Teaching Guide for Developing 3D-Printable Concrete Using Local Materials

Innovation Excellence in Construction Engineering: Novel 3D Concrete Printing Technologies and Sustainable Mixtures

EXEP3D

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1 Summary

This document presents a concise, experimentally oriented workflow for designing and characterizing 3D-printable cementitious materials. It combines particle-scale optimization, water demand assessment, admixture formulation, and rheological evaluation into a comprehensive methodology for developing 3D-printable concrete mixes using locally available materials. The dry materials are initially characterized by sieve analysis (EN 933-1/2) for the coarse fractions and laser diffraction (ISO 13320, ISO 9276) for binders, supplementary cementitious materials (SCMs), and fine fillers. All particle size distributions (PSDs) are then converted to a common volume-based basis. These data are input into the Modified Andreasen–Andersen particle-packing model, which is used to iteratively adjust the proportions of aggregates, sand, binder, SCMs, and fillers so that the combined PSD matches a target continuous grading curve, thereby maximizing the packing density of the mixture.

Once the proportion of dry components is established, the water demand is estimated using the Okamura and Ozawa method, which involves measuring the bulk volume of the mixture, calculating the solid volume from the constituent densities, and deriving the void volume as the theoretical minimum water requirement. This value is then adjusted using a lubrication factor to define an initial water-to-binder ratio. The mix is subsequently optimized through the selection and iterative adjustment of chemical admixtures, including superplasticizers, retarders and buildability-enhancing additives. Dosages are fine-tuned using mini-slump or jump table tests to ensure that the final mix meets the targeted requirements.

For precise control of fresh-state behavior, the workflow incorporates vane-in-cup rotational rheometry (e.g., Viskomat XL, eBT-V, ICAR, ConTec) combined with a stepwise protocol to determine dynamic yield stress and plastic viscosity from torque–rotational speed data using the Reiner–Riwlin equations with plug-flow correction. Complementary single-batch and multi-batch procedures are employed to track the evolution of static yield stress, quantifying structuration and setting rates, thereby directly linking rheological properties to buildability. This methodology is implemented in accordance with the recommendations of RILEM TC 266-MRP. For hardened properties, the mechanical performance under compression and tension is evaluated following the testing procedures outlined in RILEM TC 304-ADC. These procedures account for the anisotropic behavior of 3D-printed concrete.

2 Optimizing dry component proportion

2.1 Determining Particle Size Distribution (PSD)

The choice of particle size distribution (PSD) measurement technique depends primarily on the maximum particle size (D_{max}) of each ingredient in the mix. A combination of sieve analysis and laser diffraction is typically required to capture the full grading profile of aggregates, sands, binders, and supplementary cementitious materials (SCMs).

2.1.1 Sieve analysis for coarse fractions

For granular constituents such as sand and fine aggregates, sieve analysis serves as the primary characterization method. Mechanical sieving is performed to quantify mass-based retention across a specified series of sieves, with testing conducted either dry or wet depending on moisture condition and the material's propensity to agglomerate. Standardized procedures—such as those outlined in EN 933-1/2—govern sieve selection, operational steps, and data reporting. The output is a mass-based particle size distribution for the coarse fraction, typically expressed in terms of cumulative passing or retained percentages.

2.1.2 Laser diffraction for fine fractions

For the fine fraction—including cement, SCMs (e.g., fly ash, slag), and fine mineral fillers—laser diffraction provides a high-resolution PSD. The method evaluates the angular scattering of a laser beam passing through a dispersed powder sample. Particle sizes are calculated assuming spherical particles, giving a volume-based distribution. Common devices include the *Malvern Mastersizer* and *Horiba* analyzers, which report cumulative passing curves by volume. Use ISO 13320 (laser diffraction method) and ISO 9276 (statistical data treatment and distribution reporting) for cementitious materials and fine fillers. A continuous PSD for particles typically ranging from sub-micron to ~100–200 µm, depending on instrument capabilities.

2.2 Proportioning dry components

Once the particle size distributions (PSDs) of all dry constituents—aggregates, sands, binders, SCMs, and fillers—have been characterized using sieve analysis (coarse fraction) and laser diffraction (fine fraction), the combined distributions can be incorporated into the Modified Andersen–Andersen (MAA) model to determine optimal mix proportions for 3D-printable materials.

