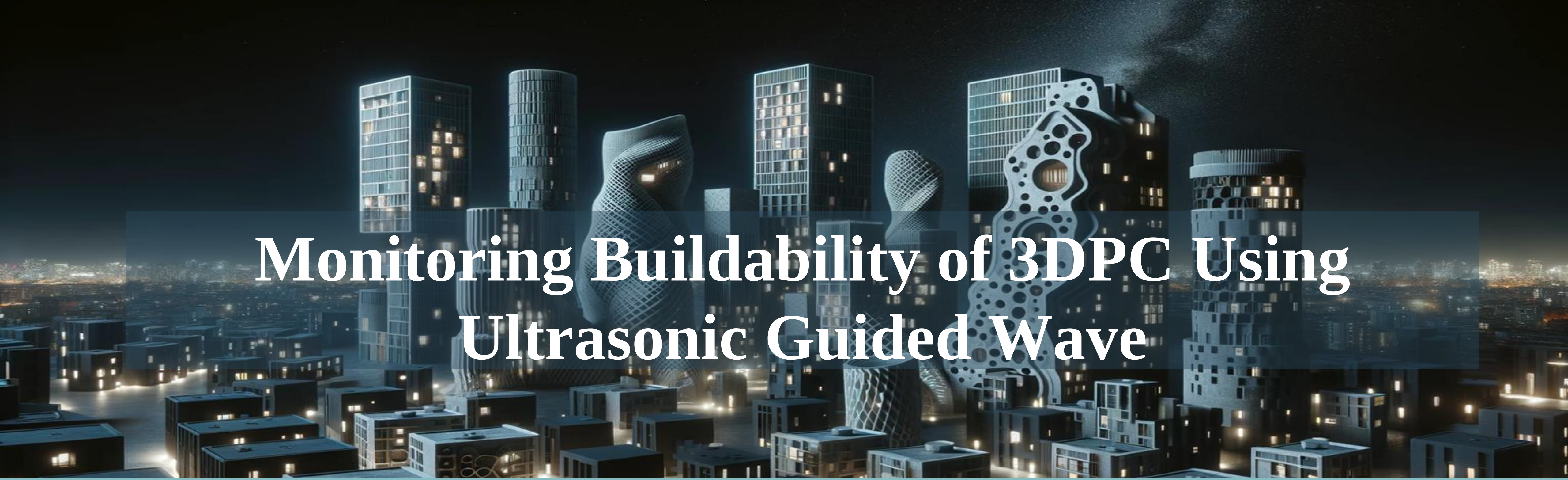

Monitoring Buildability of 3DPC Using Ultrasonic Guided Wave

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Introduction

1. Overview of the Study: Monitoring 3DPC (Early Printing Stage)
2. Introducing Guided Waves

Test Methodology

3. Materials and Mix Design
4. Early-age Material Properties
5. Printability of the Mix Design

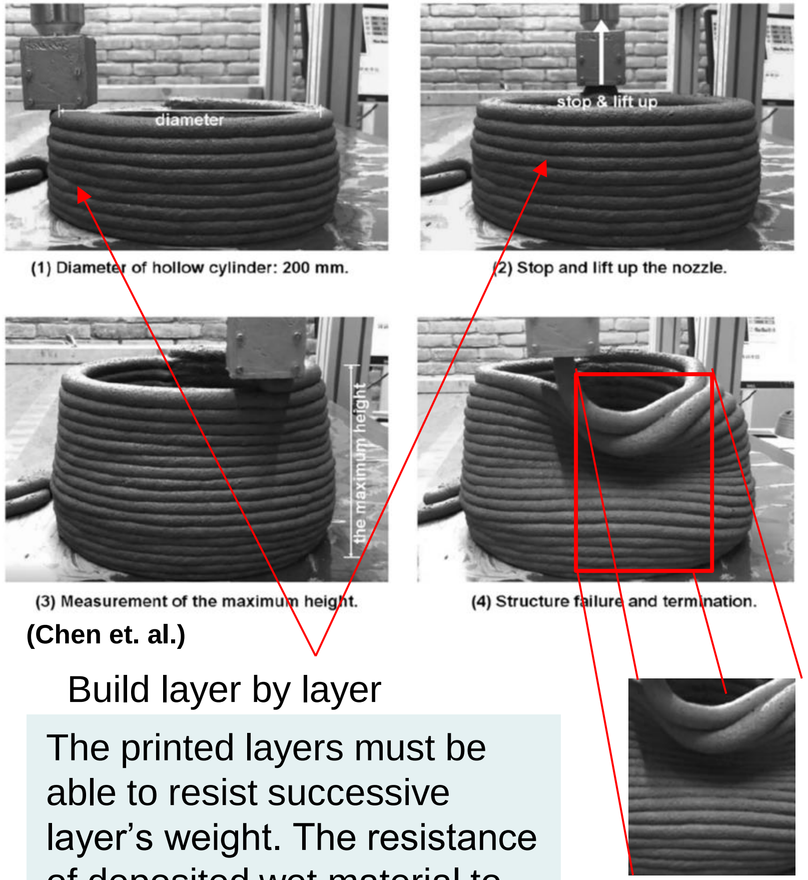
6. Ultrasonic Test Setup
   Chosen Waveguide
   Chosen Center Frequencies
7. Green Strength Test

Test Results

8. Attenuation (dB)
9. Green Strength (kPa)
10. Buildable Layer Prediction
11. Correlations

Monitoring 3DPC: Early Printing Stage

Process of 3D printing



(1) Diameter of hollow cylinder: 200 mm.

(2) Stop and lift up the nozzle.

(3) Measurement of the maximum height.

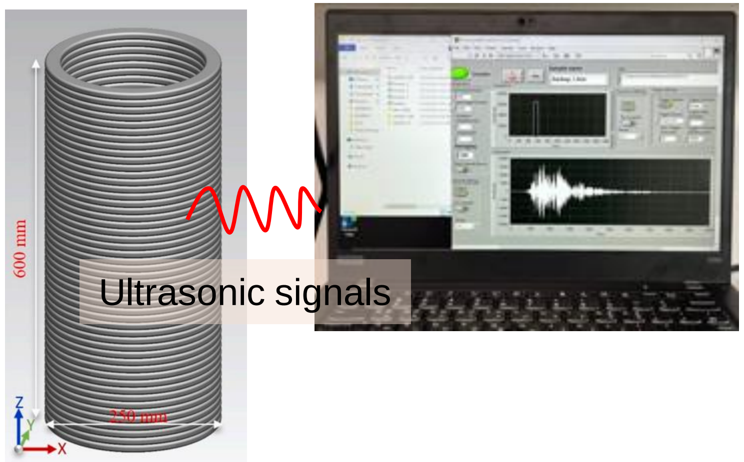
(4) Structure failure and termination.

(Chen et. al.)

Build layer by layer

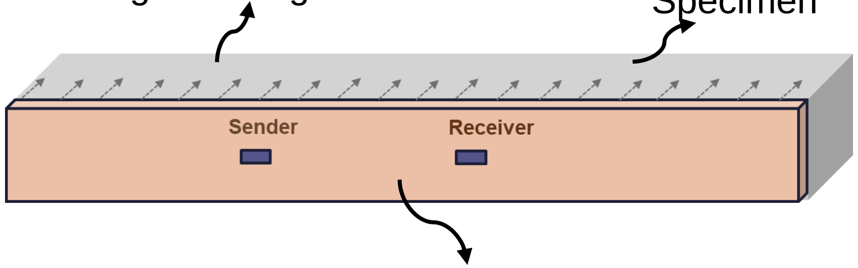
The printed layers must be able to resist successive layer's weight. The resistance of deposited wet material to deformation under load is known as **buildability**

Application of ultrasonic guided wave



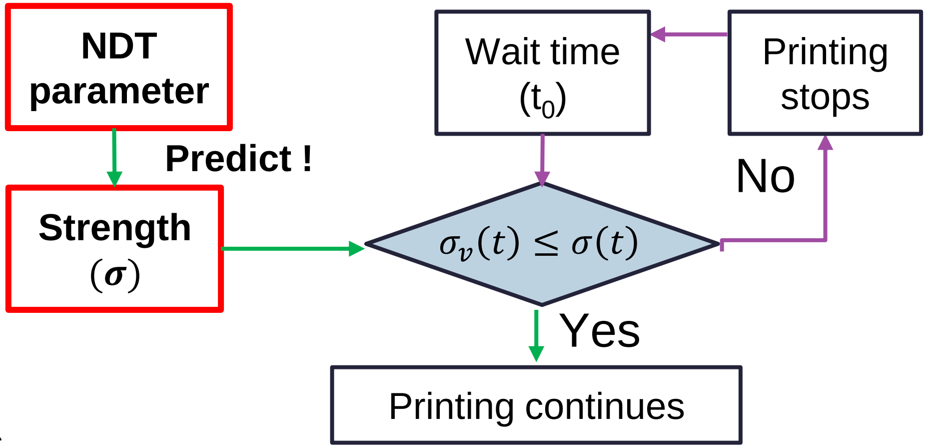
Non-destructive technique to monitor 3DPC

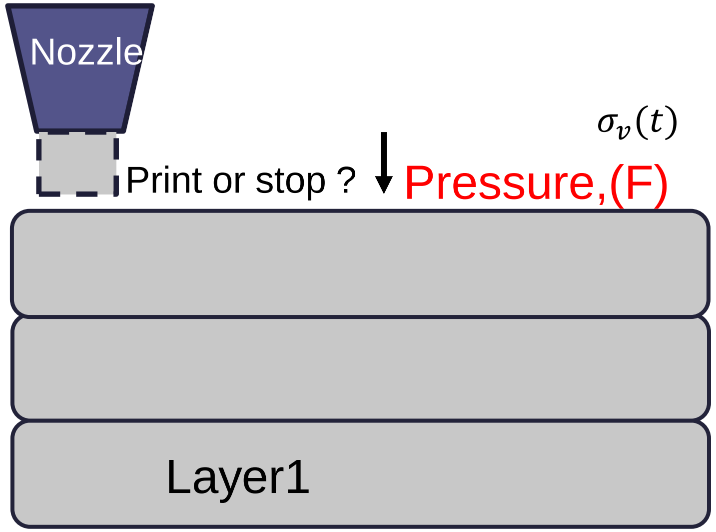
Maybe guided wave will work !



Wave propagates in the wave guide (i.e. plate)

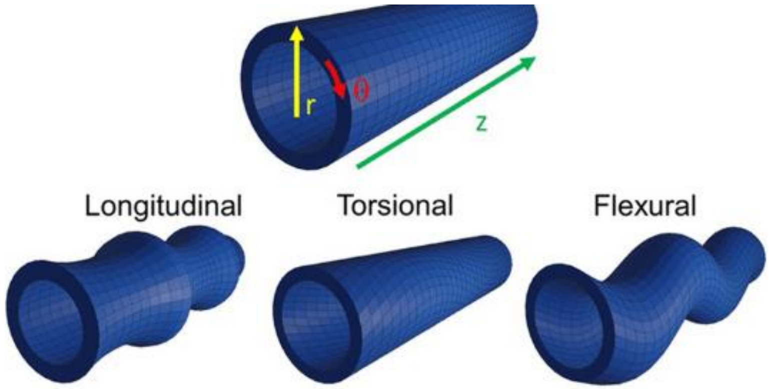
Determine green strength to predict printability



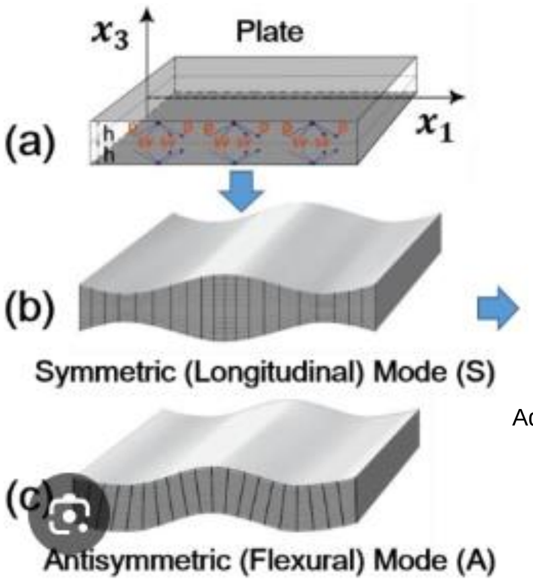


Chen, Yu, et al. "3D printing of calcined clay-limestone-based cementitious materials." *Cement and Concrete Research* 149 (2021): 106553.

