mix Designs

Examples of 3D-printable mix designs using **different polymer types, fillers** **and** **polymer wt.% content**:

Materials (kg/m^3)	Mix 1
Polymer 1	178
Aggregate	1112
Polymer wt.%	14

Materials (kg/m^3)	Mix 2
Polymer 2	393
Aggregate	1699
Polymer wt.%	19

Materials (kg/m3)	Mix 3	Mix 4
Polymer 3	428	535
Aggregate	1363	1146
Polymer wt.%	23	32

Heras Murcia, D., Abdellatef, M., Genedy, M., Reda Taha, M. Rheological Characterization of 3D Printed Polymer Concrete. ACI Materials Journal, 2021.

Preliminary Assessment

- Prior to 3D-printing, the **potential of PC mixes to be 3D-printable** could be examined by

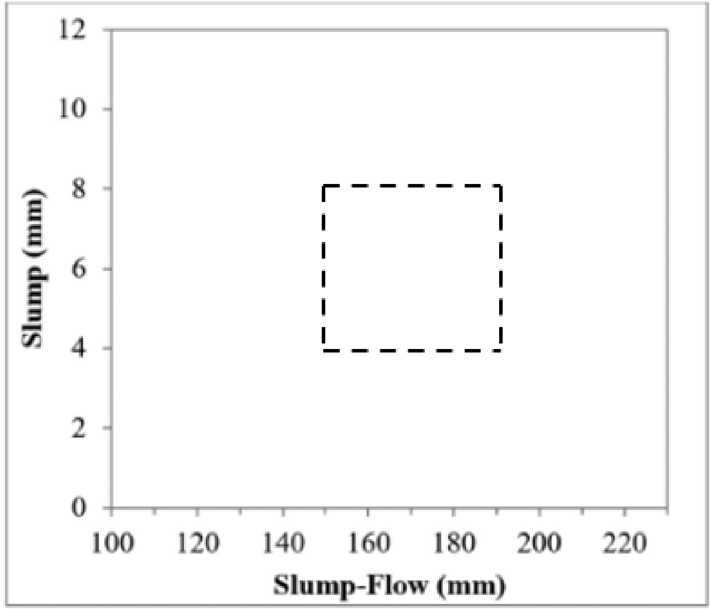
Visual Assessment

Slump Flow

[Pumpability & Extrudability]

Slump

[Structural build-up]



Acceptable Printability Region

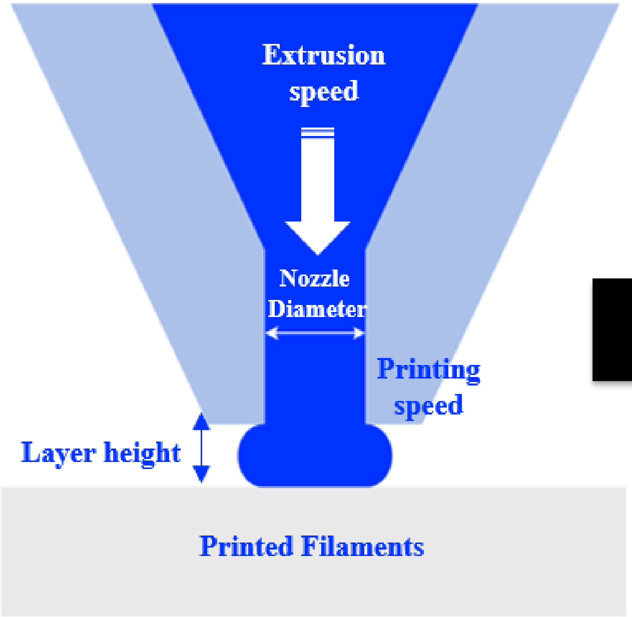
Mixtures with a slump **between 4 and 8 mm** and a slump flow value **between 150 and 190 mm** give a **smooth surface** and **high buildability**.

Tay, Y. W. D., Qian, Y., & Tan, M. J. (2019). Printability region for 3D concrete printing using slump and slump flow test. Composites Part B: Engineering, 174, 106968.

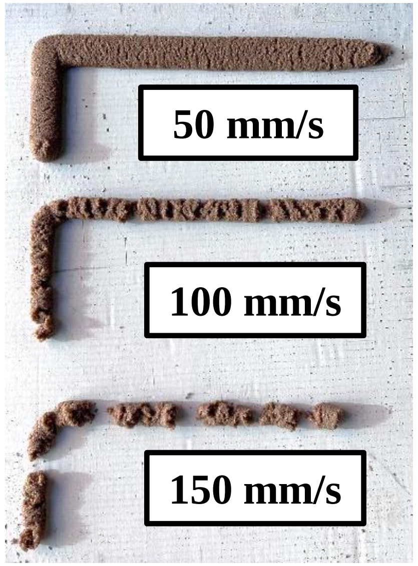
3D-Printability Performance Assessment

Defining 3D-printing Parameters

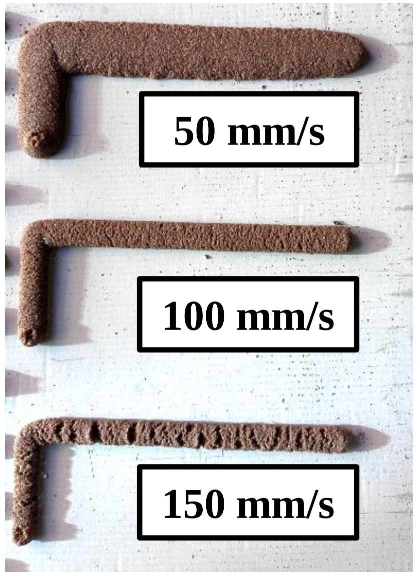
The **3D-printed PC quality** (i.e. Extrudability and dimensional stability) highly depends on the **3D-printing parameters**



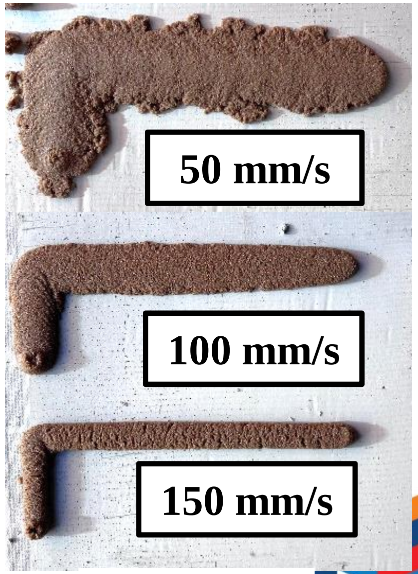
To define the **optimal 3D-printing** speed and extrusion rate:



0.5 rad/s



1 rad/s



1.5 rad/s

3D-Printability Performance Assessment

Defining 3D-printing Parameters

$$A_{p/i} = \frac{A_{printed}}{A_{ideal}}$$

$A_{printed}$ = Average filament width $*$ Length

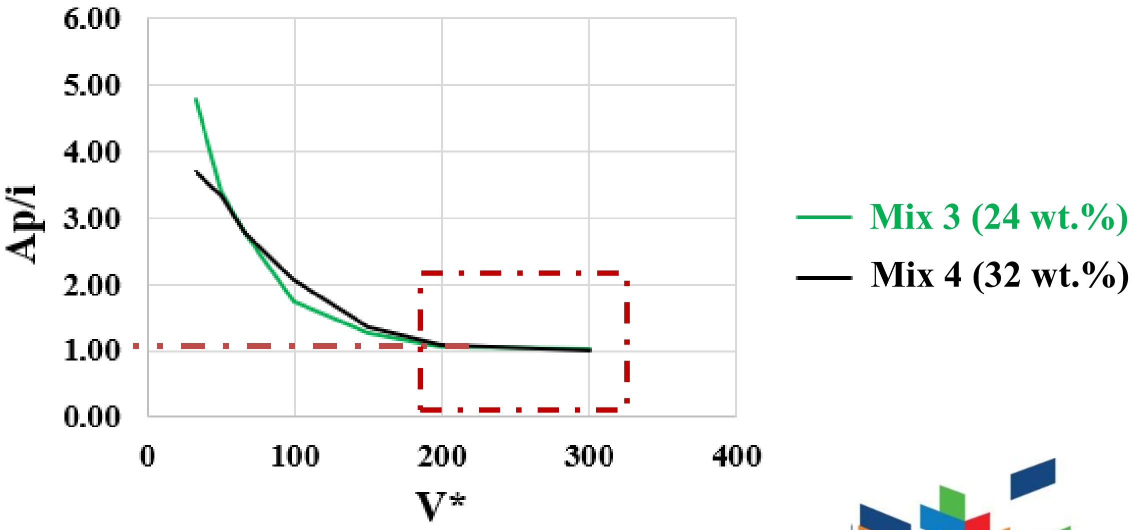
A_{ideal} = Nozzle size $*$ Length

$$V* = \frac{V_r}{V_e}$$

V_r: 3D-printing speed

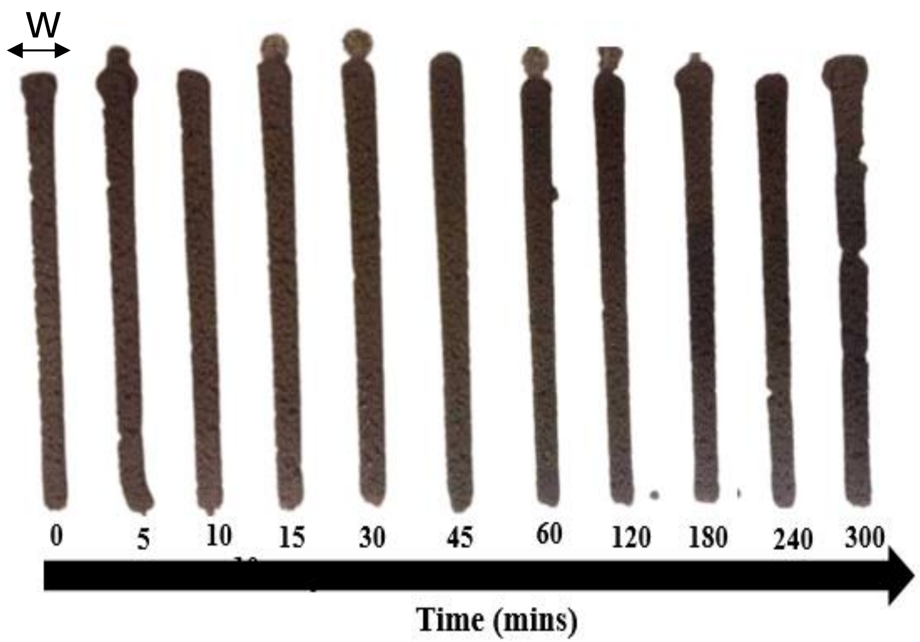
V_e: Extrusion speed

The effect of Velocity ratio (V*) on the dimensional stability of 3D-printed PC.

