Towards Sustainable Robotic Construction

Concrete 3D Printing with Quarry By-products and Low Portland Cement Content

Aranya Aumit Paul (Presenter)
PhD Student at Louisiana State University

Ali Kazemian, Charles Berryman, Carol Friedland
Louisiana State University

Introduction

Construction 3D Printing

Automated Construction

- ✓ Extrusion-based 3D printing using cementitious materials

Advantages

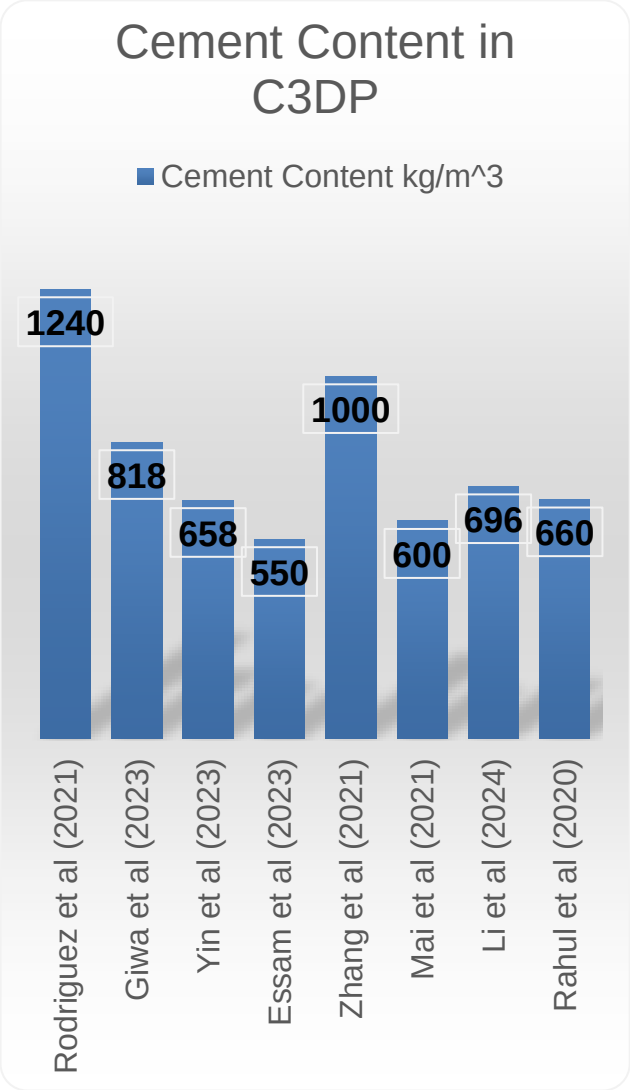
- ✓ Faster and Automated Construction
- ✓ Increased Design Freedom.
- ✓ Site Utilization
- ✓ Reduced Material waste.
- ✓ Energy Efficient.
- ✓ Lower Environmental Impact
- ✓ Extraterrestrial Construction

Introduction

Typical 3D printing relies heavily on High Cement Content

Impacts:

- ✓ Increase in overall construction cost.
- ✓ Environmental impact: Increased CO_2 Emission
- ✓ Impacts on Structural Properties.



Background of the Study

Ways of Reducing Portland Cement Content

Recycled Concrete Aggregates

In C3DP

Inka Ma et al (2021)

Cement Content – 600 kg/m3

Mold-cast concrete

Keila Robalo et al (2021)

Cement Content – 175 kg/m3

M. Hayles et al. (2018)

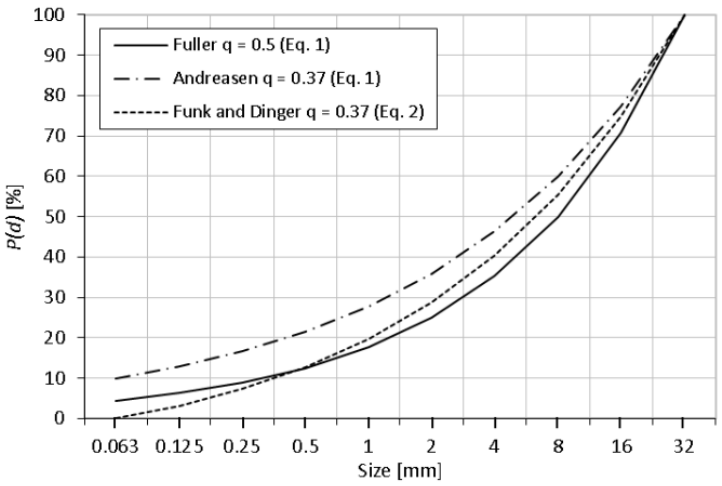
Cement Content – 162 kg/m3

Background of the Study

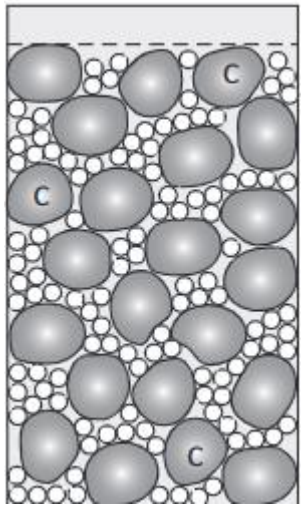
Ways of Reducing Portland Cement Content

