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ORIGINAL PAPER

Upscaling earth formworks: 3D printing strategies for material optimised reinforced concrete structures

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Abstract

There is a growing need to understand how locally sourced earthen materials can be processed to build more efficiently and sustainably. Earthen formworks combined with 3D printing technologies present a unique opportunity for the concrete construction sector to address the wastefulness and complexity of custom formworks. The current state-of-the-art projects in academia and industry demonstrate that earthen formwork strategies effectively address this challenge, but remain burdened by upscaling issues such as production speed. This research bridges the gap by exploring strategies for 3D Printed earth formworks to efficiently produce structural elements using custom self-compacting and set-on-demand concrete mixtures. A first base earth mix is developed for reduced shrinkage and later modified via a plasticizer for increased green strength, forming the final mix. Two mix iterations are deployed in two corresponding strategies where concrete is cast into the earth formwork in a dry or plastic state. The methods highlighting the setups for 3D printing and procedures for appropriate material processing such as slump flow, shrinkage and rheology are presented. The results are explored via two column prototypes leading to a final demonstrator for a 2 m high reinforced concrete column. Conclusions are drawn on the implications of the two casting strategies, the current persisting challenges and the crucial next steps for development. Thus, the research provides a foundation for how clay formworks can be upscaled effectively for more sustainable production of complex concrete structures.

Keywords Earth formworks · Concrete casting · 3D printing · In situ robotics · Digital fabrication

1 Introduction

There is a global urgency to cut down on concrete use and emissions, highlighting the demand for more material-efficient geometries and consequently more custom and complex formworks during casting. However, creating such formworks using current concrete building practices remains a labour and resource-intensive task. The use of alternative materials, such as earth for formworks, in combination with additive manufacturing techniques such as 3D printing, provides a potent recipe for overcoming the current intensity

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and wastefulness, hindering complex formwork fabrication (Perrot et al. 2018) (Jipa and Dillenburger 2022).

In 3D printing, robotics enhance production by precisely depositing fluid materials for three-dimensional components (Jipa and Dillenburger 2022). Material design is crucial for buildability (vertical building rate) and pumpability (ease of conveying material over distance and pump pressure) (Lloret-Fritschi et al. 2019). Projects like Eggshell at ETH (Burger et al., 2020) use digital casting systems, showcasing the potential of casting ultra-thin formworks with minimal material compared to traditional methods. This setup relies on a custom set-on-demand concrete mix, minimising hydrostatic pressure on formwork walls by simultaneously coordinating printing and casting into a streamlined process. Despite benefits, polymeric printing material poses challenges for demoulding, has single-use limitations, and limited end-of-life recovery/recyclability options (Burger et al., 2020).

Current research trends looking for alternative 3D printing materials provide insight into overcoming these limitations and set new grounds for exploration. The investigation into clay-based mixes is becoming increasingly appealing owing to the material`s abundance across different geographical contexts, low cost, simple processing and, most significantly, the potential for complete upcycling at the end of life. (Gomaa et al. 2021) In the absence of stabilising agents such as lime, cement or gypsum, earthen materials are limited in strength and durability, particularly when extruded (Giada et al 2019). Their application as non-load-bearing formworks is ideal for preserving their natural reversibility and potential for reuse.

Consequently, this research explores the potential for upscaling 3D-printed earth formwork for standard self-compacting concrete (SCC), whether cast with standard SCC or set-on-demand SCC (Lloret-Fritschi et al. 2020 and 2022). The exploration is contextualised around the design of a column typology that leverages the material`s state of hydration (Giada et al 2019) into two distinct production strategies. The first entails casting within earth formworks in a dry state, printed in multiple pieces that are later air-dried, assembled and cast as one formwork. The second uses set-on-demand SCC cast immediately into printed earth formworks while in a plastic state, similar to Eggshell. This project presents a material exploration between printed earth and cast concrete and attempts the following:

1. Developing a printable earth mix that is easily customised to various hardware setups.
2. Building a basic 3D printing system for architectural scale production and an advanced multi-robot setup for printing around steel reinforcement cages.
3. Exploring the possibilities of casting SCC in printed earth formworks, either in a dry or plastic state.

The research detailed in this paper unfolded across three European locations: the USI Academy of Architecture in Mendrisio, Switzerland, the Technical University of Munich, and the Technical University of Braunschweig. Overcoming challenges such as equipment and raw material changes was crucial in this exploration. Shifting locations led to a rapid method for adapting and refining the earth mix design.

2 State of the Art

In the state of the art of research, the exploration of circular 3D printed formworks using earth-based mixtures to produce architectural elements and enclosures is emerging. The current research trajectories can be divided into two categories:

1. Removable-earth-formwork for casting structural concrete components.
2. Stay-in place-formworks using earth as the main load-bearing material.

This section presents a selection of projects within the above categories to identify the crucial factors for upscaling earth formworks effectively into an architectural scale.

2.1 Removable-earth formworks for concrete casting

Removable-earth-formworks are typically used to cast durable materials like concrete, deploying earth mixtures composed of pure clay. Once the cast material sets, the formwork is demoulded and repurposed for subsequent printing; thus, they can be considered circular formworks. Three projects in this category, all exploring a column typology, are discussed.

The project “Clay Robotics” led by Wang et al. (2017) investigates the potential of using clay as a printed formwork for casting, highlighting challenges for production. The work is explored through the sequential fabrication of a bespoke 1.4 m column. Various parts, printed with a simple terracotta clay mix up to a buildable height of 500 mm, were later air-dried over 4 days, stacked and cast as one formwork using a cement mortar mix. Crucial to this process was identifying the exact dryness level of the clay before casting. The results showed that casting inside the clay in a fully-dry state is not feasible, as it absorbs water from the concrete, leading to cracking and strength reduction. Subsequent experiments thus attempted to cast within printed parts after a 3-h drying period, while the printed formwork was still in a plastic state. Three conclusions for casting within plastic-state formworks were drawn: The clay self-remoulds while drying owing to a faster shrinkage rate compared to the cement mix; lateral deformations (up to 5 mm) in the formwork appear during casting due to hydrostatic pressure on the clay walls; the hardware setup which uses a progressive cavity (or ram) pump built into a custom robotic end effector slows down production due to its limited material capacity (Wang et al. 2019). These results indicate the necessity for further study on the print mix and hardware.

The research project “Cocoon 3D” by Bruce et al. (2022) attempts to improve upon the plastic-state earth formworks of “Clay Robotics'' by instead producing a 1.3 m column using a simultaneous print-cast process inspired by Eggshell (Lloret Fritschi et al., 2019) to control deformation in the formwork. The accelerated setting of the concrete allows the buildable height limit prescribed by Wang et al. (2017) to be exceeded, resulting in a monolithic formwork. Using terracotta clay as a base print material, extrusion speeds were also synchronised to the 20-min setting rate of an accelerated glass fibre-reinforced Concrete (GFRC). In proving the feasibility of complex geometry, the project serves as a preliminary proof of concept for producing earth formworks with Eggshell´s set-on-demand strategy. Still, it does not address structural performance requirements at the architectural scale. A more pumpable print mix and larger material feed system are identified as the next steps to overcome the currently slow vertical production rate of 144 mm/hr for the 200 mm column diameter. Consequently, a faster setting concrete will also be required to handle faster print times.

The "Clay Formworks" project by Dielemans et al. (2022) employs a sequential print-cast process similar to "Cocoon 3D," using a mobile robot setup for printing around steel reinforcement during fabrication. A 2 m structural column with a steel cage is created using stoneware clay and set-on-demand self-compacting concrete (SCC). The robotic setup includes a telescopic axis on a remote-operated mobile platform for extended reach. The formwork was divided into 45 segments of 250 mm height, and 6 segments at 125 mm (5 mm layer height). Segments were printed individually from various locations, causing the mobile platform to pause between each print action. Each segment took 1.5 to 2 h to print. Consequently, the column was printed and cast gradually over two weeks, with casting happening after every third segment. A sinusoidal print pattern and vertical stiffeners enhance the effective thickness of the formwork walls to 25 mm, reducing print times while increasing stability. The project marked the first attempt at making a structural reinforced concrete element using earth formworks. Fabrication was characterised by persistent inaccuracy owing to slow vertical print rates of 150 mm/hr, giving parts enough time to shrink and misalign. Frequent robotic calibration between the virtual and real geometry extended fabrication into the 2-week timeframe.