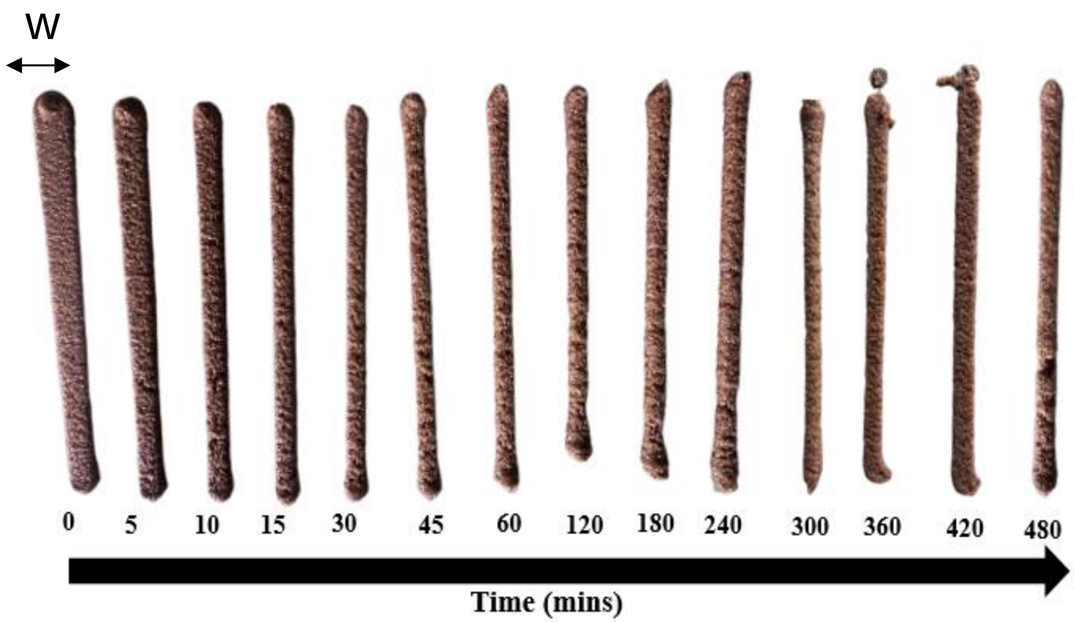


3D-Printability Performance Assessment

Printability Window (Rest Time)



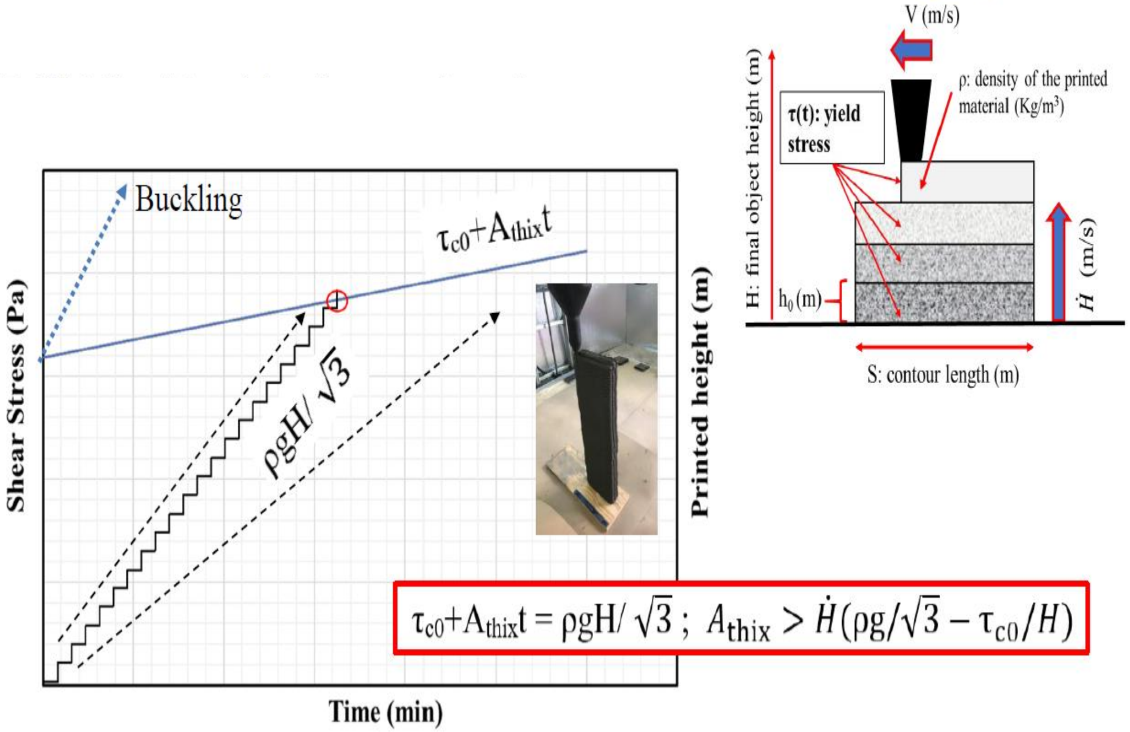
10 mins to 180 mins
(3 hours)



10 mins to 420 mins
(7 hours)

3D-Printability Performance Assessment

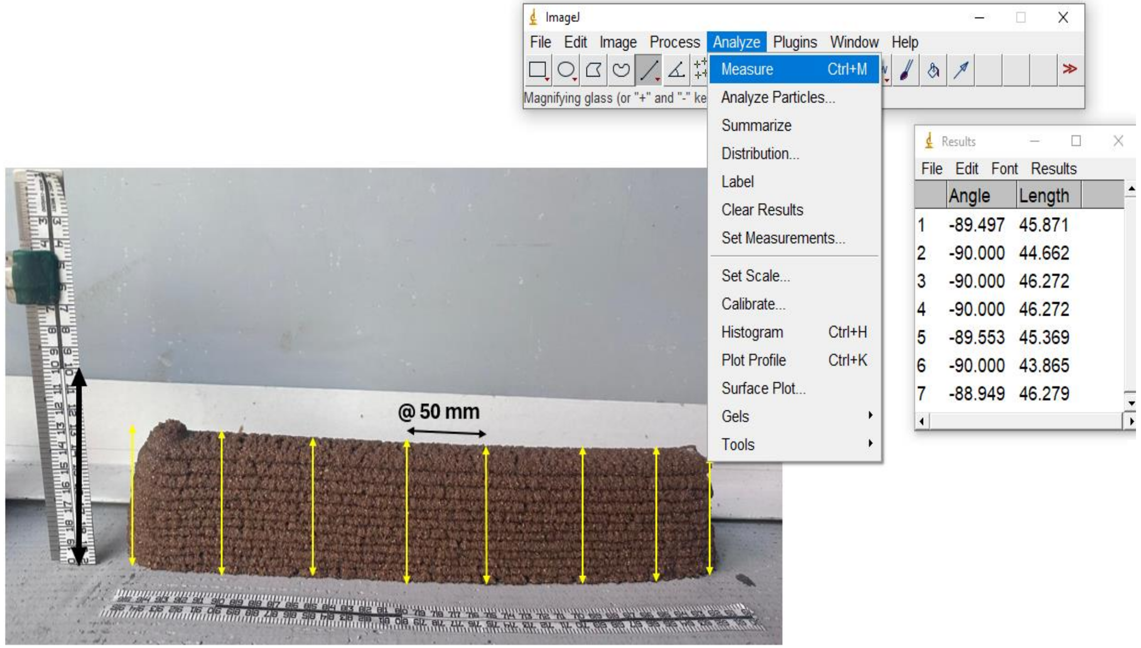
Buildability | 3D-Printing 10 layers

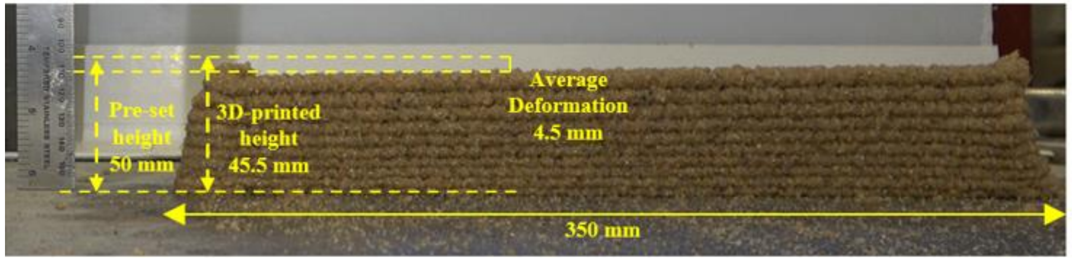


$$\tau_{c0}+A_{thix}t = \rho gH/\sqrt{3}\,;\ A_{thix} > \dot{H}(\rho g/\sqrt{3} - \tau_{c0}/H)$$