What are Guided Waves

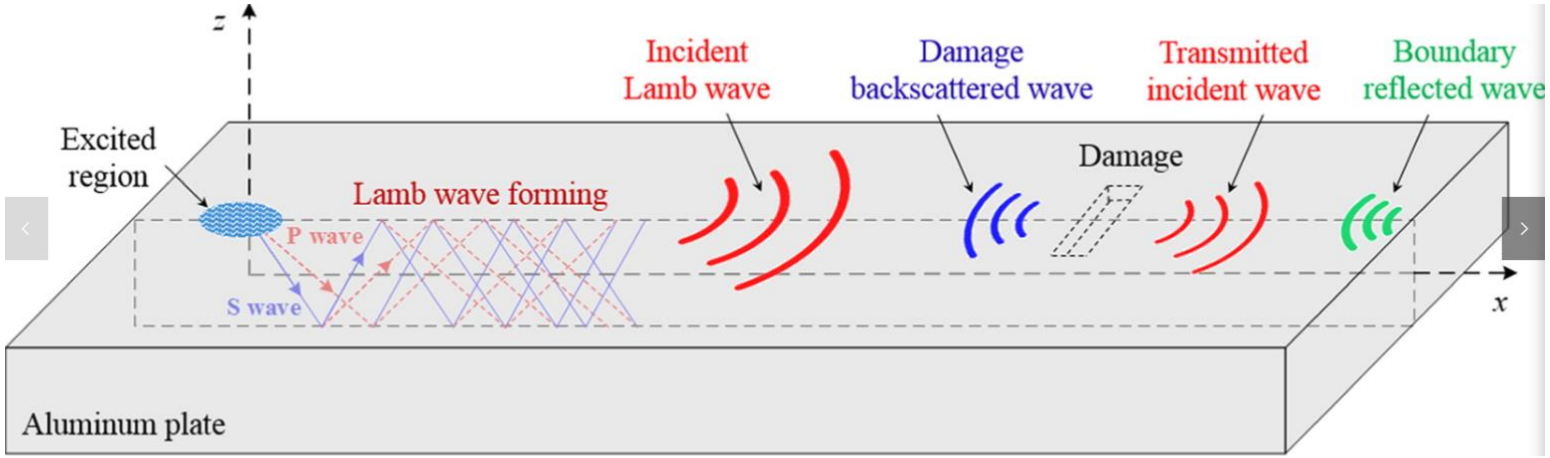


Adopted **[1]**



Adopted **[2]**

- Waves propagating in a finite boundary (Plate or cylindrical)
- Guided waves in cylindrical shapes: longitudinal, torsional and flexural modes
- Guide waves in plate structure: Lamb waves
- Lamb waves: **S**ymmetric and **A**nti-symmetric modes
- **Wave modes are decomposed due to the superposition of P- and S-waves**



Adopted **[3]**

The interaction of wave and the surface causes constructive and destructive interference, leading to specific wave modes, highly dependent on wavelength of the waves and the thickness of the plate structure

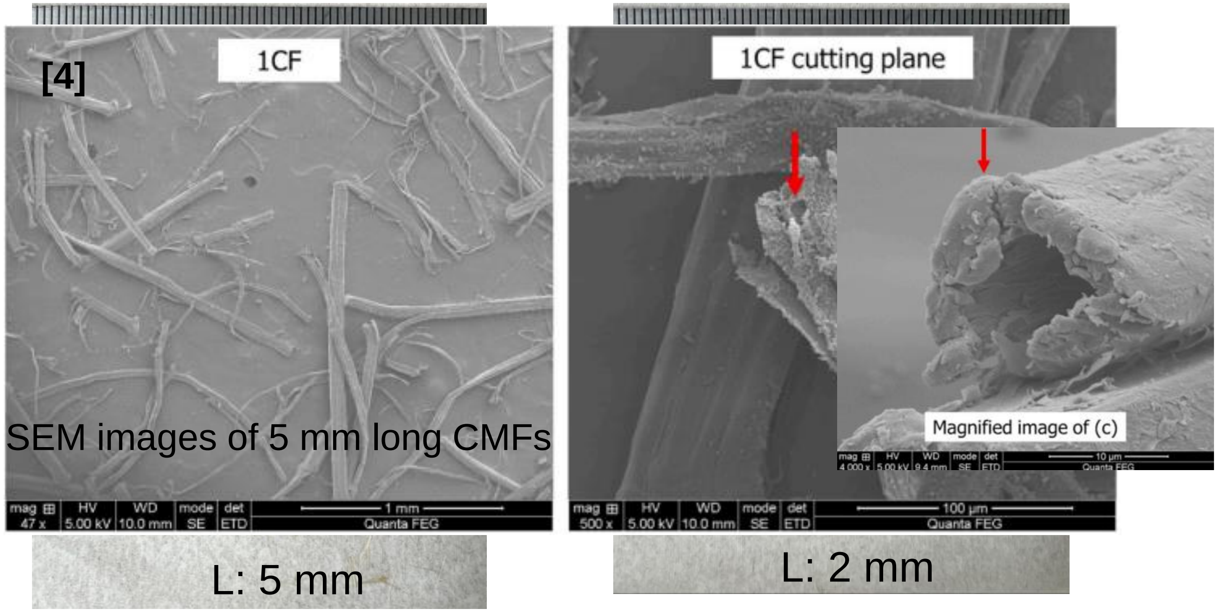
[1] *Troelstra, Marian Amber, et al. "Shear wave cardiovascular MR elastography using intrinsic cardiac motion for transducer-free non-invasive evaluation of myocardial shear wave velocity." Scientific Reports 11.1 (2021): 1403.*
[2] *Sun, Xiaoqiang, et al. "Interaction of Lamb wave modes with weak material nonlinearity: Generation of symmetric zero-frequency mode." Sensors 18.8 (2018): 2451.*
[3] *Harb, Mohammad Said, and Fuh-Gwo Yuan. "Damage imaging using non-contact air-coupled transducer/laser Doppler vibrometer system." Structural Health Monitoring 15.2 (2016): 193-203.*

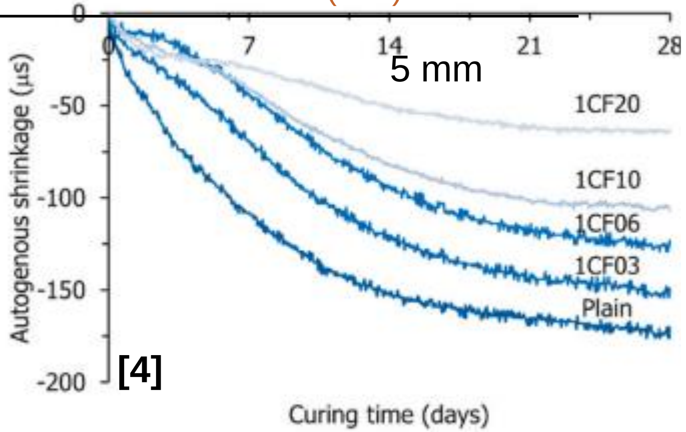
Materials and Mix Design

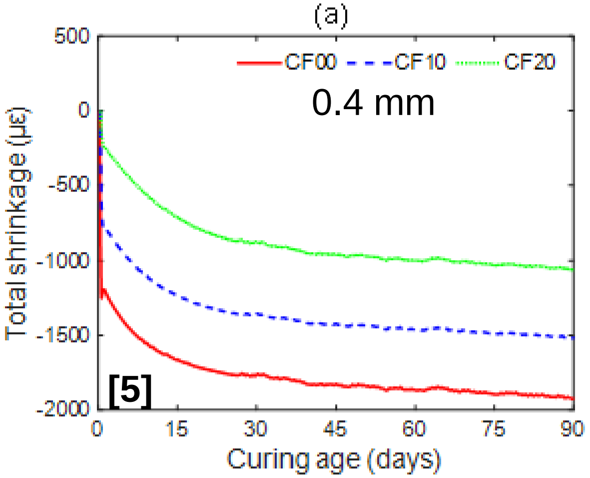
(kg/m³)

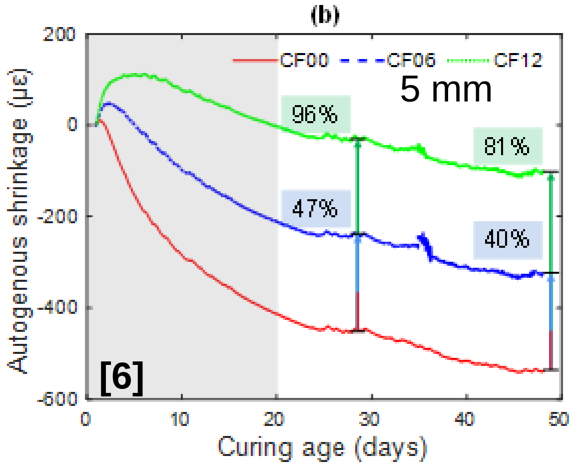
Name	W/B	OPC	Fly Ash	Silica fume	Sand	SP	CMFs	Add. water
CF00	349	764	218	109	1091	11	0	0
2CF10							11 (1 %)	32
2CF20							22 (2 %)	65
5CF10							11 (1 %)	47
5CF20							22 (2 %)	94

CMFs: Cellulose microfibers
2CF10: 2 mm fiber length added 1 %
5CF10: 5 mm fiber length added 1 %
High water absorbing capacity (internal curing agent)
Tensile strength 330 ± 29.4 MPa
Average pore diameter 3.4 μm



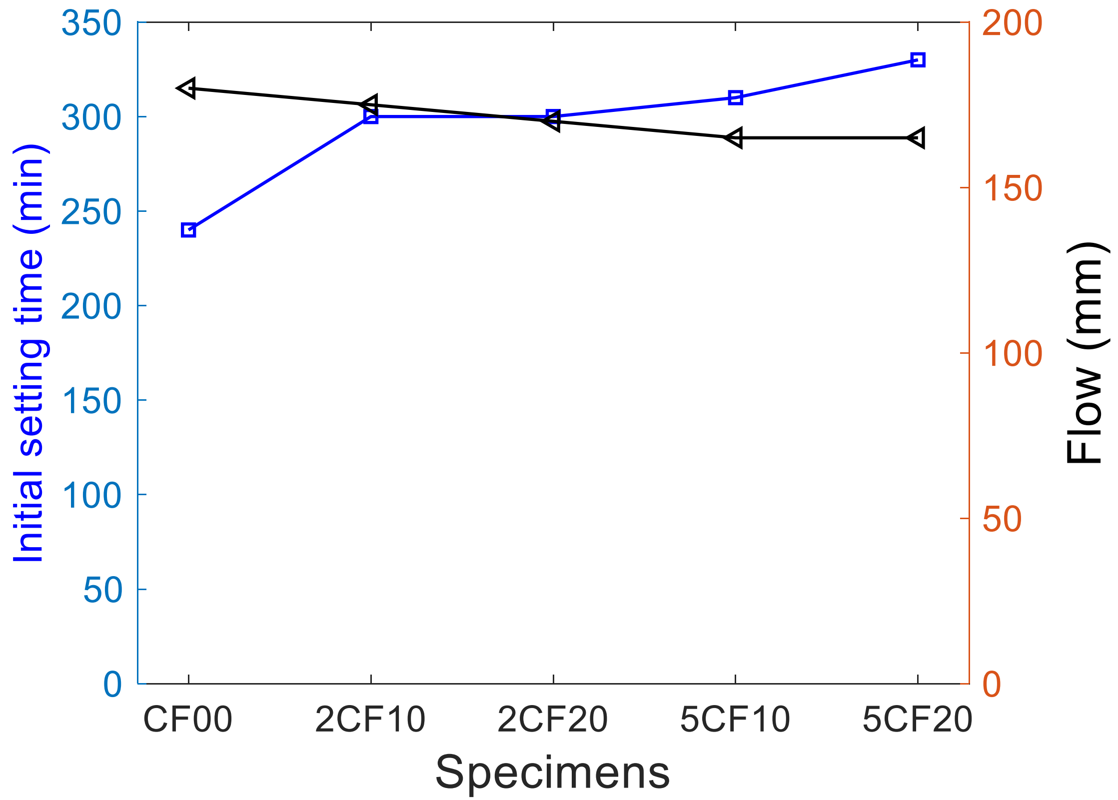






[4] S. Gwon, Y.C. Choi, **M. Shin**, *Internal curing of cement composites using kenaf cellulose microfibers, J Build Eng 47 (2022)*
[5] *E. Cho,* ***G. Chandam,*** *S. Gwon,* ***M. Shin****, Effect of Cellulose Microfibers on Shrinkage: Application of Ultrasonic Non-Destructive Testing*
[6] ***G. Chandam,*** *Y.Oinam, E. Cho, J.S. Popovics, S. Pyo* ***M. Shin****, Effectiveness of Wave Interferometry in Monitoring Autogenous Shrinkage and Mitigation Role of Cellulose Microfibers*

