

D.FAB

STANDARD OPERATIONAL PROCEDURE



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D.FAB 3D Printable Concrete

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5/1/2023	Gerius Moelich	Raw material selection additional requirements
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		Measuring KPIs
		IBS test dimensions
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INDEX

INDEX.....	3
1.1 PURPOSE	5
1.2 SCOPE	5
1.3 APPLICABILITY	5
1.4 DEFINITIONS	5
1.5 ROLES AND RESPONSIBILITIES	5
1.6 TOOLS, EQUIPMENT AND FACILITIES	6
1.7 ENVIRONMENTAL, HEALTH AND SAFETY (EHS).....	6
1.8 INDEPENDENT COMPONENTS	6
2. KEY PERFORMANCE INDICATORS (KPI).....	8
3. PROCEDURE	11
3.1 RAW MATERIALS SELECTION	11
3.1.1 CEMENT AND EXTENDERS.....	11
3.1.2 AGGREGATES.....	12
3.1.3 WATER.....	13
3.1.4 D.FAB ADMIXTURES	13
3.1.5 FIBRES.....	13
3.1.6 BONDING AGENT	14
3.1.7 CURING AGENT	14
3.1.8 CHECKLIST.....	14
3.2 MIX DESIGN.....	14
3.2.1 BINDERS (CEMENT AND EXTENDERS).....	15
3.2.2 AGGREGATES.....	15
3.2.3 ACCELERATORS (ISOXEL 5450 AND ISOXEL 899).....	16
3.2.4 FIBRES.....	16
3.2.5 PLASTICIZER (D.FAB IIID α 1.00).....	16
3.2.6 WATER.....	16
3.2.7 STIFFENER (D.FAB IIID β 1.00).....	16
3.2.8 FINAL MIX DESIGN.....	17
3.2.9 OPTIMISING FOR COST	17
3.2.10 CHECKLIST.....	17
3.3 OPERATION ON-SITE	17
3.3.1 CALIBRATING THE MIX DESIGN	17
3.3.2 CONTINUOUS PRINTING	17
3.4 PERFORMANCE TESTING	18
3.4.1 SIZE GRADING OF AGGREGATES.....	18
3.4.2 MOISTURE CONTENT OF AGGREGATES	18
3.4.3 SHEAR VANE TESTING	19

3.4.4 OPEN TIME	19
3.4.5 PUMPABILITY	19
3.4.6 SHAPE RETENTION	20
3.4.7 SURFACE FINISH	20
3.4.8 BUILDABILITY	20
3.4.9 PLASTIC SHRINKAGE CRACKING	20
3.4.10 INTERLAYER BOND STRENGTH	21
3.4.11 COMPRESSIVE STRENGTH	22
3.4.12 ACCURACY OF PRINT	22
3.4.13 WATER PERMEABILITY AND DURABILITY	22
3.4.14 COST	22
3.4.15 CHECKLIST	23
3.5 CURING AND 3D PRINTING IN HOT WEATHER	23
4. TROUBLESHOOTING	25
5. QUALITY ASSURANCE	27
6. REFERENCES	28
7. RELATED DOCUMENTS AND TOOLS	30

1.1 PURPOSE

D.fab is a materials approach that uses locally sourced aggregates and cement for 3D concrete printing. This document provides a step-by-step guide on the implementation of the D.fab solution. The aim is to produce concrete that satisfies the requirements for 3D printing – the early age rheological properties without compromising mechanical strength or long-term durability.

1.2 SCOPE

The implementation of D.fab includes the roles and responsibilities of operators, required tools and the environmental, health and safety. The Key Performance Indicators are defined. The implementation procedure can be defined in the following steps: a) raw materials selection, b) mix design, c) operation and d) performance testing. These steps are discussed in detail.

This document is intended for the D.fab admixtures and mix design. Although the approach is transferable to other materials solutions, it is not the intent of this document to be used for other admixtures or mix designs.

This document discussed the material-related issues and does not deal with the process of 3D printing concrete, or any issues caused by the printing procedure. A description of the 3D concrete printing process can be found elsewhere.

This document should be used in parallel with the SOP documents of the materials delivery system (concrete batchplant, pump and hose) and BOD 2 printer.

For technical data and experimental results on the D.fab mix, the following additional documents should be consulted:

- CEMEX - COBOD D.fab Technical datasheet
- Development of a Universal 3D Printable Concrete Solution COBOD CEMEX

1.3 APPLICABILITY

This document provides all the literature of the implementation of D.fab but is not intended to replace the training session. This document supports the Level 1 and 2 training provided by COBOD and should be used in parallel with the online and on-site training.

1.4 DEFINITIONS

Cement – A binder that reacts with water to harden.

Mortar – A mix of sand (<4,75 mm), cement and water.

Concrete – A mix of sand (<4,75 mm), gravel (>4,75 mm), cement and water.

1.5 ROLES AND RESPONSIBILITIES

It is the responsibility of the COBOD materials engineer to provide guidelines and training to the material operator. The material operator is responsible for the implementation of D.fab on-site, including the raw material selection, mix design, performance testing and curing. It is the responsibility of the material operator to share the relevant information with the COBOD materials engineer. It is the responsibility of the COBOD materials engineer to provide recommendations on the raw material selection, mix design, performance testing and curing.

1.6 TOOLS, EQUIPMENT AND FACILITIES

The following tools are required:

- General concrete handling tools: buckets, scoopers, trowels, and spades.
- Waste management: big bags, waste concrete container/bin
- Slump test tools
- Shear vane, sold by COBOD
- Moisture content test: pan, stove, scale accurate to 1 g up to 5 kg, wood spatula.

The following testing equipment is required:

- Compressive strength test: moulds, testing machine.
- Flexural strength: moulds, four-point bending setup, testing machine.

1.7 ENVIRONMENTAL, HEALTH AND SAFETY (EHS)

Waste concrete and run-off water should be discarded correctly – according to local building regulations. All hazardous substances should be discarded in a safe manner.

Cement and the powder accelerator should be stored in a dry place, on a pallet. The plasticizer, liquid accelerator and stiffener should be protected from frost, heat and direct sunlight.

Cement based products, like concrete or mortar, can cause serious skin problems such as dermatitis and burns. Therefore, workers should be protected against exposure to cement-based products.

Safety glasses, gloves, trousers and long-sleeve shirts should be worn when handling concrete. A hardhat and safety shoes is recommended. A N95 mask is recommended for cement handling.