Particle Packing Techniques

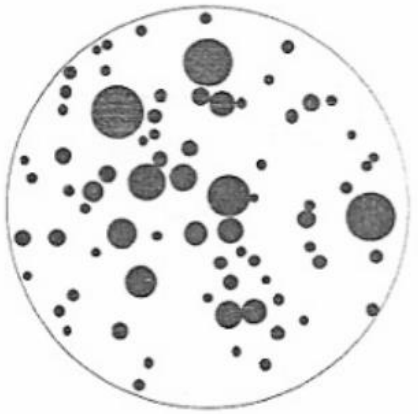
Optimization Curves | Particle Packing Density | Discrete Element Models | Compressible Packing Model



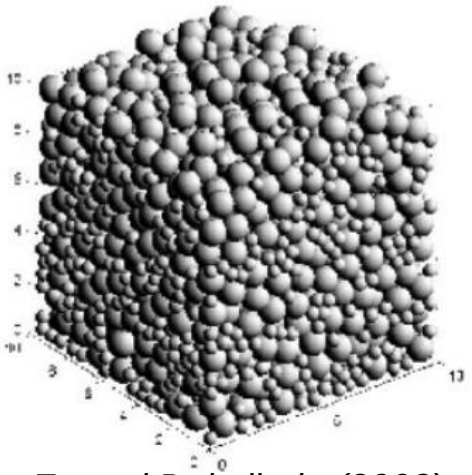
Fuller and Thompson (1907)
Andreasen and Andersen, (1930)
Funk and Dinger, (1980)



Sonja A.A.M. Fennis et. al. (2012)



Zheng and Stroeven (1999)



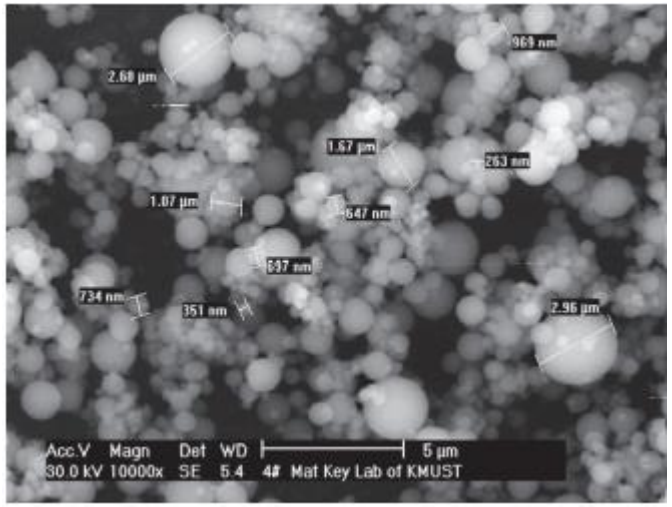
Fu and Dekelbab, (2003)

Background of the Study

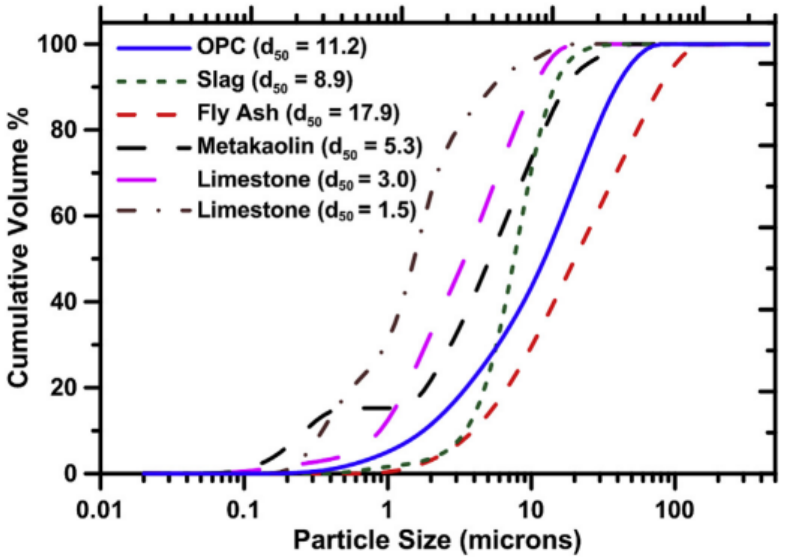
Ways of Reducing Portland Cement Content

