

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

Siham S. Al Shanti, Daniel H. Murcia, Mahmoud Reda Taha

Gerald May Department of Civil, Construction & Environmental Engineering University of New Mexico





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

• **<u>Polymer Concrete (PC)</u>** is a flowable concrete where the **polymer fully or partially replaces cement** as a binder.



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3D-Printed Polymer Concrete By-Design





CONVENTION

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 FlowSlump[Pumpability & Extrudability][Structural build-up]

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.







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:



Defining 3D-printing Parameters

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

 $A_{printed}$ = Average filament width * Length A_{ideal} = Nozzle size * Length



V_r: 3D-printing speed V_e: Extrusion speed



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





Printability Window (Rest Time)





3D-Printability Performance Assessment

Buildability | 3D-Printing 10 layers











Example of *rejected* buildability testing





Rheology of 3D-Printed Polymer Concrete





CONVENTION

Rheology of 3D-Printed Polymer Concrete

Effect of polymer wt.% on the static yield stress

At 60 mins







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





CONVENT

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









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Early-age of 3D-Printed Polymer Concrete

Time-Dependent Failure Envelope of 3D-Printed PC





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CONVENTION

Early-age of 3D-Printed Polymer Concrete

Time-Dependent Failure Envelope of 3D-Printed PC







CONVENTION

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







CONVENTION

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



CONVENTION

Early-age of 3D-Printed Polymer Concrete

Time-Dependent Failure Envelope of 3D-Printed PC





Mechanical Properties of 3D-Printed Polymer Concrete

70 60 50 40 30 20 10 0 Mix 1 (14 wt.%) Mix 2 (19 wt.%) Mix 3 (24 wt.%) Mix 4 (32 wt.%)

Compressive Strength (MPa) at 7 days



Young's Modulus (GPa) at 7 days



Simulation of 3D-printed Polymer Concrete





Stress Contour





CONVENTION

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







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

Conventional cement-based concrete is widely used as a construction material due to its ability to flow before hardening and to adopt the shape of the formwork as it is placed. Contrarily, in layered extrusion additive manufacturing, commonly known as three dimensional (3D) printing, concrete is shaped without formwork. This imposes stringent time-dependent rheological requirements of materials used for 3D printing. Polymer concrete (PC) is a material extensively used in the precast industry. This paper reports on the potential use of PC for 3D printing applications. The influence of nixture design parameters—specifically rheology modifier content, filler-polymer ratio, and aggregate-polymer ratio-on the rheological properties of a 3D-printable PC are investigated. The rheological properties of seven PC mixtures are tested and characterized. PC can be described as a Bingham pseudoplastic material, and a Herschel-Bulkley model can accurately describe its rheological behavior (dynamic shear stress) over time. The evolution of static yield stress over time was found to follow an exponential trend. The use of these models to predict the dynamic and static yield stress of PC shall enable the design of efficient and stable 3D printing. Finally, 3D-printed PC shows good mechanical performance with compressive strength above 30 MPa (4351 psi) at 7 days of age. Automation of the PC precast industry using 3D printing will create new opportunities for the use of PC in civil infrastructure.

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

INTRODUCTION

Three-dimensional (3D) concrete printing commonly relies on the deposition of layered filaments of the material. Cement-based materials have been used for this application due to their ability to stay as pseudo-solid before hardening when their flow properties are properly designed.1 Cement concrete has limitations in its tensile strength, ductility, fatigue, and resistance to chemical exposure. To overcome these limitations, polymer concrete (PC) was developed in the 1970s for applications that require protection against aggressive environments,2,3 dynamic and cyclic loads,4 high ductility,46 and fatigue.7 The main applications of PC in infrastructure include bridge deck, industrial overlays, waste-water pipes and containers, manholes, underground communication and transmission line boxes, building facade panels, machine foundations, and other elements subjected to dynamic and cyclic loads. 8.9 Numerous PC applications are directed toward precast elements, making PC amenable for 3D-printing technology

This work focuses specifically on polymer concrete (denoted PC) a composite material developed by mixing well-graded aggregate/fillers and a polymer resin that

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fully substitutes the cement binder. Other types of polymer concrete can be found elsewhere.10 The mixture design of the polymer matrix and aggregate enables engineerin specific desired properties of PC, which reduces its cost.1 PC offers numerous advantages over cement concrete as an infrastructure material, such as very low permeability, high ductility, chemical resistance, acceptable mechanical strength, and excellent bond with other materials.12 On the other hand, PC must be carefully designed for field application by accounting for temperature effects and considering the time-dependent behavior of PC under sustained stresses.12