Early-age Material Properties



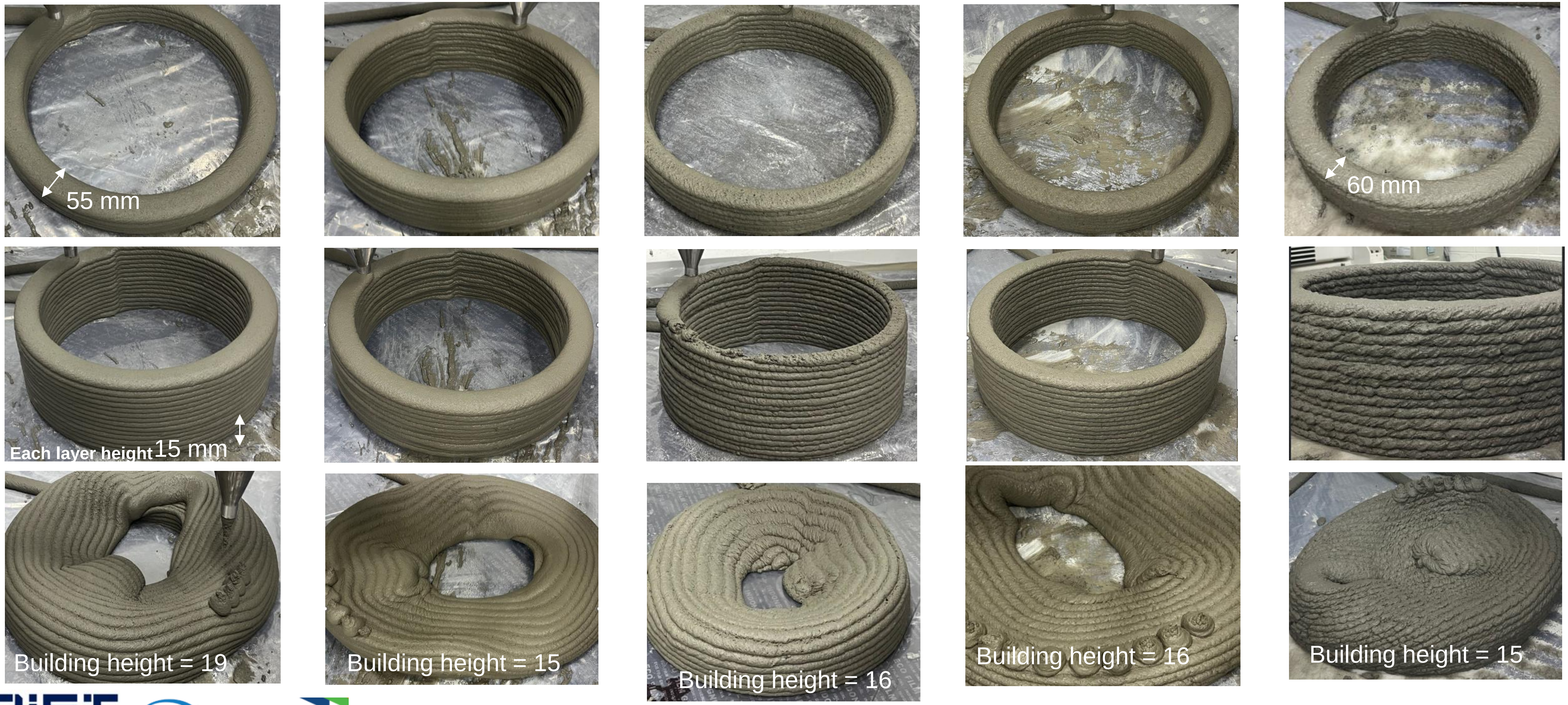
- Initial setting time increases with increase of fiber content and fiber length
- Flow decreases with increase in fiber content and fiber length

ASTM C191 using Vicat needle test apparatus

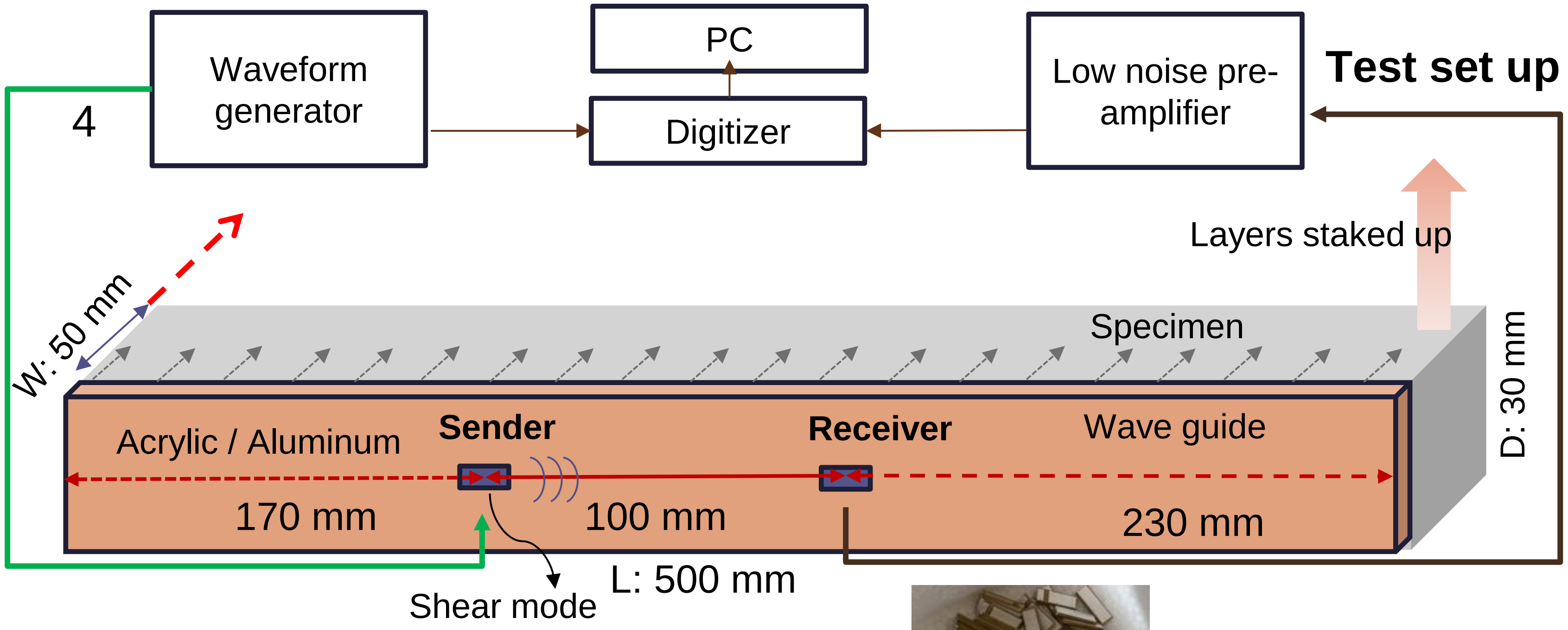
ASTM C230 mini flow table tests

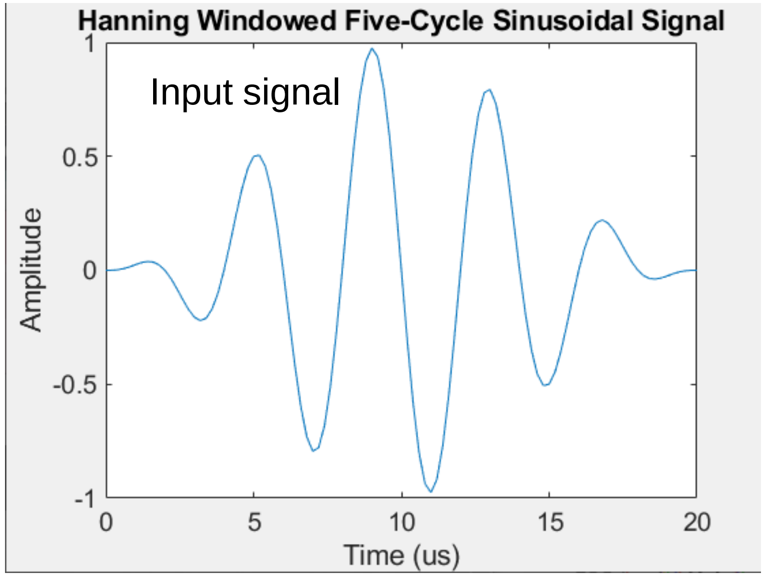
Printability of the Mix Design

CF00: No fibers	2CF10: 2mm 1 %	2CF20: 2mm 2 %	5CF10: 5mm 1 %	5CF20: 5mm 2 %

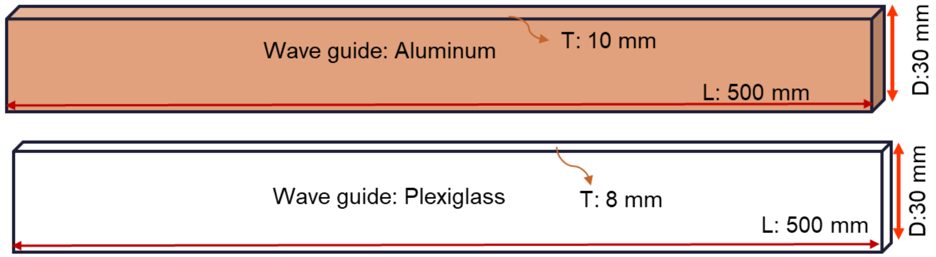


Experimental Setup

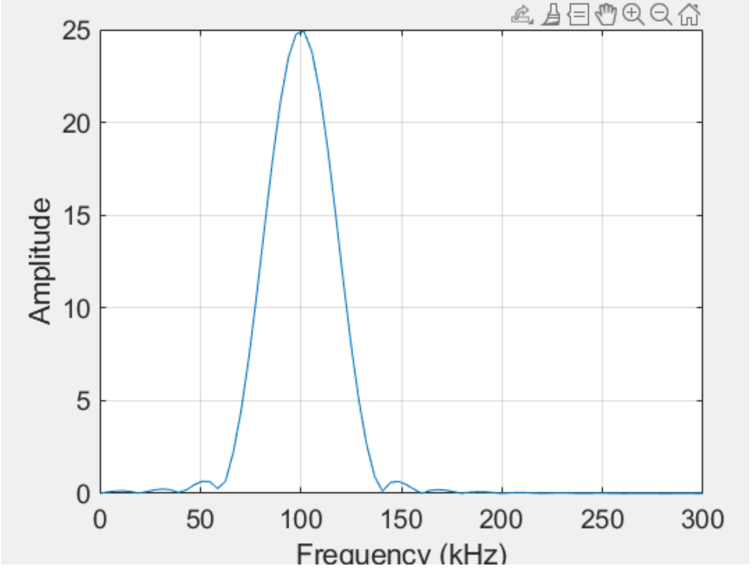




PZT sensors (15 x 5 x 1) mm^3



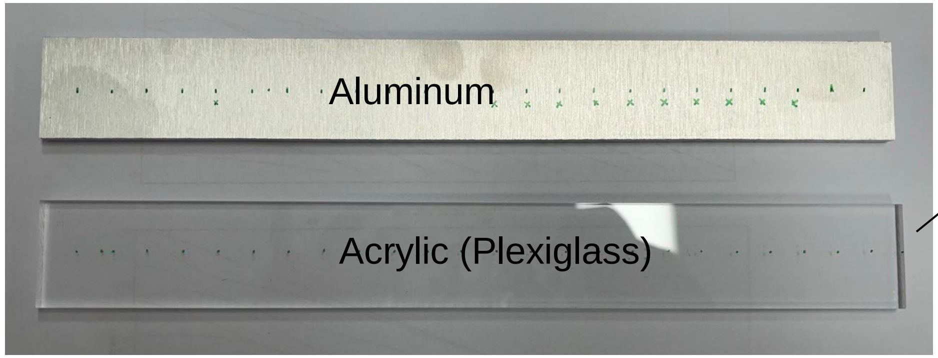
Dominated by symmetric mode (in plane motion) in the plate, which excites leaky shear waves in surrounding material

