3D CONCRETE PRINTING SIMULATING DEVICE IN COMPARISON TO REAL PRINTING AND AGGREGATE SUBSTITUTES

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Abstract

3D concrete printing appears to be a promising way to reduce costs, time and environmental impact. However, this technology is very dependent on the material used. When testing new materials on robotic printing, large amount of material is needed, and the preparation process is complex. For this purpose, a device was developed at BUT FME, enabling simplified printing. Comparative study needs to be performed to verify sufficient similarity between the results of simplified and real printing.

Keywords

3D concrete printing, manufacturing simulating device, mixture development, filler and aggregate substitutes

1 INTRODUCTION

Nowadays, emission production across industries is under scrutiny. Construction industry, with cement production responsible for around tenth of CO_2 emissions [1] is no exception. Besides developing new more environmental friendly materials, different manufacturing methods are developed to lower material consumption. Across materials used, additive manufacturing (AM) appears quite promising. The concept of AM, sometimes called 3D printing, is based on layerwise adding of material and comes from 1940s. Generally, AM allows lowering material consumption and enabling manufacturing of complex shapes from various materials (plastic, metals etc.). With development and expansion of robotics in recent years, AM in form of 3D concrete printing (3DCP) has also seeped into the construction industry.

3D concrete printing

While dealing with concrete printing (and in most cases AM generally), multiple manufacturing systems can be distinguished. Each system has its own advantages and disadvantages, mostly coming from its operating field and sub system complexity, e.g. some robotic arms are widely used across industries, and have large manufacturer support [2]. Most often, gantry (or frame) and robotic arm 3D printers can be seen. At Brno University of Technology, KUKA robot is used for experimental printing with M-tec Duomix 2000 mixing pump (see Fig. 1).

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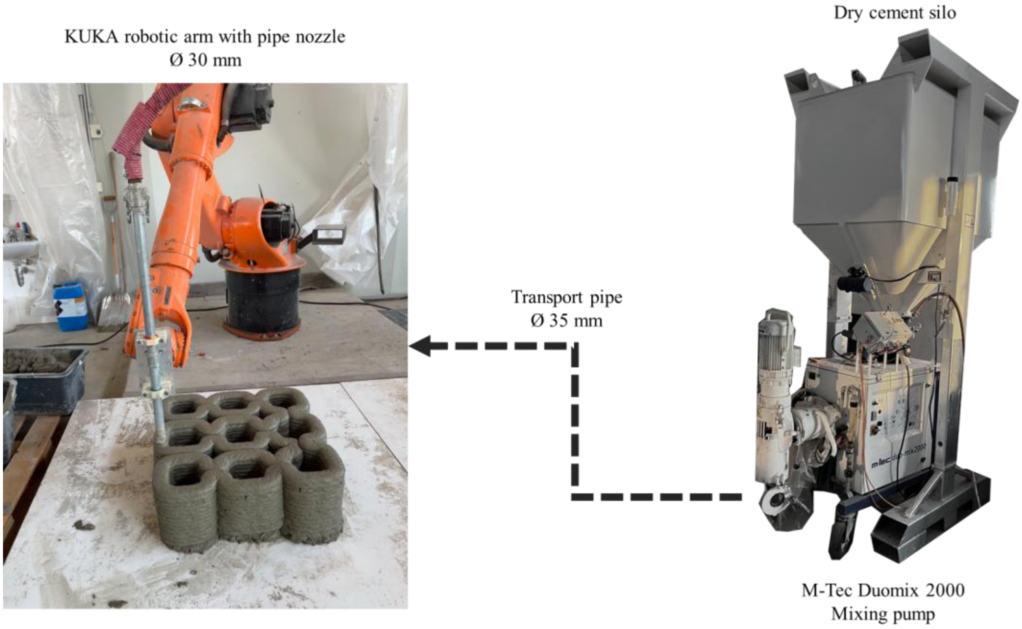

Fig. 1 Manufacturing chain for robotic 3D printing.