3D-Printability Performance Assessment

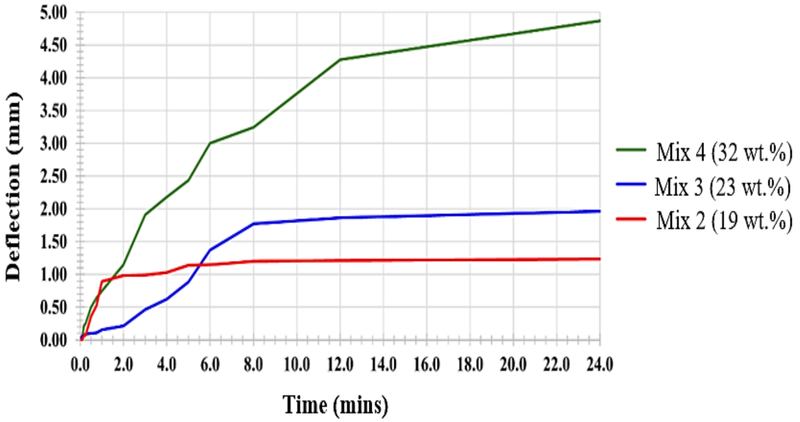
Buildability | Deformation





Time (mins)	Height (mm)	Deflection (mm)
0	49.980	0.020
5	49.943	0.057
10	49.935	0.065
15	49.911	0.089
30	49.897	0.103
45	49.893	0.107
60	49.845	0.155
120	49.786	0.214
180	49.534	0.466
240	49.377	0.623
300	49.115	0.885
360	48.626	1.374
480	48.231	1.769
720	48.135	1.866
1440	48.036	1.964

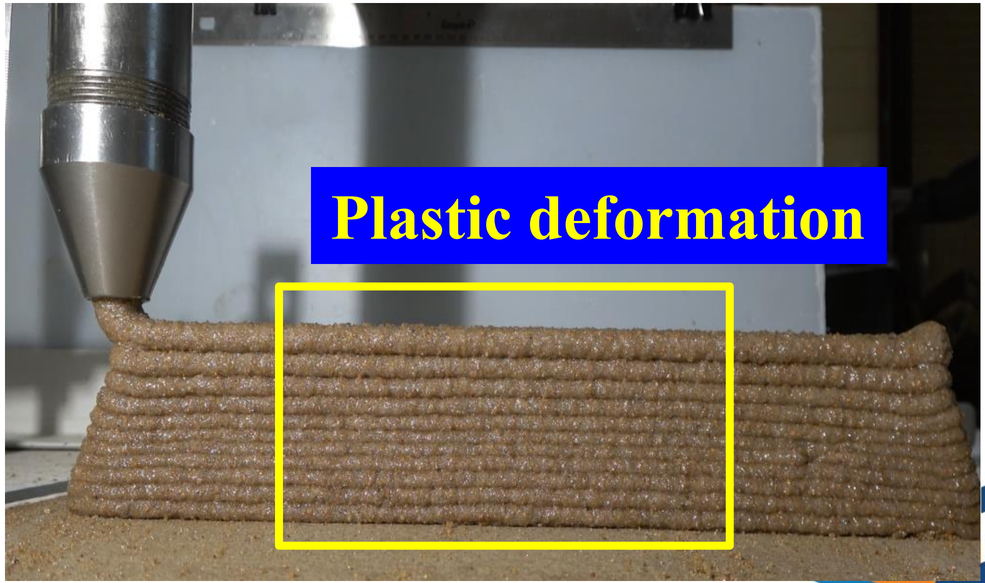
Example of buildability analysis



3D-Printability Performance Assessment

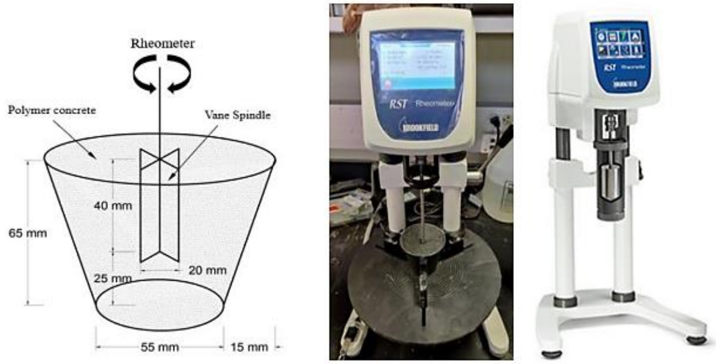
Example of *rejected* buildability testing

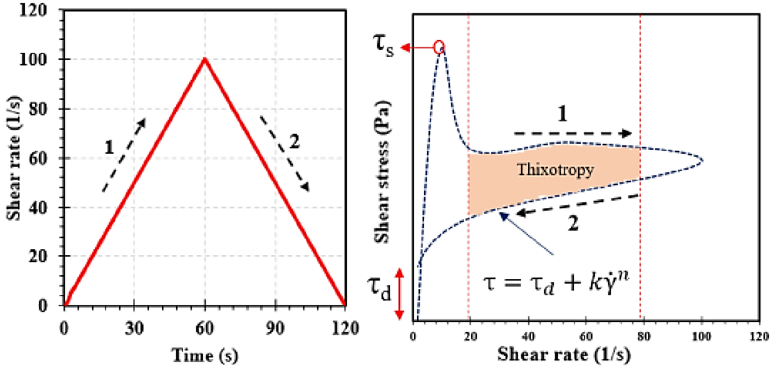
Immediately after 3D-printing



Rheology of 3D-Printed Polymer Concrete

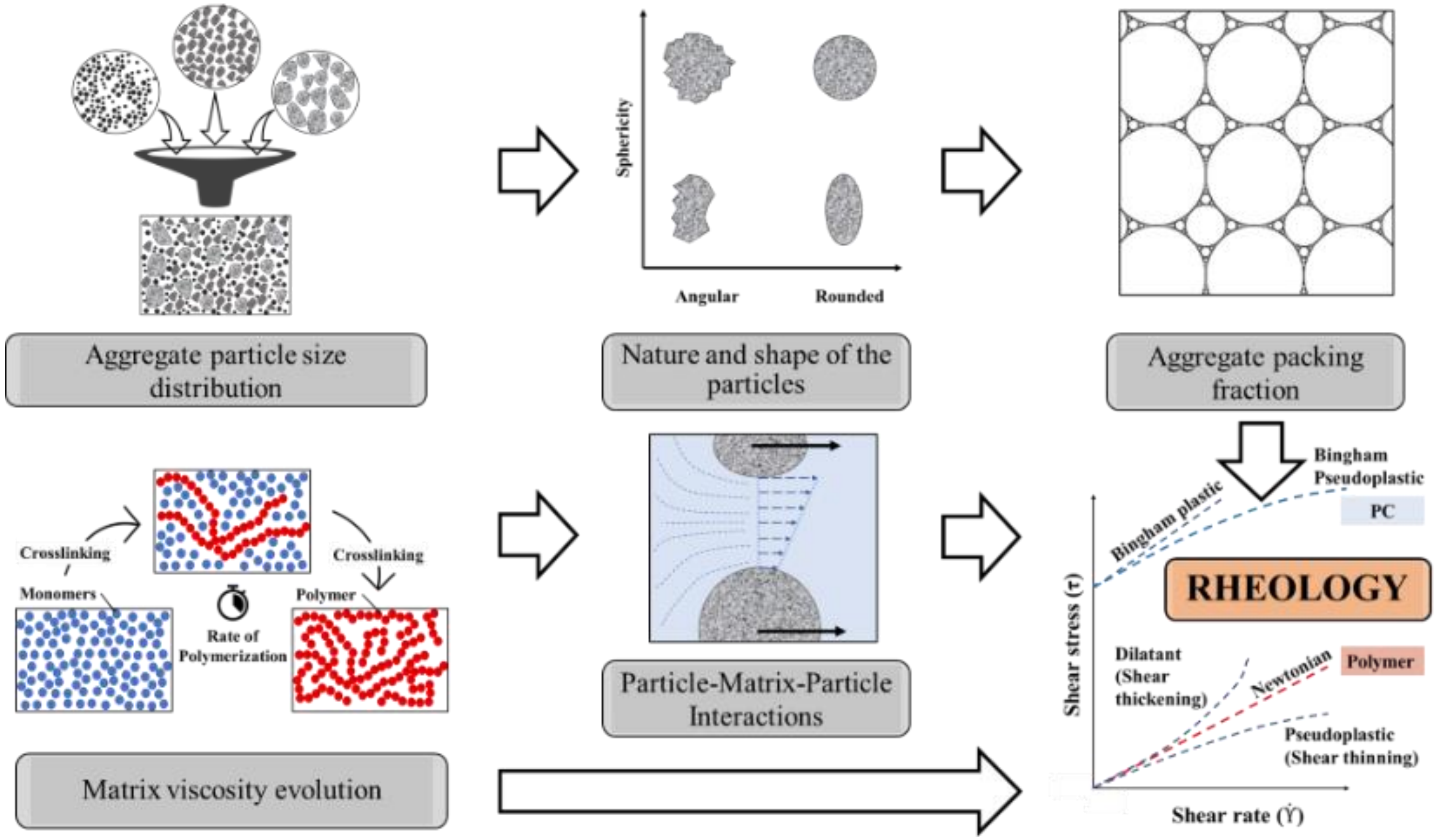
Rheological testing





Heras Murcia, D., Abdellatef, M., Genedy, M., Reda Taha, M. M. "Rheological Characterization of 3D Printed Polymer Concrete", ACI Materials Journal, Vol. 118, (6), pp. 189-201, 2021.

