

Development of a Universal 3D Printable Concrete Solution

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Abstract. The use of 3D printing in construction projects is gaining ground on a global scale given that this new construction method has the potential to deliver significant savings due to efficient use of materials and less need for labor, combating an increasingly scarce availability of skilled labor as well as offering new advantages in terms of form freedom.

However, virtually all projects to date have been printed, not with real concrete, but with 3DCP bagged / ready-to-mix dry mix mortars characterized by a very high cement content. Various suppliers have emerged on a global scale to assist the adoption of 3D printing by providing convenient ready-to-mix dry mortar solutions that are relatively easy to apply in the various 3DCP systems and demonstration projects.

A serious negative consequence of using the convenient dry mix mortar process combined with the high cement content is that the cost of the mortar per ton is many times higher than if an ordinary real concrete had been used. Hence, for large scale 3DCP “industrial” projects the potential labor savings risk being more than offset by higher materials cost with little overall economic gain from using the new construction method as a result.

For the 3DCP method to conquer market share on a global scale, an inexpensive and robust 3D printable real concrete made from local available cement and raw materials must be applied. However, thus far such a solution did not exist.

This paper presents a first solution, which has enabled the fabrication of 3D printable real concrete based on local cement and raw materials anywhere on the globe. The paper describes the results from the application of the solution in three pilots on three continents: Europe, Africa, and the Middle East, including a 190 m² 3D printed building in Oman inaugurated by the leading minister of Oman as recently as in December 2021, which so far is the largest on-site 3D printed building with real concrete in the world⁰

Keywords: Admixtures, Concrete, Mortars, 3D Printing, Digital Fabrication, Viable, Economics

1 Context – Current State of 3D Concrete Printing (3DCP)

1.1 Advantages of 3D Printing

The use of 3D printing in construction projects is gaining ground on a global scale given that this new construction method has the potential to deliver significant savings due to efficient use of materials and less need for labor, combating an increasingly scarce availability of skilled labor as well as offer new advantages in terms of form freedom.

1.2 The Challenges

Despite the advantages of 3D Printing construction using cement-based materials, there are still challenges to overcome if the technology is to become more accessible, industrialized, harness it's the aforementioned benefits, and detonate a true transformation in construction.

Virtually all 3D Printing construction projects that have been demonstrated until now have relied on pre-packaged / dry mortar mixes, which are very specific tailor-made formulations that are 3D Printer-specific. Typically, the mortar mixes [1,2,3,4] have a high cement content ($>600 \text{ kg/m}^3$ of cement), require expensive premixing of heated and dried materials and relatively high logistical costs to get the dry mix to the printing site as the manufacturing location of the dry mix often is far away from the printing site. The result is a very expensive material lacking the universal versatility that would render 3D Printing competitive when compared to traditional construction solutions.

2 Evolving 3D Printing in Construction – The Approach

CEMEX and COBOD decided to confront the challenges head-on, recognizing that a close collaboration between a construction materials company and a 3D Printer manufacturer was fundamental in advancing the technology to its next era.

It was clear, from the beginning, that the printing material had to be a true concrete with a mix design comparable to the most widely used conventional concrete typical of buildings and structures – economic viability is key. Secondly, the concrete solution had to be universal in its applicability – independent of the constituents (sand, gravel, cement, and mineral additions) and location in the world, the material response in the 3D Printer had to be the same independent of location as well as reliable. Thirdly, the 3D Printing had to be a highly industrialized and continuous process. Finally, durability of the material is key and determinant in the lifecycle of structures.

The development of a universal and conventional concrete for 3D Printing construction was achieved through a proprietary admixture system (4 products) accompanied by equipment adaptations. Industrialization of the 3D Printing process was achieved by evolving to a ready-mix concrete solution where the printing unit is either connected to

a batching plant or the concrete is delivered to the jobsite via trucks from a batching plant relatively close by.

The breakthrough in the proposed solution is the proprietary admixture system belonging to the CEMEX D.fab admixtures family designed for digital (D) fabrication (fab) in concrete. D.fab concrete for 3D Printing has been designed to provide a fluid concrete mix (S4-S5 consistency / EN 12350-2 or spread >17inches / ASTM C 143) with an achievable open time up to 8 hours without retardation, thus making it an easy to transport, pump and secure continuity of operations at the jobsite. As the material exits the printing nozzle the admixture system is designed to impart the concrete mix with an immediate transformation – material undergoes stiffening. The stiff mix is able to hold its volume as well as provide the necessary green strength to allow immediate stacking of a successive print layer, thereby speeding up the printing process and saving material. Despite the rapid stiffening, the admixture system is also conceived to prevent drying of the printed mix (i.e. designed for moisture retention) avoiding cold joints and differential shrinkage cracking. Furthermore, depending on the jobsite and printing steps required, the concrete mix can be tailor designed to achieve rapid hardening. More importantly, the key advantage and characteristic of the proposed solution is that the D.fab system coupled with key 3D Printing machine features renders the concrete technology very robust – independent of the cement, sand, supplementary cementitious materials (e.g. slag or fly ash) or gravel used, the concrete will fulfill the fresh, hardened, and durability properties required for a 3D Printing job.