Even though 3DCP promise lowering human labour and manufacturing time, this approach seems too complex during experimental print. Thus, for experiments based on printing, such as material composition, it is not a suitable experimental method. Because of large-scale manufacturing pumps and pipes, each new composition test requires preparation of large volume of material. Thus, in contemporary literature, experimental devices in different scale can be encountered, varying from smaller than usual [3], [4] to almost desktop scale printers [5].

Conventional materials

The concrete mixture consists of several parts. This is a binder part, most often Portland cement, and a filler of a given fraction, e.g. sand or other aggregates. This mixture, when mixed with water, creates a slurry that sets and subsequently hardens due to the hydration of the cement. Furthermore, several additives are required (not only) in 3DCP to achieve ideal properties of fresh and hardened material. Commonly evaluated properties of such mixture are:

- pumpability - ability of material to be pumped (suitable rheology and flowability),
- printability – ability of material to be continuously printed,
- buildability – ability of material to support weight of following layers,
- open time – time interval, in which can bond between layers develop,
- setting time – time, in which concrete hardened.

For modifying mentioned properties, setting time modifiers, polymer additives, additives limiting shrinkage and rheological properties, etc. are used. Fresh and hardened concrete properties are further dependent on print parameters (nozzle speed, amount of material, print strategy, time gap between layers).

Generally, 3DCP can reduce construction waste and material (concrete) consumption. Still, an important disadvantage of 3DCP can’t be neglected. Compared to the conventional casting method, it requires more cement to ensure proper extrudability and printing [6]. Thus, efforts can be observed to replace the above-mentioned dry ingredients, i.e. binder and filler, to improve environmental and economical balance of such build.

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Substitute materials

Binder substitutes (SBM, SCM)

Talking about binder substituting, so called substitute cementitious materials (SCMs) can partially replace Portland cement (marked CEM I). SCMs are mainly wastes from the metallurgical industry, such as silica fume, slag and fly ash, and are considered an important part in chain for lowering environmental impact of cementitious mixtures [7] . Mixtures, with SCMs are the marked as Portland mixed cement (CEM II).

Filler and aggregate substitutes (SFM, SAM)

Concrete filler is usually aggregate of multiple types. Aggregates can be divided according to their fraction (fine, coarse), origin (natural, artificial), and type. It should be noted that following and later used SFM have variable fraction.

Recycled brick aggregate

The brick recycled aggregate used in this paper was a recycled material obtained from construction waste and demolition debris. Initially, this material was processed using a jaw crusher, one of the most common devices for crushing construction materials. Jaw crushers operate on the principle of compressing the material between a fixed and a movable jaw, which allows for the efficient crushing of concrete pieces into smaller fragments. After crushing, the recycled aggregate was sieved through a screen with a 2 mm mesh size. This process separated finer particles from larger fragments and debris present in the recycled material, such as remnants of foil, wood, paper, and wires. The result was a material with a more uniform grain size, suitable for further use, for example, as a substitute for natural aggregate in construction mixtures. Subsequently, a sieve analysis was performed on the obtained aggregate to determine the grain size distribution curve.

The use of brick recycled aggregate in 3D printing offers several advantages. These include environmental sustainability, cost reduction, and easy availability. The low density of brick recycled aggregate contributes to lighter structures, while its good thermal insulation properties enhance the energy efficiency of buildings. The disadvantages include lower strength and inconsistent material quality, which can affect the properties of the final products. High water absorption can reduce the workability and strength of the mixture [8]. Additionally, brick recycled aggregate may be less resistant to frost and weather conditions and could contain contaminants.

Fly ash

The fly ash used in this paper, sourced from the Tušimice power plant, is a byproduct of coal combustion. It shows significant potential in construction, especially as an additive in concrete mixtures to enhance properties.

Using fly ash as a partial replacement for aggregate in 3D concrete printing offers several advantages. It is cost-effective, helps reduce waste, and lowers the carbon footprint of concrete production. It improves the rheology and pumpability of the mix, essential for 3D printing precision. By replacing natural aggregates, fly ash also supports resource conservation and sustainable construction practices.