Supplementary Cementitious Materials

Super Fine Fly ash

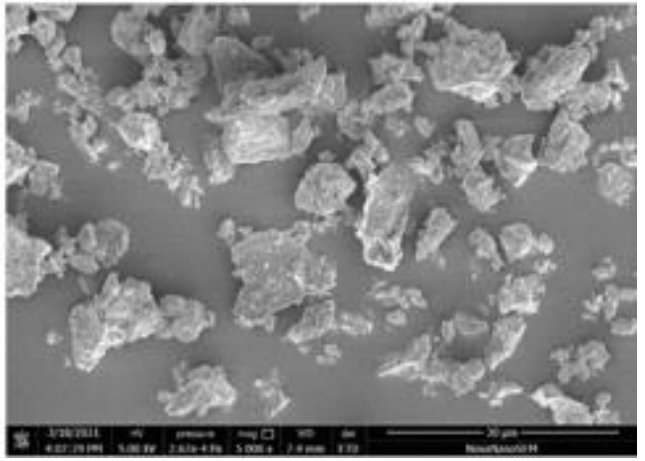


A.K.H. Kwan et al (2013)



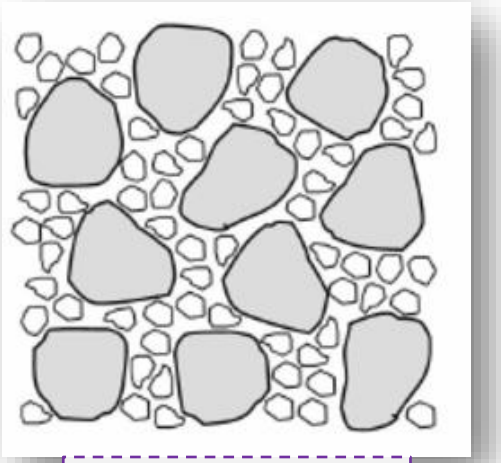
Aashay Arora et al (2019)

Steel Slag



Guorui Sun et al (2022)

Objectives



Dense Particle Packing

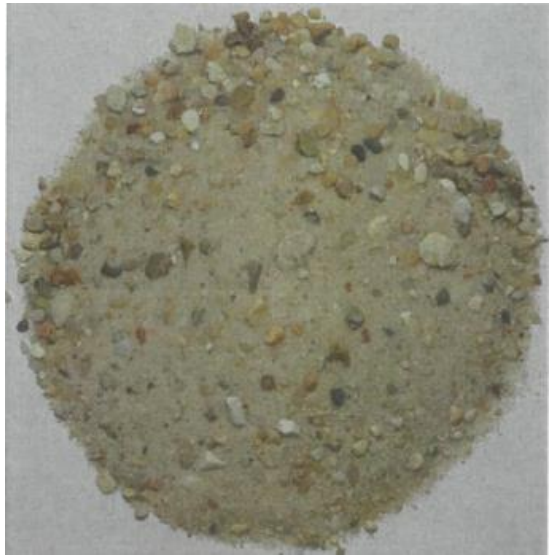
Incorporation of Quarry By-products in Printing Materials

Sustainable Concrete 3D Printing

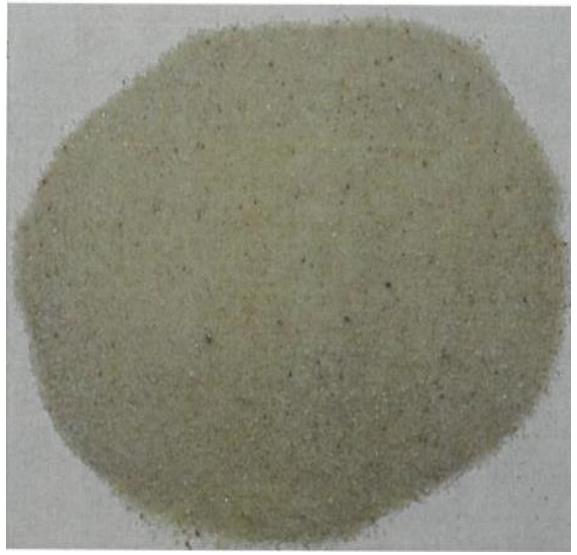
Comprehensive Performance Evaluation (Printability and Structural Requirements)

Methodology

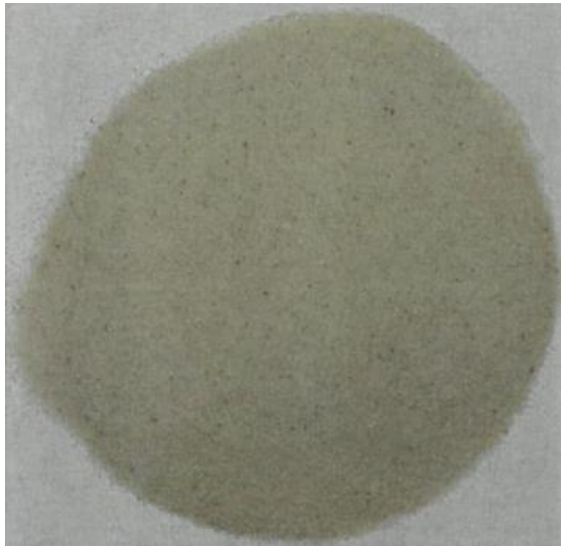
Incorporation of Quarry By- Products and Pea-Gravel