The MAA model describes an idealized continuous particle-size curve that maximizes packing density, improving both pumpability and buildability in 3D-printable mixes. The target distribution is expressed as:

$$P\ (D) = (\frac{D^q - D_{min}^q}{D_{max}^q - D_{min}^q}) \quad \text{(Eq 1)}$$

where:

- $P(D)$= cumulative volume fraction passing size D,
- D_{min} and D_{max}= minimum and maximum particle sizes of the mix,
- q= distribution modulus (typically 0.22–0.28, lower values correspond to finer, more cohesive systems).

To apply the Modified Andersen–Andreasen (MAA) model for proportioning the dry components of a 3D-printable mix, the particle size distributions (PSDs) obtained from sieve analysis and laser diffraction must first be merged and expressed on a consistent basis. In this process, sieve analysis typically provides mass-based PSDs for the coarse fraction, while laser diffraction yields volume-based PSDs for the fine fraction. To generate a unified PSD suitable for particle-packing calculations, the sieve-based mass percentages are converted to volume fractions by dividing the mass retained (or passing) in each size class by the particle density of the material, then normalizing these calculated volumes so that the cumulative distribution spans from 0 to 100%. Once both coarse and fine PSDs have been aligned on a volume basis, they are combined into a continuous distribution and compared to the target MAA curve, defined by equation 1. The proportions of each dry ingredient (aggregates, sand, binders, SCMs, and fillers) are then iteratively adjusted so that the weighted sum of their individual PSDs best matches the ideal MAA curve, thereby maximizing particle packing and producing a well-graded, highly printable material. Finally, the optimized volume fractions are converted back into mass fractions using the material densities to obtain practical batching proportions.

Microsoft Excel–based and MATLAB-based tools have been developed by the authors to implement the fundamentals of the Modified Andreasen–Andersen particle-packing model and to compute optimal proportions of dry constituents for 3D-printable concrete based on the input particle size distributions of the individual materials. The tools are available for access through the following links.

Microsoft Excel: << TTK server which can be accessed by the students>>

MATLAB: << TTK server which can be accessed by the students >>

2.3 Chemical–mineralogical characterization of local Supplementary Cementitious Materials (SCMs)

Once the optimal particle-packing–based proportions are established, the proposed blend must be evaluated against additional mix-design constraints, particularly the required balance between Ordinary Portland Cement (OPC) and supplementary cementitious materials (SCMs). Because the performance of SCMs is highly dependent on their chemical and mineralogical characteristics, an assessment of their reactivity is essential. This typically involves X-ray fluorescence (XRF) analysis to quantify oxide compositions relevant to hydraulic and pozzolanic behavior; X-ray diffraction (XRD) to identify crystalline phases, amorphous content, and potential deleterious minerals; and isothermal calorimetry (IC) to characterize the early-age reaction kinetics of SCM–cement blends. Together, these methods ensure that locally sourced SCMs provide sufficient reactivity, compatibility, and contribution to strength development to satisfy the functional requirements of a 3D-printable cementitious system.

Once the optimal proportions are obtained, the resulting blend must also be checked against additional mix-design criteria—such as the required ratio between Ordinary Portland Cement and supplementary cementitious materials (SCMs). The reactivity of the local SCMs needs to be analyzed using necessary chemical analysis such as XRF for oxide compositions, XRD for mineral phases of the SCMs and ICT to determine the reactivity of the SCMs in the cementitious systems.

From the XRF analysis, the primary oxides of interest for assessing SCM suitability are CaO, SiO_2, and Al_2O_3. Although additional oxides can influence reactivity, focusing on these three provides a sufficiently robust basis for a concise mix-design roadmap. After determining the oxide composition, the next step is to evaluate whether these constituents are present in crystalline or amorphous form—typically using XRD—since amorphous phases generally exhibit significantly higher pozzolanic or latent hydraulic reactivity. Based on this chemical–mineralogical assessment, an initial cement-replacement percentage can be proposed.