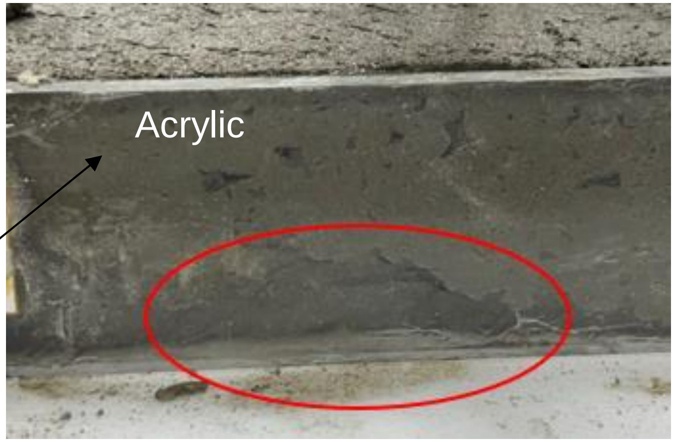


Tests were conducted on cast specimens

The specimens were tested for 2 hours right after casting

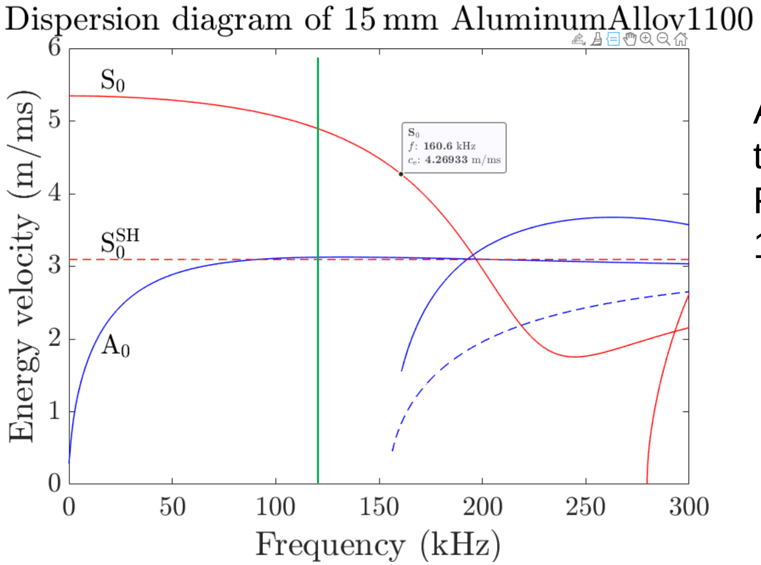
Waveguides





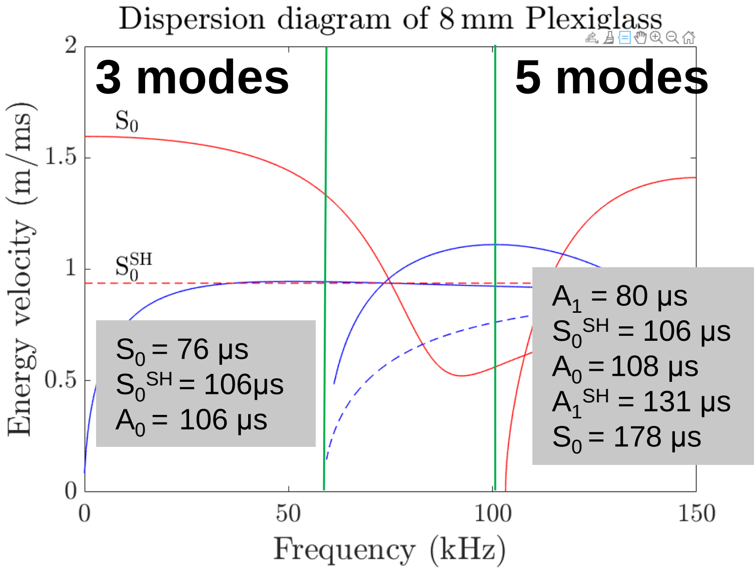
Material properties

Name	Density (ρ) kg/m^3	*E* (Gpa)
Aluminum	2710	69
Acrylic (Plexiglass)	1190	2.75



Dispersion Calculator v2.4

Aluminum wave guide thickness 15 mm
Frequency: 130 kHz and 150 kHz

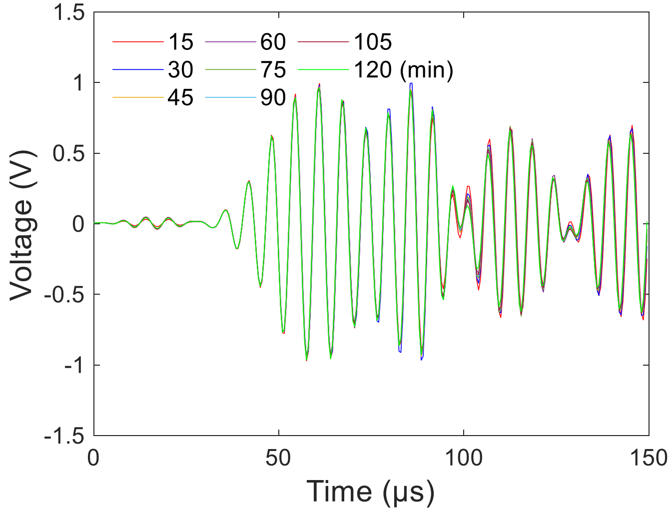


Dispersion Calculator v2.4

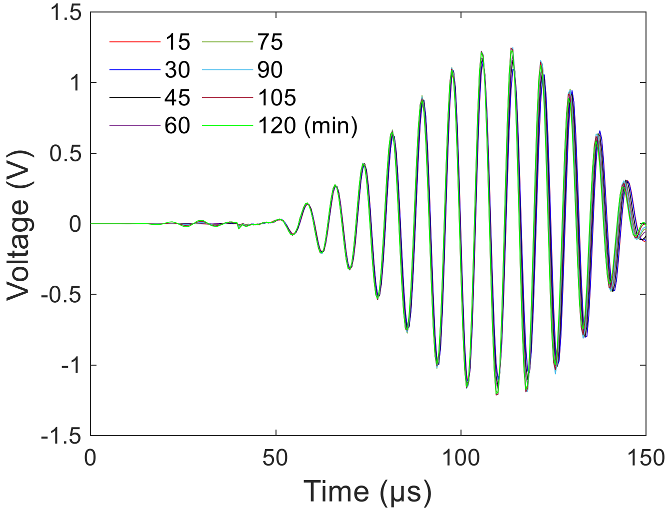
Acrylic wave guide thickness 8 mm
Frequency: 60 kHz and 100 kHz