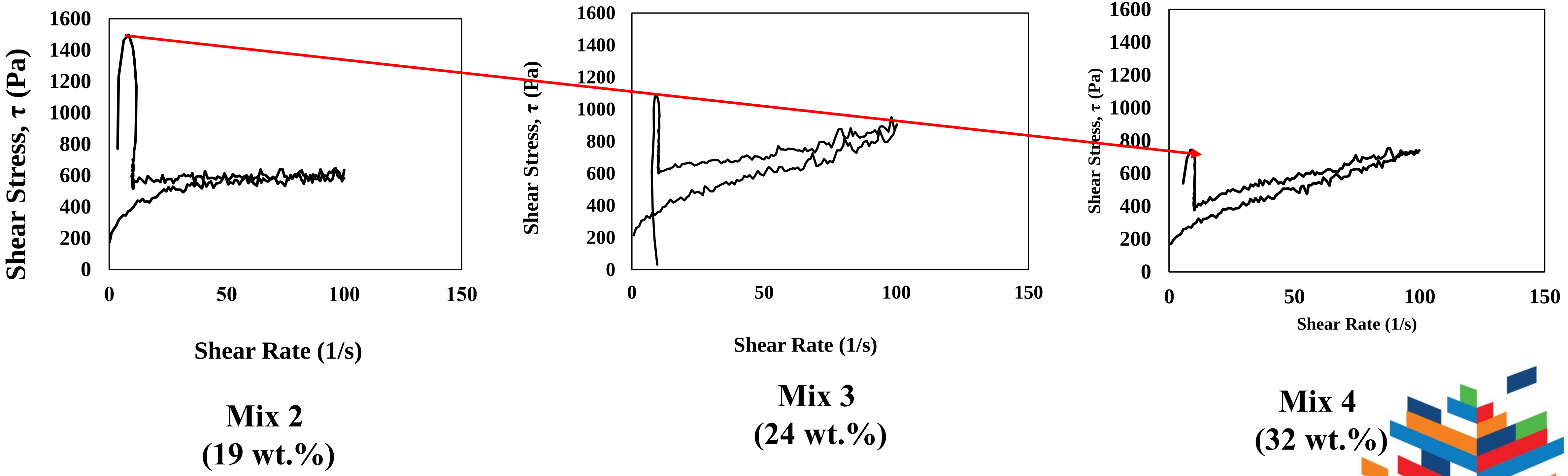
Factors affecting the rheology of PC



Rheology of 3D-Printed Polymer Concrete

Effect of polymer wt.% on the static yield stress

At 60 mins



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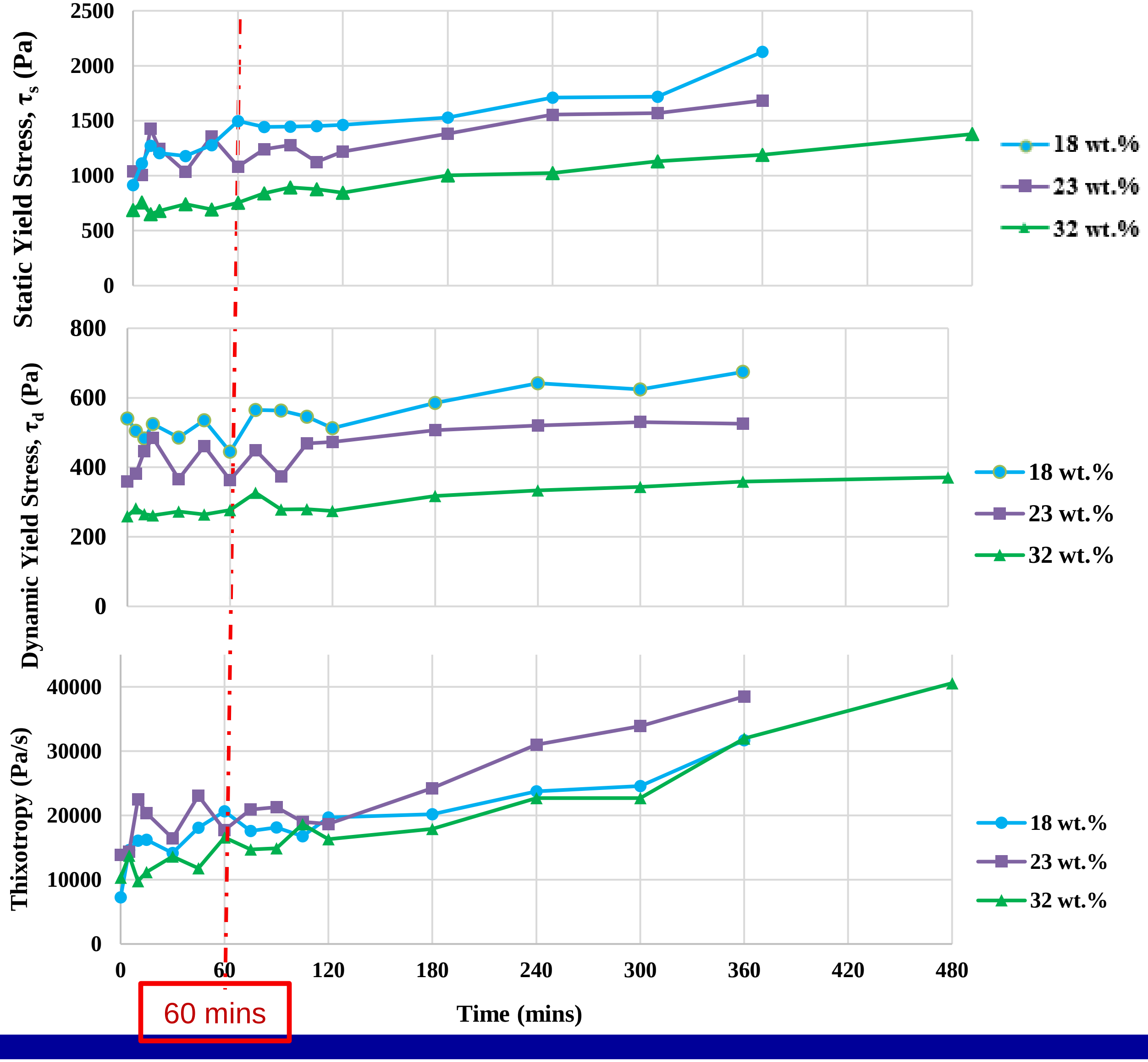


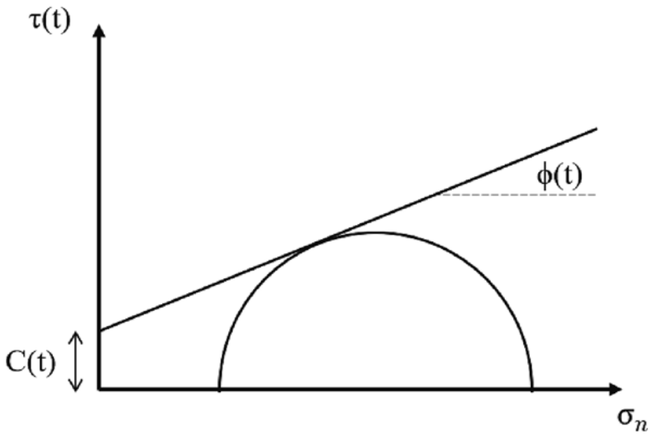
Rheology of 3D-Printed Polymer Concrete

Rheological Criteria for 3D-printability (0 – 60 mins)

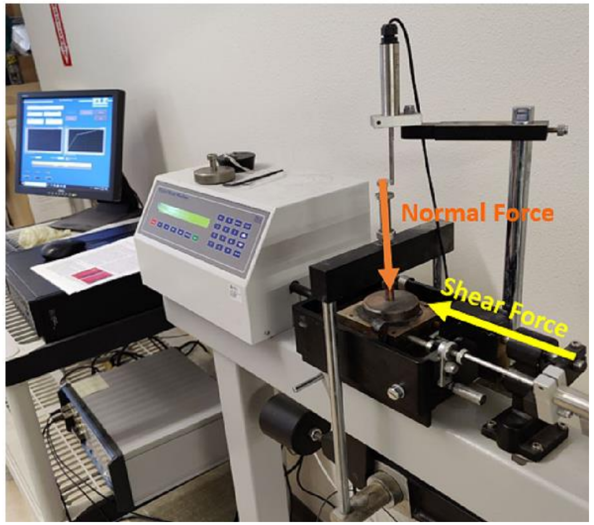
Parameters	Minimum	Maximum
Static Yield Stress (Pa)	700	1500
Dynamic Yield Stress (Pa)	250	400
Thixotropy (Pa/s)	8000	20000

Early-age of 3D-Printed Polymer Concrete

- The Early-age, '***Green Strength***' of fresh polymer concrete allows it to carry its own weight when printed.
- The '***Green Strength***' represents the combined particle friction and cohesion developed by the material.
- We describe the '***Green Strength***' by quantifying the ***Mohr-Coulomb failure criterion***