It should be noted, that fly ash can be also used as SCM (see chapter Binder substitutes).

Bio char

Dried sewage sludge from the Brno-Modřice wastewater treatment plant was used for the production of biochar. The sewage sludge was dried using a contact paddle dryer at a temperature below 100°C. The dry matter content of the sample before pyrolysis reached 90.69%.

Subsequently, the production of pellets from the dried sewage sludge was carried out using a pelletizing press. The prepared pellets were further processed in a small laboratory unit for medium-temperature thermal pyrolysis at 600°C, operated at the AdMaS research centre. The specific density was 1.91 g/cm³.

The pellets were then ground using a planetary mill. After grinding, the material was sieved through a 0.063 mm mesh screen to achieve the required fineness.

Waste foundry sand

The foundry sand from ArcelorMittal used in this study is bonded with sodium silicate, which enhances its strength and durability. Sodium silicate, known for its adhesive properties, improves the cohesion between sand grains, resulting in a strong and stable material suitable for various industrial applications. The foundry sand is supplied in larger solidified clusters, which must be mechanically crushed into individual sand grains and subsequently sieved using a 2 mm mesh screen.

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2 METHODOLOGY

Test equipment

In this study, influence of supplementary filler materials (SFM) should be investigated. As mentioned in section “3D concrete printing” above, using full scale 3DCP robotic arm is not effective. Thus, new small-scale device called “3DCP tray” was developed at BUT, Faculty of Mechanical Engineering, as shown at Fig. 2.

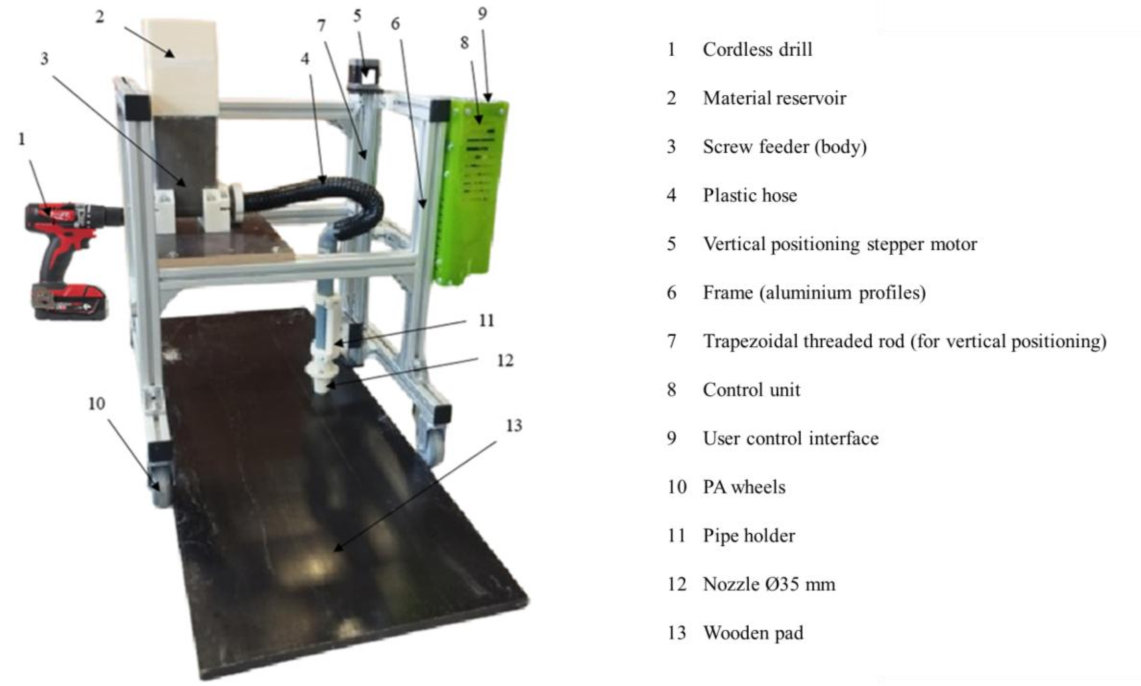

Fig. 2 Concrete printing (3DCP) simulating tray.