Using the preliminary replacement level as a starting point, prepare a series of cement pastes with progressively higher SCM replacement fractions and evaluate their reaction kinetics by isothermal calorimetry. For each paste, record the heat-release rate curve and

cumulative heat evolution over a chosen measurement window (e.g., 0–72 h). Compare key calorimetric metrics — total heat at specified ages (e.g., 24, 48, 72 h), peak heat-release rate and its time to peak — against a reference OPC paste. The objective is to determine the maximum SCM incorporation for which the cement–SCM blend demonstrates cumulative heat release and reaction kinetics that are comparable to, or exceed, those of the OPC reference (within a predefined acceptance tolerance).

Once the optimal replacement levels of OPC with SCMs have been established through calorimetric and chemical–mineralogical evaluation, these values should be compared with the SCM–OPC ratios generated by the MAA-based particle-packing optimization. If the ratios are not aligned, two approaches are possible:

1. Option A: Impose a constraint in the MAA optimization. The MAA calculation can be rerun with a fixed SCM–OPC ratio equal to the experimentally determined optimum. This ensures chemical and hydration performance are preserved, although it may reduce the achievable packing density and therefore alter rheological behaviour.

2. Option B: Prioritize particle packing without constraining the SCM–OPC ratio. This option is acceptable only when the SCM–OPC ratio produced by the MAA model is *lower* than the maximum viable SCM replacement level identified through isothermal calorimetry. In this case, the blend still remains within the safe bounds of reactivity and strength development, while benefiting from improved packing density.

In summary, constraints should be applied only when the MAA-derived SCM content exceeds the reactivity-validated limit; otherwise, the particle-packing solution may be retained to maximize fresh-state performance.

3 Determining the wet components of the printable mix

3.1 Estimating water demand according to Okamura and Ozawa

Okamura and Ozawa (1995) proposed a systematic method to estimate the water requirement of a granular cementitious system based on particle size distribution and packing density. The procedure aims to determine the minimum water content needed to fill the voids between particles while achieving target workability.

Weight the dry component proportions determined using the Modified Andreasen–Andersen method (see Section 1) and blend them thoroughly using a mixer (eg. Hobart

mixer). Next, measure the bulk volume V_{bulk} of the mixture by filling a container, which includes the voids between particles. After that, calculate the theoretical solid volume of each component V_i from the component mass m_i and particle density ρ_i supplied by the manufacturer:

$$V_i = \frac{m_i}{\rho_i} \quad \text{(Eq 2)}$$

The total theoretical solid volume of the mixture is then:

$$V_{\text{solids}} = \sum_i V_i \quad \text{(Eq 3)}$$

Subsequently, calculate the void volume V_{void} as the difference between the bulk volume and the total solid volume:

$$V_{\text{void}} = V_{\text{bulk}} - V_{\text{solids}}$$

$$V_{w,\min} = V_{\text{void}}.$$

This void volume represents the absolute minimum quantity of fluid required to fill the interparticle spaces. To achieve a workable and extrudable mix, an empirical lubrication factor k is applied—typically between 1.1 and 1.4—to account for the additional paste needed to coat particles and provide sufficient flow under shear. The required water volume is thus estimated as $V_{w,\text{req}} = k\,V_{\text{void}}$, which is then converted to mass using $m_w = V_{w,\text{req}}\rho_w$, where ρ_w is the density of water. The resulting water mass is used to compute the initial water-to-binder ratio, which may subsequently be refined based on the standard mini-slump or jump table test. The required slump or spread diameter after the respective tests is dependent on the 3D printing system. For the MAI Multimix 3D system with a pumping length of 10 m, a target spread diameter of 170 mm is required to ensure smooth pumpability and extrudability.

3.2 Addition of chemical admixtures

Even with optimized dry-component proportions and water content, a 3D-printable mix may not achieve the desired fresh and hardened properties for the printed structure. In such cases, chemical admixtures are required to adjust the rheology, and setting characteristics to meet the performance requirements.