2.2 Stay-in-place formworks for 3d printed earth structures

The projects in Sect. 2.1 on removable-earth-formworks consistently emphasise the need for a print mix and feed system that can handle faster production at an architectural scale. To achieve these advancements, it becomes crucial to understand how earth materials are currently used in 3D printing for human-scale architectural enclosures. Unlike removable-earth formworks, this category involves earth mixtures that can support weight to variable extents, and instead use cast or infilled materials for insulation. Projects like "Tecla House" by WASP (as cited in Youssef and Abbas 2023), "Prototype TOVA" by IAAC (2022), and "Emerging Objects" by Virginia San Fratello and Ronald Rael (Burry et al., 2020) have developed special earth-based mixes to enhance pumpability and buildability during extrusion. Using off-shelf rotary pump systems, these mixtures are fed to various robotic setups (such as Crane WASP or 3-axis SCARA robot). Instead of being directly mounted onto the robot, these systems externally supply material to the end-effector using a mechanical rotor and hydraulic hose. Combining these material mixes with the current hardware consistently achieves fast average flow rates of 0.7 L/min, theoretically facilitating efficient production. Even at such supply speeds, however, structures remain hindered by an average vertical build rate of 400 mm per day owing to drying times spanning days for such large volumes of material (Burry et al., 2020). Chemical stabilisers such as cement are sometimes used to improve the earth mix design’s buildability—but come at the cost of its circularity. Nonetheless, this research paper recognises the significant benefits of using the material and hardware systems adopted by stay-in-place formwork strategies in the context of removable ones. A plasticiser is also alternatively explored as a means to improve the green strength of the print mix while preserving its reusability at end-of-life.

2.3 Opportunities for further development

While our research is exclusively concerned with removable-earth formworks for architectural scales, the material and hardware strategies demonstrated in stay-in-place formworks provide a strong answer to the constraints plaguing the former category: supply, speed and scale. This paper attempts to bridge this gap by developing an efficiently produced removable-earth formwork on par with stay-in-place without compromising the print material’s circularity. It entails developing a natural base mix easily adapted to various off-shelf rotary pump systems and robotic setups. The findings of the “Clay Formworks” project here provide a solid foundation for evaluating the behaviour of the earth as formwork, and thus the same criteria will be used to discuss our results. Our work additionally explores modular and monolithic formwork, casting in a dry-state and plastic-state, respectively. For the latter case, we developed a similar print-cast process to "Cocoon 3D", using a faster-setting SCC mix typical of digital casting processes (Lloret-Fritschi et al. 2022) but produced around a steel reinforcement cage, as in the "Clay Formworks" research. The benefits of casting in dry-state and plastic-state formwork settings are consequently explored and compared. With new production speeds unlocked, we ultimately demonstrate the feasibility of a "wet-in-wet" casting method for producing a reinforced column using a dual robotic printing process.

3 Materials and methods

This section is divided into two parts. The first part highlights the general hardware, software and design-to-production workflow implemented across the prototyping experiments and final demonstrator. The second part describes the material mix designs for the two printable earth mixes and two concrete mixtures used in producing dry-state and plastic-state formworks, respectively.

3.1 Fabrication procedure for printing and casting earth formworks

3.1.1 Hardware for pumping and printing of formworks

The general procedure for printing and casting earth formworks is illustrated in Fig. 1 and is divided into three steps. First, the base materials for both earth and concrete are mixed according to a set procedure outlined in the following material Sects. (3.3 and 3.4). To adequately cater to material supply requirements during prototyping, an 80-L pan mixer (PAGEL PA-BEC V, Collomix XM 2/650 or equivalent) is used for all earth and concrete mixtures during the mixing phase. A 20-L Hobart A200N mixer is used exclusively to analyse the printable earth mix for samples under five litres.

In the second step, the workability of the mixture is evaluated using a standard flow Table (700 × 700 mm with 15 shocks). The standard slump-flow test with the Abrams cone (base ⌀250 mm) is conducted for concrete, and a modified slump-flow test with the Hägermann cone (base ⌀100 mm) is used for earth mixtures.

In the third step, the earth mix with correct workability is loaded into a rotary pump (PFT Swing L or equivalent, D4-2 rotor–stator) and a 10 m hydraulic hose (⌀25 mm). The hose delivers the material to a UR10e robotic with 7 Degrees of Freedom (DoF) equipped with a custom end-effector, extruding the earth mix into position through a 16 mm nozzle. For the final demonstrator of a reinforced column, a

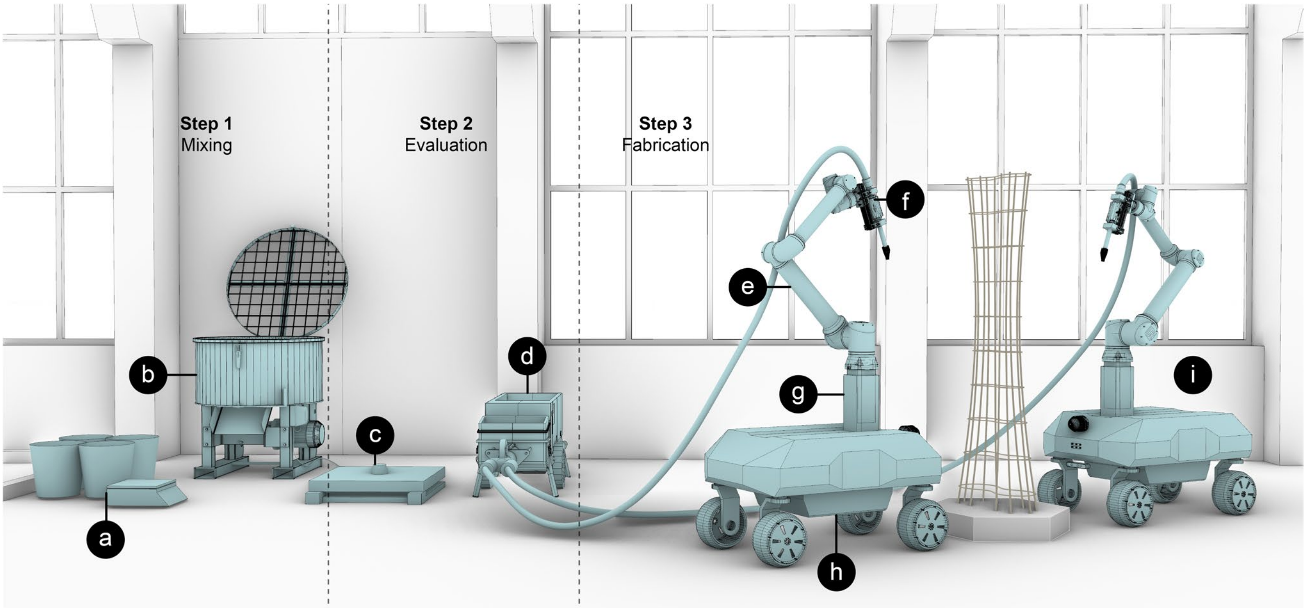

Fig. 1 General print procedure using final setup as reference. Main steps include mixing, evaluation and fabrication. Earth/ Concrete is prepared via Weighing scale (**a**) and Pan Mixer (**b**), and evaluated with Flow Table and relevant flow cone (**c**). Earth mix is loaded into Rotary Pump (**d**) feeding material to UR10e Robot (**e**) via custom end-effector (**f**) while mounted on vertical axis (**g**) and mobile platform (**h**). A second robot is installed for final setup (**i**)

second identical robot and end-effector are connected to the same pump, utilising a custom forked connection to feed both hoses simultaneously.

3.1.2 Design-to-fabrication workflow

The overall design-to-fabrication workflow involves several steps. First, a solid object is input into a customised slicing script generated in Grasshopper 3D (McNeel). This script prepares the solid for 3D printing by dividing it into layers and joining them into one continuous polyline. The script maintains a constant print width of 16 mm in all experiments, corresponding to the nozzle size and fixed print height of 8 mm. Print velocities for the UR10e robot varied between setups owing to minor variations in pump hardware used in Mendrisio, Braunschweig and Munich, respectively. A common extrusion flow rate of 0.3 L/min maintaining a 20 Bar pressure within the hose and rotor–stator was established for comparative purposes. All pump and robot speeds were adjusted accordingly. Once set, the first print layer is calibrated, and a JSON file compatible with the UR10e robot is sent to initiate printing.