Aluminum Waveguide

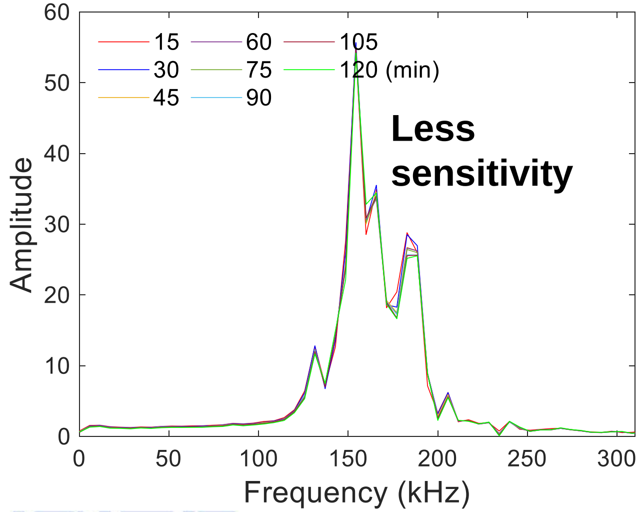
Time Domain



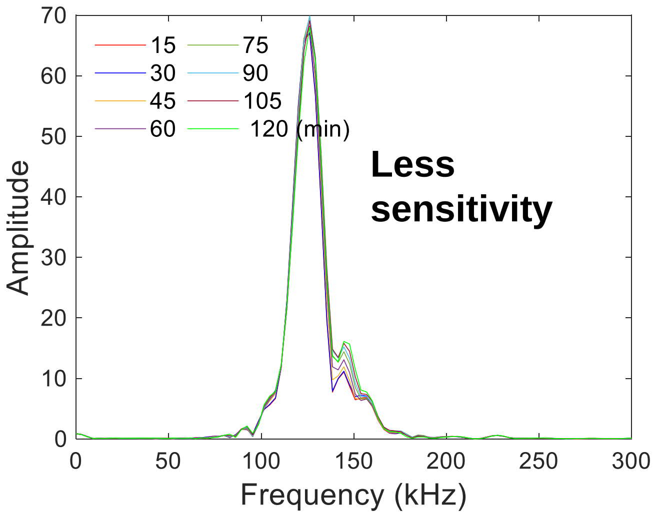
Time Domain

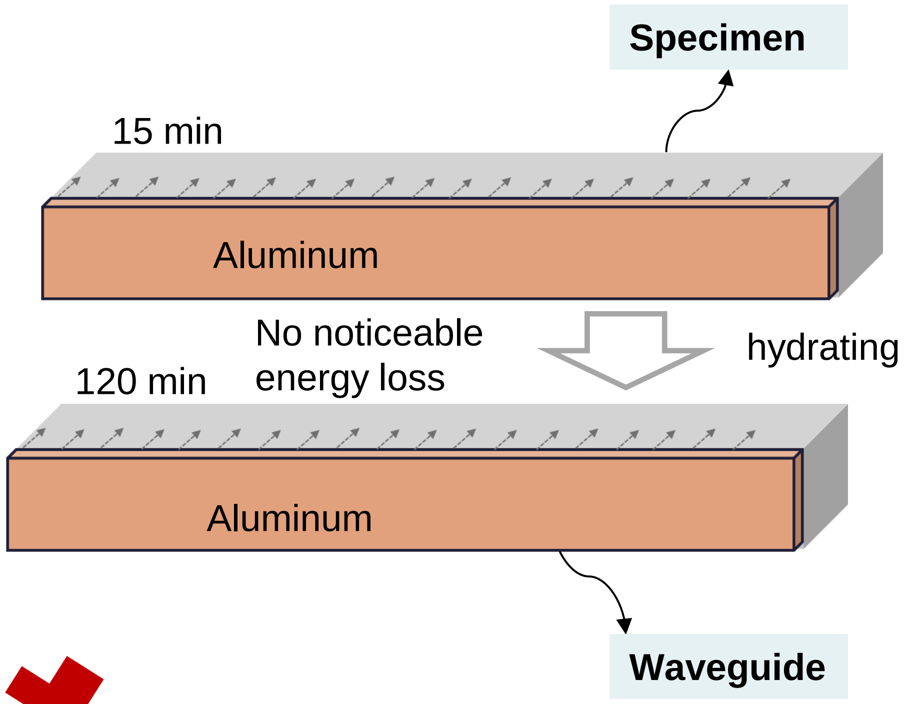


FFT to Frequency domain

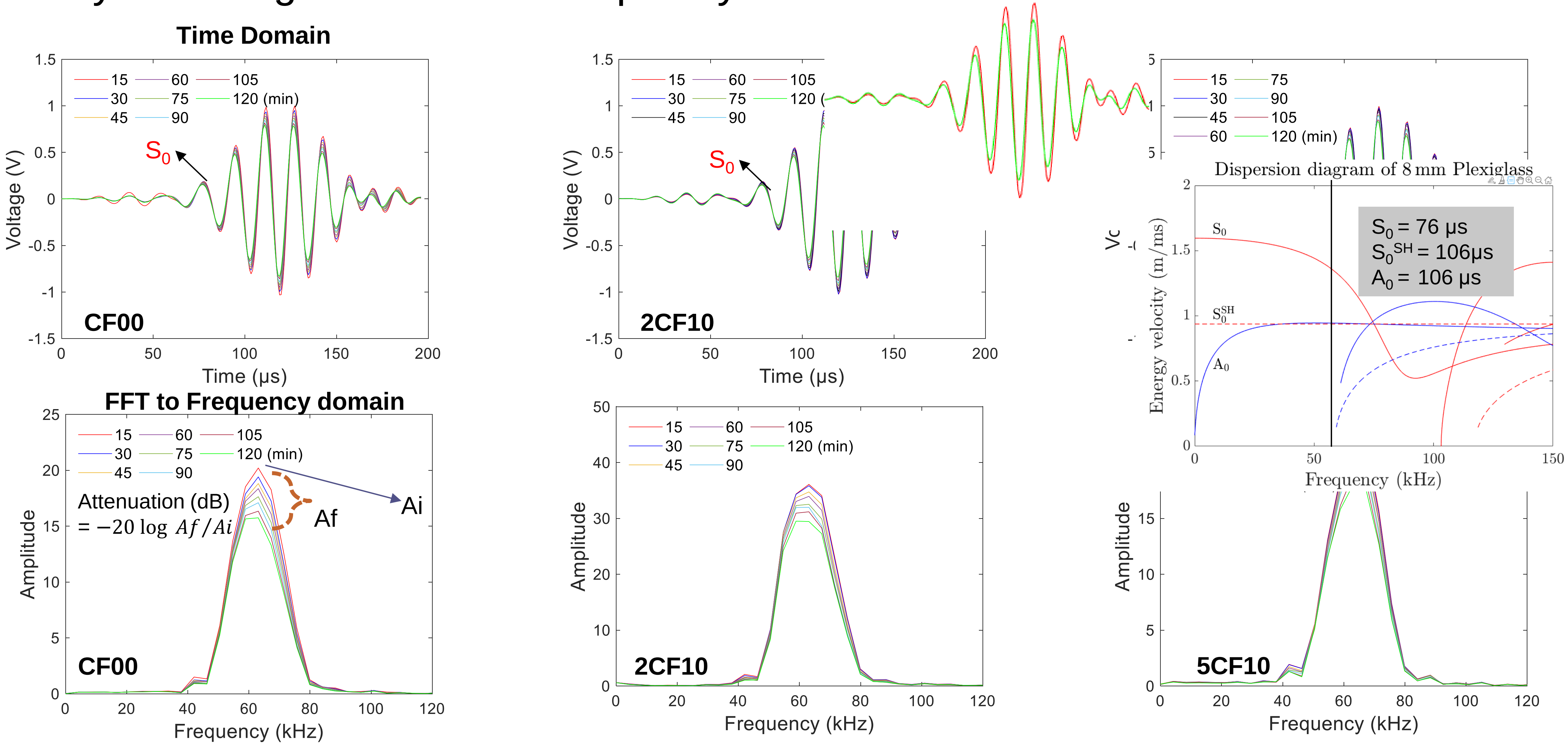


FFT to Frequency domain





Acrylic Waveguide: Center Frequency 60 kHz



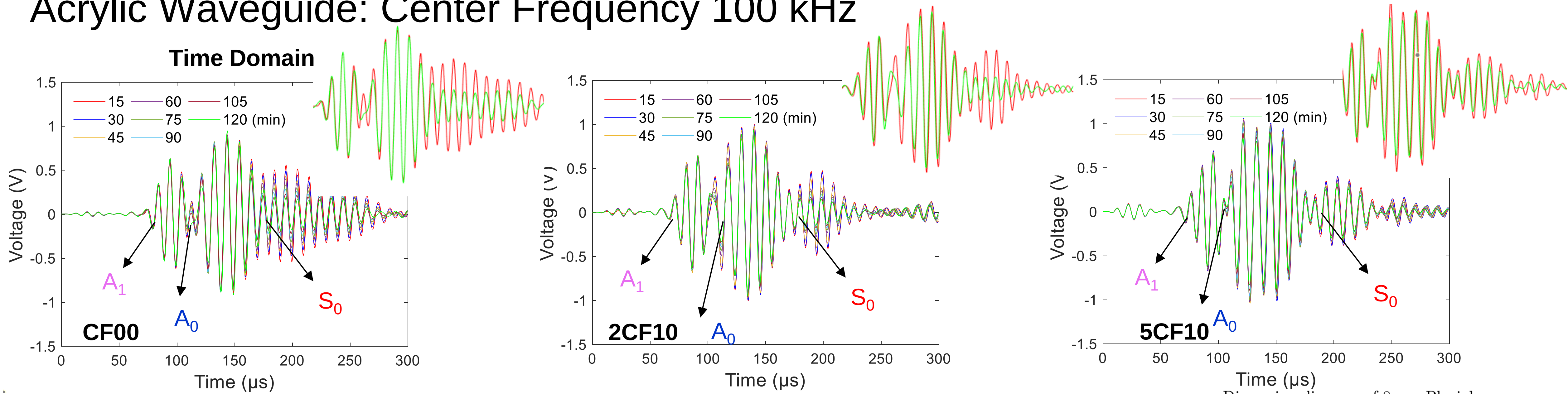
Attenuation (dB) = $-20 \log Af/Ai$

Ai = Initial Amplitude (15 min)

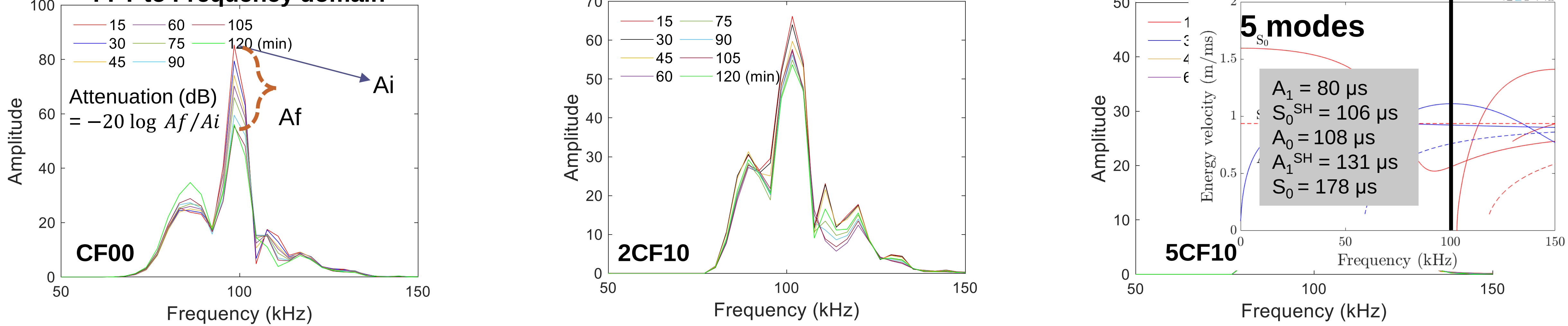
Af = Amplitude afterwards

Acrylic Waveguide: Center Frequency 100 kHz

Time Domain



FFT to Frequency domain

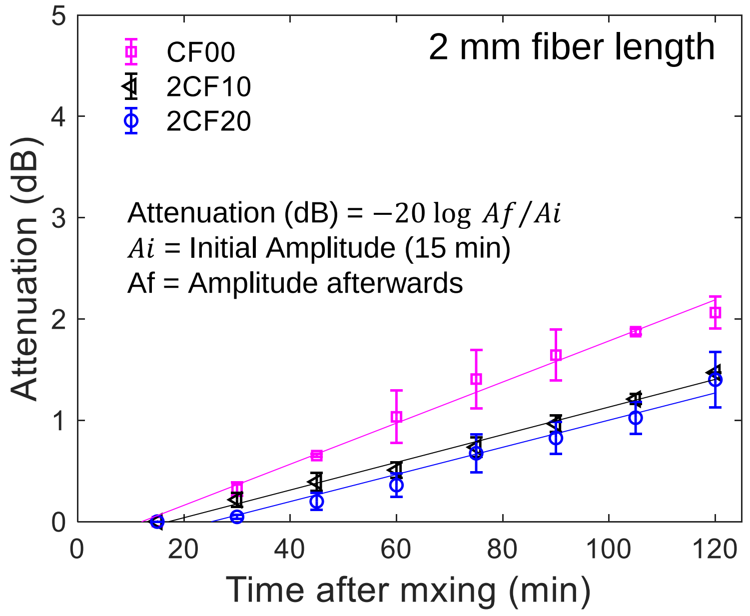


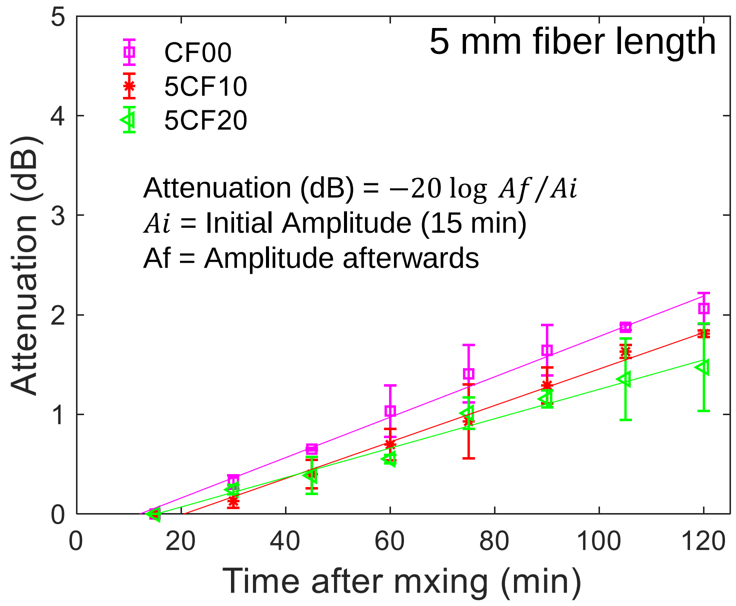
Attenuation (dB) $= -20 \log Af/Ai$

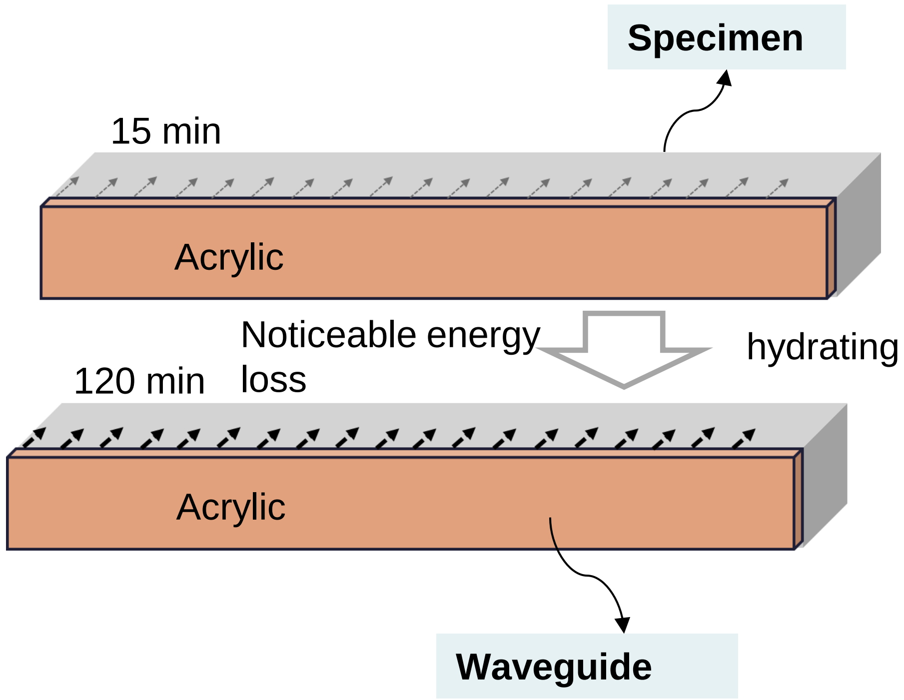
Ai = Initial Amplitude (15 min)

Af = Amplitude afterwards

Acrylic Waveguide (60 kHz)







- Regardless of test variables, attenuation increases with increasing curing time
- CF00 exhibited higher attenuation when compared to specimens with CMFs
- Attenuation decreases with incorporation of CMFs, 2 % incorporation exhibited lowest increase possibly due to the delayed hydration characteristics from the inclusion of CMFs

As hydration continues in the specimen, impedance (ρ.v) difference between the wave guide and specimen decreases leading to increase of energy loss for the propagating guided waves, eventually subjecting to higher attenuation