3.2.1 Superplasticizers

Superplasticizers (SPs), also known as high-range water-reducing admixtures, are essential chemical additives in 3D concrete printing for controlling the rheology and workability of cementitious mixes. In low water-to-binder (w/b) systems typical of 3D-printable concrete or mortar, SPs enable sufficient flow and pumpability without increasing water content, thereby preserving the structural buildability and early-age strength of the printed layers. By dispersing cement and fine particles, SPs reduce interparticle friction and yield stress, allowing the mix to be extruded smoothly through the nozzle while retaining shape stability after deposition.

Several types of superplasticizers are used in 3DCP, each with distinct chemical compositions and mechanisms. Polycarboxylate ether (PCE)-based SPs are the most commonly used in modern 3D printing due to their high water-reducing efficiency and tunable side-chain chemistry, which allows control over flow retention and thixotropy. Naphthalene sulfonate (NS) and melamine sulfonate (MS)-based SPs are older formulations that provide good initial fluidity but are less effective in controlling long-term rheology and may lead to faster slump loss. The choice of SP type, dosage, and combination with other admixtures such as retarders directly affects the printability of the mix.

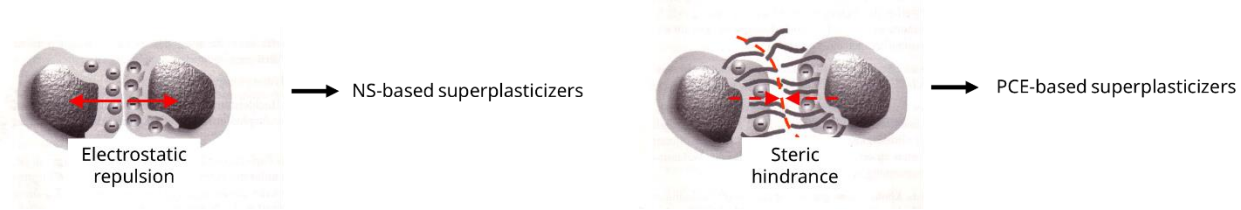

Figure 1. Schematic representation highlighting Working mechanisms of the PCE based and NS and MS based SPs. More details can be found in https://doi.org/10.1680/aecp.34075.0001.

Optimizing superplasticizer use in 3DCP requires iterative testing, often in conjunction with mini-slump or jump table tests. The initial SP dosage should be selected based on the manufacturer's recommendations. Once the SP is incorporated, the water content can be fine-tuned to achieve the target slump or spread diameter required for the specific 3D printing system.

3.2.2 Retarders

Retarders are chemical admixtures used in 3D concrete printing to control the hydration rate of cement, thereby extending the setting time of the mix. They are particularly critical

for large-scale construction projects, where concrete must be transported over long distances or through extended delivery systems before deposition.

In practice, the dosage of retarders is carefully adjusted to achieve the desired open time without compromising early-age buildability or structural stability of printed layers. Retarders are often used in combination with superplasticizers (SPs), as these admixtures act synergistically: while SPs reduce yield stress and improve flow, retarders prevent premature stiffening. However, compatibility between SPs and retarders must be ensured, as certain chemical combinations can reduce the effectiveness of one or both admixtures. Polycarboxylate ether (PCE)-based SPs are generally compatible with most commonly used retarders, but laboratory trials are recommended to optimize dosage ratios for both pumpability and shape retention.

Optimizing retarders in 3D concrete printing typically requires iterative testing, using mini-slump or jump table methods. In addition to determining the target slump or spread diameter for the 3D printing system, it is also necessary to monitor the evolution of these values over time to assess the rate of stiffening and ensure sufficient open time for pumping and extrusion. The selection of the retarder type and its initial dosage should be guided by the manufacturer's recommendations.

Suggested book for concrete admixtures: *Science and Technology of Concrete Admixtures by Pierre-Claude Aïtcin and Robert J Flat.*

3.2.3 Buildability enhancement

Once the 3D-printable mix has been optimized for pumpability and extrudability through the appropriate selection and dosage of superplasticizers (SPs) and retarders, attention must be given to enhancing the buildability of the material. Buildability refers to the ability of the printed layers to support subsequent layers without excessive deformation or collapse, which is critical for achieving the intended geometry and structural stability of the printed element.