Two casting strategies are tested using this setup, The first relies on prefabricating the earth formworks and allowing them to dry and harden to cast them. The second deploys casting during the print process, essentially pouring within the formworks while in a plastic state. These two strategies define the main methodology of this research and are presented in detail in the Results section. A variation of this workflow is adopted for a final demonstrator using a dual robot setup, which sends information simultaneously to both UR robots over a shared network. This dual setup enables the seamless printing of earth formworks around a steel reinforcement cage.

3.2 Materials for printing and casting

3.2.1 Base materials for earth mixture

A standardised material composition comprising clay powder, sand, fibres, and a plasticizer is developed for this project. Two variations of this mix are presented. Mix A refers to a preliminary composition without a plasticiser, while Mix B refers to the final composition comprising all the above base ingredients. The material compositions of Mix A and B respectively are outlined in Table 1 below.

Table 1 Table indicating composition for Mix A without plasticizer and Mix B with 0.3% additive, measured as percentages of overall volume of the mix

	Material composition by % volume				
	Sand	Clay	Fibres	Plasticizer	Water
Mix A	34.2	23.5	7.5	–	32.4
Mix B	38.4	22.4	6.1	0.3	30.9

To ensure uniformity across the collaborating institutes in Braunschweig, Munich, and Mendrisio, an identical industrial clay and straw fibre product was used up to 8 mm long (Conluto, Blomberg/Istrup, Germany). The loam (mixture of clay and quartz) is a dry crushed powder up to 0.5 mm, with a binding strength of up to 80 g/cm^2 and a bulk density of 1800 to 1,900 kg/m^3. The loam encloses clay particles (illite and montmorillonite). The density of the powder determined by a helium pycnometer is 2600 kg/m^3.

The sand used in this project is sourced locally and analysed through sieve testing to ensure a consistent aggregate distribution. The size of the sand is limited to a maximum particle diameter of 4 mm to meet the specifications of the pump's rotor–stator, declared in the hardware Sect. (3.1.1). The sand density was measured using a helium pycnometer. Figure 2 shows the cumulative particle size distribution of the locally sourced sands in Mendrisio, Munich, and Braunschweig, with respective densities of 2640, 2720 and 2650 kg/m^3.

The sourced clay powder, fibres and sands highlighted above comprise Mix A. Later in the project, a plasticiser (Zschimmer & Schwarz GmbH & Co KG Chemische Fabriken, Lahnstein, Germany) is used in the mix design to produce Mix B. The plasticiser is formulated from Polycarboxylic acid and sodium salt, and has a density of approximately 1.30 g/cm^3. This substance acts as a deflocculant for the clay, reducing the water needed in the mixture. This, in turn, positively impacts the shrinkage and green strength of the earth mixture. These values are described in further detail in Tables 2 and 3 in subSects. 3.3 and 3.4 respectively.

3.2.2 Mixing procedure for earth mixture

The preparation of the earth mixture involves several steps. First, the dry components are mixed for three minutes in the Hobart A200N mixer at the lowest mixing velocity (107 rpm). Second, water, with or without a dissolved plasticizer, is added and mixed for an additional three minutes. After this period, the bottom of the mixing container is visually examined to ensure that all dry components have been thoroughly and homogeneously mixed into the mixture. If this is not evident, the dry components must be scraped from the bottom of the container. After scraping the mixing bowl, the fourth step of a three-minute mixing at high velocity is (198 rpm). The same procedure is repeated for all prototyping using the 80 L pan mixers specified in the previous section.

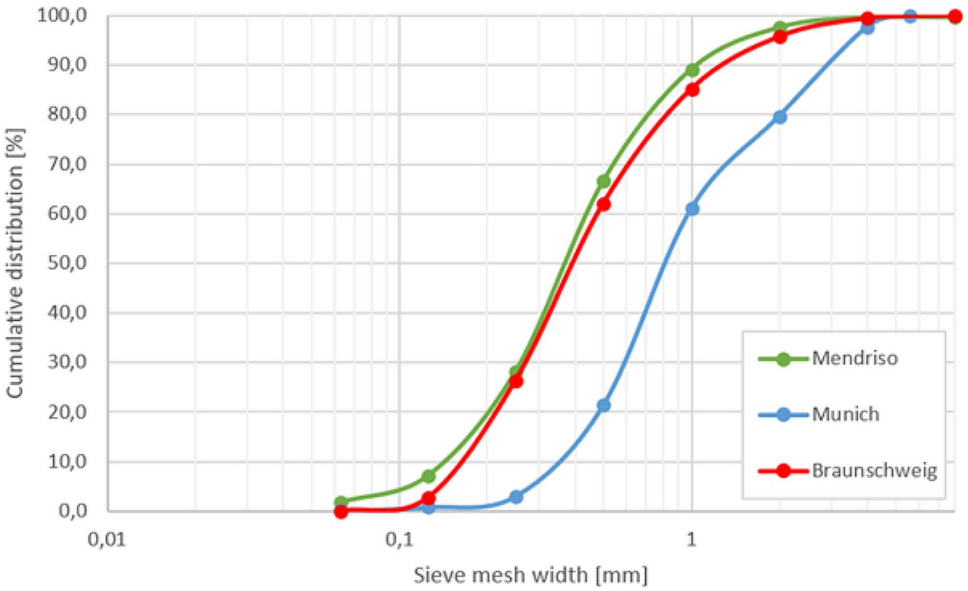

Fig. 2 Graph showing sieve mesh width (mm) in X axis and cumulative distribution % of locally sourced sand in Mendrisio, Munich, and Braunschweig in Y Axis

Table 2 Tabulation of material shrinkage (%) across 28 days. Highest shrinkage rate observed during the first 3 days, after which the shrink rate slows down

	% Shrinkage over time (days)					
	1	3	7	14	21	28
Test Mix	–	–	6.41	6.73	7.12	7.08
Mix A	1.70	4.09	4.34	4.32	4.33	4.32
Mix B	1.85	3.77	3.94	4.03	4.17	4.26

Shrinkage values for final dry-state at 28 days indicate an average of 4% for both mix A and B. and 7% for a test mix without fibres

Table 3 Table illustrating change in rheology for Mix A and B over 24 h. Mix B with plasticiser demonstrates a higher and faster rate of stiffness within the same timeframe, resulting in improved green strength

	Yield stress development (Pa) over time (min or hr)				
	15 min	30 min	60 min	120 min	24 h
Mix A	6,041	6,857	7,021	8,653	54,533
Mix B	5,551	6,694	8,327	12,735	72,166

3.3 Shrinkage evaluation over time

As outlined in the state-of-the-art section, material shrinkage plays an important role in the self-demoulding process, particularly when casting within formworks while still in their plastic state. While this research is not concerned with optimising shrinkage behaviour, a base understanding of the influence of fibres and the plasticizer upon the behaviour of the mix was required. A steel prism mould was used to produce 3 samples (50 × 50 × 200 mm) for each mix and measured at various intervals over 28 days. In Table 2, Mix A and B are compared with a Test Mix using the same clay and sand but without fibres and plasticizer. The tests reveal the influence of fibres, present in both Mix A and B in reducing shrinkage by 3% when compared to the Test Mix after 28 days. Conversely, the plasticizer has a negligible influence.

3.4 Rheology evaluation in fresh state

The extruded clay mixture must withstand several load cases, as it is used as a concrete column's formwork. To achieve this, the mixture must be stiff enough to support its weight (buildable) and the out-of-plane stresses from the concrete mixture yet still be liquid enough to be extruded (pumpable).

The clay mix formulation is designed based on a target slump, which indicates the rheological characteristics and is a crucial parameter for evaluating the pumpability and buildability of the mixture. After mixing, the rheology is qualified by conducting a slump test using the Hägerman cone specified in Sect. 3.1. The upper and lower limits for the slump shock diameter play a crucial role in determining material behaviour. Ideally, this range spans from 125 to 150 mm. However, the lower limit, particularly influenced by hardware—especially when utilising a different pump setup with a larger hose diameter—may lead to a lower slump diameter in the material mixture. This hardware dependency and its impact on the range are further explored in subsequent result testing.

Fast penetration tests, conducted at a speed of 5 mm/s, utilised a shotcrete penetrometer (Mecmesin, West Sussex, UK) to quantify the initial strength of the clay composite. The specific penetrometer tip featured a 12 mm diameter, 15 mm cylindrical height, and a 10 mm cone height. The earth mix's yield stress was determined using the method developed by Lootens et al. (2009). These derived values offer valuable insights into the mixture's early-stage strength, significantly influencing its subsequent buildability. Achieving higher penetration values, synonymous with a higher yield stress, is pivotal for assessing the mechanical integrity of extruded clay structures as it directly relates to their capacity to bear stress. Table 3 illustrates the beneficial influences of the plasticiser used in Mix B to achieve an equivalent rheology to Mix using less water and a higher overall green strength after 24 h.

