Inline mixing of accelerator for concrete 3D printing application: Numerical simulation using computational fluid dynamics

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Outline

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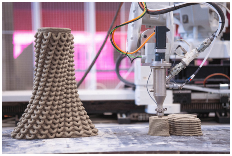
Concrete 3D printing

- *Concrete 3D printing* (C3DP) refers to construction through precise layer-wise deposition of specially designed concrete,
- C3DP allows for the precise fabrication of complex topologies with reduced material wastage.
- The most significant advantage is realized in the form of rapid construction, owing to improved efficiency realized from partial/complete automation of certain construction tasks.



[1] Image credit-C3DP

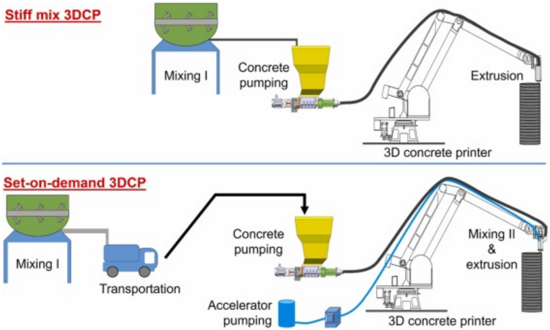
Comparisons with FDM

- *Fused deposition modelling* (FDM), a popular form of additive manufacturing (of thermoplastic filaments), is a precursor to the current C3DP technology.
- Unlike FDM, conventional C3DP systems lack a precise control mechanism for the material's rheological and setting properties.
- In FDM, the setting behaviour is reversibly modified through temperature control, whereas hardening is monotonous in cementitious systems.

[2]Image credit-Mohan, et al.(2021)

Set-on-demand Printing

- Special set activators are introduced at certain locations to control the setting properties of the concrete.
- The set activators aid by accelerating the setting process and enhancing the capacity to bear further layers without significant deformation.



[3] Image credit-Rehman, et al.(2023)

Static vs Dynamic mixer for inline mixing

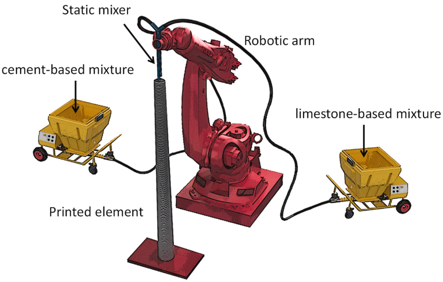
Static printheads have been the popular choice for inline mixing of accelerators in the recent past. However, it has a few drawbacks:

- Large length needed for static mixer, constrains printing operation and reduces available print volume.
- The pressure drop due to the static mixer can be very high (typically $2\times$ to $4\times$ of that of mixer free printing).

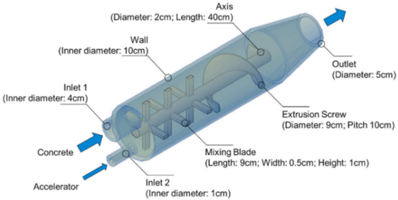
Dynamic mixers, on the other hand, are touted for their small size. They, however, face issues related to:

- Potential mishaps due to premature stiffening can be fatal to the operation and the machinery.
- Heterogeneity is (more significantly) influenced by the material properties.

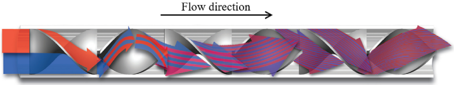
Static vs Dynamic mixer for inline mixing



(a) Operation with static mixer
(Image credit: Tao, et al.(2022))



(b) Operation with dynamic mixer
(Image credit: Tao, et al.(2021))



(c) Internal schematic of static mixer
(Image credit: Admixer^{TM})