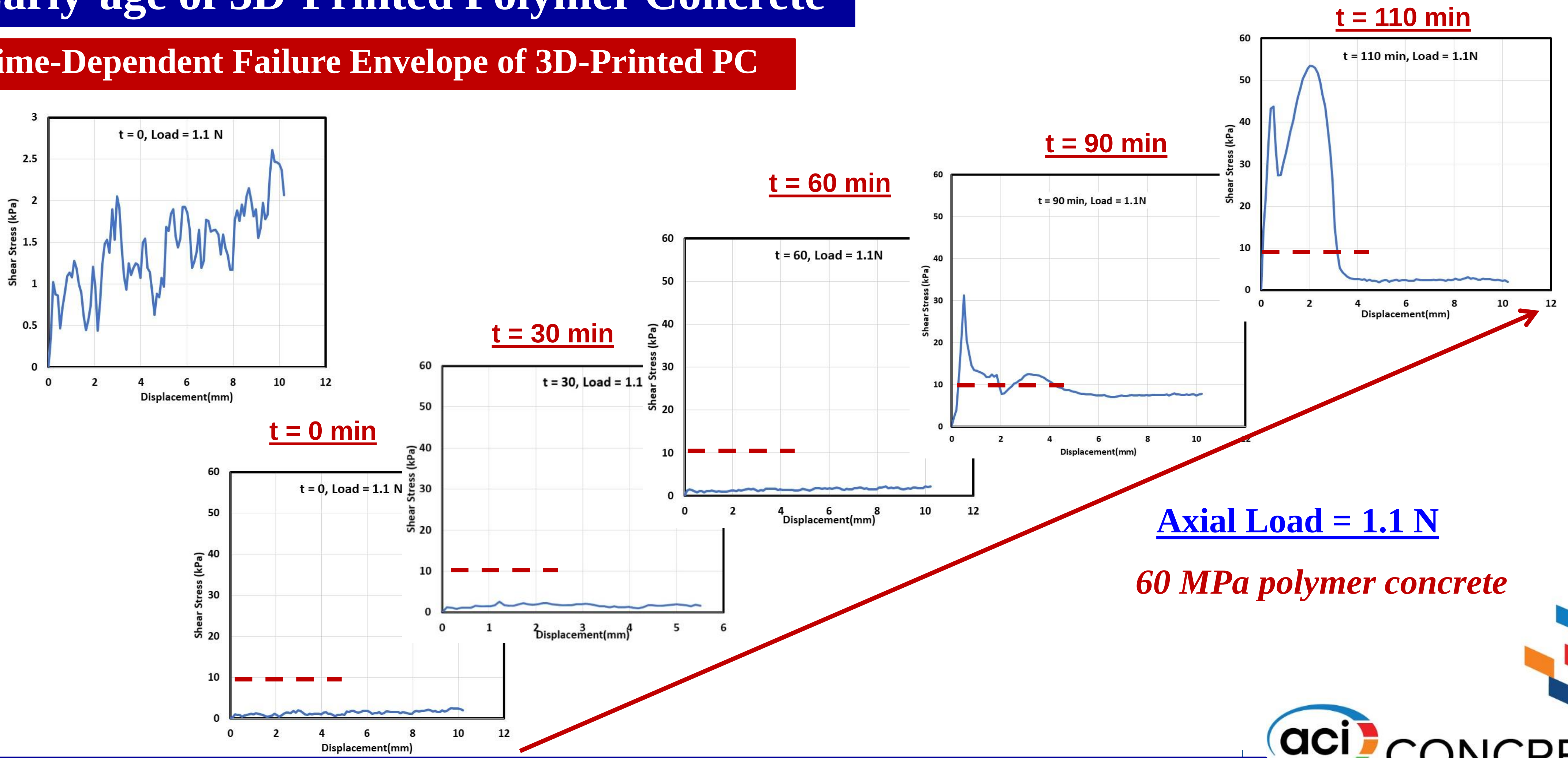


$$\tau(t) = C(t) + \sigma_n \tan \phi(t)$$



Early-age of 3D-Printed Polymer Concrete

Time-Dependent Failure Envelope of 3D-Printed PC



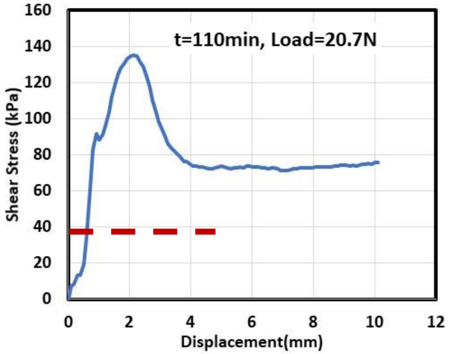
Axial Load = 1.1 N

60 MPa polymer concrete

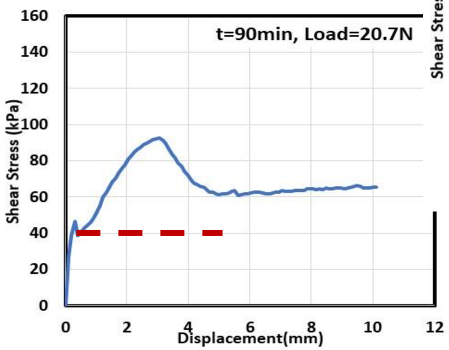
Early-age of 3D-Printed Polymer Concrete

Time-Dependent Failure Envelope of 3D-Printed PC

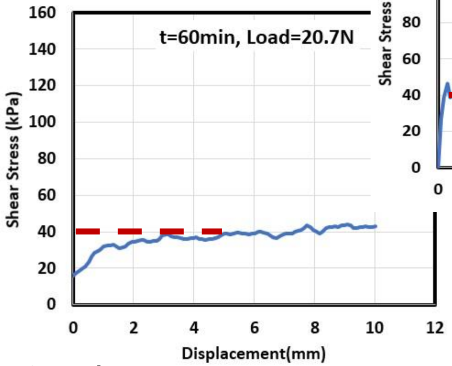
t = 110 min



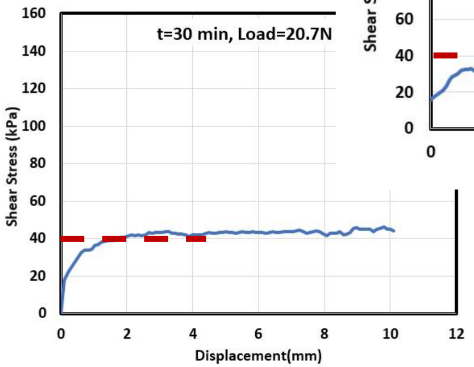
t = 90 min



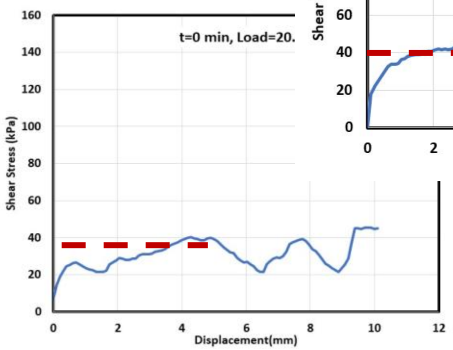
t = 60 min



t = 30 min



t = 0 min

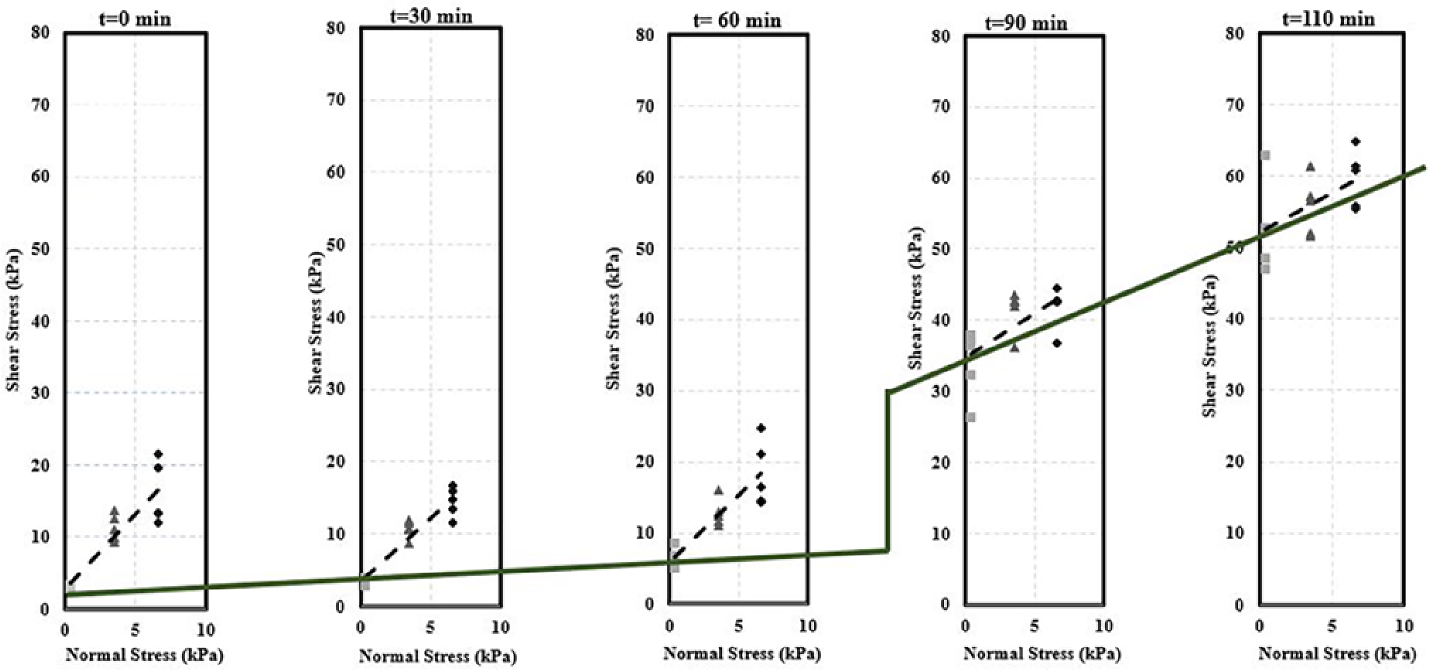


Axial Load = 20.7 N

60 MPa polymer concrete

Early-age of 3D-Printed Polymer Concrete

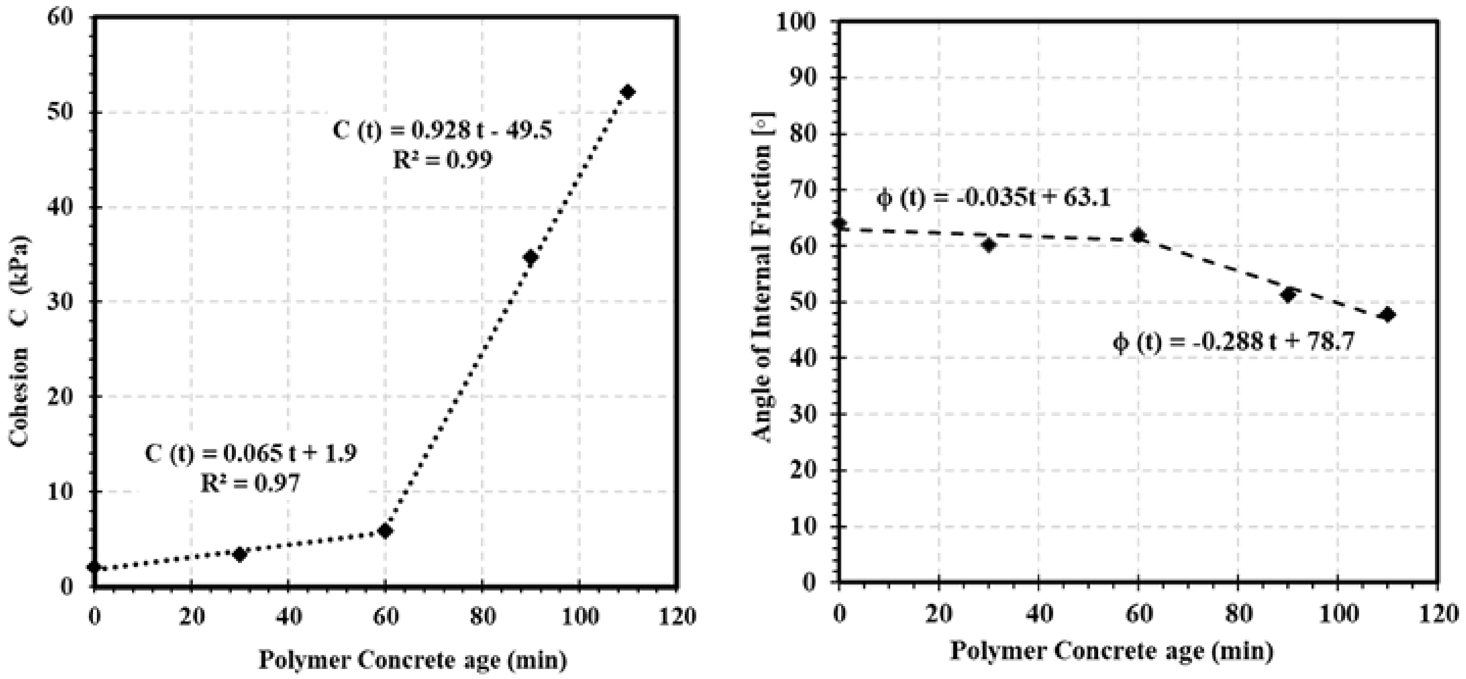
Time-Dependent Failure Envelope of 3D-Printed PC