3.5 Concrete mixtures

For the casting of the dry-earth formworks, a standard self-compacting concrete was used containing cement (CEM II/A-LL 52,5N), blasted aggregate with grain size distributions of 0–4 mm and 4–8 mm (Müller Steinag AG, Switzerland), (Calcite MS70F) and superplasticizer (Master Glenium ACE 404). This mix is used in preliminary studies to investigate the casting of earth formworks in their dry-state and is referred to as SCC_MS.

For the wet earth-formworks, a self-compacting concrete accelerated with calcium aluminate cement was used (further described in Lloret-Fritschi et al 2022) referred to as SCC_ACC. The workability for all concrete mix designs was verified before casting using the standard slump-flow test procedure highlighted earlier (ensuring a slump flow of 70 cm).

4 Results

Using the hardware setups described in Sect. 3.1.1 and the earthen mix designs described in Sect. 3.2.1, two specific formwork production strategies are investigated, leveraging the material's inherent properties as it transitions from a plastic state to a dry state. This section presents the key outcomes for the two fabrication strategies using dry-state and plastic-state formworks. Relevant development to the overall earth mix design is presented with necessary prototypes for each strategy, for the final demonstrator, detailed in the third section.

4.1 Prototyping for dry-state formworks with concrete casting

The first strategy explored printing earthen formworks that are given time to reach a dry state. This research defines this state as the lowest value for moisture content within the printed elements, typically equalising with humidity levels of the surrounding environment. This was frequently recorded as 33% for an average ambient temperature of 15 °C in March-April. In this dry state, the printed formwork can be freely handled by users and positioned accordingly. Leveraging such handleability, this first strategy sought to overcome the material's buildability and robotic fabrication constraints by producing the overall formwork in segments and assembling them into a 1.5 m-high column with a constant circular cross-section of 200 mm.

4.1.1 Earth mix development for dry-state formworks

For the following tests on dry-state formworks, Earth Mix A (without plasticiser) is used. This mix is designed based on extrusion tests using the sand from Braunschweig. An iterative process determined a target slump shock diameter of 130 mm ± 5 mm. The mixture consisted of a water-to-clay (w/c) ratio of 0.53, a sand-to-paste volume ratio (Vs/Vp) of 0.62, and 2.33% fibres of the clay mass. The green strength of the mixture was measured using the penetration test described in Sect. 3.3, yielding a value of 3243 Pa, indicating good pumpability and printability.

4.1.2 Preliminary printing, casting and demoulding tests

Additional studies were conducted using Earth Mix A, reproduced in Mendrisio, to understand the mixture`s real-time behaviour during fabrication empirically. A comparative assessment was conducted to understand the height deviation between the digital formwork model and its printed counterpart. For the given mix, a maximum printing height of 350 mm was achieved before a plastic collapse. Three cylindrical tests with a circular diameter of 200 mm were thus fabricated at different target heights of 100, 200, and 300 mm, respecting the maximum buildability limit. During production, the initial layers of each print were visibly seen to compact slightly during buildup, exhibiting a maximum width difference of 5 mm between the top and bottom. The resulting printed formwork in its dry state and cross-section are illustrated in Fig. 3.

Overhang tests were also conducted to investigate the maximum horizontal reach of printed earth mix for a fixed layer height of 5.5 mm. The results, illustrated in Fig. 4, indicate overhang stability up to 15°, after which a vertical deformation of layers becomes apparent. These overhang tests were conducted as a general study to understand

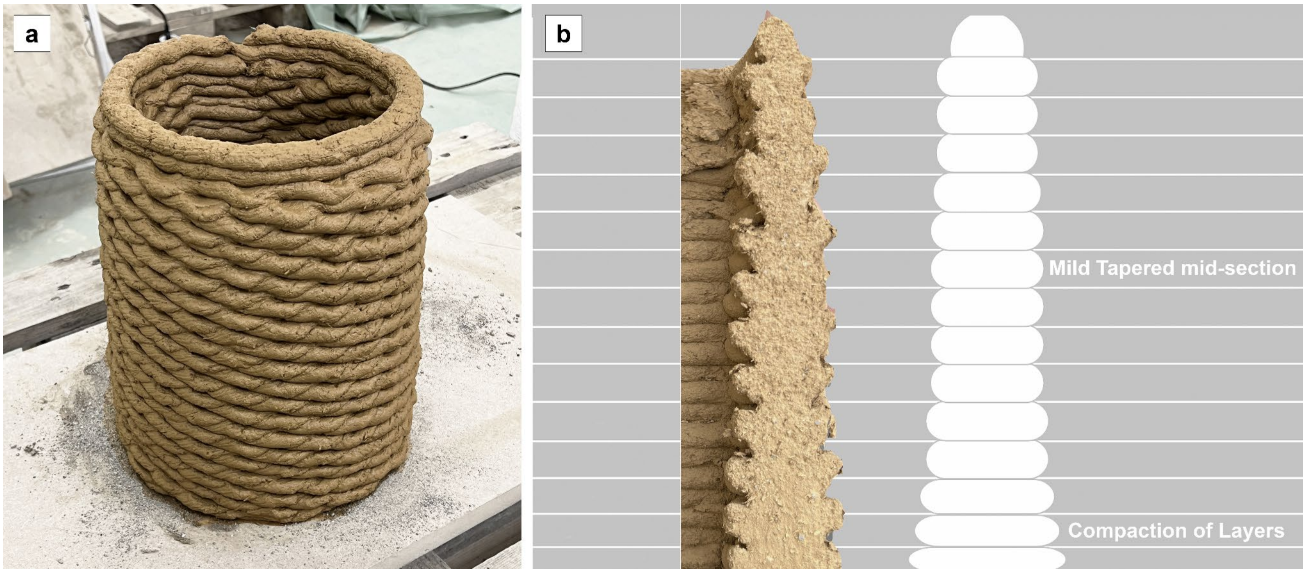

Fig. 3 **a** 200 × 300 mm earth formwork using Earth Mix A. **b** Wall cross-section for formwork showing bottom layers progressively compacting as the printing builds up more layers. The top layer always results 5 mm thinner than the initial base layer

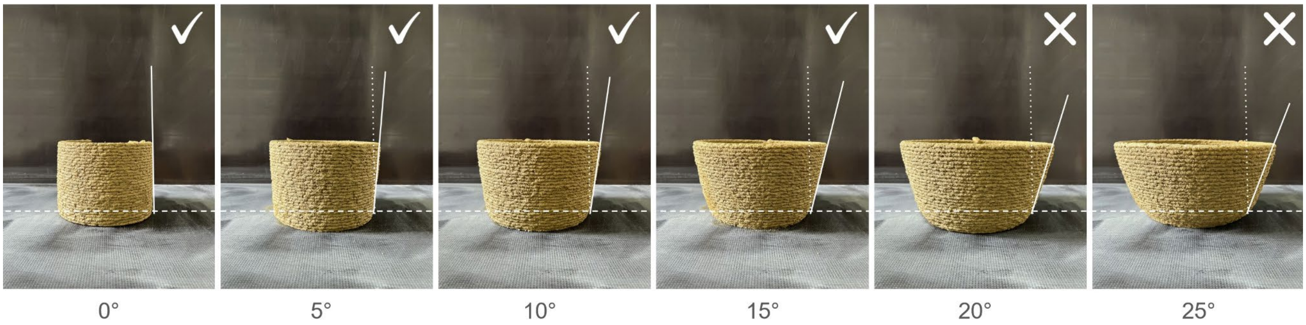

Fig. 4 Overhang limit tests for cylindrical samples were conducted for angles 0°–25°. Instability is visible at 15° owing to the downward displacement of layers

the geometric limits of the material, and were later used to inform the design of the final demonstrator in Sect. 4.3.2.