1.8 INDEPENDENT COMPONENTS

D.fab consists of the following compounds:

- Cement
- Sand
- Gravel
- Water
- Plasticizer

- Liquid accelerator
- Powder accelerator
- Fibers (recommended)
- Stiffener

These components are combined to produce a concrete mix that satisfy the requirements of 3D printing, as seen in Figure 1.

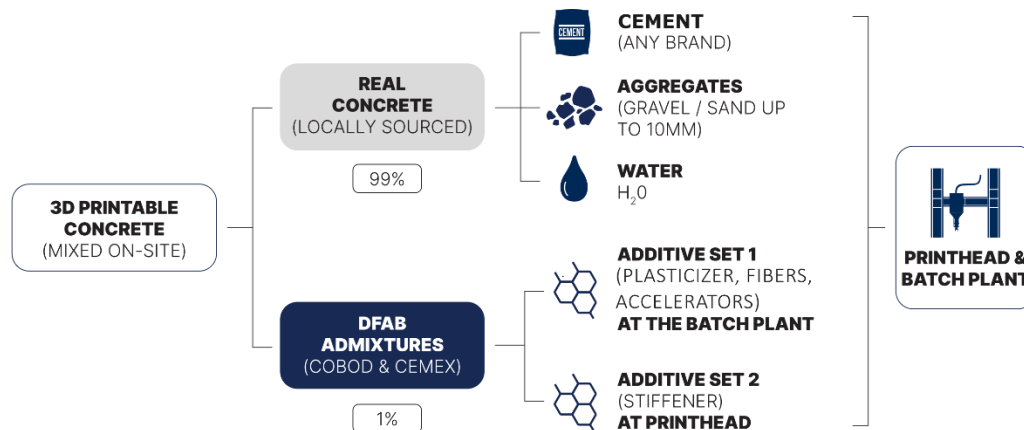


Figure 1: D.fab components.

2. KEY PERFORMANCE INDICATORS (KPI)

The following key performance indicators are relevant for D.fab:

1. *Pumpability* – The mix can be transported from the mixer to extrusion.
2. *Open time* – The mix remains pumpable for an adequate amount of time after mixing, allowing for homogeneous placement.
3. *Extrudability* – The filament retains its shape on extrusion (*Shaper retention*) and does not tear (*Filament tearing*) resulting in a continuous rectangular layer cross-section.
4. *Buildability* – Bottom layers can carry the weight of the new freshly placed layers with the specified layer time.
5. *Cracking and durability* – The printed element does not show any signs of cracking and can resist weathering action, chemical attack, and abrasion while maintaining its desired engineering properties.
6. *Structural integrity* – The mix satisfies the requirement of compressive and flexural strength.
7. *Cost* – The cost is competitive with local ready-mix suppliers.

Figure 2 depicts the D.fab KPI.

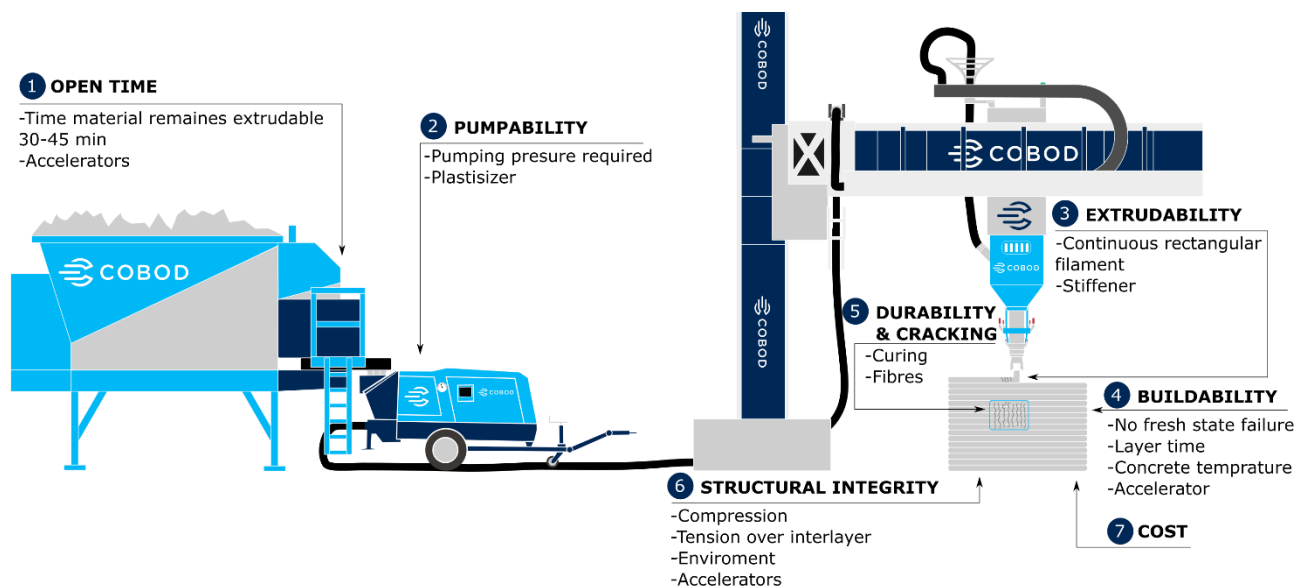


Figure 2: D.fab KPI

These KPIs can be measured against the criteria below, Table 1.

Table 1: Measuring KPI.

KPI	Description	Recommended test	Unit of measure	Outcome		
				Good	Average	Bad
Pumpability	Hose blockages		Blockages/month	0	1	>1
Open time	Shear vane performance testing	D.fab SOP (pg 18): Open time test	Time	>45 min	30-45 min	<30 min
Extrudability	Visual inspection and distance measurements of printed concrete	D.fab SOP (pg 21): Accuracy of print	Filament tearing and dist. deviation from expected	No filament tearing, 5 mm tolerance	10 mm tolerance	Filament tearing, 20 mm tolerance
Buildability	Shear vane performance testing	D.fab SOP (pg 18): Buildability test	Vertical buildup rate (m/h)	>0,4 m/h	0,25-0,4 m/h	<0,25 m/h
Cracking and durability	Visual inspection at 28 days after printing	D.fab SOP (pg 20, 22): Cracking, Durability	Nr. cracks wider than 0,2 mm per meter	No cracks	Zero cracks wider than 0,2 mm	>0 cracks wider than 0,2 mm
Structural integrity	Compressive strength test	D.fab SOP (pg 29): Compressive strength	MPa	>40 MPa	30 - 40 MPa	<30 MPa

Cost	Comparison to a local concrete mix with similar properties delivered by RMC	D.fab SOP file	Mix design sheet	Price difference	>10% cheaper	Similar price	>10% more expensive
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3. PROCEDURE

This section is structured in the following chronological order: (3.1) raw materials selection, (3.2) mix design, (3.3) operation, (3.4) performance testing and (3.5) curing practices.