Before testing new mixtures, 3DCP tray must be validated, using reference mixture (see section “Conventional materials”). Because new mixtures will be validated based on layer bond strength of hardened material, reference mixture will be subjected to uniaxial tensile strength, using samples cut out from 3DCP tray and robotic arm manufactured walls, after 28-day setting on room temperature and air humidity.

Reference mixture

Mixed Portland cement was therefore used as a silicate binder, namely the CEMII/B-M(S-LL) 32.5 R from Českomoravský cement, a.s. (Mokrá production plant). Mineral composition testing via X-ray powder diffraction (XRD) identified as main minerals alite (C_3S), belite (C_2S), ferrite (C_4AF), aluminate (C_3A), calcite ($CaCO_3$) and gypsum ($CaSO_4 \cdot 2H_2O$).

As filler, siliceous sand of fraction 0 – 1 mm marked PR 31 and sand of fraction 1 – 2 mm marked PR 1/2 (Provodín sands) were chosen. Fine quartz powder ST2 (manufacturer Sklopísek Střeleč) has been chosen to complement the grain size curves.

To optimize mixture properties, multiple modificators were added. Superplasticizer based on ether polycarboxylate Peramin CONPAC 500 in combination with an anti-foaming agent AGITAN P 8850, were used to reduce w/c coefficient and to increase the physical-mechanical properties. Styrene acrylate-based compound with the designation NEXIVA CT 714, as polymer additive was added to optimize the utility properties of final material, and rheology was modified by methylcellulose-based material Tylose MH 6000 YP4.

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Substitute materials mixtures

Based on previous set of experiments, 4 mixtures with SFMs were chosen for this paper, to further investigate their suitability for 3DCP. Dry mixtures were prepared as follows:

Tab. 1 Raw materials used for 1000 g of dry mixture.

	RBA 30	FA 10	WFS 50	BCH 3
Cement CEM II	350.0	350.0	350.0	350.0
Sand PR 31/30	311.2	389.0	194.5	389.0
Sand PR 1-2	128.8	161.0	80.5	161.0
Fine quartz powder	78.1	32.9	48.8	78.1
Recycled brick aggregate	129.5	-	-	-
Fly ash	-	64.8	-	-
Waste foundry sand	-	-	323.5	-
Biochar	-	-	-	19.4
Superplasticizer	0.35	0.35	0.35	0.35
Defoaming agent	2.0	2.0	2.0	2.0
Polymer admixture (EVA)	5.0	5.0	5.0	5.0
Biopolymer admixture	0.1	0.1	0.1	0.1

The following symbols explain the coding system of the mix formulations. The letters indicate the material replacing the aggregate in the mix (Tab. 2). The number that follows represents the percentage of aggregate replacement, considering the particle size distribution curves.

Tab. 2 Mixture abbreviation description.

Abbreviation	Meaning
RBA	Recycled brick aggregate
FA	Fly ash
WFS	Waste foundry sand
BCH	Biochar

The raw materials for the production of prism specimens were weighed on a scale with an accuracy of 0.01 kg. The weighed dry mix was then homogenized in a small mixer for 3 minutes to achieve a uniform distribution of all particles within the mixture. Water was added until the required consistency was reached. One minute after the first contact with water, mixing was paused to scrape off any dry mix sticking to the walls of the mixing bowl, contributing to proper homogenization. The mixing process then continued for an additional two minutes.

3 RESULTS

3DCP tray validation

First step should be validating experimental approach. As mentioned in section methodology, 3DCP simulating tray was used for sample preparation. Because interlayer bond strength is the main characteristic in following experiments, values of bond strength of samples prepared on robotic arm and tray were compared (see Fig. 3).