Buildability can be enhanced using additives that influence the thixotropic behavior, initial yield stress, and structural build-up of fresh concrete. Common examples include viscosity-modifying agents (VMAs), cellulose-based thickeners, and fine fillers. The selection and dosage of these additives depend on the specific geometry and rate of printing, as well as the desired long-term mechanical performance and durability of the printed structure.

For one-component mixes, the dosages of buildability-enhancing additives must be optimized simultaneously with those of superplasticizers and retarders, as the mix development is inherently iterative and relies on experimental evaluation of both pumpability and buildability. In contrast, for multi-component mixes, a modular approach can be employed. In this strategy, the dosages of superplasticizer and retarder are first optimized independently to achieve the desired pumpability. Subsequently, the dosage of buildability-enhancing additives is determined. Since these additives are typically introduced near the nozzle during printing, any modification to the rheology at this stage does not affect the pumpability of the mix. This approach allows separate optimization of the concrete's behavior during pumping and during the building stage, enabling more precise control over both fresh-state flow and structural build-up. For multi-component mixes, an in-line mixer is required to combine the pumpable base mix with the buildability-enhancing additives immediately before extrusion. These in-line mixers can be either static or dynamic, depending on the required mixing intensity and homogeneity. Further details on the design and application of in-line mixers in 3D concrete printing can be found in https://doi.org/10.1016/j.cemconcomp.2021.103972.

Suggested paper for buildability enhancing additive in 3D concrete printing:

Technologies for improving buildability in 3D concrete printing by Shravan Muthukrishnan, Sayanthan Ramakrishnan and Jay Sanjayan, Cement and Concrete Composites, Volume 122, 2021, 104144, ISSN 0958-9465, https://doi.org/10.1016/j.cemconcomp.2021.104144

4 Characterization of fresh properties using Rheometers

Precise characterization of the rheological properties of 3D-printable concrete is critical in the case of simulating or predicting printability the mix. Among the rotational rheometers, vane-in-cup setup is widely used for 3D concrete printing. Some of the rheometers used for characterizing fresh properties for 3D concrete printing is shown in Figure 2.

Viskomat XL Schleibinger | eBT-V Schleibinger | ICAR Rheometer Plus | ConTec Viscometer 5

Figure 2. Commonly used vane-in-cup rheometers for 3D concrete printing.

4.1 Testing methodology to determine dynamic rheological properties

- Step 1: Apply the predetermined maximum rotational velocity to the fresh concrete sample. For reference, the recommended maximum velocities for the different rheometers are: 0.50 rps (ICAR), 0.26 rps (ConTec), 0.60 rps (eBT-V), and 0.46 rps (Viskomat XL).
- Step 2: Record the torque during pre-shear and visually determine, to within ±5 s, the time at which the torque stabilizes. This duration is taken as the required pre-shear time.
- Step 3: Prepare a new sample and apply pre-shear for previously determined duration, then perform a stepwise decrease in rotational velocity consisting of eight steps, each held for 5 seconds.
- Step 4: For each of the eight rotational velocity steps (N_1 to N_8), compute the average torque over the final four seconds of the step. In some cases, a substantial rebuild of torque may occur—particularly at the lowest velocity step (N_8)—resulting in torque values that exceed those from step N_7. When this occurs, the torque measurement from step N_8 should be omitted from the analysis.
- Step 5: After calculating the average torque and rotational velocity for the seven retained steps, apply the Reiner–Riwlin equation with plug-flow correction in an iterative procedure to determine the yield stress and plastic viscosity of each mixture at the corresponding test time.
  - This iterative process consists of calculating the shear stress at the inner radius by eq. 4:
  - $\tau = \frac{T}{2\pi R_i^2 h}$ (eq. 4)

- After that calculate the shear at the inner cylinder, using the updated flow domain determined for each step. This calculation depends on the a-priori unknown rheological properties of the concrete (eq. 5):

$$\frac{\partial \gamma}{\partial t} = \frac{2}{R_i^2}\left(\frac{1}{R_i^2} - \frac{1}{R_s^2}\right)^{-1}\left(2\pi N + \frac{\tau_0}{\mu_p} ln\left(\frac{R_s}{R_i}\right)\right) - \frac{\tau_0}{\mu_p} \quad \text{(eq. 5)}$$