3.1 RAW MATERIALS SELECTION

It is imperative that the suitable raw materials are selected, since these raw materials constitute 99% of the final concrete volume. The purpose of this section is to guide the user in selecting suitable, locally sourced, raw materials. The golden rule is to select raw materials that are typically used by concrete contractors. These raw materials are combined in the configuration seen in Figure 3.

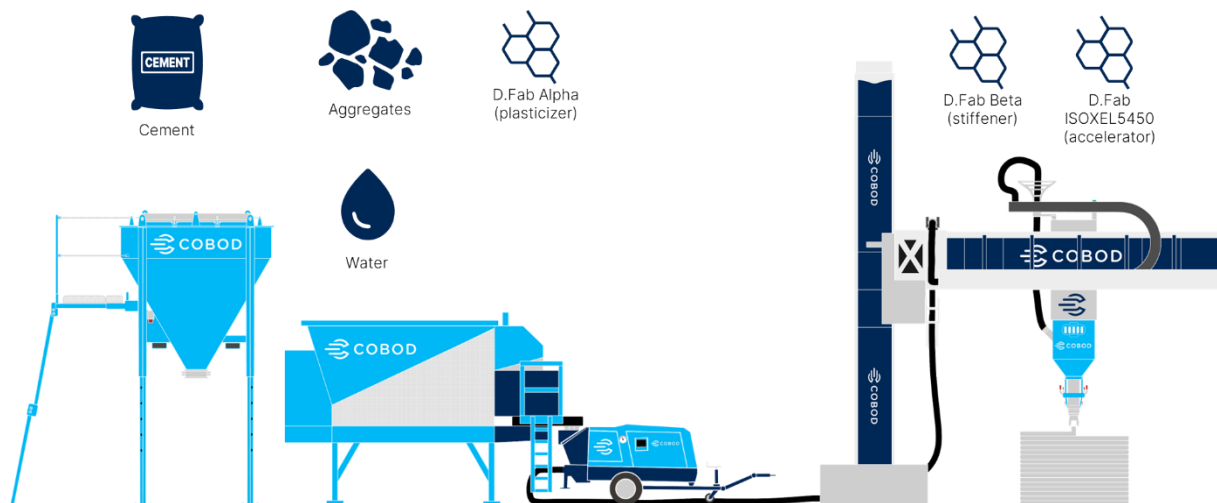


Figure 3: Configuration of raw materials.

3.1.1 CEMENT AND EXTENDERS

Cement that is used for ordinary concrete projects is also recommended for D.fab. Cement producers blend pure Portland cement (clinker) with extenders during production to decrease cost and CO₂ emissions. The blend of pure Portland cement and different extenders is sold as the product we know as cement. The composition and constituents of the blended cement depend on the availability and cost of the extenders. Selecting the suitable cement entails knowing what extender is used, and in what quantity. Typically, the cement technical data sheet contains the type and amount of extender.

Extenders such as pozzolans (fly ash, silica fume, natural pozzolanas, calcined clay) and fillers (limestone and slag) can also be added in addition to the cement to enhance its properties. Extenders would improve the surface finish and can reduce the raw material cost of your 3D printed concrete but would require the purchase of an additional silo (storage and delivery system). Pozzolans (fly ash, natural pozzolanas, calcined clay) is the recommended extender,

but it can be expensive. Fillers (limestone and slag) is the second-best option. Silica fume can be added to reduce water permeability.

For 3D printing we prefer using a blended cement that contains both the pure Portland cement and extenders.

Cement requirements:

1. Blended cement with a 28-day target compressive strength exceeding 40 MPa. Table 2 shows the suitable cement blends.
2. Both normal and rapid strength development is acceptable.

Ask your cement supplier:

“I need cement for general concrete use, with a target strength of 40 MPa (5800 Psi) at 28 days. I prefer using blended cement with fly ash but slag, limestone or other pozzolana extenders are also suitable. Please see below Table 2 with suitable cement types.”

Please share the technical data sheet and quote with your COBOD materials scientist to confirm.

Table 2: The cement blends suitable for 3D concrete printing.

Extender	EN 197-1 2011 standard	US ASTM C595 standard
Slag	CEM II A or B – S	Type IS (up to 40% replacement)
Other pozzolanas	CEM II A – P or Q	
Fly ash	CEM II A or B – V	Type IP (up to 40% replacement)
Limestone	CEM II A – L or LL	Type IL (up to 20% replacement)
Composite	CEM II A – M	Type IT (up to 20% replacement)

3.1.2 AGGREGATES

Sand and gravel are added to D.fab as aggregates. Selecting aggregates that are not normally used in concrete production can result in low compressive strengths and long-term durability issues. It is therefore important that aggregates that are normally used in concrete production are considered for D.fab. The aggregates significantly influence the concrete's fresh state and strength properties. The sieve grading datasheet of each aggregate should be obtained from the local queries to select the best aggregates for the project.

Aggregate requirements:

- Typically used by concrete producers.
- Water absorption value below 1-2%
- For the sand
 - 0 – 2 mm or 0 – 4,75 mm.
 - 15% – 30% passing the 0,3 mm (US No. 50) sieve.
 - 5% – 15% passing the 0,15 mm (US No. 100) sieve.
 - <5% passing 0,075 mm (US No. 200) sieve.
- For the gravel
 - If the gravel is naturally well-rounded (preferred):
 - the maximum particle size should be limited to 8 mm.
 - If the gravel is artificially crushed (second option):
 - the maximum particle size should be limited to 6,5 mm.
 - If a 0 – 2 mm sand is used:
 - at least 30% of the gravel should pass the 4,75 mm (US No. 4) sieve.

- If a 0 – 4,75 mm sand is used:
 - at least 20% of the gravel should pass the 4,75 mm (US No. 4) sieve.
- The gravel should be washed or double-washed to remove dust.
- <2% passing 0,075 mm (US No. 200) sieve.
- Particle density: 2500-2700 kg/m³.

If a reliable supplier is found that can satisfy these requirements, please share the aggregate data sheets and quotes with your COBOD material scientist.

3.1.3 WATER

Potable water should be used for concrete production.

3.1.4 D.FAB ADMIXTURES

COBOD 3D printing concrete relies on a specific combination of admixtures developed by CEMEX Admixtures. Using the D.fab admixtures with any other admixtures can compromise the performance of the solution. An overview of the D.fab admixtures is given in Table 3. The technical data sheets of these admixtures are attached (Admixture data sheets).