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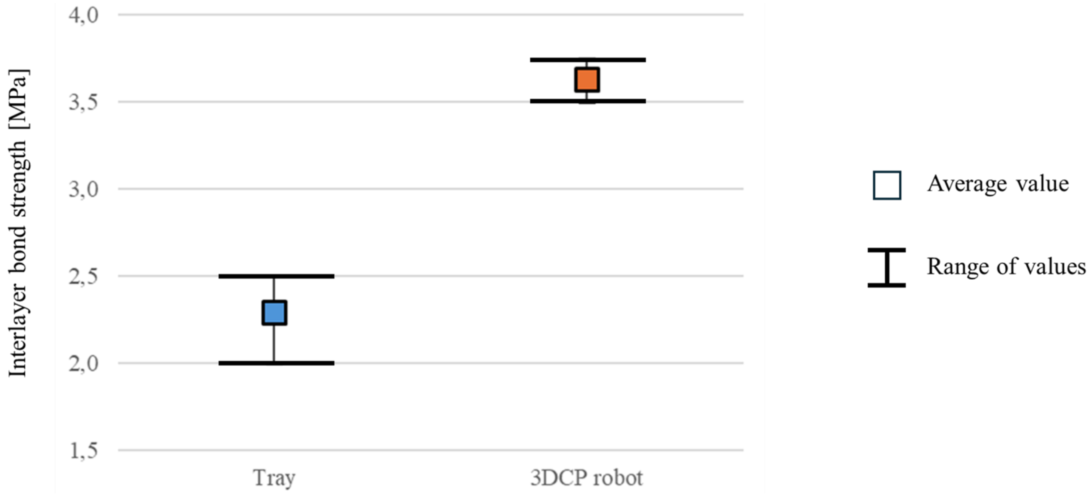

Fig. 3 Bond strength of samples from tray compared to robotic arm.

Displayed values are average from samples with dimensions 40 × 40 × 40 mm subjected to uniaxial tensile strength, after 28-day curing.

Supplementary filler materials

Because SFMs are known to modify w/c ratio, amount of water leading to similar consistency for each mixture was pre-determined in laboratory, leading to similar consistency (see Fig. 4).

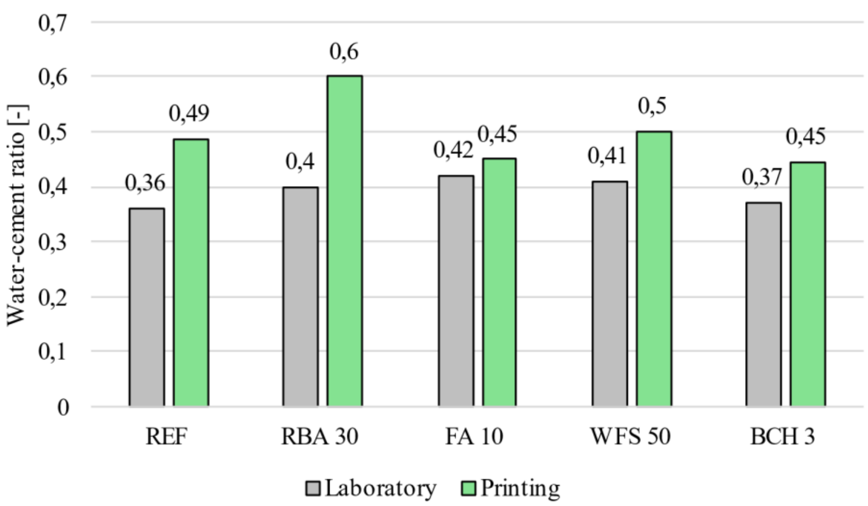

Fig. 4 Comparing of w/c ratios in laboratory and during printing.

At the time of print, amount of water had to be modified, to achieve sufficient pumpability. Differences of used amount of water achieved 27 % in average. For individual increases, see Tab. 3. At these w/c ratios, mixtures were easily pumpable and performed sufficient buildability.

Tab. 3 Necessary water increase during print compared to laboratory.