The use of fillers to modify the rheological properties of polymers has been of paramount importance to enable innovative applications of polymers.11 Research has also been performed to understand the effects of using different filler materials on the behavior of PC. Fly ash13-15 and silica fume15 were investigated as potential fillers for PC and showed an increase in mechanical strength and overall durability performance of PC. The improvement of mechanical strength in PC incorporating silica-based pozzolanic fillers is not attributed to the pozzolanic reaction as in cement concrete but to the ability of those fillers to improve the packing fraction of the particles16 and to form with the fine and coarse aggregate a well-graded system of particles with reduced overall porosity.17 Fly ash and silica fume are often used due to their wide availability and proven to provide PC with improved workability, high strength, 18,19 good thermal stability,20-22 improved fire resistance,23 good electrical conductivity,22,24 and shielding features.25 The addition of fly ash was also proven to lead to better mechanical performance than silica fume.1

Engineering the rheology of 3D-printed concrete is critical to achieving a balance between the hardened state properties while maintaining good processability of the material for pumping and extrusion. Rheology is also essential to predict material response during the printing process. Rheological properties for concentrated suspensions of particles in a low viscosity matrix have been widely investigated.26-32 Figure 1 shows a schematic representation of the different rheological models used to describe polymer and PC. Polymers usually do not display initial shear stress (required to

ACTMaterials Journal, V. 118, No. 6, November 2021. MS No. Mc2020-491.81, doi:10.1493/971703123, mc2020. March 1. 2021, and Boston, ACI and Science and Science and Science and Science Activation Concession Boston, ACI and Francesco, Landard Be analysis of costs unless permission is obtained from the copyright proprietor. Partiage discussion including middre's closure, if any with be publicable and mostly from the journal? A doi: 16 discussion for the proprietor of the science of th d within four months of the paper's print publi

Murcia et al., ACI Materials Journal, 2021



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

Mohammad Amin Dehghani Najvani 🔩 Daniel Heras Murcia 🖲 Eslam Soliman b. Mahmoud M Reda Taha

⁶ Gendel May Department of Civil, Construction & Environmental Engineering, University of New Mexico, MSC01 1070, 1 University of New Mexico, NM 87131, USA ⁶ Department of Civil Engineering, Assist University, Assist 71516, Egypt

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1. Introduction

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Additive manufacturing (AM), also known as 3D printing, is the computer-controlled sequential layering of materials to produce threensional shapes. It is beneficial for prototyping and fabricating geometrically complex elements. Over the last two decades, this tech-nology has attracted many researchers globally as the construction industry slowly shifts away from traditional methods toward automation of operations. Architects and builders can use 3D concrete printing to develop innovative and novel designs and produce intricate and asymmetric patterns with minimal human errors [1,2]. 3D printing eliminates traditional formwork by placing a particular material volume in sequential layers

The rheology of 3D printed concrete must be controlled to achieve a balance between the hardened state qualities and the material's proessability for pumping and extrusion. The ability to anticipate material behavior throughout the printing process is critical and depends on its theology [3]. Polymer concrete (PC) is a type of concrete in which the binder is made of polymer rather than cement. Since the 1950s, PC has been used in various field applications such as precast architectural facades, underground utilities, wastewater pipes and tanks, manholes, machine foundations, bridge deck overlays and closures, and other applications [4]. Compared with conventional Portland cement concrete,

than traditional concrete, PC usage is limited [7,8]. The impro-PC compared with conventional cement concrete is due to the major ement in PC microstructure resulting in low permeability, which is often a governing factor of concrete durability [8,9]. This research focuses on PC, a composite material created by mixing aggregate, fillers, and a polymer resin that entirely substitutes the cement binder. PC properties and its vast application in the industry make it an excellent material for 3D printing [10,11]. To be able to design the printing process, print product quality and prevent failure (during and after printing). PC's mechanical properties must be determined in the fresh state. This study researches the time-dependent growth of the mechanical characteristics of fresh PC, denoted here as early-age strength characteristics, including modulus of elasticity, Poisson's atio, and failure criteria The shape stability of the material during the printing period is an essential property of 3D printing [3,12,13]. The ability of fresh concrete to maintain its shape and self-support its weight immediately after mixing or compacting, known as early-age strength, is the result of the ation of inter-particle friction and cohes

PC has higher tensile strength, improved bond strength to existing

concrete, and superior durability [5.6], However, due to its higher cost

Fresh concrete mechanical behavior can be modeled using the Mohr-

Coulomb model. The Mohr-Coulomb is a simple approach that can

* Corresponding author at: Department of Civil, Construction & Environmental Engineering, MSC01 1070, 1 University of New Mexico, Albuquerque, NM 87131-0001, USA. E-mail address: Najvani@unm.edu (M.A. Dehghani Najvan

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Najvani et al. CBM Journal, 2023

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

Mohammad Amin D. Najvani¹ [0009-0002-1089-2842], Daniel Heras Murcia¹ [0000-0001-5301-1510], and Mahmoud Reda Taha^{1[0000-0002-3707-9336]}

¹ Department of Civil, Construction & Environmental Engineering, University of New Mexico, Albuquerque, NM 87131, USA 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.

Introduction

1

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 façades, 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

CONVENTION

ACI Concrete Convention, Toronto, ON, Canada, March 30 – April 2, 2025

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Selected Journal Publications by Taha's Research Team taha.unm.edu

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Acknowledgment







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QUESTIONS?