Table 3: D.fab admixtures

Necessary	Category	Purpose
D.FAB IID α1.00	Plasticizer	Improves workability, facilitates pumpability, workability retention
D.FAB IID β1.00	Stiffening admixture	Improves printability, facilitates shape retention on extrusion
Optional admixture		
ISOXEL 5450	Accelerator	Allows the concrete to set faster and enhances buildability
ISOXEL 899	Accelerator	Allows the concrete to set faster and enhances buildability

3.1.5 FIBRES

Fibres are typically added to 3D printed concrete to prevent plastic and drying shrinkage cracking.

Preferred fibre

Polypropylene fibres with a length between 10 and 12 mm.

Second option

Any fibre design to prevent plastic shrinkage cracking with lengths between 10 and 12 mm.

Ask your local admixture provider

“Can you please provide me with 10-12 mm fibres designed to prevent plastic shrinkage cracking in concrete? I prefer working with polypropylene fibres.”

Please share the datasheet and quote with your COBOD material scientist.

3.1.6 BONDING AGENT

A high-quality bonding agent is necessary for adhesion between old and new concrete. The compound is applied to the old concrete before the start of printing. Nitobond from Fosroc performed the best in COBOD's tests, but alternatives also performed well.

Ask your local admixture provider

“Can you please provide me with a concrete bonding agent?”

Please share the datasheet and quote with your COBOD material scientist.

3.1.7 CURING AGENT

Applying curing agents to the surface of the printed concrete after extrusion can prevent plastic and drying shrinkage cracking and increase strength.

Ask your local admixture provider

“Can you please provide me with a concrete curing agent?”

3.1.8 CHECKLIST

You have ordered:

- D.fab admixtures
- Cement
- Extenders (optional)
- Sand and gravel
- Fibres
- Bonding agent
- Curing agent

3.2 MIX DESIGN

This section aims to guide the user through the mix design process. The D.fab mix design procedure is outlined as follows:

Pre-installation

1. Determine the binders (cement, fly ash, limestone, slag) proportions based on local availability.
2. Determine gravel to sand ratio, based on aggregate sieve gradings and binders available.
3. Determine accelerator dosages, based on local conditions.
4. Optimise selection for cost

During installation

5. Determine water quantity based on mixing trails.
6. Increase stiffener dosage based on shape retention.

7. Increase accelerator based on buildability.
8. Increase fibre dosage based on cracking.

Post-installation

9. Amend mix design if target strength is not achieved.

3.2.1 BINDERS (CEMENT AND EXTENDERS)

The binders used depends on the availability of extenders. Generally, the cost of cement is responsible for 40-60% of the concrete cost. Using extenders can therefore significantly reduce the cost of the concrete mix. The binder quantities are recommended in Table 4.

Table 4: Binder quantities for three mix options.

Blended cements	Option A	Option B	Option C
Cement (CEM I or Type I/II) [kg/m ³]	350-400	350-400	450
Fly ash or Calcined Clay [kg/m ³]	100-150		
Slag or limestone [kg/m ³]		100-150	

The Excel file *COBOD D.fab mix design* should be used to simplify the mix design calculations. Do the following in your file:

In sheet Raw materials

1. Add the name, density and cost of the cement, extender and aggregates options that were available.

In sheet Cement and accelerators

2. Select the binder option (Option A, B or C) you have chosen.

3.2.2 AGGREGATES

The aggregates play a significant role in the fresh and hardened state properties of concrete. The *Raw materials selection section* stated the requirement of the aggregates for 3D concrete printing. Now, the sieve gradings of the aggregates available to you can be used to determine the optimal gravel to sand ratio. There is a theoretical ideal curve, which we aim to replicate by changing the gravel to sand ratio. In the Excel sheet do the following:

In sheet Gravel to Sand ratio

3. Add the sieve gradings for the various aggregates that were selected in the yellow cells.
4. Add the quantity of extender used by your binder selection. This is only the amount of fly ash, natural pozzolana, limestone, or slag.
5. Select a combination of sand and gravel from the options you entered from the dropdown list. Iterate through the combinations to find the closest fit to the ideal curve (this means the lowest RMS error, blue cell).
6. For each combination, solve the gravel to sand ratio (green cell) using Excel's solver function. This solver minimizes the error between the ideal and actual grading curves to determine the best gravel to sand ratio for the combination you entered.
7. Note down the error for each combination of the different aggregate options.
8. Select the combination of aggregates with the lowest error.

9. The final gravel to sand ratio transfers to the mix design sheet, so solve again for the lowers error combination.

In sheet Mix design

10. Make sure the G/S value is updated in cell AH3.

3.2.3 ACCELERATORS (ISOXEL 5450 AND ISOXEL 899)

The accelerator dosage required depends on the temperature of the raw ingredients. In the Excel sheet do the following:

In sheet Cement and accelerators

11. See the climate map and select your climate from the drop-down box (yellow cell, B13). The accelerator dosage should change below.

3.2.4 FIBRES

The minimum fibre dosage is 0,1% (per concrete volume) since fibres also prevent filament tearing. This dosage can be increased if cracking occurs during the project. Too high a fibre dosage would reduce pumpability and cause clogging at the nozzle and occasionally in the hose. The maximum dosage depends on the type and size of fibre that is selected. Therefore, on-site mixing trials are required to determine the maximum dosage.

3.2.5 PLASTICIZER (D.FAB IIID A1.00)

The plasticizer dosage can range between 1,5-2% per weight of cement depending on the raw materials. However, a high plasticizer dosage is recommended, typically 1,8%. If a delay occurs during the print and the fresh concrete is continuously mixed, an additional plasticizer dosage can be added. Additional plasticizer can be added in the event of a delay, to regain the fluidity, but the interval and dosage should be determined experimentally. The open time test in the performance testing section is recommended.

3.2.6 WATER

Water is added depending on the consistency of the fresh concrete and the quantity is therefore determined during the mixing trials. A water to cement ratio between 0,4 and 0,5 is recommended.

The moisture content in the aggregates influences the water quantity added. On each day of printing, the moisture content should be determined according to the standard moisture content test.

In sheet Mix design

12. Change the moisture content values according to the test result. Note that the water quantity changes (in cell F12). The moisture content should be updated every day of printing, to adjust the quantity of water added.

3.2.7 STIFFENER (D.FAB IIID B1.00)

The stiffener improves shape retention on extrusion, and the dosage is determined during the mixing trials. The typical dosage is between 200 ml/h to 1000 ml/h, but this can vary from day to day or even during the print.