Outline

Objectives

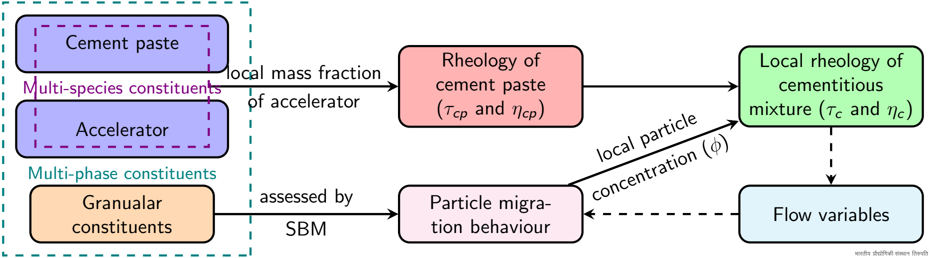
Numerical simulation of inline mixing of accelerator in dynamic mixers for C3DP application

1. Development of a multi-species computational fluid dynamics (CFD) model for modelling flow of accelerator and cementitious suspension.
2. Use it to study the advective mixing performance of two types of mixers: ribbon and paddle-type mixers.
3. Derive numerical insights on the mixing performance of the system for the particular application for different mixtures and generate system characteristic charts.

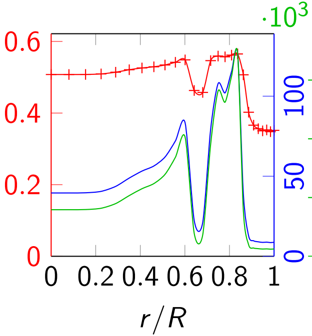
Outline

Framework for modelling inline mixing in 3D printable concrete mixtures

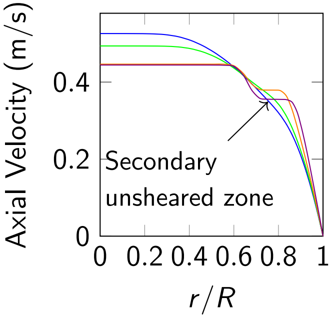
- The accelerator is assumed to be a different chemical species (with its own properties) of the cement paste phase.
- Only advective mixing is studied (Diffusive mixing is ignored).



Suspension rheology-based modelling of cementitious mixtures



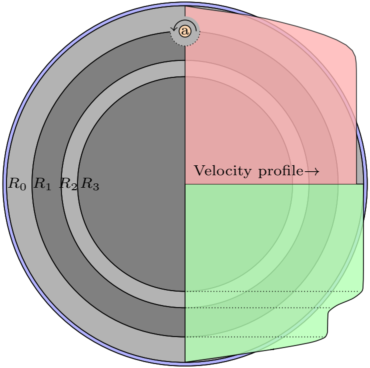
(a) Particle Volume Fraction(—+—); Plastic Viscosity of the mixture(——); Yield Stress of mixture(——)

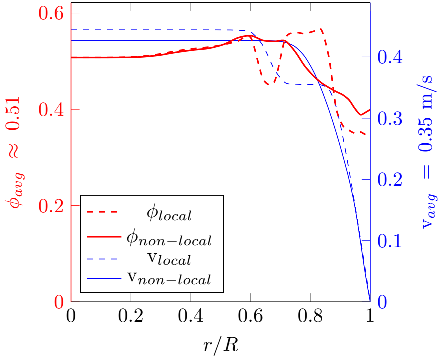


(b) Velocity (m/s) at x = 0.5 m (——), x = 1 m (——), x = 2.5 m (——), x = 5 m (——)

[4] Image credit-Vishwanath, et al.(2024)

Non-local model to study finite size effects





[5] Image credit-Vishwanath, et al.(2024)

Corroboration with global pressure loss

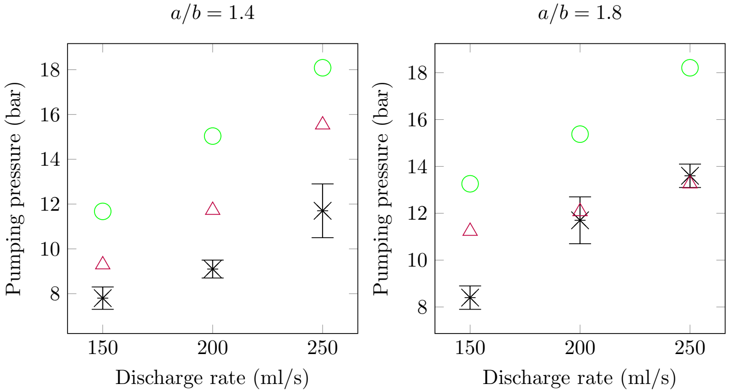


Figure: Simulated pressure loss using the local model ($\epsilon = 0$) ($\circ$), Pressure loss computed based on terminal pressure gradient at the designated outlet ($\triangle$), Experimental values with error bounds, reported in Mohan et al. 2021 ($\times$)