A preliminary cast test using two dry-state earth formworks measuring 200 × 300 mm stacked upon each other was conducted to empirically assess earth-concrete bonding using the SCC-MS concrete mix, as specified in Sect. 3.4. The formwork was left to dry for 72 h before casting and an additional 24 h after casting. No visible cracking in the formwork was observed after curing. The earth formwork was visibly more humid after concrete curing and was found to have increased moisture content, measuring an average humidity of 60% at three different points and suggesting an absorption of water from the concrete mixture. The 600 mm high cylindrical formwork was manually removed over a three-hour period using running water and hand scrubbing. The extended demoulding time underscores the robustness of the concrete's adhesion to the dry earth and the problem of reusing the formwork. The finished result is illustrated in Fig. 5. Demoulded formwork pieces also exhibited traces of a thin concrete layer (see Fig. 5c), suggesting a rapid drying reaction at the interface.

4.1.3 Prototype P1-dry-state formwork

Following preliminary tests, a first-column prototype (P1) using the same Earth Mix A and SCC-MS was used to print and cast a 1.5 m column using dry-state formwork. The prototype attempted to identify casting height limitations caused by the increasing hydrostatic pressure during pouring. Five cylindrical formworks measuring 200 × 300 mm were stacked and cast sequentially, as shown in Fig. 6. The maximum possible height for casting was reached without any visible cracking in the

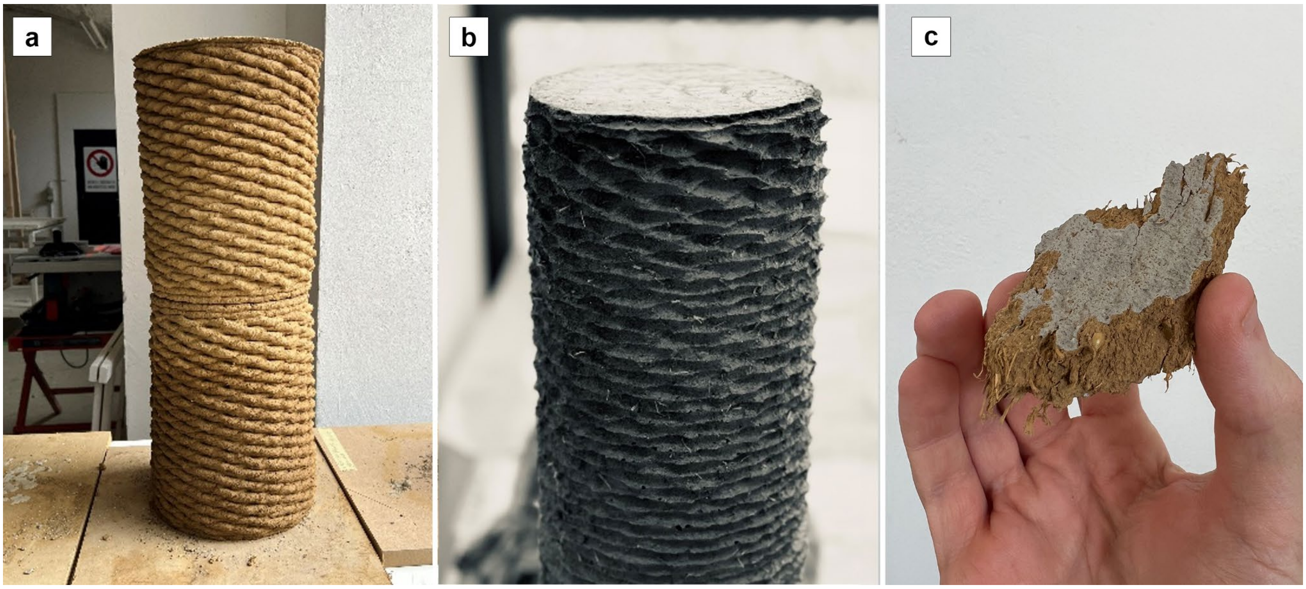

Fig. 5 **a** Assembled Earth formwork in dry state, **b** Demoulded concrete sample, **c** A thin layer of concrete remains attached to the fully-dry demoulded formwork

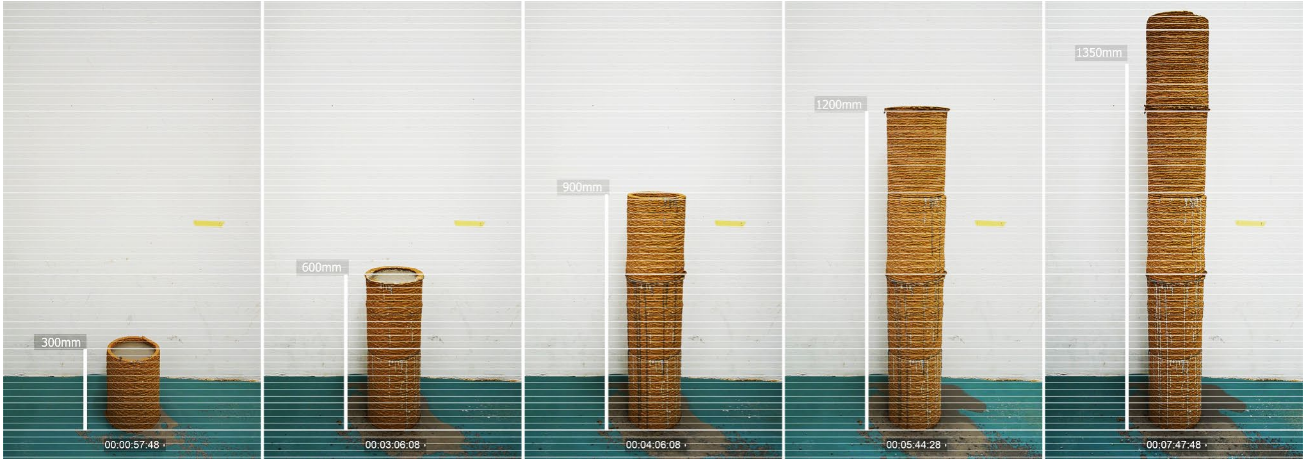

Fig. 6 Incremental assembly and casting of prototype P1

formwork, suggesting that 16 mm printed formwork walls are sufficient for the given casting volume.

Leaking was frequently observed at the junction between parts due to surface imperfections preventing a proper seal. These leaks persisted for 30 s while casting until the concrete was observed to visibly seal the gaps, presumably due to the same setting reaction highlighted in the previous casting test. Demoulding difficulties persisted in the prototype, requiring water-jetting to remove the earth from its concrete core.

4.2 Prototyping for plastic-state formworks with set-on-demand concrete

As highlighted in Sect. 4.1.2, the current Earth Mix A exhibited a maximum reliable build height of 350 mm during robotic printing, creating the need for pre-fabricating dry-state formworks in segments. A continuous print-cast process involving a set-on-demand concrete (SCC-ACC), as specified in Sect. 3.4, was investigated to explore the potential for printing and casting higher structures. Several physical experiments were conducted and later validated through a second-column prototype (P2) in Munich to find the correct cast and print rates.

4.2.1 Prototype 2-plastic-state formwork

The goal of Prototype P2 was to demonstrate that the buildability can surpass the 350 mm build height achieved in P1 for printed earth formworks. Again, a cylindrical column, with a circular cross-section measuring 200 mm in diameter and a height of 1000 mm, was aimed. Since automating the casting process was not feasible for this experiment, the SCC – ACC mix had to be manually cast. To reach the desired height, 11 batches of the accelerated concrete were poured in intervals of 15 min while the robots continuously printed the earth formwork. Each interval resulted in an approximately 900 mm increase in height due to the density of the mix used. The column was printed and cast over three hours without any collapse of the earth formwork throughout the process. Visible lateral deformations to the formwork were observed during casting. These primarily occurred between casting intervals and caused visible cross-section variations along the height. After completion, the prototype was left to dry for 24 h, during which 3–5 mm cracks became visible on the earth formwork. The cracks facilitated the demoulding process, which could be easily managed using a chisel and hands within 10 min, resulting in a demolding time 18 times faster compared to P1.

The demoulded concrete column displayed clear horizontal divisions, corresponding to the individual casting intervals seen in Fig. 7c. Such divisions are visually undesirable and indicate cold joints within the concrete. After conducting a series of tests (not detailed in this paper), we aimed to determine the optimal casting intervals. The ultimate casting interval of 5 min resulted in fewer visible connections.

4.3 Full-scale demonstrator

Expanding on the now validated print-cast workflow used in P2, a complex 2 m reinforced concrete column could be developed using plastic-state earth formwork. The primary focus was to evaluate the feasibility of simultaneous actions (printing and casting around reinforcement) in this process. The experiment, conducted in Munich, utilises a dual mobile robotic system enhanced with a vertically mounted linear axis. This was necessary to circumvent the limited build space of a single robot due to the reinforcement cage at the formwork`s centre. The robots worked collaboratively on each print layer throughout production, synchronising their movements. Together, they covered the required build volume for this experiment, as depicted in Fig. 8.