3.2.8 FINAL MIX DESIGN

The final mix design can now be calculated in the Excel file as follows:

In sheet Mix design

13. Under description, select the cement and extender from the drop-down list. Enter the quantities under key parameters.
14. The fibre and plasticizer dosages are fixed.
15. The accelerator dosage should update from the water temperature you entered.
16. The gravel to sand ratio should update based on the last aggregate combination.
17. The final quantities are shown under Quantities kg/m³. The batch size can be changed in cell G9 to calculate the quantities of a smaller batch. You can also increase the batch size to the concrete volume of your project to estimate the quantities of the raw materials needed.

3.2.9 OPTIMISING FOR COST

The total cost of the raw materials (per m³) is available in the Mix design sheet. The binder option (combination of cement and extenders) and aggregate combinations can be changed to optimise for cost. Remember that changing the aggregate combination would affect the gravel to sand ratio.

3.2.10 CHECKLIST

You have selected:

- A binder option, based on the cement and extenders that are locally available.
- Calculated the best gravel to sand ratio, based on the sieve gradings of the available aggregates.
- Estimated the accelerator dosage, based on the water temperature.

The water, fibre and stiffener dosages will be determined during the mixing trials.

3.3 OPERATION ON-SITE

3.3.1 CALIBRATING THE MIX DESIGN

The initial mix design will need some adjustment. Calibration is recommended when the raw materials change, or at the start of a new project. The following steps are recommended to tuning the mix design:

1. Set the water to cement ratio to 0,5 and plasticizer to 1,5%.
2. Adjust the mix design for the aggregate moisture content
3. Prepare a 100 l mix on the batch plant
4. Add/reduce plasticizer to achieve a shear vane value 500 – 700 Pa.
5. Remember that adding the plasticizer during mixing is more effective than adding after mixing. Therefore, underdose 5 L of water per 1 m³ of concrete when inserting the new recipe in the batch plant.

3.3.2 CONTINUOUS PRINTING

The mix will need continuous adjustment, on every batch, as the raw materials and site conditions change. Follow this procedure:

1. Load the raw materials in the morning before printing

2. Conduct the moisture content test on the aggregates in the batch plant's silos. Adjust the mix accordingly.
3. Start with 100 L batches in order to adjust the mix.
4. Initially, check the shear vane value of each batch.
5. Underdose 5L of water per 1 m³ of concrete and add additional water after mixing to achieve desired consistency.
6. Continuously mix if too fluid.
7. To estimate the batch size, divide the material volume (l/h) in the COBOD Slicer by 3. For example, the material volume (l/h) is 450 l/h, use a batch size of 150 l. For this calculation, the print speed should be set to a realistic value in the Slicer.

3.4 PERFORMANCE TESTING

This section recommends testing protocols to evaluate the performance of your D.fab concrete mix. Since 99% of the raw materials are locally sourced, these tests should be conducted to verify the quality of the concrete. This document discussed: 1) which tests are recommended, 2) why the test is important, 3) states who can conduct this test and 4) a short summary.

3.4.1 SIZE GRADING OF AGGREGATES

The *Raw material selection section* elaborates on the importance of the size of the aggregates. Most local concrete testing laboratories can conduct this test (sieve grading of aggregates). Local codes should be consulted for a detailed description of this test. This test should be performed during the pre-installation phase of the project.

In summary

A sample is collected from the aggregate stockpile. The sample is dried in an oven for a specified period. The sample is then sieved through a series of sieves, starting from coarse to fine. The mass retained on each sieve is noted. The sieve sizes vary depending on the local code.

3.4.2 MOISTURE CONTENT OF AGGREGATES

The moisture content of the aggregates influences the total amount of water that is added to the mix. The moisture content in the aggregates is therefore accounted for in the amount of water that is added

In summary

1. Weigh the pan and record the weight in the *Excel file D.fab Performance testing, sheet Moisture content*.
2. Take samples from the aggregate silo. Remove the top layer from the stockpile and take small samples from different locations.
3. Fill approximately 1 kg of aggregates from the bucket into the pan.
4. Weigh the pan with aggregates.
5. Heat up the pan to maximum.
6. Gently stir the aggregates in the pan every 5 min.
7. After 10 minutes, weigh the pan and put it back on the stove.
8. After a couple of minutes, weigh the pan again and put it back on the stove.
9. Continue this process until the weight is constant. This is defined as the saturated surface dry (SSD) condition.

$$MC = \frac{W_{wet} - W_{ssd}}{W_{ssd}}$$

The pan method is preferred (find a video [here](#)).

3.4.3 SHEAR VANE TESTING

The shear vane test is useful to estimate the rheological properties of the fresh concrete.

In summery

1. Set the value of the shear vane apparatus to zero.
2. Insert the shear vane blades into the material, so it is fully covered.
3. Turn it clockwise at a constant speed.
4. When noticing a decrease in the force needed to turn the shear vane tester, take it out and note the value.
5. The shear vane result can be converted to a shear stress with the following formula:

$$\text{Shear stress [kPa]} = 0,5 \times \text{Shear vane result [mm]}$$

3.4.4 OPEN TIME

The open time of the mix is important to quantify the time allowed before the mix becomes unextrudable. This test can be conducted on-site, with the final mix design.

Test

1. Prepare a mix in the batch plant.
2. Stop mixing after the 180 s
3. Fill two buckets with concrete from the mixer.
4. Use the shear vane to measure the yield stress at intervals of 10 min. Do not test the same area twice.
5. Enter the yield stress results in Excel sheet *COBOD D.fab performance testing* (Sheet *Open time*, yellow cells).
6. When the yield stress exceeds 1000 Pa (shear vane is 20 mm) the material is deemed unextrudable, and the time can be noted.
7. Empty the buckets
8. Add additional plasticizer to the concrete inside the mixer, at a 0,2-0,3% dosage, to achieve the initial yield stress of 600-700 Pa. Note down the dosage of plasticizer required to achieve a yield stress of 600-700 Pa.
9. Stop mixing after 180 s.
10. Refill the two buckets with the freshly mixed batch.
11. Redo the shear vane tests at 10 min intervals until a yield stress exceeds 1000 Pa.
12. Additional plasticizer can be added for a second time to reduce the yield stress.
13. Refill the two buckets with the freshly mixed batch.
14. Redo the shear vane tests at 10 min intervals until a yield stress exceeds 1000 Pa.