Outline

Paddle vs Ribbon mixer

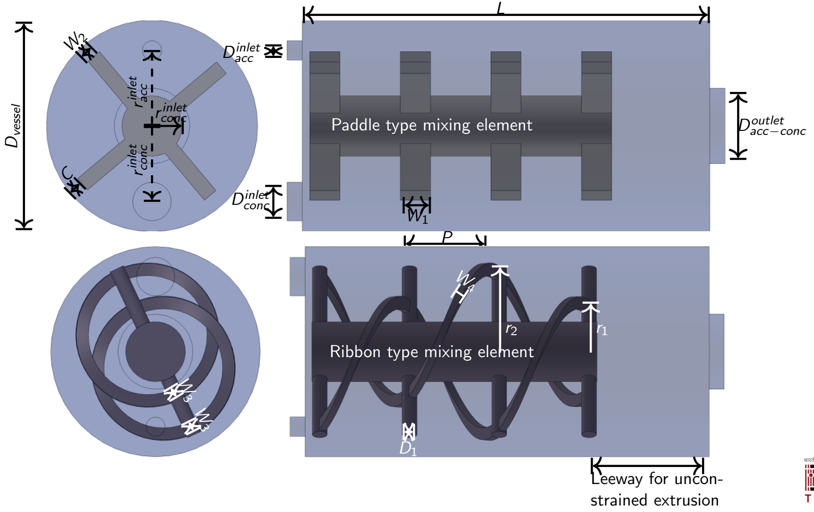
Paddle mixer:

- A paddle mixer generates advective currents through pressure imposed by the faces of the paddles.
- It is relatively easy to fabricate.

Ribbon mixer:

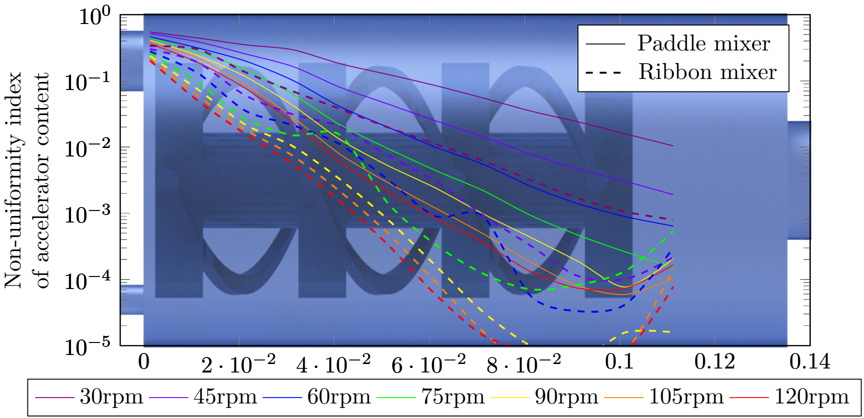
- Generates advective currents through the shearing action of the ribbon. For mixtures with a yield stress, it is known that a plug zone is not desired for the transport/mixing of species. Thus, shearing action is expected to be better for high-yield stress mixtures like concrete.
- It is relatively complex to fabricate.