4.3.1 Earth mix optimisations for final production

Extrudability challenges were encountered when attempting to replicate Earth Mix A using the proposed hardware setup for the full-scale demonstrator. The mixture was too stiff to

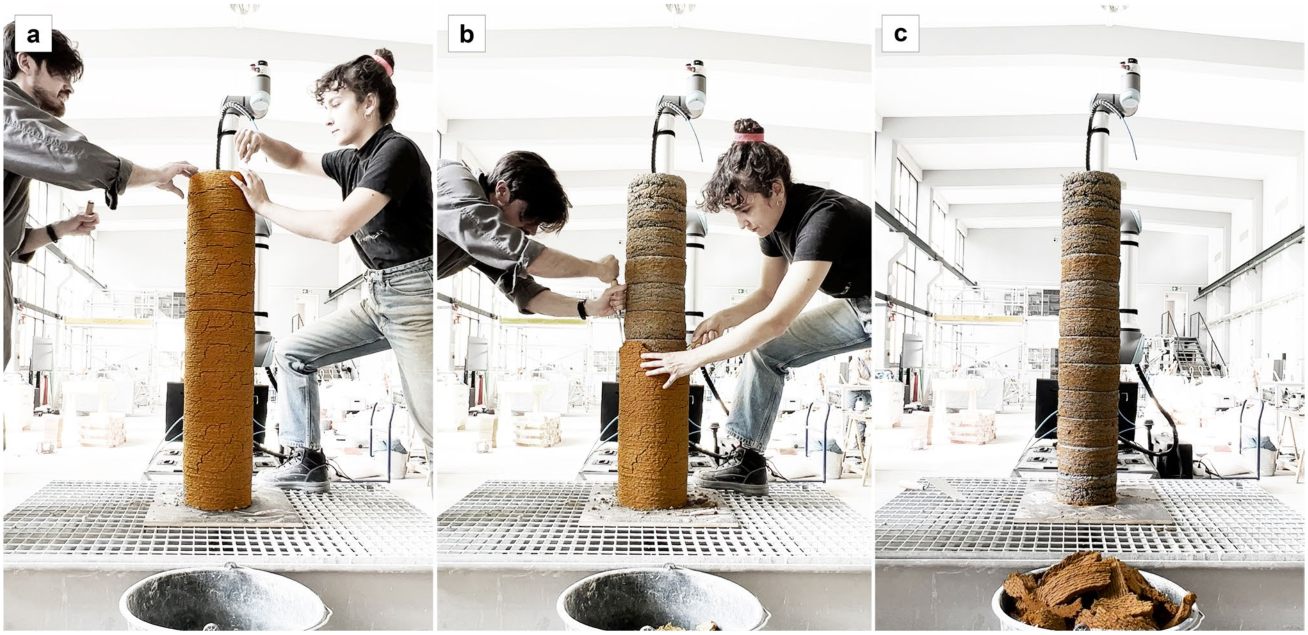

Fig. 7 Demoulding sequence of Prototype P2. **a, b** shows manual formwork removal in process, **c** shows finished result displaying horizontal divisions corresponding to casting intervals

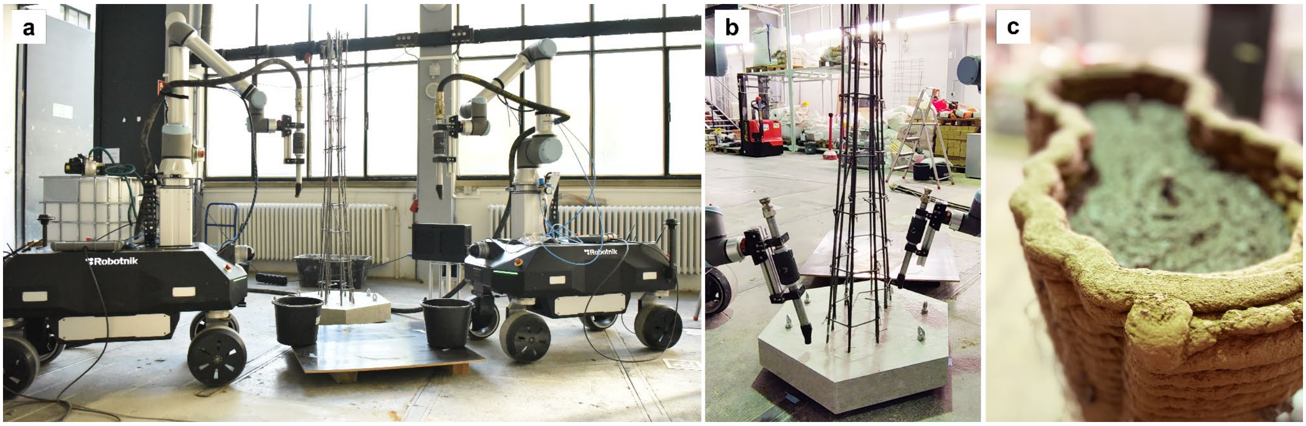

Fig. 8 **a**, **b** Dry-run for dual Robot Setup printing around reinforcement cage, **c** Cast earthen formwork

extrude, requiring a redesign of the clay mixture. Consequently, the specified slump value had to be tailored to meet the pumpability requirements of the pumping system, now fitted with a 25 mm diameter dual hose system, each 10 m long. The revised target slump was set at 140 mm ± 5 mm. To achieve this new slump target, various changes had to be made to the mix design's water, sand and fibre content. The water content can be increased, or the volume of sand or fibres would have to be reduced. The second formulation, Earth Mix B, also aimed to improve the green strength of the mix. Therefore, a plasticiser was added to increase the workability/slump value of the mix. The sand ratio was also increased, adding green strength to the mix. This mixture, with a slump of 143 mm, consisted of a water-to-clay (w/c) ratio of 0.53, a sand-to-paste volume ratio (Vs/Vp) of 0.72, 2.00% fibres of the clay mass, and 0.3% plasticiser of the clay mass. This mix was reproduced in Munich and received a similar slump of 144 mm.

4.3.2 Column geometry

We designed a complex column geometry to explore the capabilities of the 3D printing formwork workflow. This approach leveraged the geometric freedom provided by printing, allowing for the creation of overhangs and scaling, all while being printed around a reinforcement cage. Maximum overhangs were kept within the 15° limit established in Sect. 4.1.2 as a conservative estimate. The path length and cast volume per layer have also changed due to varying column cross-sections. Ideally, adjusting the batch size, print velocity, and pump speed throughout maintains a steady build rate. However, this study opts to maintain constant batch size and print speed since this complexity was not feasible through manual casting. The print path was designed as an oscillating pattern with alternating joint locations to create 30 mm thick walls to ensure stable layer-by-layer construction and robust bonding between formwork segments. Segments of the print path guided by the robots' reach formed an interlocking pattern inspired by timber finger-jointing techniques. This AM finger joint method yielded a near-seamless formwork, minimising the break between segments. As illustrated in Fig. 9, both robots´vertical axes were repositioned four times, every 500 mm, to print the column.