REF	**RBA 30**	**FA 10**	**WFS 50**	**BCH 3**
+35 %	+50 %	+7 %	+22 %	+20 %

After tuning of w/c ratio as above, samples with at least 5 layers were printed. After 28 day curing period, cutouts were made and subjected to uniaxial tensile test (see section Methodology). From multiple samples of each mixture, following average values of bond strength were gained (Fig. 5).

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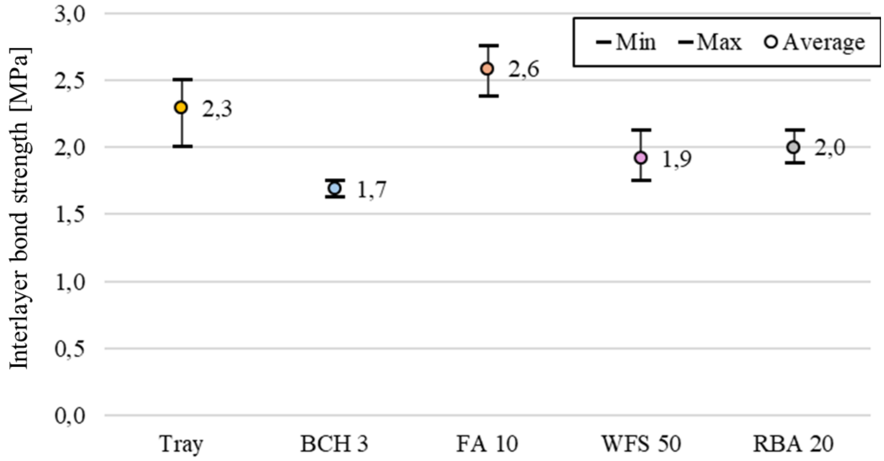

Fig. 5 Averaged interlayer bond strength.

Mixture FA 10, containing 10 % of fly ash, achieved interlayer bond strength, even higher than reference mixture by 0.3 MPa in average. Other mixtures bond strength varies from 74 % to 87 % of reference mixture bond strength.

4 DISCUSSION

Significant deviation in bond strength between samples from tray and robotic arm can be observed. Samples prepared with tray achieve only 64 % of bond strength in average, compared to samples from robotic print. Even though this can appear as high deviation that can contradict results similarity and question method validation, one influence is probably at fault. During mixture preparation for tray, time was measured. Due to high sensitivity of buildability on mixture rheology, and low power of trays pump (and thus pumpability), mixture has to be stirred for longer period of time (up to 10 minutes), with resting time to ensure sufficient pumpability and buildability. In case of the robotic arm, according to pump manufacturer (M-tec), mixture is transported to nozzle in approximately 2 minutes after mixing with water. As stated by authors [9, 10], bond strength of layers is very time dependent, as shown by previous research, probably with exponential dependency. Thus, such deviation of bond strength can be explained.

For further research and for better interchangeability of results between tray and robotic print, multiple improvements can be done. Necessity for increased w/c ratio of reference mixture compared to laboratory can be explained by not sufficiently homogenized mixture. In case of robotic print, dry material is transported in big-bags, and stored in silo with feeding worm shaft, which precisely mix dry material before adding water. This leads to lower differences in composition of used dry material, and it then performed more predictably. Another way to lower water consumption and gained higher interlayer bond strength is in improving pump at tray. Inability to pump mixture was the main reason for adding low amounts of water. This complication is connected to other possible improvement, generally shortening delay time between adding water and print itself, to the scale of the robotic arm with a 2-minute delay. Under such improvements, results should be in a closer match and second data set can be made.