Time (min)	0	30	60	90	110
Cohesion C	0.28	0.40	0.64	14.59	37.70
Friction Angle ϕ	79.8	81.1	81.3	82.0	84.8

Early-age of 3D-Printed Polymer Concrete

Time-Dependent Failure Envelope of 3D-Printed PC

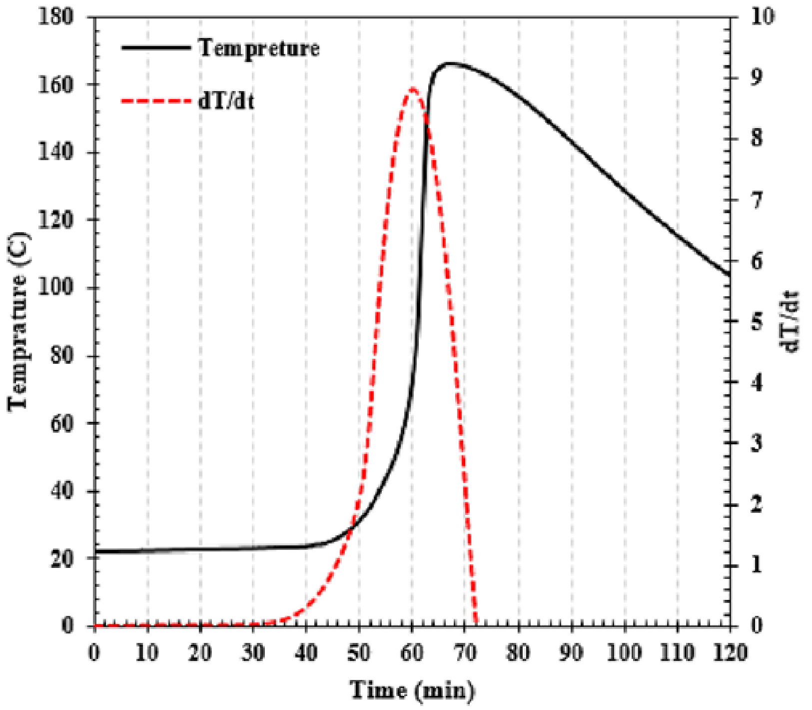


$$\tau(t) = C(t) + \sigma_n \tan \phi(t)$$

Najvani, M. A. D., Murcia, D. H., Soliman, E., & Taha, M. M. R. (2023). Early-age strength and failure characteristics of 3D printable polymer concrete. Construction and Building Materials, 394, 132119. 2023

Early-age of 3D-Printed Polymer Concrete

Time-Dependent Failure Envelope of 3D-Printed PC



Resin gelation time curve by ATD method; the solid line represents the resin temperature vs. time, and the dotted line shows the first derivative of resin temperature vs. time curve.

Najvani, M. A. D., Murcia, D. H., Soliman, E., & Taha, M. M. R. (2023). Early-age strength and failure characteristics of 3D printable polymer concrete. Construction and Building Materials, 394, 132119. 2023

Early-age of 3D-Printed Polymer Concrete

Time-Dependent Failure Envelope of 3D-Printed PC

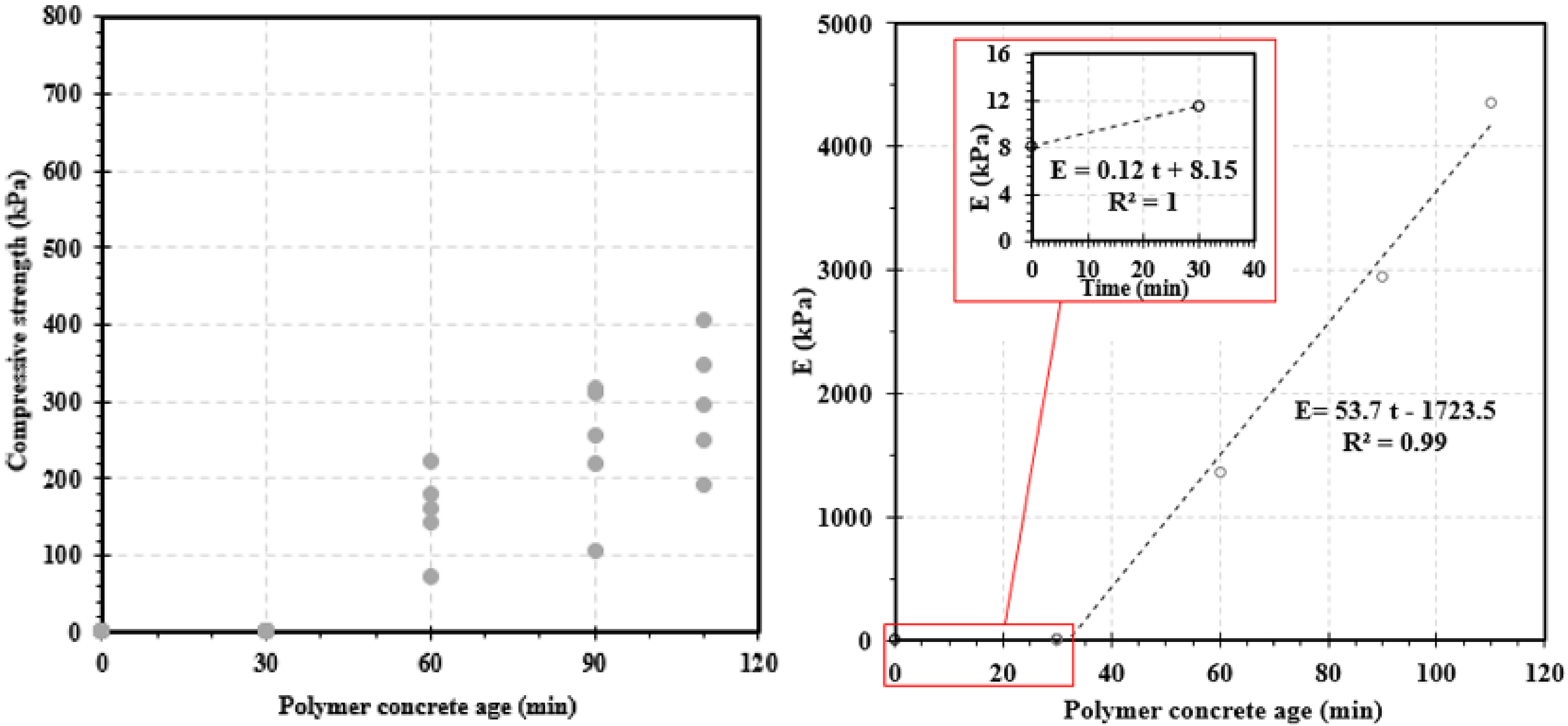
The test set up for the uniaxial unconfined compression test of fresh PC

Failure modes observed in compression tests on fresh concrete

Najvani, M. A. D., Murcia, D. H., Soliman, E., & Taha, M. M. R. (2023). Early-age strength and failure characteristics of 3D printable polymer concrete. Construction and Building Materials, 394, 132119. 2023

Early-age of 3D-Printed Polymer Concrete

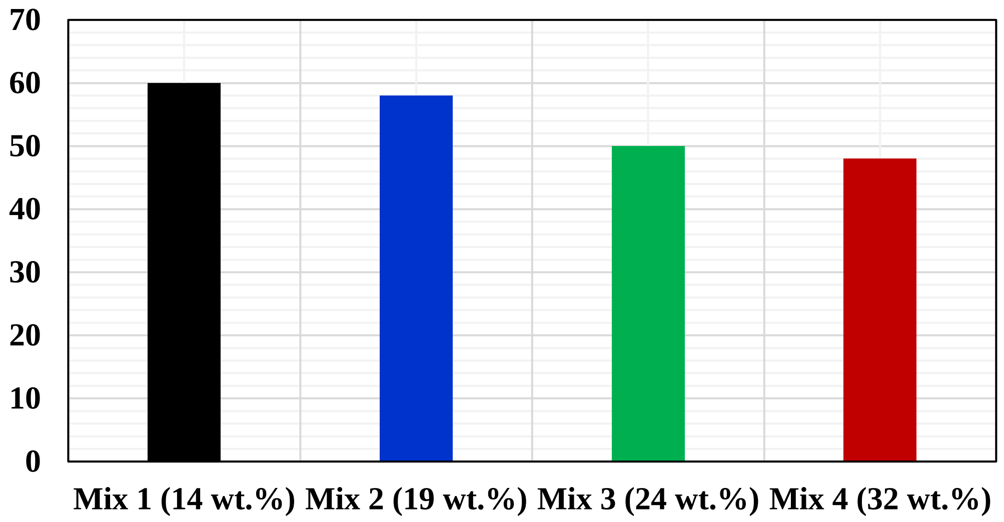
Time-Dependent Failure Envelope of 3D-Printed PC