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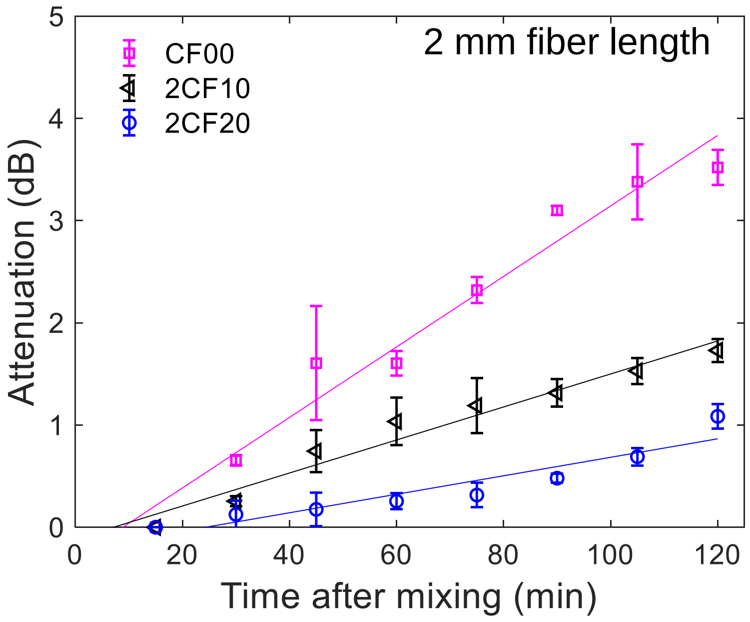
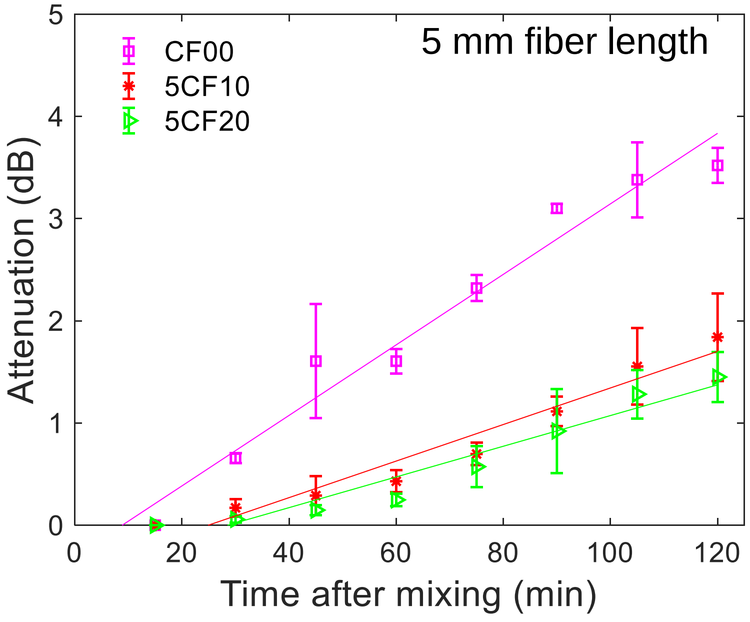
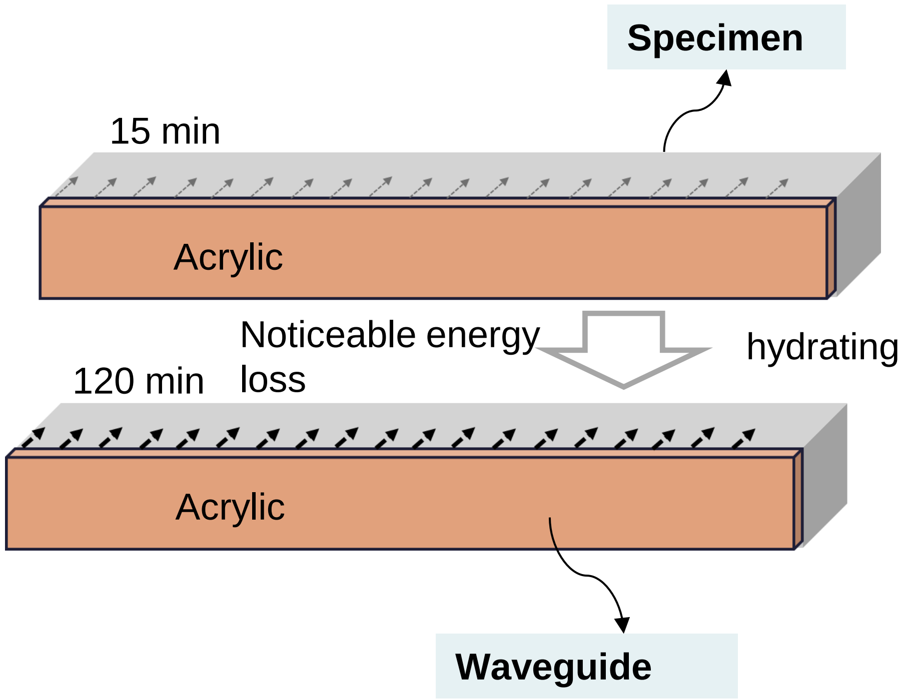
Acrylic Waveguide (100 kHz)





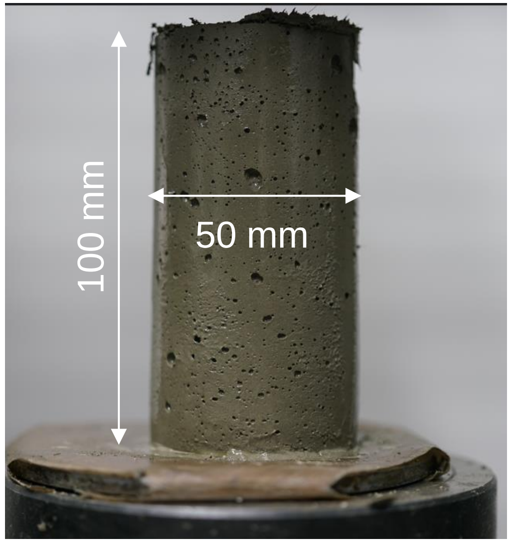


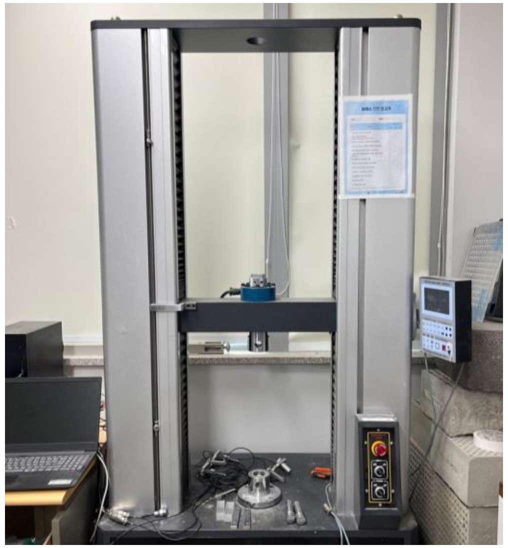
- Similarly, regardless of test variables, attenuation increases with increasing curing time
- CF00 exhibited higher attenuation when compared to specimens with CMFs
- Attenuation decreases with incorporation of CMFs, 2 % incorporation exhibited lowest increase possibly due to the delayed hydration characteristics from the inclusion of CMFs

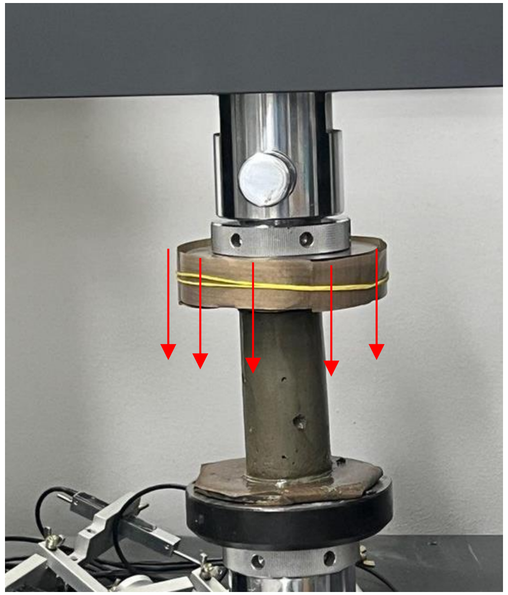
As hydration continues in the specimen, impedance (ρ.v) difference between the wave guide and specimen decreases leading to increase of energy loss for the propagating guided waves, eventually subjecting to higher attenuation

Green Strength Test

Loading rate: 2 mm/min







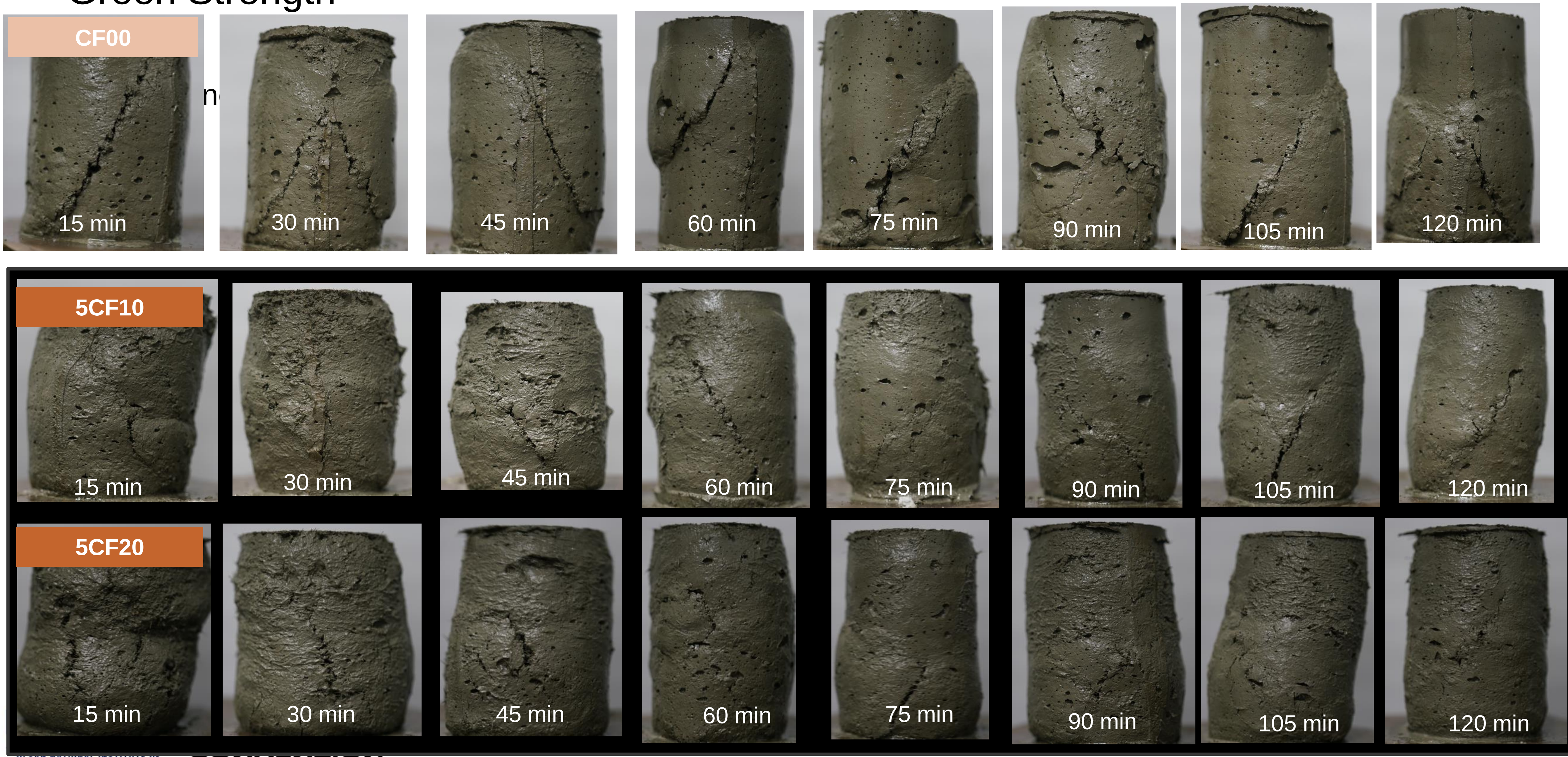
Green strength test was conducted with 15 min interval for 2 hours

3 batches for each mix design were used to determine the green strength

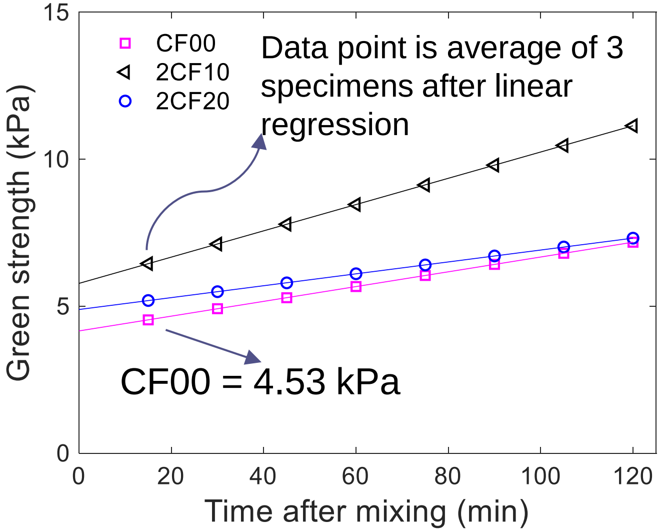
Name	W/B	OPC	Fly Ash	Silica fume	Sand	SP	CMFs	Add. Water
CF00	349	764	218	109	1091	11	0	0
2CF10		x 3					11 (1 %)	32
2CF20							22 (2 %)	65
5CF10							11 (1 %)	47
5CF20							22 (2 %)	94