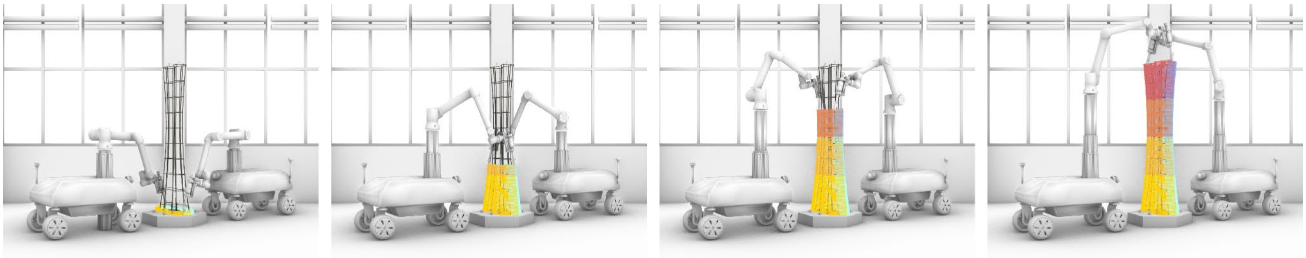

Fig. 9 Sequence of formwork fabrication, using two robots to print from opposite sides with finger joints created in the shared workspace. Colours indicate the four segments that correspond to the discrete vertical linear axis positions

4.3.3 Print-cast process calibrations and outcome

To synchronise the automated print buildup of earth mix B with the casting process and the curing of the concrete, several fabrication parameters had to be taken into account. For casting, three batches of concrete 100 L (SCC-ACC) were prepared and divided into 27 accelerated batches, cast in an average of 5-min intervals. Respecting these values, the following corresponding variables were used: a pump rate of 0.3 L/min, print velocity (movement of the robot) of 14 mm/s, layer height of 8 mm, 8 L of accelerated concrete was cast for every 8 cm in formwork height. Overall fabrication lasted 8 h, with 5 h dedicated solely to printing. To produce the 2 m-tall formwork, 76 L of earth mix was used for an overall print length of 430 m. After completion, the structure underwent a 2-week drying and curing period, revealing crack formations similar to those observed in P2. Manual demoulding occurred within a timeframe of 20 min and is comparable to that of P2. The end result, before and after demoulding, together with tactile effects of printing can be seen in Fig. 10. Deviations between digital and printed formwork were recorded at visible points of lateral deformation. Largest deviations occurred at the base due to partial buckling on one side, resulting in a lateral deflection of 5 cm. Deflections in all other areas averaged out at 10-15 cm.

5 Discussion

This section is divided into two parts. The first outlines the project's contributions in terms of material and fabrication strategy. The second presents a qualitative comparison between the potentials, limitations and architectural effects of dry-state and plastic-state formworks.

5.1 Contributions

Through the collaborative efforts of members from USI Accademia di Architettura and the Technical Universities of Munich and Braunschweig, the following contributions to the field of alternative formworks for concrete were possible:

1. Creating a robust earth mix with reduced shrinkage and enhanced green strength for stable and easily-built 3D printed formworks.
2. Establishing a slump test process and standard for a printable mix compatible with various rotary pump setups and hydraulic hoses.
3. Exploring the effects of earthen formworks on concrete casting, both in dry and plastic states for structural elements.
4. Confirming the viability of rotary pump setups for 3D printing earthen formworks to address the current challenges in the state-of-the-art research.

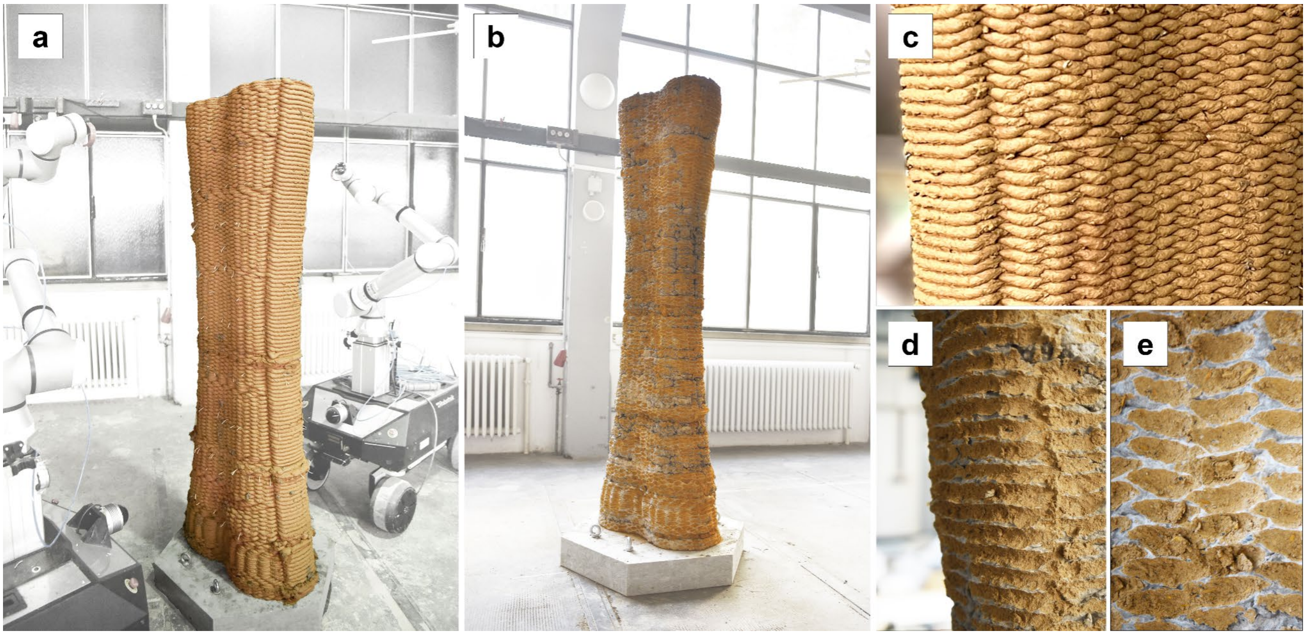

Fig. 10 **a** Completed formwork in plastic state, **b** demoulded column demonstrator, **c**, **d**, **e** Impressions of formwork and demoulded finishings

5.2 Formwork qualitative comparison

This research effectively showcased a method to create a pumpable and buildable (printable) mix across various geographic locations, navigating multiple variables. The printability of earthen mixtures, comprising clay, sand, fibres, and a plasticizer, was investigated for dry and wet formwork and standard and set-on-demand casting processes. By sourcing materials from different locations in Germany and Switzerland, adapting the concrete slump test for earthen mixtures proved crucial in ensuring proper pumpability. Moreover, the consistent correlations between the slump value and print quality attest to this method`s high degree of robustness in guaranteeing printable mixes for rotary pump setups. The slump test's effectiveness was evaluated using only Conluto clay. Future research should also assess its further robustness through different clay constituents.

5.2.1 Stay-in-place dry-state formworks

The two explored formwork strategies uniquely possess very different benefits and hindrances towards the efficient production of a column at an architectural scale. The initial tests and prototype for dry state formwork strategy validated the feasibility of printing formwork in segments that can be handled once dry. In contrast to the plastic-state strategy, no visible cracking was observed after casting due to the parts having already undergone shrinkage before pouring concrete. This makes this strategy ideal to use the earth as a stay-in-place formwork with concrete, potentially providing other functional and architectural benefits. This strategy is also less fabrication intensive as it does not rely on the simultaneous print-cast process used in the latter, making it less sensitive to the setting rate of the concrete, as seen with the set-on-demand mixture. Limitations here exist concerning the visual continuity of the geometry, where joints between the segmented parts are visible in both formwork and concrete if demoulded. Minor deformations during printing were present owing to slight vertical compaction of the lower layers, suggesting limitations in stiffness within the current earth mix recipe. This deformation was still present but far less visible in the final demonstrator due to the addition of the plasticiser, which improved green strength.

5.2.2 Removable plastic-state formworks

The current state-of-the-art revealed that the earth's buildability rate (rheology) mostly influences the time limitations of the printing process, the material-feed rate of the extrusion setup and the print-path length of the formwork for a given layer. For plastic-state formworks, the final demonstrator`s 8-h completion time proves that a more rapid production process for full-scale concrete components using earth formworks is possible. In contrast to the three state-of-the-art projects described in Sect. 2.1, the addition of sand, fibres and plasticiser proved crucial in enabling faster printing rates in all experiments. While deformation is commented upon in previous projects, a lack of quantitative data makes it difficult to benchmark our previously declared mean deformations of 10–15 mm fall relative to other work. Nonetheless, it is expected that lower layer heights can minimise this value further, at the cost of extending the print time. Table 4 below summarises and compares the distinct setups for the state-of-the-art and this research.