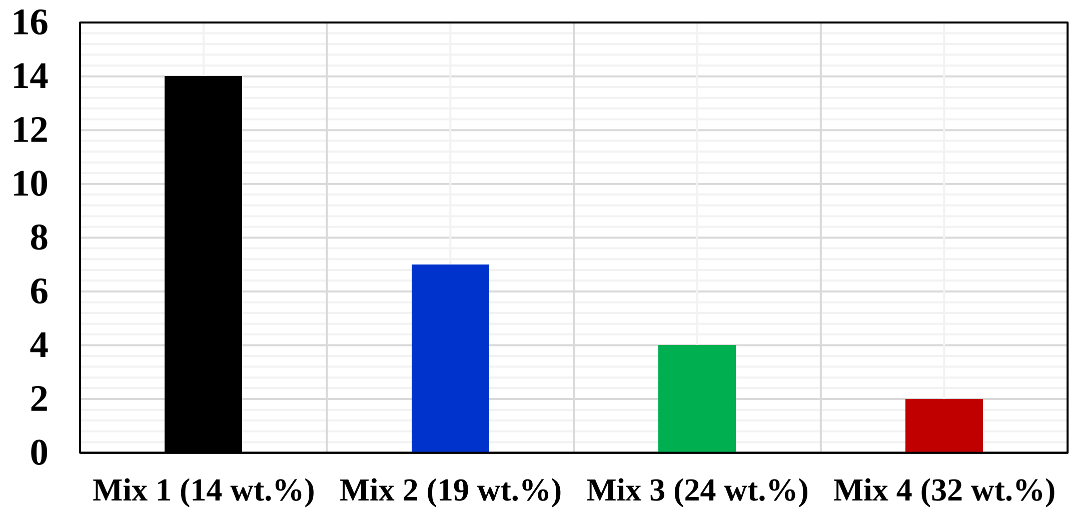
Najvani, M. A. D., Murcia, D. H., Soliman, E., & Taha, M. M. R. (2023). Early-age strength and failure characteristics of 3D printable polymer concrete. Construction and Building Materials, 394, 132119. 2023

Mechanical Properties of 3D-Printed Polymer Concrete

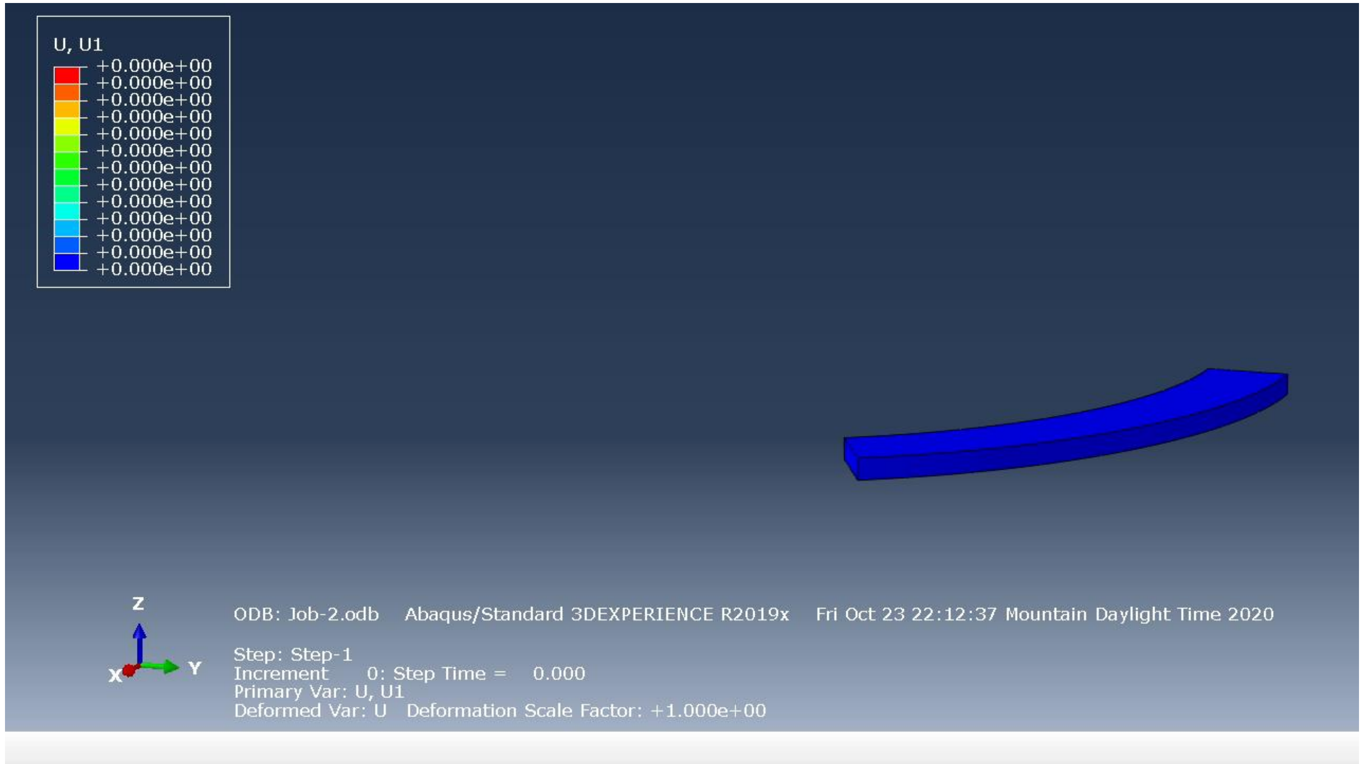
Compressive Strength (MPa) at 7 days



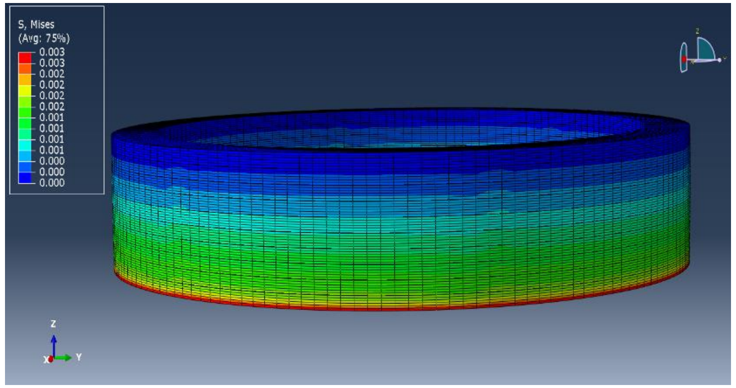
Young's Modulus (GPa) at 7 days



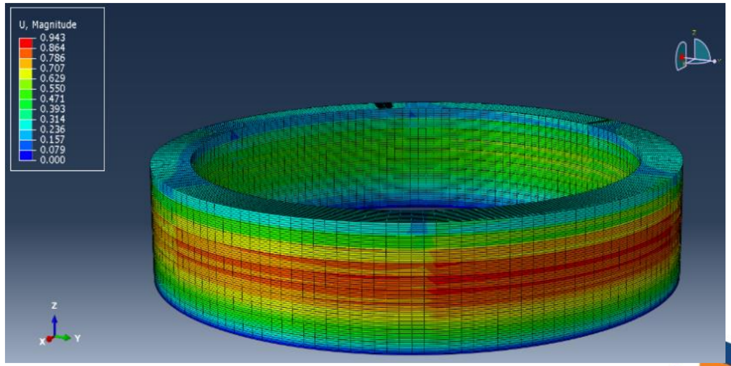
Simulation of 3D-printed Polymer Concrete



Simulation of 3D-printed polymer concrete tank



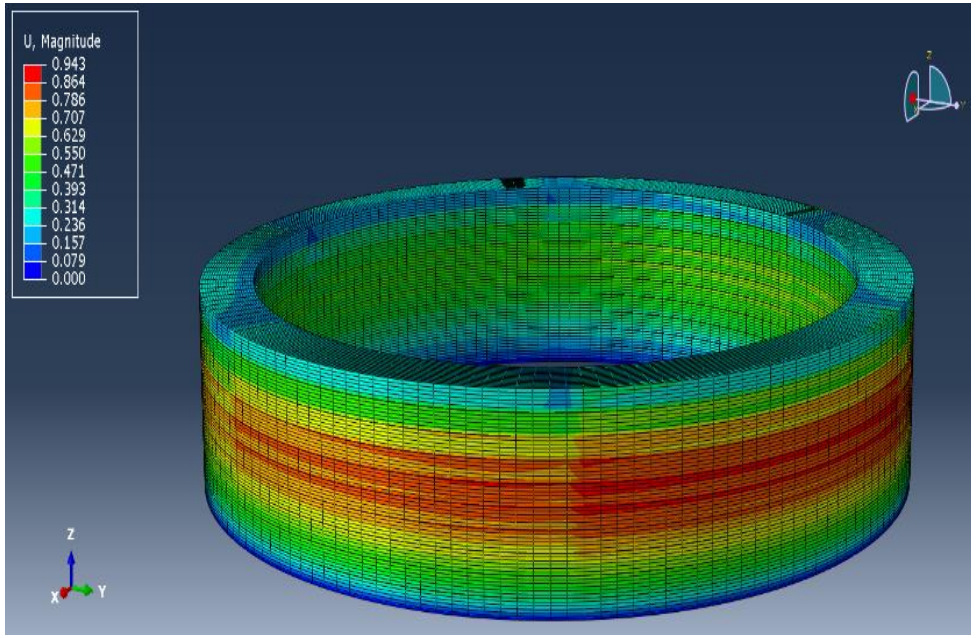
Stress Contour



Displacement Contour

Simulation of 3D-printed Polymer Concrete

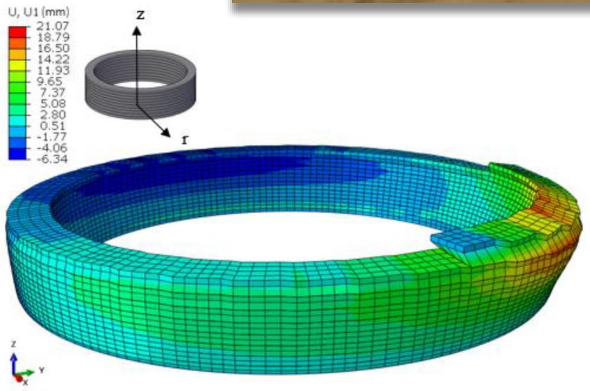
The model is being validated with 3D-printed concrete to predict the deformation and our ability to predict the printing process.