Water consumption cannot be neglected in order to responsibly evaluate environmental impact of cementitious materials. Some mixtures use supplementary materials to lower CO_2 emissions, but on the other hand, such materials increase water consumption during the process. Presented mixtures are no exception. In laboratory, 11% increase in water for modified mixtures is required, compared to the reference mixture. In case of print experiment, this value widely ranged. As can be seen at **Chyba! Nenalezen zdroj odkazů.**, although some exceptional mixtures require less water than the reference (during print), still in average, mixture with supplementary materials use 2.7% more water to be workable. As stated, printing modified mixtures requires additional water (2.7–11% more), which in most of the cases, lowers interlayer bond strength (13–26% lower). This is in accordance with Christen [8], who observed 16–29% water necessary increase and 20% interlayer bond strength decrease using recycled brick aggregate (RBA).

As stated above, supplementary filler materials can lead to changes in w/c ratio. Amount of water, mixed with cementitious materials modify overall mechanical properties, due to change in hydration process. More water leads to less dense mixture, such varied reaction leads to larger shrinkage and thus cracking of print. Furthermore, water drops that do not react, later evaporate, which causes pore structure formation. Thus, comparing mixtures with different w/c ratio can be misleading. For future comparison study, modifying the amount of superplasticizer to achieve similar w/c ratio in SFM mixtures is recommended. Other approach is lowering water absorption of SFMs.

While comparing new materials for 3D printing, bond strength cannot be the one and only leading factor, but multiple parameters should be taken into consideration. These parameters were not measured, but mixture behaviour was visually assessed during experiments (see Tab. 4).

Tab. 4 Mixture suitability for print evaluation.

	REF	RBA 30	FA 10	WFS 50	BCH 3
Pumpability	good	good	perfect	bad	good
Printability	good	good	perfect	bad	good
Buildability	perfect	perfect	good	bad	good
Print quality	good	good	good	good	good
Workability	good	perfect	good	bad	good
Shrinkage caused cracks	no	yes	no	yes	no

As shown above, mixture FA 10 with 10% of fly ash as SFM performed best at uniaxial tensile strength. Improvement of mechanical properties in mixtures using fly ash is in correlation with statements of other authors, which attribute improvement to pozzolanic reaction [11] [12]. Reason for FA 10 mixture having higher interlayer bond strength should be noted. Fly ash can be used also as supplementary cement material and thus, mixture FA 10 does not have comparable amount of binder with other SFM mixtures. It should be noted that mixtures have a variable amount of filler replacement, from 3% to 50% (see Tab. 1). Presented mixtures were chosen based on previous tests. For better evaluation of each SFM influence on bond strength, further research with comparable amount of replacements and multiple values should be performed.

5 CONCLUSION

This study aimed at validating new experimental approach, which consist of simulating 3D concrete printing “tray”. Such device enables developing new mixtures in small volumes and thus lowering the costs. Even though experimental process with tray could benefit from improvements, bond strength of samples from robotic print tray appears on a similar scale. The above mentioned improvements, such as improving material pumping and material homogenization, could bring better closeness of results. Taking in consideration possible small deviations of results, new mixtures were tested at tray, to investigate their suitability for 3D concrete printing.

The presented mixtures use supplementary filler materials, to lower costs and environmental impact. These mixtures were compared based on their suitability for 3D printing (pumpability, buildability, cracks) and by their interlayer bond strength. Mixture FA 10, containing 10% replacement of filler by fly ash gained highest bond strength, even better than reference mixture. Other suitable supplementary filler material is recycled brick aggregate, which shows 2nd highest bond strength from mixtures with SFMs, with 87% bond strength of reference mixture. Negative aspect of using recycled brick aggregate is higher water consumption and increased shrinkage during curing.

Significant attention should be given to amount of water needed for mixture to be useable, and thus water-cement ratio. SFM mixture in general requires more additional water compared to reference mixture. To eliminate negative impact of additional water on bond strength results, modifying amount of superplasticizer or finding other ways to lower water absorption of filler material is recommended.