Independence Shaker Sand



Indian Village Fill Sand



Independence Fill Sand

Pea- Gravel

Methodology

Optimization Curves

Fuller -Thompson Curve
(Fuller and Thompson, 1907)

$$P(d) = \left(\frac{d}{d_{max}}\right)^{q}$$

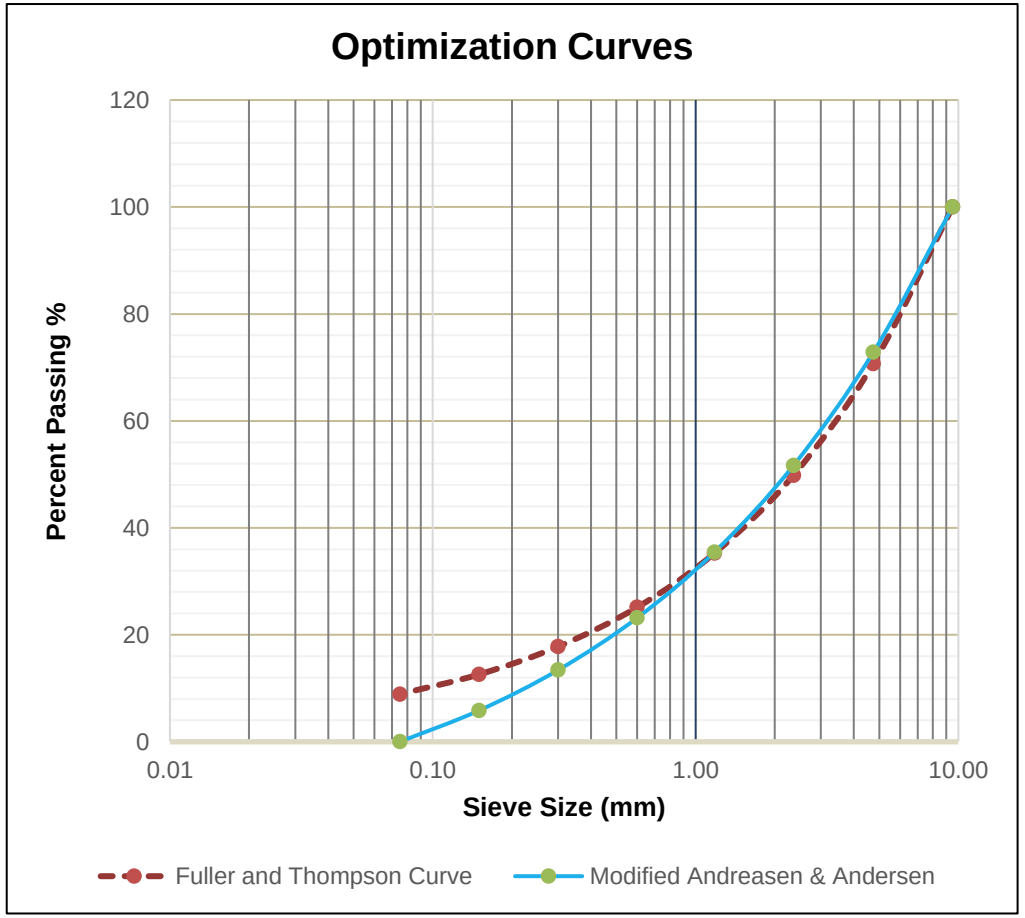
$$q = 0.5$$

Modified Andreasen and Andersen Curve
(Funk and Dinger, 1980)