A novel material solution and materials processing system has been developed for 3D Printing with universal application, economically viable and industrialized. Underlying this development is a family of admixtures composed of 2 admixtures designed to control rheological properties, and 2 accelerator admixtures to tailor the strength development of the D.fab concrete. Given that a portion of the admixture system is added in the batching plant, while the remaining components are added just before the concrete is extruded, modification of the printhead was necessary to enable the use of the solution. A special dosing unit adding an admixture in the printhead just before the concrete is extruded was therefore developed as part of the solution. It was key to control the precise admixture dosing and material throughput in order ensure proper mixing.

A base mix design was developed at the CEMEX laboratory, and later validated by printing inside a cold warehouse in Denmark. This base was to act as the starting point for any recipe adjustments that would need to happen on local building sites across the globe to account for different temperatures and moisture conditions.

Hereby, a synergistic system consisting of an admixture Toolbox, a base concrete mix design and enhanced equipment to handle these has been developed for 3D Printing of ready-mix concrete.

3 The First Concrete 3D Printing Material – Properties

The concrete mixes developed for 3D Printing have been designed following the parameters given in Table 1, which are typical of pumped concrete.

Table 1. D.fab Concrete Mix Design characteristics for 3D Printing

Cement	Minimum 350 Kg/m ³
Aggregates size	Maximum 12mm
Gravel/Sand ratio	Between 0.9 - 1.2
Water cement ratio	Maximum 0.5

3.1 Mechanical Performance

The mechanical properties [5] of the D.fab concrete is compared to conventional concrete as well as evaluated with the option to accelerate the strength development at the early ages, especially in the first 24 hours and up to 7 days.

Sampling of the D.fab concrete was taken before and after going through the printing nozzle and compared to a conventional concrete with the same mix design, but without the D.fab technology. The graph in Figure 1a compares the pumped (before nozzle) and printed (after nozzle) D.fab concrete, and the result shows the same strength development, therefore there are no effects of the admixtures on the mechanical performance (e.g. retardation of strength development). Additionally, the performance of the D.fab concrete has the same strength development of a comparable conventional concrete.

There exists also the option to accelerate the D.fab concrete's hardening (i.e. strength development) at the very early ages. Figure 1b shows that the range of the early age strength development of the D.fab concrete can be tailored to the project requirements and can achieve up to 4 MPa at 4 hours, 20 MPa at 10 hours or 35 MPa at 24 hours. This becomes relevant for 3D Printing in terms of printing and construction speed.

Mechanical properties of the D.fab concrete is in line with the expected performance of a conventional concrete, and with characteristics designed for 3D Printing.

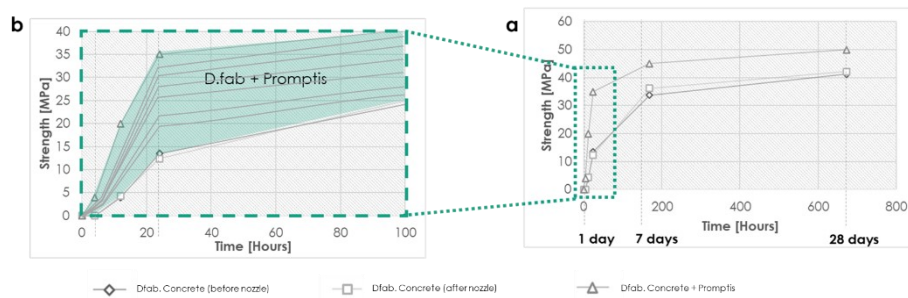


Fig. 1. Strength development of D.fab concrete: a) D.fab concrete before and after nozzle, b) use of CEMEX's rapid hardening technology Promptis® to provide option to increase early age strength development.

3.2 Durability Performance

Properties like shrinkage, freeze-thaw resistance, and water absorption are important for the durability of structures. Consequently, measurements were carried out on the D.fab concrete to assess its response with respect to conditions that can determine its service life.