Mixer geometry employed in simulation

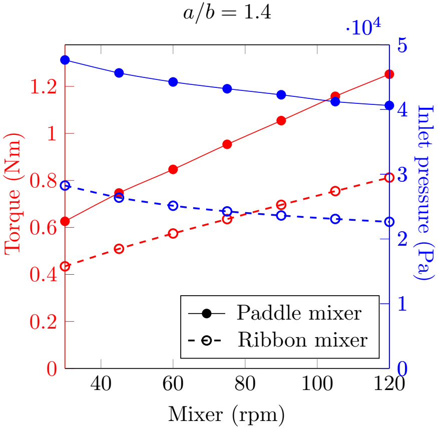


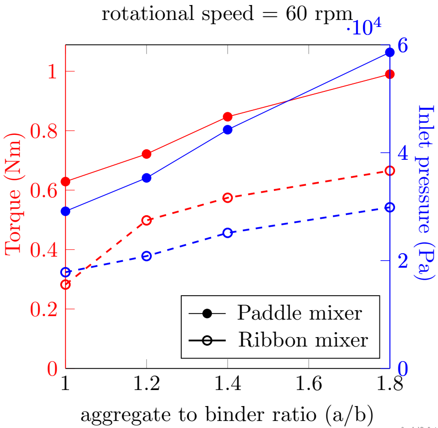
Outline

Variation with rotation rate

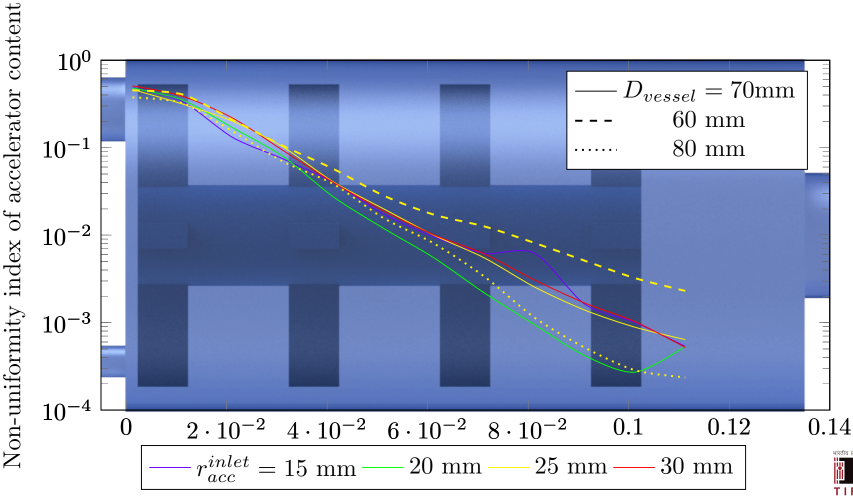


System characteristics





Influence of mixer topology and size parameters



Outline

Key conclusions

1. The ribbon-type mixer offers better performance in comparison to a paddle-type mixer for advective mixing of an admixture as well as in torque-rotation rate characteristics.
2. The difference may not be significant enough to warrant the need for the ribbon-type mixers. As the realized advantage in terms of power, is not a stiff constraint in practical situations.
3. At a higher aggregate-to-binder ratio (in 3D printable mixtures), higher torque and higher inlet pressure are required for the operation of the system.
4. Particle migration is noticed to not be a significant problem during advective mixing as the time/length scale involved is small.

Way forward

Some of the drawbacks of the work are stated below:

- The model neglects the effect of the accelerator on the instantaneous rheology of concrete.
- Only a narrow range of size parameters of the possible mixer geometry is studied in this work (but the opted values were based on practically relevant dimensions)

Some future scope of this work may include:

- Corroborating numerical prediction with experimental observations.
- Studying correlations between mixing homogeneity and mechanical properties of printed specimens.
- Employing the model in other geometric domains to study flow behaviour.

Select references

- Vishwanath Ravindran, Thiyagarajan Ranganathan, A.V. Rahul, **Migration of particles suspended in yield stress fluids: Insights from numerical simulation of pipe flow of 3D printable concrete**, *Journal of Non-Newtonian Fluid Mechanics*, Volume 332, 2024.
- Manu K. Mohan, A.V. Rahul, Kim Van Tittelboom, Geert De Schutter, **Rheological and pumping behaviour of 3D printable cementitious materials with varying aggregate content**, *Cement and Concrete Research*, Volume 139, 2021.
- Yaxin Tao, A.V. Rahul, Manu K. Mohan, Kim Van Tittelboom, Yong Yuan, Geert De Schutter, **Blending performance of helical static mixer used for twin-pipe 3D concrete printing**, *Cement and Concrete Composites*, Volume 134, 2022.