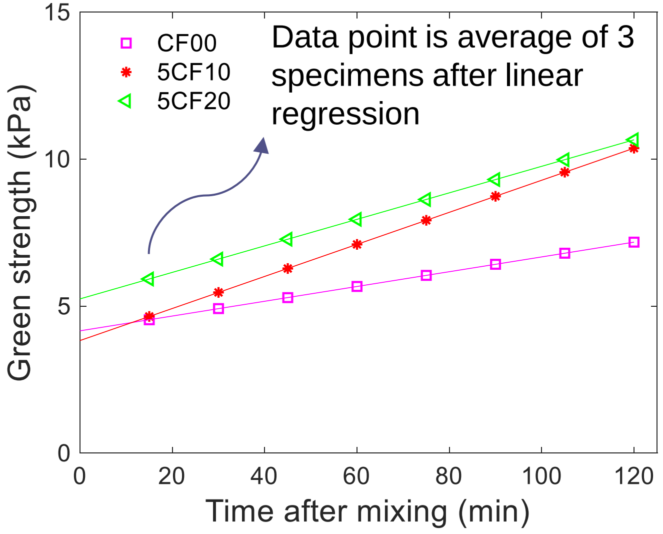
Green Strength

At displacement 20 mm



Green Strength





No. of Buildable Layer

$$\sigma_v(t) = \rho g h(t) \quad \textbf{[7]}$$

$$\sigma_v(t) = \frac{mg}{bl} . X \quad \textbf{[8]}$$

$$X = \frac{\sigma_v(t) b}{\rho A g}$$

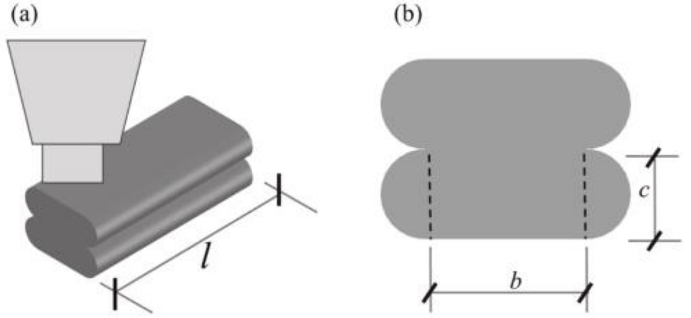
$$X = \left(\frac{4\sigma_v(t) b}{\rho \pi D^2 g}\right)$$

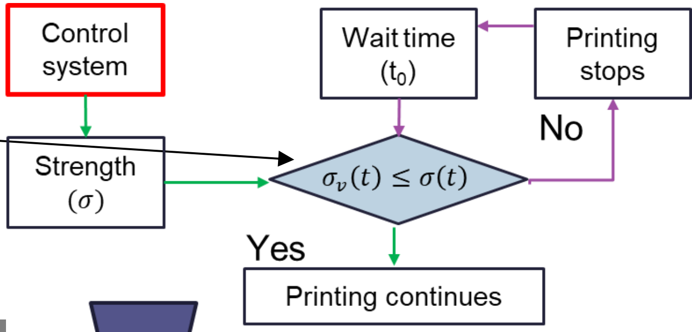
$$X . \left(\frac{\rho \pi D^2 g}{4b}\right) = \sigma_v(t) \leq \sigma(t)$$

$$X = No.\ of\ layers$$

$$H = (X+1).c$$

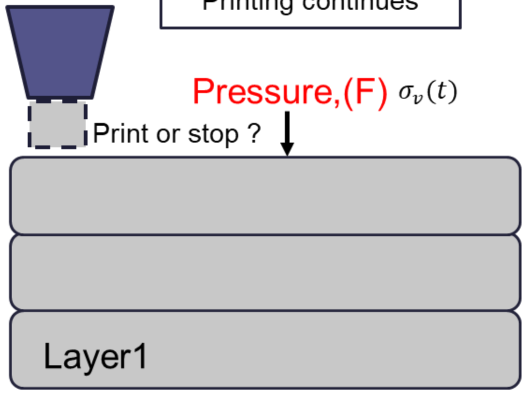
$$H = \left(\frac{\sigma_v(t) b}{\rho A g} + 1\right).c$$





ρ = *density of 3DPC*
g =*gravitational acceleration*
D= *nozzle diameter*
b = *width of printed layer*
c = *each layer height*
H = *total layer height*
$\sigma(t)$ = *obtained green strength*

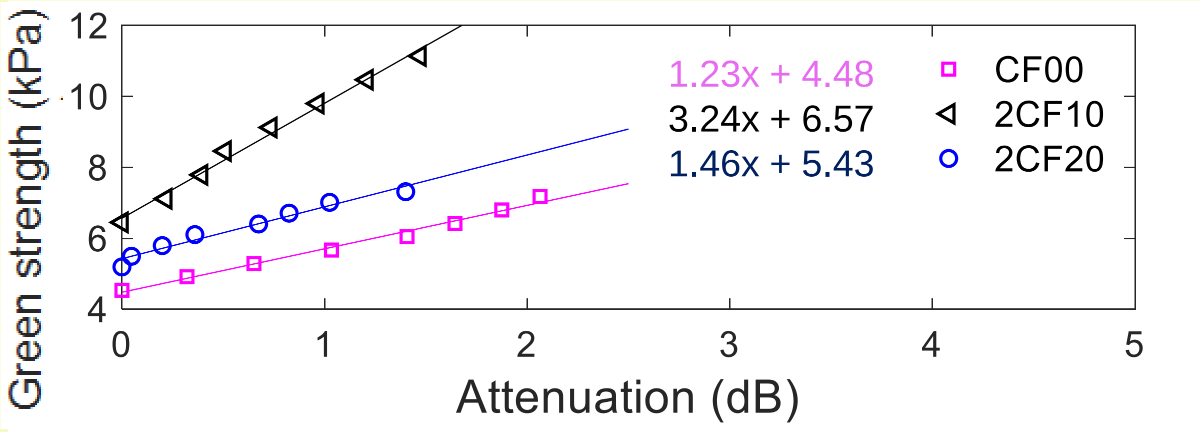
For H = 5
1.89 kPa < $\sigma(t)$
Printing continues
For X = 12 (critical height)
4.53 kPa =$\sigma(t)$
Printing stops

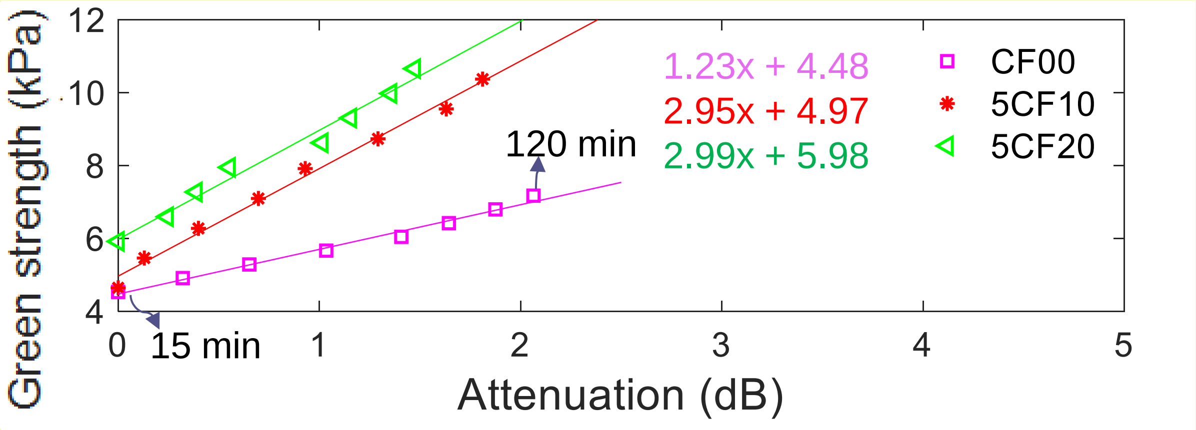


[7] Panda, Biranchi, Jian Hui Lim, and Ming Jen Tan. "Mechanical properties and deformation behaviour of early age concrete in the context of digital construction." *Composites Part B: Engineering* 165 (2019): 563-571.
[8] Zhang, Yu, et al. "Study on the predictive model for continuous build height of 3D printed concrete (3DPC) based on printability and early mechanical properties." *Journal of Building Engineering* 99 (2025): 111640.

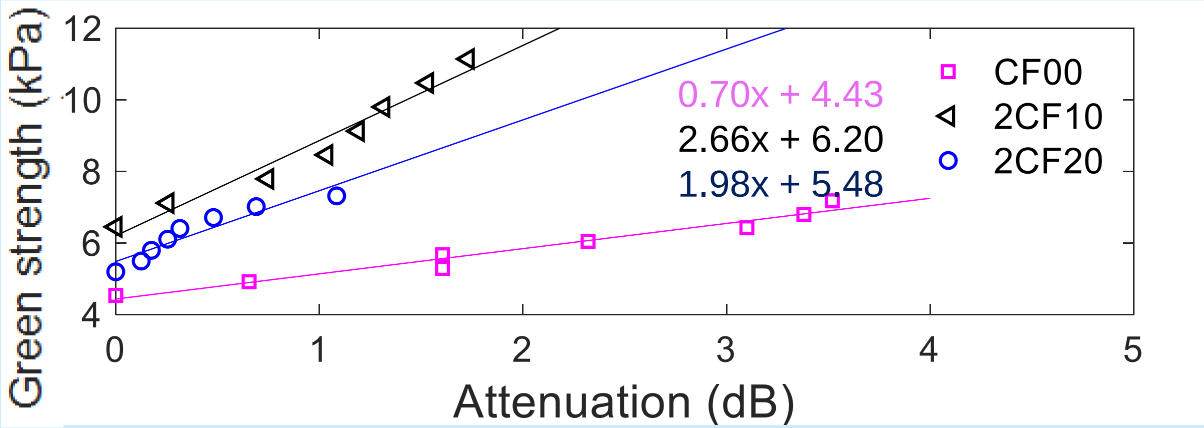
Correlations Between Attenuation and Green strength