The open time is defined as when the yield stress exceeds 1000 Pa after the additional plasticizer has been added twice. In the event of a printer delay, the noted plasticizer dosage can be added after the noted time to regain the initial yield stress of 600-700 Pa. A mix designed for printing large structures should have an open time of at least 45 min.

A concrete rheometer can also be used to conduct this test and will significantly improve the sensitivity of this test.

3.4.5 PUMPABILITY

Pumpability is defined by the pumping pressure of a fresh concrete batch that is pumped through the hose system. This test can be done on-site.

1. The hose should be primed with a suitable slurry.

2. The mix should then be pumped at a speed of 2.
3. Prepare at least two concrete batches and note the pumping pressure for both.
4. The target pressure is <60 bar. 80 bar is acceptable, while >100 bar is unacceptable.

A concrete rheometer can also be used to significantly improve the sensitivity of this test and estimate the pumping pressure required for the specific rheological properties of the material and hose system.

3.4.6 SHAPE RETENTION

The dimensions of the filament should be monitored to ensure shape retention. This can be done on-site, during printing. The target deviation is below 10 mm in width, and 5 mm in height.

3.4.7 SURFACE FINISH

The term surface finish refers to the smoothness of the wall element. Figure # shows an acceptable surface finish.

3.4.8 BUILDABILITY

Buildability is important to ensure an optimal vertical building rate, without plastic or buckling collapse. This test can be conducted on-site, with the final mix design. The buildability model used here was proposed by Kruger et al. 2020.

Test

1. Collect a concrete sample from the print head. Fill two buckets.
2. Take shear vane measurements at time intervals of 1, 2, 5, 10, 20, 40 and 60 min. Test twice at each interval, one test per bucket. Do not test in the same location twice.
3. Enter the yield stress results in Excel sheet *COBOD D.fab performance testing* (Sheet *buildability*, yellow cells). The 0 min value is the yield stress result from the batchplant mixer.
4. In the sheet, the default filament dimensions are 50x40 mm and print speed is 50 mm/s.
5. The height of failure is indicated at the bottom of the sheet.
6. Now print the prescribed file called *Materials acceptability test* with the estimated layer time in the excel sheet.
7. Note the actual height of failure. Enter this value in the excel sheet to calculate the safety factor.
8. A safety factor above 0,7 is acceptable.

The aim is a stiffening rate that is adequate to facilitate infinite printing, at the given parameters. The model is only an estimation, and the actual result may differ.

A concrete rheometer can also be used to significantly improve the accuracy of this test.

3.4.9 PLASTIC SHRINKAGE CRACKING

The mix should be designed to be resistant to cracking, under a worst-case scenario. The following test is therefore recommended on a typical hot day on-site:

Test

1. With the final mix design, print the specimens as defined by the file *Materials acceptability test*. A filament height of 20 mm is recommended for this test.
2. After obtaining a height of 100 mm (5 layers), insert the following device into the printed element immediately. This device is designed to induce a crack in the specimen.

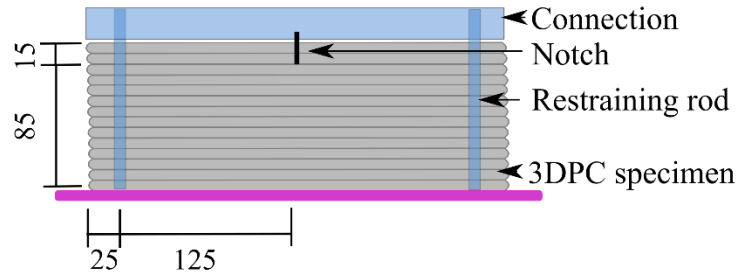


Figure 4: Plastic shrinkage cracking induction method proposed by Moelich et al. 2020.

3. The test should be conducted on the concrete slab.
4. The device should be monitored for the next 24 h, to see if a crack occurs.
5. If the crack spans the specimen from top to bottom the mix fails the test. The fibre dosage should be increased, and the test should be redone.
6. If a small crack develops no longer than 50 mm, the mix is acceptable. Good curing practices will prevent this crack from forming in the actual structure.

3.4.10 INTERLAYER BOND STRENGTH

The tensile bond strength between sequentially placed layers depends on many factors, including the printing process, raw materials, mix design and printing environment. Therefore, it is imperative that the interlayer bond strength is determined for the mix placed on-site, with similar environmental conditions and layer times.

Test from EN 196–1:2016 (Document *Flexural strength test of mortars* support this description)

1. With the final mix design, print the specimens as defined by the file *Materials acceptability test*. A filament with height 20 mm and width 50 mm is recommended for this test.
2. Cast the same mix in the moulds described by *Flexural strength test of mortars*.
3. The print path generates an element 200 mm (10 layers) high.
4. Once the element is complete, cure the specimens in the same way the printed structure is cured.
5. The specimens should be tested 7 and 28 days after printing. The cast specimens should be tested with the printed specimens.
6. Specimens should be saw-cut directly before testing. The width should be cut to 40 mm. This creates a prism of 40x40x160 mm.
7. At least six of the printed specimens should be tested at each age. Three cast specimens should be tested at each age.
8. The specimens should be tested using four-point bending, with the layers alight vertically and the saw-cut faces at the bottom and top. See Figure 5 a, below.

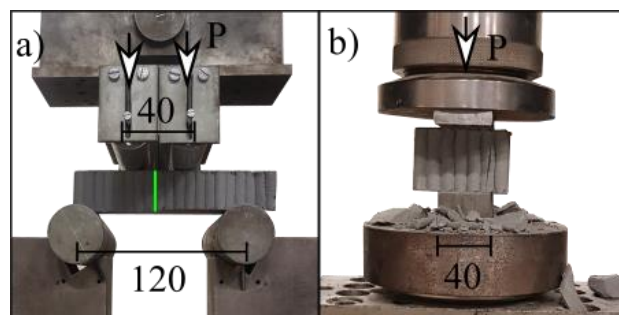


Figure 5: Mechanical testing on 3DPC: a) interlayer bond strength and b) compressive strength (EN 196–1:2016, ASTM C 496–96).

9. A loading rate of 50 N/s is recommended. EN 196–1:2016 and ASTM C 496–96 can be used as a guide.
10. After failure, the dimensions of the failure plane should be noted to calculate the stress capacity.
11. Excel sheet *COBOD D.fab performance testing (Sheet Strength)* assists with calculations.
12. The tensile capacity of a cold joint can also be tested in this way.

D.fab should have a flexural strength exceeding 2,5 MPa.

3.4.11 COMPRESSIVE STRENGTH

Once the mix design has been finalised the compressive strength should be determined as soon as possible. The standard compressive strength test should be conducted regularly, as a quality control measure.