Free-Drying shrinkage measurements, executed according to EN 12390-16, are given in Figure 2, which show that the D.fab concrete exhibits a higher dimensional stability (lower shrinkage) when compared to conventional concrete and mortar [6,1]. Note, the typical high cement content in mortars leads to a higher shrinkage. Additionally, it is interesting to note that the D.fab concrete has an especially lower shrinkage during the early ages, which is important for 3D printed structures given the layered nature of construction method.

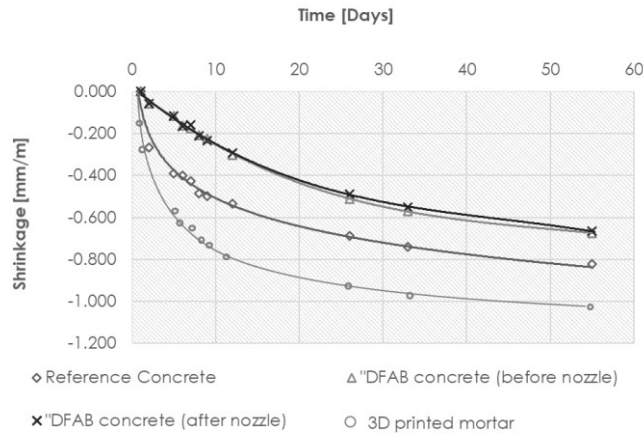


Fig. 2. Shrinkage response of D.fab concrete for 3D Printing. The admixture system enhances the performance of the concrete.

Freeze-thaw test (NF P 18 420) results, given in Figure 3, yield very positive performance showing that the D.fab admixtures system combined with a proprietary air entrainer (AE*) is also very effective in resisting numerous cycles of freezing and thawing, thereby minimizes material degradation. This result is particularly important for the application of 3D Printing in cold countries.

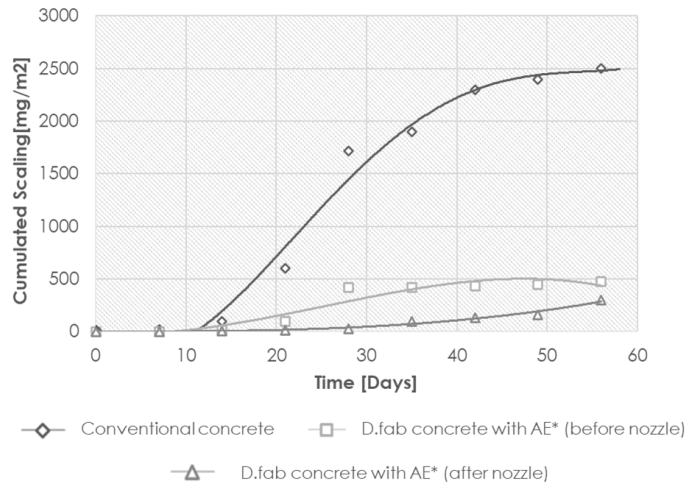


Fig. 3. Freeze-Thaw response of D.fab concrete. The D.fab concrete showed a very low cumulated scaling, and therefore material degradation was a minimum.

Water tightness of a structure contributes to minimizing any risk of material degradation (e.g. steel corrosion) as well as impacting comfort, which can be impacted due to variations in humidity. Results from the EN 480-5, measurement of coefficient of capillary water absorption, given in Figure 4, indicate that the D.fab concrete combined with a waterproofing admixture, either externally applied or directly added to the concrete, lead to a reduced water absorption. Thus, the D.fab concrete can incorporate admixtures with additional functionalities, without compromising its fresh and hardened properties, therefore demonstrating its versatility.

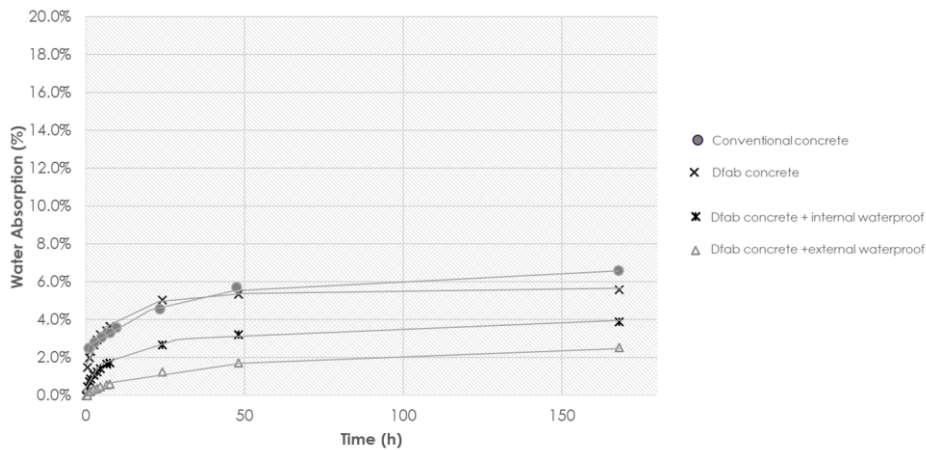
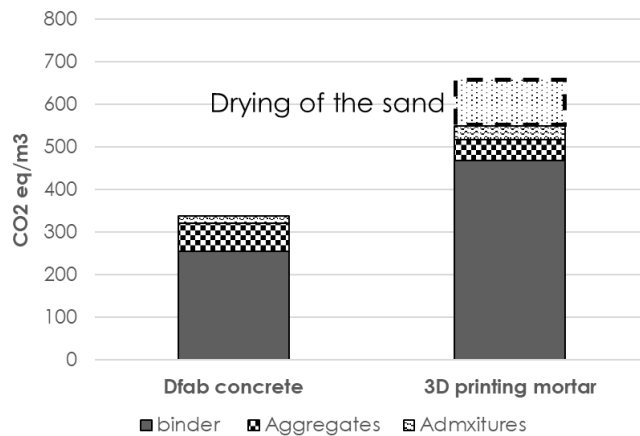