In this equation, R_s is the minimum value of Rp or Ro. Rp is calculated for each velocity step separately as follows (eq. 6):

$$R_p = \sqrt{\frac{T}{2\pi\tau_0 h}} \quad \text{(eq. 6)}$$

Because the plug-flow radius $R_p$depends on the unknown yield stress, the shear-rate calculation requires an iterative approach. A best-fit line is established between shear stress and shear rate using all T–N data points for the test, from which the yield stress and plastic viscosity are obtained. The yield stress and viscosity estimated at step i are then used as input parameters for step $i+1$. The iteration continues until convergence is reached, defined as the point where the sum of squared differences in yield stress and viscosity between successive iterations (n and $n+1$)is less than 10^{-4}. The final converged values of yield stress and plastic viscosity obtained from the iterative procedure represent the dynamic rheological properties of the mixture.

Suggested papers:

1) *RILEM TC 266-MRP: round-robin rheological tests on high performance mortar and concrete with adapted rheology—rheometers, mixtures and procedures. Mater Struct 56, 90 (2023) by Dimitri Feys et al.* https://doi.org/10.1617/s11527-023-02173-1
2) *RILEM TC 266-MRP: round-robin rheological tests on high performance mortar and concrete with adapted rheology—a comprehensive flow curve analysis. Mater Struct 56, 105 (2023) by Dimitri Feys et al.* https://doi.org/10.1617/s11527-023-02176-y

4.2 Testing methodology to determine static rheological properties

Single batch

- Step 1: After mixing, carefully transfer the fresh concrete into the rheometer cup.
- Step 2: Apply a shear rate of 0.3 rps for 5 seconds at predetermined resting times of 10, 20, 30, and 50 minutes.
- Step 3: Record the maximum torque at each interval and convert it to shear stress using Eq 4.

- Step 4: The calculated shear stress corresponds to the static yield stress at the respective resting period. Plotting the evolution of shear stress over time provides information on the material's setting rate or structuration rate.

Multi batch approach

- Step 1: Prepare separate fresh concrete samples for each resting period to be tested (e.g., 10, 20, 30, and 50 minutes). Each sample is taken from the same batch but is independently handled to avoid the effects of prior shearing.
- Step 2: For each sample, carefully transfer it into the rheometer cup at the start of its designated resting period.
- Step 3: After the specified resting time has elapsed, apply a shear rate of 0.3 rps for 5 seconds to the sample.
- Step 4: Record the maximum torque during this short shear interval and convert it to shear stress using Eq 4.
- Step 5: The calculated shear stress represents the static yield stress of the fresh concrete at that specific resting period.
- Step 6: Repeat Steps 2–5 for all other resting periods using freshly prepared samples.
- Step 7: Plot the evolution of static yield stress versus time to determine the setting rate or structuration rate of the material.

Suggested papers:

1) RILEM TC 266-MRP: round-robin rheological tests on high performance mortar and concrete with adapted rheology—a comprehensive flow curve analysis. *Mater Struct* 56, 105 (2023) by Dimitri Feys et al. https://doi.org/10.1617/s11527-023-02176-y
2) Possibilities and challenges of constant shear rate test for evaluation of structural build-up rate of cementitious materials by Irina Ivanova and Viktor Mechtcherine, Cement and Concrete Research, Volume 130, 2020,105974, ISSN 0008-8846 https://doi.org/10.1016/j.cemconres.2020.105974

At the time of writing, RILEM TC PFC is in the process of preparing testing procedures for the measurement of static rheological properties using methods such as penetration tests,

portable vane tests, and uniaxial compression tests. It is recommended to consult these forthcoming documents for guidance on additional tools and methodologies for characterizing the rheological behavior of fresh concrete.

5 Characterization of hardened properties and durability

At the time of writing, no formal standards exist for evaluating the hardened mechanical properties and durability of 3D-printed concrete specimens. RILEM TC 304-ADC (chaired by Viktor Mechtcherine, TU Dresden) has developed detailed testing protocols for assessing mechanical behavior under compression and tension, as well as durability-related properties including shrinkage, water absorption, chloride ingress, and carbonation. These documents can be accessed at: doi:10.14459/2023mp1705940