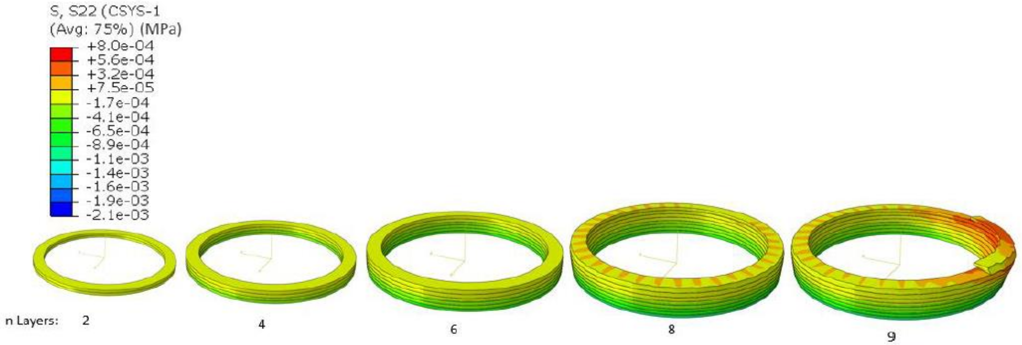


Simulation and printing of 3D-printed polymer concrete

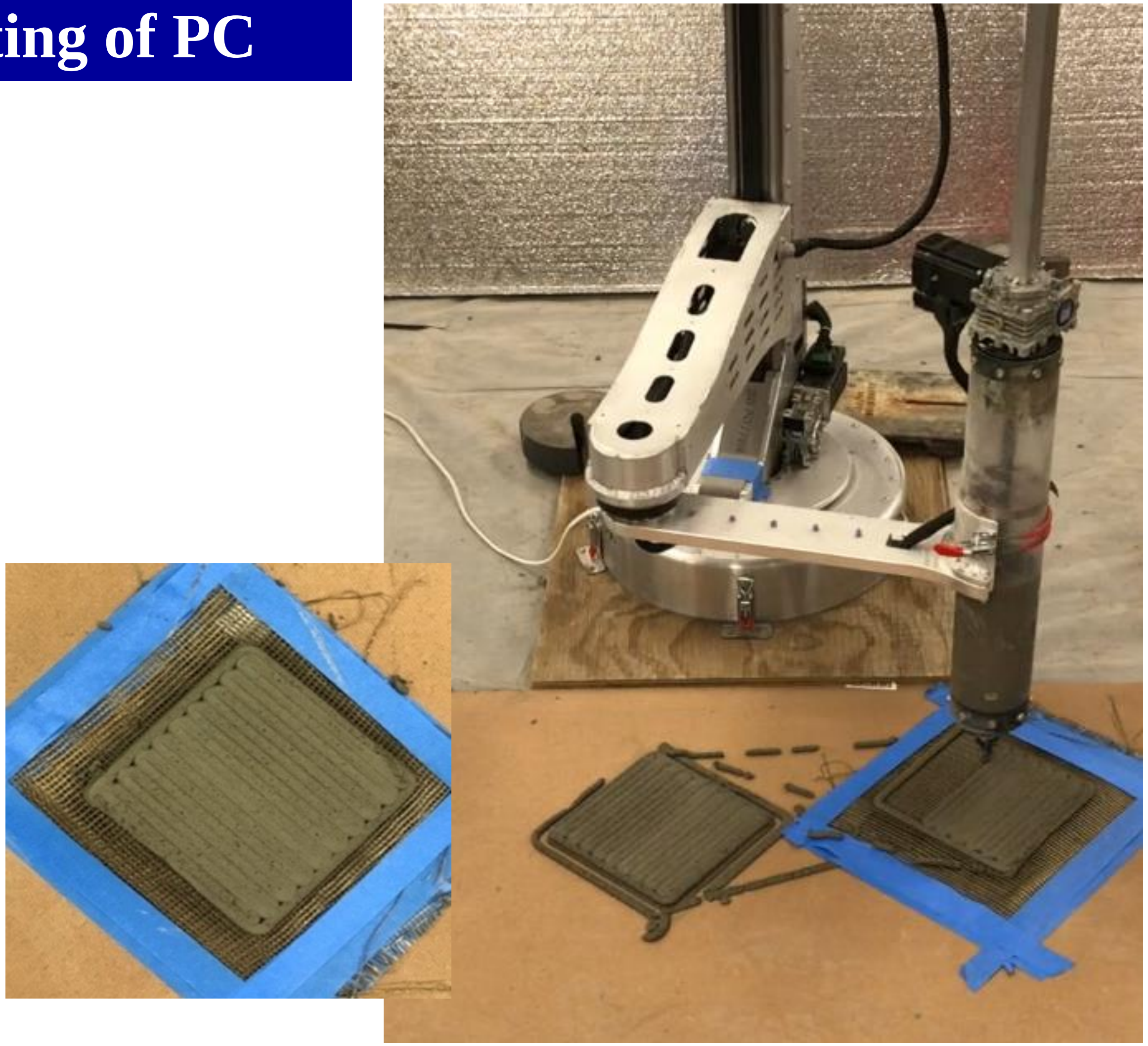
Simulation of 3D-printed Polymer Concrete

The model can predict failure due to local buckling at the **10th layer** of 3D printed PC.

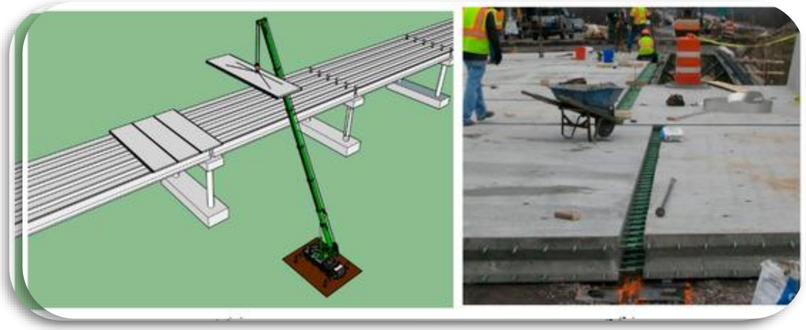




Full-Scale 3D-printing of PC



Application of 3D-printed Polymer Concrete



Closure joints for ABC

Architectural façade

Drainage pipes

Vibration Damping material

Manholes

Tanks

Flooring

Conclusions

- ***Polymer concrete*** can lead the way as emerging technologies in the construction field.
- A ***next generation 3D-printable polymer concrete-by-design*** is being developed and includes variety of polymers, aggregate, and nano-materials to achieve desired 3D-printed PC.
- The rheological behavior of ***3D-printed polymer concrete*** is governed by the ***polymerization rate of the polymer*** and can be adjusted to enable successful ***3D printing.***
- ***The time-dependent failure envelope*** of polymer concrete is essential to ***predict the failure mode of 3D-printed PC***.
- Integrating experimental measurements and simulation of the 3D-printing process ***is critical for the successful*** development of ***3D-printed polymer concrete by-design***

ACI MATERIALS JOURNAL TECHNICAL PAPER

Title No. 118-M97

Rheological Characterization of Three-Dimensional-Printed Polymer Concrete

by D. Heras Murcia, M. Abdellatef, M. Genedy, and M. M. Reda Taha

Keywords: additive manufacturing; polymer; polymer concrete; rheology; three-dimensional (3D) printing.

INTRODUCTION

ACI Materials Journal/November 2021 189

Murcia et al., ACI Materials Journal, 2021

Construction and Building Materials 394 (2023) 132119

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journal homepage: www.elsevier.com/locate/conbuildmat

Early-age strength and failure characteristics of 3D printable polymer concrete

Mohammad Amin Dehghani Najvani, Daniel Heras Murcia, Eslam Soliman, Mahmoud M. Reda Taha

ARTICLE INFO

ABSTRACT

Keywords: Early-Age Strength, Rheology, Polymer concrete, 3D Printing

1. Introduction

https://doi.org/10.1016/j.conbuildmat.2023.132119

Najvani et al. CBM Journal, 2023

Evolution of Early-age mechanical and failure behavior of 3D printed polymer concrete

Mohammad Amin D. Najvani[1] [0009-0002-1089-2842], Daniel Heras Murcia[1][0000-0001-5301-1510], and Mahmoud Reda Taha[1][0000-0002-3707-9336]

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mrtaha@unm.edu

Abstract. The increasing interest in 3d printing of concrete for infrastructure applications necessitates having a design for this process. Previous research has mostly focused on 3D printable cement-based concrete mixes, with less attention given to 3D printed polymer concrete (PC). PC is a concrete type that uses polymer instead of cement as a binder. It offers improved compressive and tensile strengths, crack resistance and bond strengths, and superior durability than traditional Portland cement concrete, making it an excellent material for 3D printing. This study aims to understand the evolution of the early-age mechanical properties of fresh polymer concrete and its potential failure during printing. Unconfined uniaxial compression and direct shear tests were performed on fresh polymer concrete for the first 110 minutes after mixing to determine the evolution of mechanical and failure characteristics with time. Such characteristics include compressive strength, modulus of elasticity, cohesive strength, and friction angle. A time-dependent early-age Mohr-Coulomb failure envelope is established to describe the mechanical and failure behavior of 3D printed polymer concrete.
Keywords: Polymer Concrete, Green Strength, 3D Printing, Rheology.

1 Introduction

3D printing is a computer-controlled method of sequentially layering materials to create three-dimensional shapes. This process helps fabricate complex geometries and produce prototypes. The construction industry's gradual shift towards automation has prompted growing research to explore the potential of this technology. 3D concrete printing, in particular, enables architects and builders to produce intricate and asymmetric patterns while minimizing human error leading ways to innovative designs [1,2].

Concrete made from polymers as a binder, called Polymer Concrete (PC), has been used in various field applications since the 1950s. Such applications include precast architectural facades, underground utilities, wastewater pipes and tanks, manholes, machine foundations, bridge deck overlays, and closures [3]. PC exhibits superior properties such as high tensile and bond strength and outstanding durability [4,5]. However, its use is often restricted due to its comparatively higher cost [6,7]. The enhanced characteristics of PC to being impermeable concrete with very high durability [7,8].

Najvani et al., ICPIC 2023

Selected Journal Publications by Taha's Research Team

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QUESTIONS?