$$P(d) = \left(\frac{d^q - d_{min}^q}{d_{max}^q - d_{min}^q}\right)$$

$$q = 0.37$$

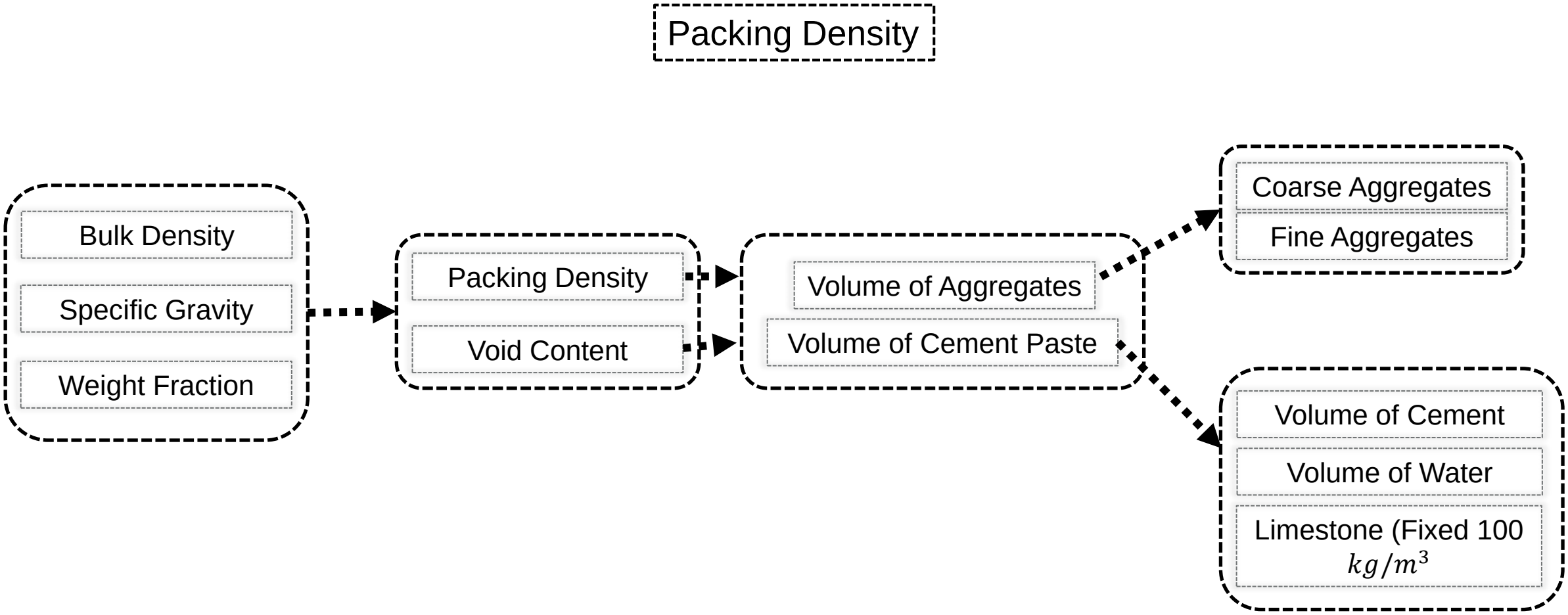
$P(d)$	size cumulative distribution function [-]
d	particle diameter being considered [m]
d_{max}	maximum particle diameter in the mixture [m]
d_{min}	minimum particle diameter in the mixture [m]
q	parameter (0.33-0.5) which adjusts the curve for fineness or coarseness [-]