Standard compressive strength of the mix

1. Cubes or cylinders should be cast from concrete obtained from the print head.
2. The compressive strength test should be conducted with the local standards on 7 and 28 days after casting.
3. The specimens should be cured in the same way as the printed structure.

D.fab should have a cast compressive strength exceeding 35 MPa.

Minimum compressive strength of printed concrete

1. The two halves of the failed flexure prisms can also be tested in compression. See Figure 5 b.
2. The interlayer should be aligned with the top and bottom plates before each test.
3. Excel sheet *COBOD D.fab performance testing (Sheet Strength)* assists with calculations.

D.fab should have a printed compressive strength exceeding 25 MPa.

3.4.12 ACCURACY OF PRINT

It is very important that the structure placed on-site has the intended dimensions. This can be verified by measuring the dimensions of the printed structure and comparing it to the CAD model.

3.4.13 WATER PERMEABILITY AND DURABILITY

The simplest way to test the water permeability is to fill a printed element with water and see if watermarks appear on the outside of the element. Alternatively, a water sorptivity test can be conducted on the disks extracted from the printed concrete. The sorptivity test is described in the Durability Index Testing Procedure Manual. Furthermore, the Durability Index Testing Procedure Manual describes the Oxygen permeability and Chloride conductivity tests which can be conducted if required. Durability testing is very time-consuming and requires specialised equipment.

3.4.14 COST

The cost of the mix should be noted and considered. The Mix design sheet shows the total cost of the mix if the raw material costs were updated for the local market.

3.4.15 CHECKLIST

The following tests are strongly recommended:

- Sieve gradings of aggregates
- Open time
- Plastic shrinkage cracking
- Buildability
- Compressive strength
- Interlayer bond strength
- Accuracy of print
- Cost calculation

The following tests are optional:

- Water permeability or sorptivity
- Oxygen permeability and chloride conductivity

3.5 CURING AND 3D PRINTING IN HOT WEATHER

This section aims to recommend good practices for 3D concrete printing in extremely high ambient temperatures. Such conditions prove challenging for 3DCP due to 1) early age cracking and 2) the short open time of the concrete.

The rate of cement's hydration reaction (responsible for hardening) is temperature-dependent. Therefore, at higher concrete temperatures the time allowed to deposit the fresh concrete is shorter. The open time can be extended by adding a retarder to the mix and reducing the cement clinker content. However, reducing the concrete temperature is a more reliable solution.

The high evaporation rate results in a loss of pore water from the freshly placed concrete, causing shrinkage and cracking within the first 24 hours after placement. 3D printed concrete is especially vulnerable to drying-related cracking due to the high surface area to concrete volume ratio and high fines content. For this reason, mitigating measures and curing methods used to prevent cracking in conventional concrete elements are insufficient for 3D printed concrete. With regards to the mix, polypropylene microfibers can be added, and the gravel quantity can be increased to some extent. Curing is however the easiest and most effective way to prevent cracking in 3D printed concrete. The key to curing is to preserve the pore water inside the fresh concrete by any means necessary.

The on-site evaporation rate can be calculated with the following equation (also in Performance testing sheet):

$$ER = 5((T_c + 18)^{2,5} - rh(T_a + 18)^{2,5})(V + 4) \times 10^{-6}$$

- ER = evaporation rate, kg/m²/hr,
- T_c = concrete (water surface) temperature, °C,
- T_a = air temperature, °C,
- rh = (RH percent)/100, and
- V = wind velocity, km/h.

Based on the ER value we can estimate the fibre dosage and curing photocalls required:

- If ER < 0,5 kg/m²/hr (indoor environment), fibres (0,1%) and some curing is required.

- If $ER > 0,5 \text{ kg/m}^2/\text{hr}$ (outdoor), fibres (0,1-0,2%) and moderate curing is required.
- If $ER > 1 \text{ kg/m}^2/\text{hr}$ (arid), fibres (0,2-0,3%) and extensive curing is required.
- Printing is not recommended at $ER > 1,5 \text{ kg/m}^2/\text{hr}$.

The following measures should be implemented to address the issues of early-age cracking and short open-time during hot weather 3D concrete printing (Uno, 1998):

1. The concrete should be placed at the lowest temperature possible to reduce the evaporation rate. A concrete temperature below 25°C is recommended at placement. This can be achieved by cooling the water and aggregates before mixing. The mixing and pump equipment should also be cooled down as much as possible during operations.
2. The evaporation rate of the printing environment should be reduced. This means increasing the humidity, reducing the wind speed, reducing the ambient temperature and shading the concrete. A water misting system, erecting wind barriers, and sun shading are all viable solutions.
3. During printing, a water mist should be sprayed onto the freshly placed concrete continuously.
4. After printing, the concrete should be covered in wet burlap. The burlap should be kept wet for as long as possible.
5. The burlap should be covered in plastic sheets to prevent it from drying, in cases where extensive curing is required.
6. Continuous wetting is required in cases where extensive curing is required.

The concrete mix can be designed to be resistant to drying cracking, but only to a limited extent. Drying cracking is most often due to insufficient curing.

4. TROUBLESHOOTING

All changes to the mix design should be communicated to the COBOD materials engineer since there may be adverse consequences.

Table 2: Troubleshooting guide for the fresh state properties of D.fab.

Issue	Cause	Solution	Adverse consequence	Likelihood
Pumpability	Printing process	Discussed elsewhere		Most common
	Dry material from mixer	Increase plasticizer Increase water	Cost Segregation	Common
	Segregation	Reduce gravel to sand ratio Conduct sieve analysis, recalculate G/S Decrease water and increase plasticizer	Cracking Time-consuming, cracking Cost	Less common
	Open time	-	-	Less common
Open time	Accelerators	Reduce accelerators	Reduced buildability	Common
	High temperature	Reduce raw material temperatures	Buildability	Common
	Cement	Use more extenders Reduce quantity	Reduce strength Reduce strength	Less common
Extrudability	Dry material in mixer	Decrease target shear vane at mixer	Shape retention	Most common
	Stiffener	Reduce stiffener	Shape retention	Less common
	Fibres	Reduce fibre	Cracking	Common
	Open time	-	-	Less common
Buildability	Low structuration rate	Increase accelerators Increase concrete temperature	Open time, interlayer bond Cracking, open time	Most common
Surface finish	More fines	Increase cement Increase extenders	Cracking, cost None	Most common
	Less coarse aggregates	Change gravel Replace gravel with sand	Time-consuming Cracking	Common

Table 3: Troubleshooting guide to hardened state properties of D.fab.