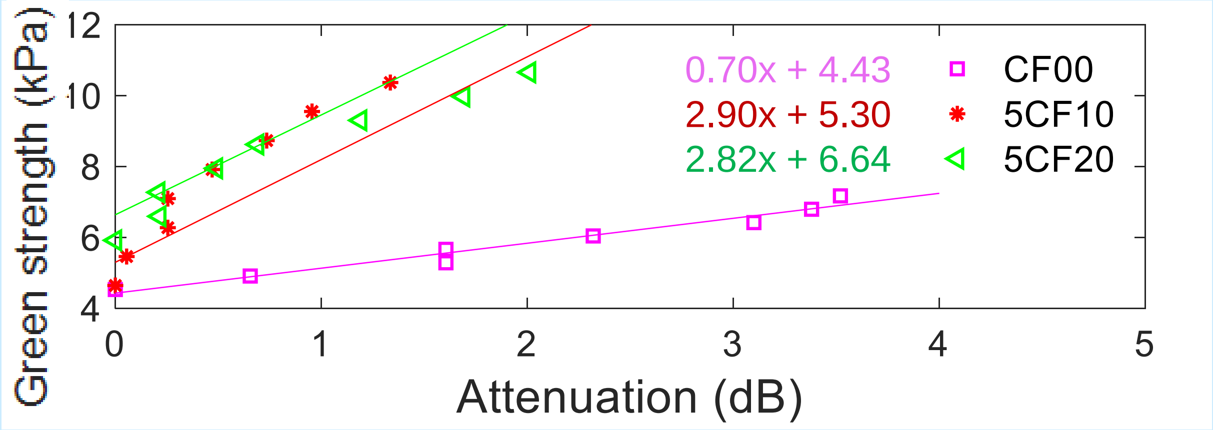
60 kHz



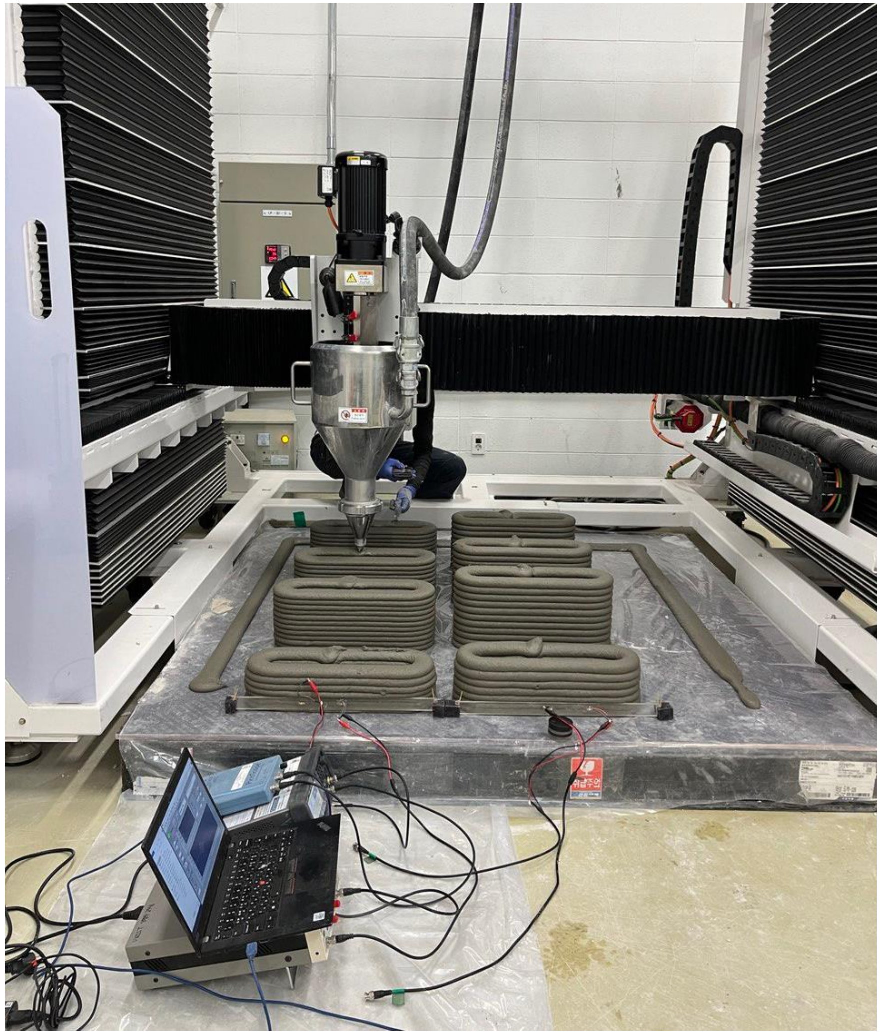


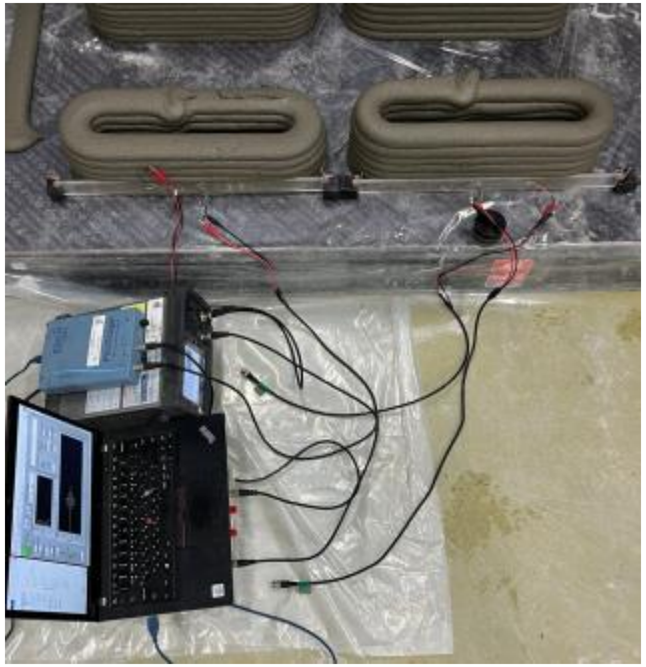
100 kHz





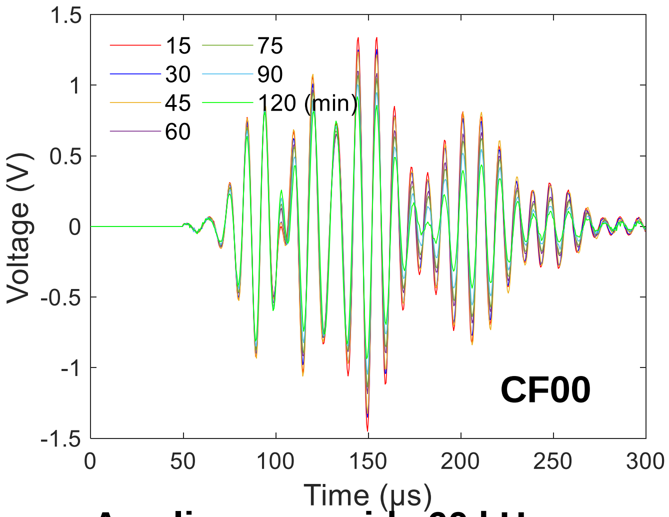
Inline Application

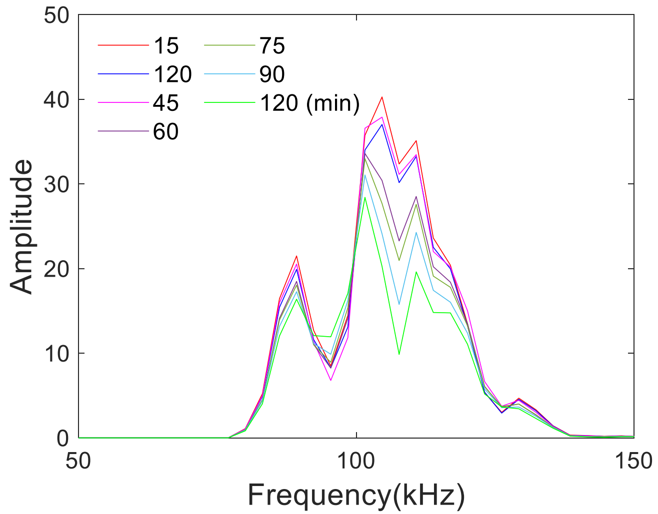


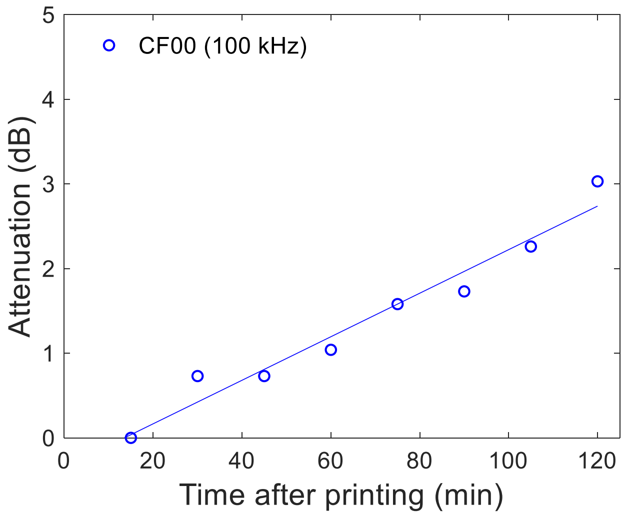


3D Printed Specimen

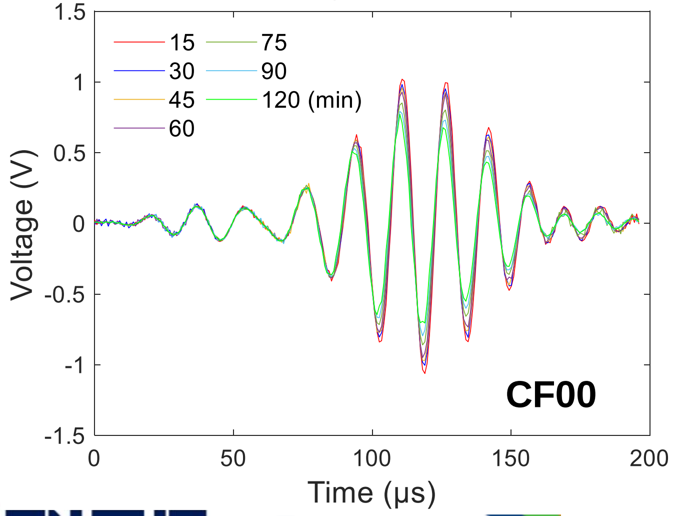
Acrylic waveguide 100 kHz

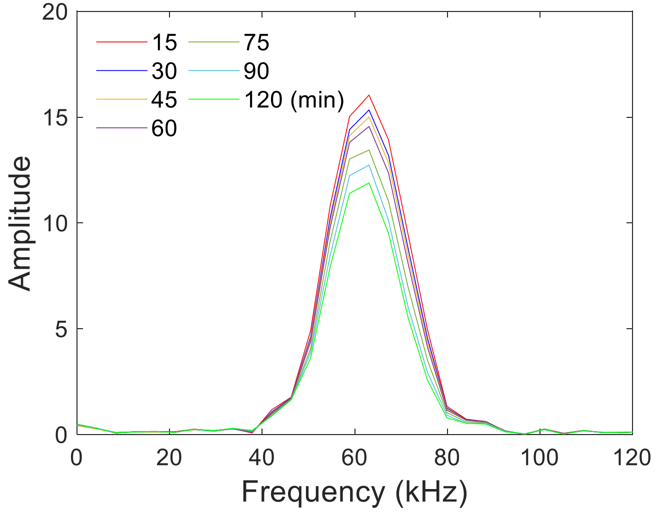


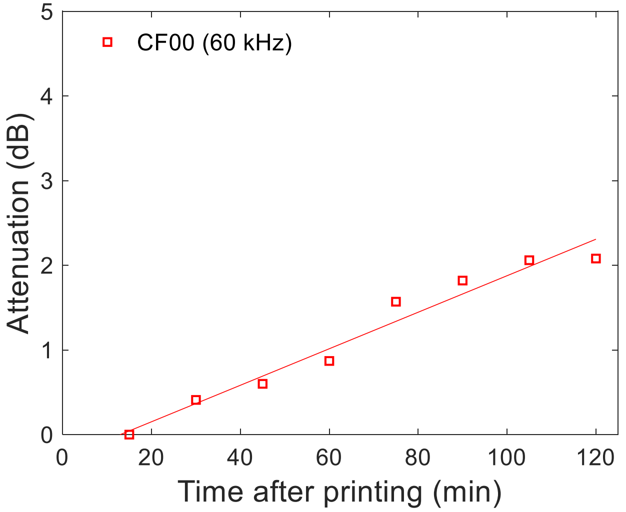




Acrylic waveguide 60 kHz







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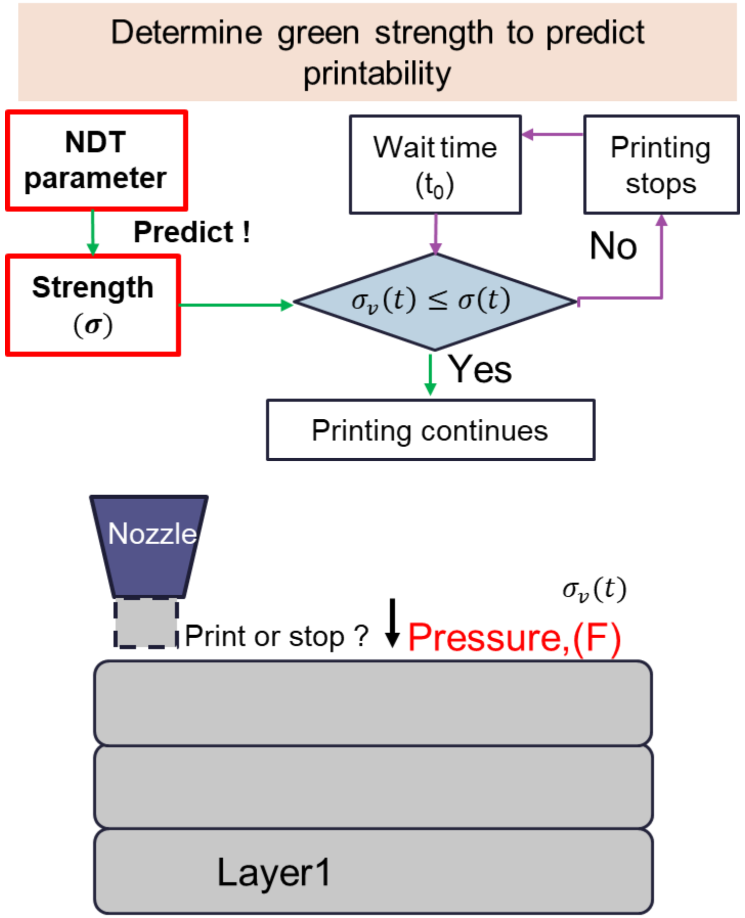
Conclusion



1. This study conducted the effectiveness of guided wave to monitor of buildability for 3DPC
2. Acrylic is found to be more effective, given the material property at this stage
3. Correlation between green strength and attenuation was developed
4. No. of buildable layer can be indirectly predicted using guided wave technique

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THANK YOU

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