Range: $d_{min} = 75\ \mu m\ , d_{max} = 9.5mm$

Sonja A.A.M. Fennis et. Al., 2012

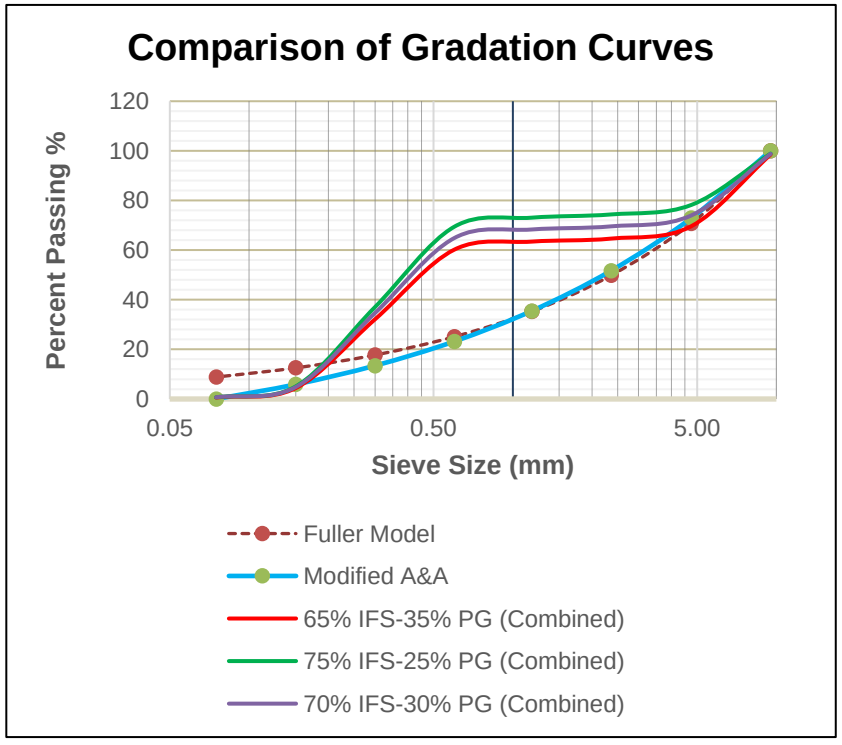
Methodology

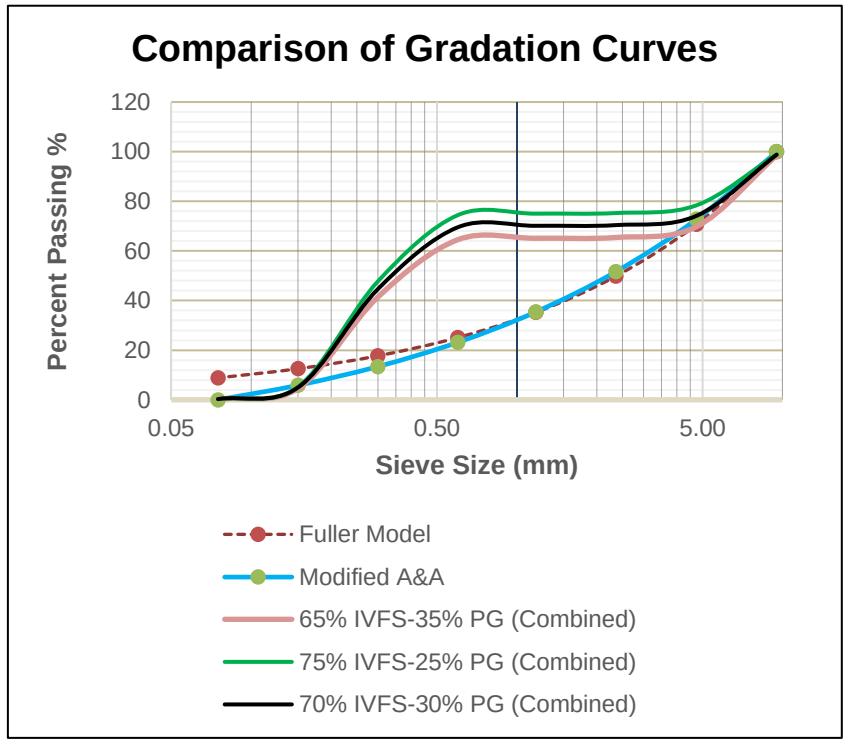


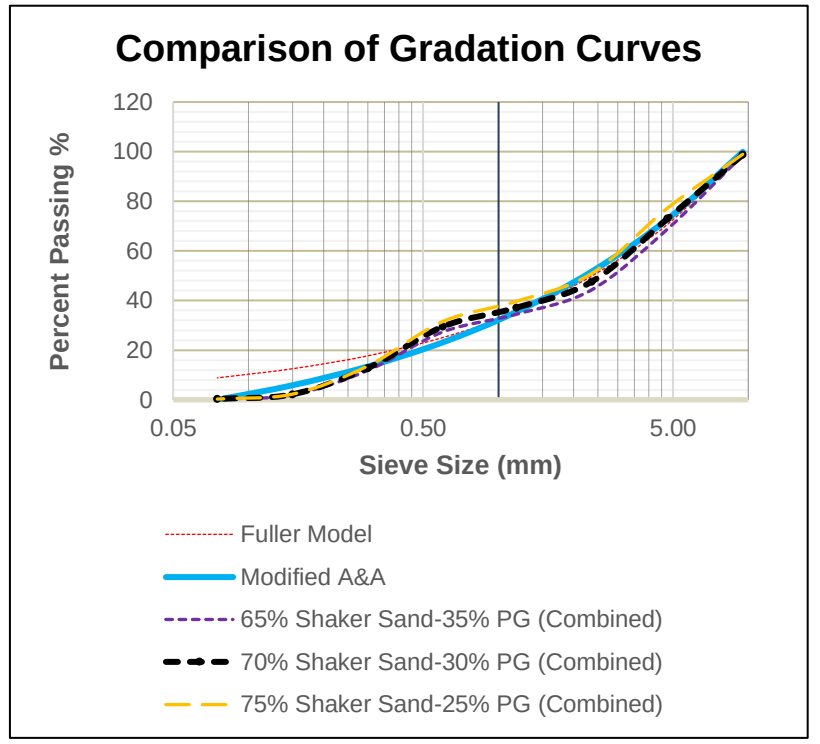
Narasimha Raj et el., 2014, Badrinarayan Rath et al., 2020
Pradhan et al. (2024), Particle Packing Method for Recycled Aggregate Concrete, Springer.