Issue	Cause	Solution	Adverse consequence	Likelihood
Cracking	Environment	Curing Reduce wind speed, increase humidity Mist concrete during and after printing	None None None	Most common
	Mix design	Increase fibres Increase gravel	Pumping pressure, clogging Segregation	Less common
Water permeability	Lack of fines	Increase binders Add silica fume	Open time, cost Cost	
Durability	Aggregates	Change aggregates	Time-consuming	
Compressive strength	Mix design	Reduce water, increase plasticizer	Cost	
	Cement	Change cement	Time-consuming	
Bond strength	Mix design	Reduce accelerators	Buildability	Common
	Environment	Reduce evaporation rate	None	Less common
	Printing process	Reduce layer time	Buildability	Common
Cost	Mix design	Replace cement with extenders	Strength	

5. QUALITY ASSURANCE

The following parameters should be monitored to ensure D.fab perform to expectation:

1. Fresh state properties (*Pumpability, Extrudability*) – The shear vane should be used as a quality control measure for the early age properties. The aim is to have consistent material at the nozzle for multiple batches of concrete.
2. Solidification properties (*Buildability, Open time*) – The shear vane, at rest intervals, is used to determine the rate of stiffening.
3. Hardened state properties (*Structural integrity*) – A cylinder/cube compressive strength test provides sufficient information to determine if the hardened properties are consistent.

6. REFERENCES

The following publications were useful in compiling this document, and provide useful background information to the reader (Academic literature):

Review articles

Le, T.T., Austin, S.A., Lim, S., Buswell, R.A., Law, R., Gibb, A.G. and Thorpe, T., 2012. Hardened properties of high-performance printing concrete. *Cement and Concrete Research*, 42(3), pp.558-566.

Marchon, D., Kawashima, S., Bessaies-Bey, H., Mantellato, S. and Ng, S., 2018. Hydration and rheology control of concrete for digital fabrication: Potential admixtures and cement chemistry. *Cement and Concrete Research*, 112, pp.96-110.

Mechtcherine, V., Bos, F.P., Perrot, A., da Silva, W.L., Nerella, V.N., Fataei, S., Wolfs, R.J., Sonebi, M. and Roussel, N., 2020. Extrusion-based additive manufacturing with cement-based materials—production steps, processes, and their underlying physics: a review. *Cement and Concrete Research*, 132, p.106037.

Buswell, R.A., De Silva, W.L., Jones, S.Z. and Dirrenberger, J., 2018. 3D printing using concrete extrusion: A roadmap for research. *Cement and Concrete Research*, 112, pp.37-49.

Pumping concrete

ACI Committee 304.2-96, 2008. Placing concrete by pumping methods. American Concrete Institute.

Secieru, E., Khodor, J., Schröfl, C. and Mechtcherine, V., 2018. Formation of lubricating layer and flow type during pumping of cement-based materials. *Construction and Building Materials*, 178, pp.507-517.

Feys, D., De Schutter, G., Fataei, S., Martys, N.S. and Mechtcherine, V., 2022. Pumping of concrete: Understanding a common placement method with lots of challenges. *Cement and Concrete Research*, 154, p.106720.

Perrot, A., Pierre, A., Nerella, V.N., Wolfs, R.J.M., Keita, E., Nair, S.A.O., Neithalath, N., Roussel, N. and Mechtcherine, V., 2021. From analytical methods to numerical simulations: A process engineering toolbox for 3D concrete printing. *Cement and Concrete Composites*, 122, p.104164.

Secieru, E., Mohamed, W., Fataei, S. and Mechtcherine, V., 2020. Assessment and prediction of concrete flow and pumping pressure in pipeline. *Cement and Concrete Composites*, 107, p.103495.

Rheology and Buildability

Roussel, N., 2006. A thixotropy model for fresh fluid concretes: theory, validation and applications. *Cement and concrete research*, 36(10), pp.1797-1806.

Kruger, J., Zeranka, S. and van Zijl, G., 2019. 3D concrete printing: A lower bound analytical model for buildability performance quantification. *Automation in Construction*, 106, p.102904.

Interlayer bond strength

Kruger, J. and van Zijl, G., 2021. A compendious review on lack-of-fusion in digital concrete fabrication. *Additive Manufacturing*, 37, p.101654.

Wolfs, R.J.M., Bos, F.P. and Salet, T.A.M., 2019. Hardened properties of 3D printed concrete: The influence of process parameters on interlayer adhesion. *Cement and Concrete Research*, 119, pp.132-140.

Keita, E., Bessaies-Bey, H., Zuo, W., Belin, P. and Roussel, N., 2019. Weak bond strength between successive layers in extrusion-based additive manufacturing: measurement and physical origin. *Cement and Concrete Research*, 123, p.105787.

Moelich, G.M., Janse van Rensburg, J.J., Kruger, J. and Combrinck, R., 2022. The Environment's Effect on the Interlayer Bond Strength of 3D Printed Concrete. In *RILEM International Conference on Concrete and Digital Fabrication* (pp. 222-227). Springer, Cham.

Plastic shrinkage cracking

Uno, P.J., 1998. Plastic shrinkage cracking and evaporation formulas. *ACI Materials Journal*, 95, pp.365-375.

Moelich, G.M., Kruger, P.J. and Combrinck, R., 2022. Mitigating early age cracking in 3D printed concrete using fibres, superabsorbent polymers, shrinkage reducing admixtures, B-CSA cement and curing measures. *Cement and Concrete Research*, 159, p.106862.

Fire

Cicione, A., Kruger, J., Walls, R.S. and Van Zijl, G., 2021. An experimental study of the behavior of 3D printed concrete at elevated temperatures. *Fire Safety Journal*, 120, p.103075.

Curing

ACI Committee 308R-01, 2008. *A Guide to Curing Concrete*. American Concrete Institute.

7. RELATED DOCUMENTS AND TOOLS

For technical data and experimental results on the D.fab mix, the following additional documents should be consulted (located in Experimental result and Admixture data sheets folders):

- CEMEX - COBOD D.fab Technical datasheet
- Development of a Universal 3D Printable Concrete Solution COBOD CEMEX
- Technical data sheets of the admixtures

The following Excel files and tools aid this document:

- On mix design:
 - COBOD D.fab mix design sheet
- On performance testing
 - COBOD D.fab performance testing
 - Information on durability testing: Durability testing
 - Print path for buildability testing: Material acceptability tests
 - To determine the interlayer bond strength: Flexural strength test of mortars