Further geometric restrictions exist where the initial hydrostatic pressure of the set-on-demand concrete still

Table 4 Comparative assessment between state-of-the-art projects described in Sect. 2 and final results and parameters for final demonstrator in this research

	"Clay robotics" by Wang et al. (2019)	"Cocoon" by Bruce et al. (2022)	"Clay formworks" by Dielemans et al. (2022)	"Earth-Concrete column" by Authors
Print mix	Terracotta clay (35–40%)	Terracotta clay (unspecified)	Stoneware clay (unspecified)	Clay loam with sand, fibres, plasticiser
Cast mix	Cement Mortar	Acceler. GFRC (1.7%)	SCC + superplasticizer	SCC + 0.3% superplasticizer
Reinforcement	no	Glass fibre in mix	Steel Cage	Steel Cage
Setup	External ram pump with robot, 6 DOF	Integrated ram pump on robot, 6 DOF	Integrated ram pump on robot, 7 DOF	Rotary pump, D4-2 Rotor–stator, dual robot, 7 DOF
Total height (mm)	1400 × 300⌀	1300 × 200⌀	2000 × 500⌀	2000 × 600⌀
Layer height (mm)	1–3	1	5	8
Wall thickness (mm)	20	Unspecified	25	25
Supports	No	Yes	Yes	No
Production time	Unspecified	9 h	2 weeks	8 h

The project achieved 2 m buildup in 8 h due to a fast print-rate afforded by the strengthened earth mix B and rapid setting rate of the SCC mix enabling further buildability causes small deformation upon immediate casting. Geometric flexibility for both dry-state and plastic-state earth formworks also requires further investigation, particularly in correlating casting rates for set-on-demand concrete mixtures. Initial explorations with the final demonstrator already indicate a greater tendency for sloped formwork walls to deform due to variable cross-sections along the height, as evidenced by largest deformation occurring towards the base.

5.2.3 Further material development and sustainability potential

Improvements may be needed for the set-on-demand mixture, which showed inconsistent quality in both P2 and the final demonstrator due to its high viscosity, causing gaps and pockets against the earthen formwork's textured walls. The presence of reinforcement heightens the urgency for a more fluid mix to ensure proper concrete flow and adhesion to the steel. Manual casting may also be responsible for these imprecisions, emphasising the need for an automatic feed system with variable flow rates to enhance process feasibility and quality. Research on deflocculants to mitigate earthen mix vibration in the pump would also contribute to overall automation efficiency.

The use of earth as formwork in this research is more broadly driven by a need for a low-energy and highly reusable material for producing complex and material-efficient geometries. The designed earth mixtures A and B were however produced with the goal of improving fabrication efficiency. A follow-up to this research is thus required to understand to what extent these new optimised mixtures preserve or compromise the reusability of the printed earth for further formwork production. Natural alternatives to the current synthetic plasticiser also merit investigation, whereas cementitious contamination of the demoulded earth formwork requires proper examination in how it affects material properties after single or multiple reprocessings.

5.2.4 Architectural potential

Architecturally, both sequential and simultaneous print-cast strategies for removable-earth formworks possess a unique tectonic expression. With dry-state formworks, the bonding, assessed via P1, indicated serious difficulty in demoulding the earth from the concrete. Conversely, P2 and the final column demonstrator still exhibited a self-demoulding effect in line with the state-of-the-art projects despite the mix design's reduced shrinkage behaviour. This implies that while the latter strategy is better suited to exposing the patterned concrete as an architectural finish, the former can more reliably utilise the earth as an active component within the structure. This bears unique design potential for building with earth formworks and expressing them in different ways as well as merits investigation into potential passive effects provided by stay-in-place earth moulds such as moisture and thermal control.

6 Outlook

This research project showcased the progress in scaling up earth formworks at the architectural level to meet the needs of modern construction in terms of form complexity and speed. It also highlighted the potency of digital fabrication in sharing and synthesising knowledge across different institutions. The various prototypes and full-scale demonstrators establish that earthen materials have a high potential for upscaling complex formworks for concrete, particularly when mixtures can be robustly synchronised to available equipment. Addressing the limitations outlined in the discussion section becomes crucial to provide a more accurate assessment of the circularity of earth formworks. Here, too, lie the next steps, namely qualifying earth-concrete bonding on a chemical level, conducting a full quantitative structural assessment of the resulting building elements and mapping the design space for what is possible with 3D-printed earth. Only in doing so can earth materials continue to expand their utility as formworks and potentially beyond, as self-supporting earth structures, to provide tangible answers for sustainable construction.

Author contributions All authors contributed to the study conception and design. Material preparation, prototyping, data collection, analysis and initial drafts for this manuscript were prepared by Sacha Cutajar, Gido Dielemans, Ema Krakovska and Evelien Dorresteijn, while corrections and changes were handled by Sacha Cutajar and reviewed by Ena Lloret-Fritschi as corresponding authors.

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Data availability Additional data supporting the findings of this study are available on request from the corresponding author: Sacha Cutajar.

Declarations

Conflict of interest The authors of this paper declare no conflict of interest.

References

Joris B, Lloret-Fritschi E, Scotto F, Demoulin T, Gebhard L, Mata-Falcón J, Gramazio F, Kohler M, Flatt RJ (2020) Eggshell: Ultra-Thin Three-Dimensional Printed Formwork for Concrete Structures. Printing and Additive Manufacturing 7(2):48–59. https://doi.org/10.1089/3dp.2019.0197

Burry J, Sabin J, Sheil B, Skavaram M, Fratello VS, Rael R (2020) Mud frontiers. In: Fabricate 2020: making resilient architecture. UCL Press, pp 22–27. https://www.uclpress.co.uk/products/154646

Bruce M, Gabrielle C, Ruxin X, Salma M, Arash A (2022) Cocoon: 3D printed clay formwork for concrete casting. https://deepblue.lib.umich.edu/handle/2027.42/176006. Accessed 13 May 2023

Dielemans G, Lukas L, Tobias R, Lidia A, Christian H, Carla M, Annika R, Kathrin D (2022) Mobile additive manufacturing: a case study of clay formwork for bespoke in situ concrete construction. In: Third RILEM international conference on concrete and digital fabrication, Digital Concrete 2022, pp 15–21

Giada G, Caponetto R, Nocera F (2019) Hygrothermal properties of raw earth materials: a literature review. Sustainability 11(19):5342. https://doi.org/10.3390/su11195342

Gomaa M, Jabi W, Reyes AV, Soebarto V (2021) 3D printing system for earth-based construction: case study of cob. Autom Constr 124:103577. https://doi.org/10.1016/j.autcon.2021.103577

IAAC. n.d. 'IAAC Builds TOVA: Spain's First 3D Printed Prototype Using Earth' *IAAC* (blog). https://iaac.net/project/3dpa-prototype-2022/. Accessed 10 Jan 2024

Jipa A, Dillenburger B (2022) 3D Printed formwork for concrete: state-of-the-art opportunities challenges and applications. 3D Print Addit Manuf. https://doi.org/10.1089/3dp.2021.0024

Lloret-Fritschi E, Wangler T, Gebhard L, Mata-Falcón J, Mantellato S, Scotto F, Burger J et al (2020) From smart dynamic casting to a growing family of digital casting systems. Cem Concr Res 134:106071. https://doi.org/10.1016/j.cemconres.2020.106071

Lloret-Fritschi E, Quadranti E, Scotto F, Fuhrimann L, Demoulin T, Mantellato S, Unteregger L et al (2022) Additive digital casting: from lab to industry. Materials 15(10):3468. https://doi.org/10.3390/ma15103468

Lloret-Fritschi, Ena, Fabio Scotto, Fabio Gramazio, Matthias Kohler, Konrad Graser, Timothy Wangler, Lex Reiter, Robert J. Flatt, and Jaime Mata-Falcón. 2019. 'Challenges of Real-Scale Production with Smart Dynamic Casting'. In: Timothy Wangler, Robert J. Flatt (ed) First RILEM International Conference on Concrete and Digital Fabrication—Digital Concrete 2018. RILEM Book series. Springer International Publishing, Cham, pp 299–310

Lootens D, Jousset P, Letitia Martinie N, Roussel, and Robert J. Flatt. (2009) Yield stress during setting of cement pastes from penetration tests. Cem Concr Res 39(5):401–408. https://doi.org/10.1016/j.cemconres.2009.01.012

Perrot A, Rangeard D, Courteille E (2018) 3D printing of earth-based materials: processing aspects. Constr Build Mater 172:670–676. https://doi.org/10.1016/j.conbuildmat.2018.04.017

Wang S, Stylianos D, Philippe M, Ho K (2017) Clay robotics: a hybrid 3D printing casting process. In: Challenges for technology innovation: an agenda for the future. CRC Press, pp 83–88. https://doi.org/10.1201/9781315198101-20

Wang S, Zack XC, Felix R (2019) Optimization of clay mould for concrete casting using design of experiments. In: Intelligent & informed, Proceedings of the 24th international conference of the association for computer-aided architectural design research in Asia (CAADRIA), vol 2, pp 283–292

Youssef M, Abbas Lena (2023) Applying 3d printing technology in constructing sustainable houses. Archit Plan J (APJ). https://doi.org/10.54729/2789-8547.1190