Methodology

Comparison with optimization curves for Different Combination of Pea-Gravel with 3 types of Sands (Quarry By-product)







Methodology- Identification of Printable Mix Design

Identification of Closest Packing Curve for Each type of Quarry Sand

⇨

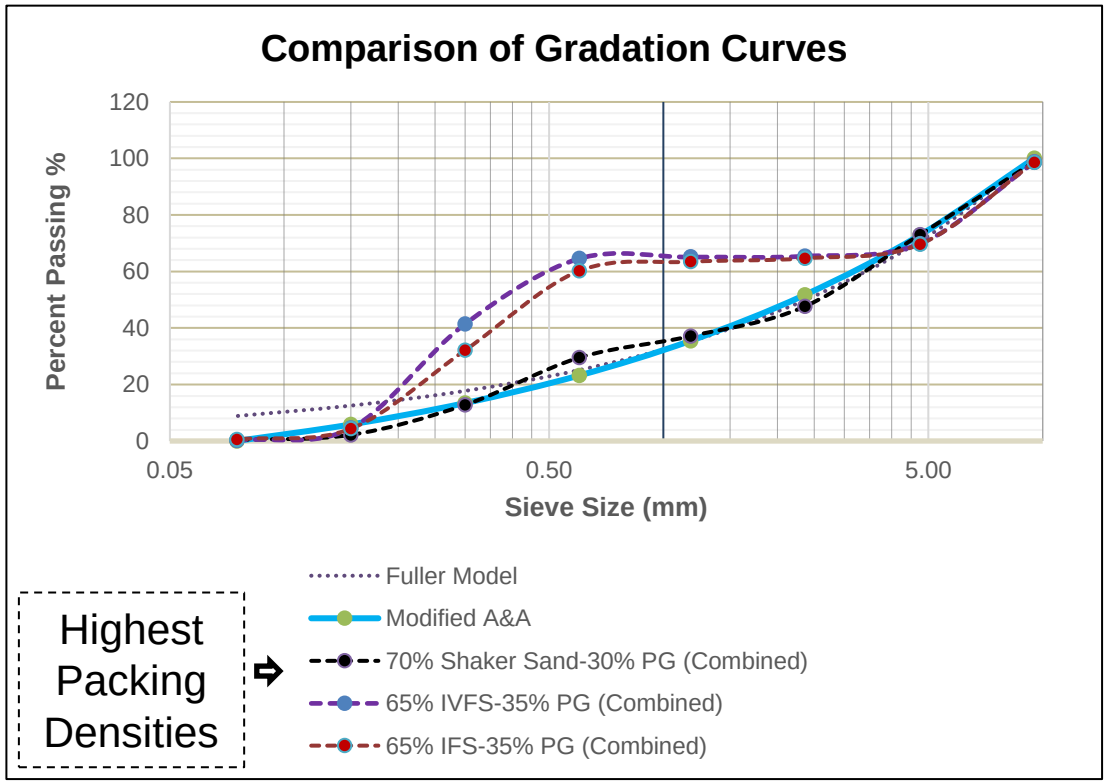
Testing Bulk Density for Each Combination

⇨

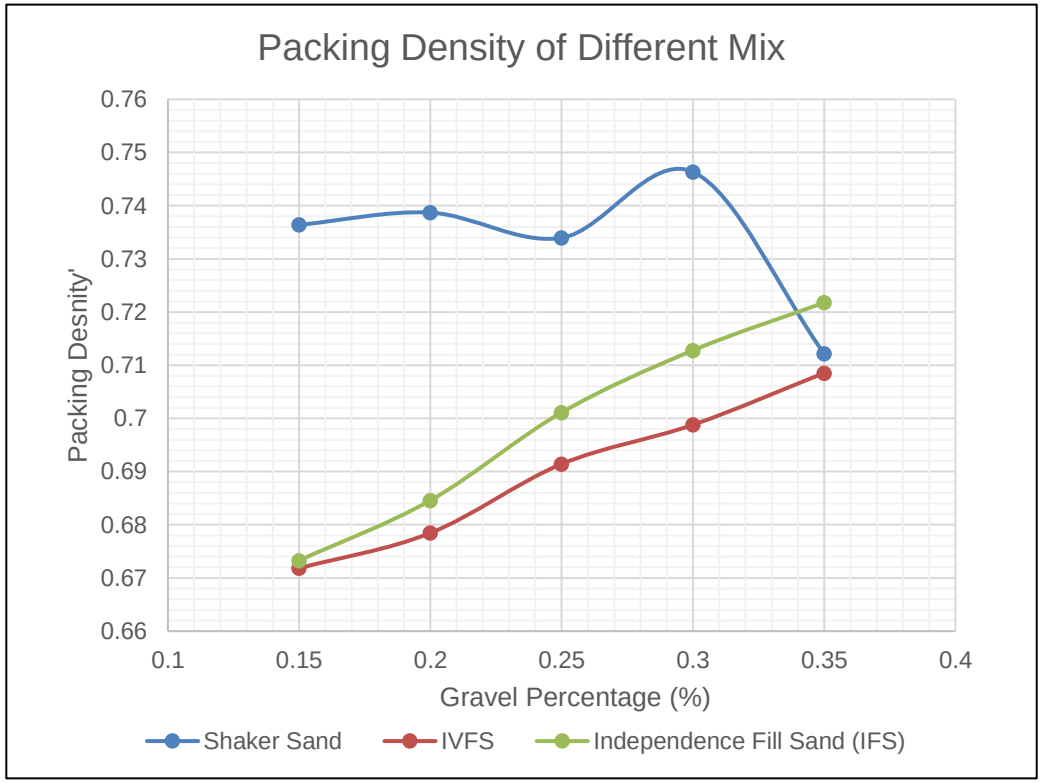
Comparison of Packing Density for Each Combination