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References

[1] ANDREW, Robbie M. Global CO2 emissions from cement production, 1928-2017. *Earth System Science Data* [online]. 2018, **10**(4), 2213–2239 [accessed. 2023-12-29]. ISSN 18663516. Available at: doi:10.5194/ESSD-10-2213-2018

[2] CAO, Xiangpeng, Shiheng YU, Hongzhi CUI and Zongjin LI. 3D Printing Devices and Reinforcing Techniques for Extruded Cement-Based Materials: A Review. *Buildings* [online]. 2022, **12**(4), 1–19. ISSN 20755309. Available at: doi:10.3390/buildings12040453

[3] ZHANG, Hanghua and Jianzhuang XIAO. Plastic shrinkage and cracking of 3D printed mortar with recycled sand. *Construction and Building Materials* [online]. 2021, **302**(July), 124405. ISSN 09500618. Available at: doi:10.1016/j.conbuildmat.2021.124405

[4] SKIBICKI, Szymon, Monika PUŁTORAK, Maria KASZYŃSKA, Marcin HOFFMANN, Ewa EKIERT and Daniel SIBERA. The effect of using recycled PET aggregates on mechanical and durability properties of 3D printed mortar. *Construction and Building Materials* [online]. 2022, **335**(March 2021). ISSN 09500618. Available at: doi:10.1016/j.conbuildmat.2022.127443

[5] WANG, Li, Zehao TIAN, Guowei MA and Mo ZHANG. Interlayer bonding improvement of 3D printed concrete with polymer modified mortar: Experiments and molecular dynamics studies. *Cement and Concrete Composites* [online]. 2020, **110**(July 2019), 103571. ISSN 09589465. Available at: doi:10.1016/j.cemconcomp.2020.103571

[6] HAN, Yilong, Zhihan YANG, Tao DING and Jianzhuang XIAO. Environmental and economic assessment on 3D printed buildings with recycled concrete. *Journal of Cleaner Production* [online]. 2021, **278** [accessed. 2023-12-29]. ISSN 09596526. Available at: doi:10.1016/j.jclepro.2020.123884

[7] NODEHI, Mehrab, Togay OZBAKKALOGLU and Aliakbar GHOLAMPOUR. *Effect of supplementary cementitious materials on properties of 3D printed conventional and alkali-activated concrete: A review* [online]. B.m.: Elsevier B.V. 2022. ISSN 09265805. Available at: doi:10.1016/j.autcon.2022.104215

[8] CHRISTEN, Heidi, Gideon Van ZIJL and Wibke De VILLIERS. The incorporation of recycled brick aggregate in 3D printed concrete. *Cleaner Materials* [online]. 2022, **4**(June 2021), 100090. ISSN 2772-3976. Available at: doi:10.1016/j.clema.2022.100090

[9] CHEN, Yu, Ze CHANG, Shan HE, Oğuzhan ÇOPUROĞLU, Branko ŠAVIJA and Erik SCHLANGEN. Effect of curing methods during a long time gap between two printing sessions on the interlayer bonding of 3D printed cementitious materials. *Construction and Building Materials* [online]. 2022, **332**(March). ISSN 09500618. Available at: doi:10.1016/j.conbuildmat.2022.127394

[10] SANJAYAN, Jay G., Behzad NEMATOLLAHI, Ming XIA and Taylor MARCHMENT. Effect of surface moisture on inter-layer strength of 3D printed concrete. *Construction and Building Materials* [online]. 2018, **172**, 468–475 [accessed. 2023-03-29]. ISSN 09500618. Available at: doi:10.1016/J.CONBUILDMAT.2018.03.232

[11] ALMUTAIRI, Ahmad L., Bassam A. TAYEH, Adeyemi ADESINA, Haytham F. ISLEEM and Abdullah M. ZEYAD. Potential applications of geopolymer concrete in construction: A review. *Case Studies in Construction Materials* [online]. 2021, **15**(September), e00733. ISSN 22145095. Available at: doi:10.1016/j.cscm.2021.e00733

[12] USHAA, T. G., R. ANURADHA and G. S. VENKATASUBRAMANI. Performance of self-compacting geopolymer concrete containing different mineral admixtures. *Indian Journal of Engineering and Materials Sciences*. 2015, **22**(4), 473–481. ISSN 09751017.

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