⇨

Testing of Printability with Highest Packing Density Mixtures



Highest Packing Densities ⇨



Preliminary Results

Highest Packing Density

Cement Paste

Printable Mixture at Minimum Cement Content

70% Shaker Sand+ 30% Pea Gravel

75%

Cement Content
353 kg/m^3
w/c= 0.40
No LS

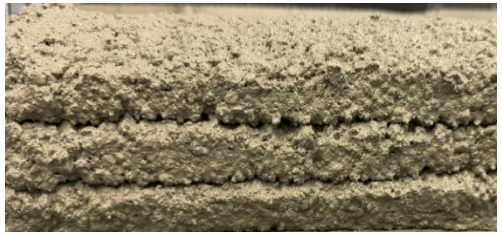
Not Printable

Cement Content
550 kg/m^3
w/c= 0.45
LS= 100 kg/m^3

Printable

Structural Properties

Not Satisfied



- Surface Finish not good
- Deformed Layers

Result

Not Printable

Cement Content Goal <400 kg/m^3

Not Satisfied

Preliminary Results

Highest Packing Density

Cement Paste

Printable Mixture at Minimum Cement Content

65% Independence Fill Sand + 30% Pea Gravel

72%

Cement Content
362 kg/m^3
w/c= 0.40
No Lime Stone

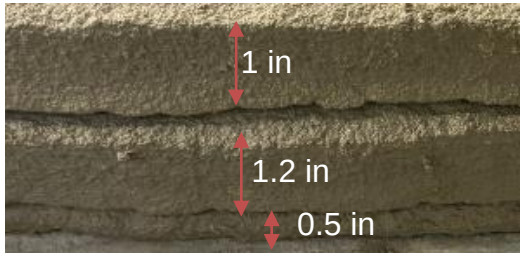
Not Printable

Cement Content= 388 kg/m^3
w/c= 0.45
LS= 100 kg/m^3

Printable

Structural Properties

Not Satisfied



- Deformed Layers

Result

Not Printable

Cement Content Goal <400 kg/m^3

Satisfied

Preliminary Results

Highest Packing Density

Cement Paste

Printable Mixture at Minimum Cement Content

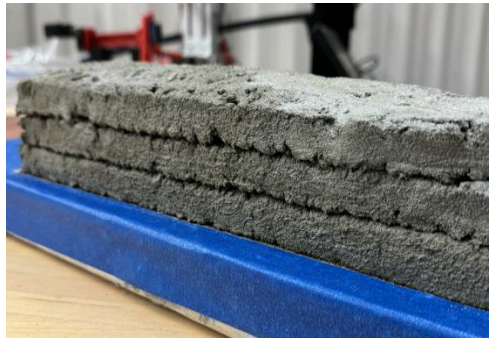
65% Indian Village Fill Sand + 30% Pea Gravel

70%

Cement Content
392 kg/m^3
w/c= 0.40
No Lime Stone

Not Printable

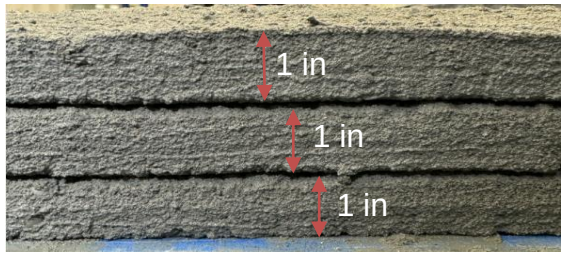
Cement Content= 395 kg/m^3
w/c= 0.45
LS= 100 kg/m^3



Printable

Structural Properties

Satisfied



- Uniform Layers

Result

Printable

Cement Content Goal <400 kg/m^3

Satisfied

Conclusion and Next Steps

Additional constraints related to printability:

- ✓ Flowability of Cement Paste
- ✓ Water Content ratio.
- ✓ Satisfactory Structural Properties at lower cement content.

Next Steps:

- ✓ Further mix design optimization.
- ✓ Targeted cement content from packing density.
- ✓ Printing with lowest cement content.
- ✓ Characterization of Structural and Mechanical Properties of low-cement printed materials.

Acknowledgment

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Thank You