Fig. 4. Waterproofing of D.fab concrete – absorption tests. Use of the waterproofing admixture internally and externally.

3.3 Lower Embodied CO₂

Given that the proposed printing material is concrete, the CO₂ footprint is lower than that of the mortar currently used. The graph in Figure 5 compares the CO₂ footprint of the D.fab concrete compared to a typical mortar typically used for 3D Printing. The D.fab solution offers a more environmentally friendly solution with a CO₂ footprint 1.5 times lower than mortars typically used in 3D Printing.



** Average estimated value for available products on the market*

Fig. 5. CO₂ footprint of D.fab concrete versus typical mortars currently used in 3D Printing.

4 Application of Concrete 3D Printing

4.1 Pilot projects in Europe, Africa and the Middle East.

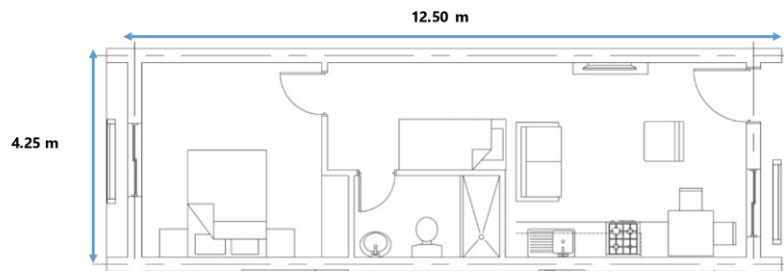
Africa: Luanda, Angola

The D.fab solution was first used in a real-life project in Luanda, Angola – Figure 6



Fig. 6. Power2Build's site in Luanda, Angola and home to the first building 3D printed with the D.fab concrete solution. The printer – in the middle – and the batch plant – to the left – has been set up to print the building.

The building, a one floor house of 53 m² (Figure 7) containing a kitchen, bedroom, living room and bathroom was a project aimed at demonstrating that the 3D construction printing technology could be the answer to Angola's affordable housing challenge – deficit of much needed units, affordable, safe, and high quality.



Drawing 1: 2D floor plan of the 53 m2 house in Luanda, Angola

Fig. 7. House floor plan of Power2Build's affordable house offer.

The wall design consisted of double cavity walls, and these were printed with an 80 mm width and a layer height of 30 mm. The building is 3 m high. A total of 17 m³ of materials was used for the project.

The printing crew consisted of local operators from Power2Build, assisted by 2 employees from COBOD for a couple of weeks and one employee from CEMEX for a week. In total the house was printed in 48 hours, but these hours were spread over many days as the local operators was also trained during the printing, as well as the mix design optimized to local conditions and materials. After printing the house, as shown in Figure 8, both the outside and inside of the house was rendered with plaster, which is customary in Angola.



Fig. 8. The finished 53 m2 house in Luanda, Angola. The first 3D printed building with the D.fab concrete solution.

During the concrete fine tuning in Angola, an outcome was the significant reduction in accelerator dosage compared to the base mix. Therefore, accelerators could be used at a lower rate, and thereby optimizing performance and costs.

Europe: Holstebro, Denmark.

The second location where the D.fab solution was implemented was in Holstebro, Denmark (Figure 9), where a printer from COBOD was set up to print a small one floor house.



Fig. 9. The printer set up in Holstebro, Denmark to print the second 3D printed building with the D.fab concrete solution.

The building, a small one floor house of 37 m² (Figure 10) was built as a demonstration of how tiny houses could be designed and made with the help of the 3D printing technology.

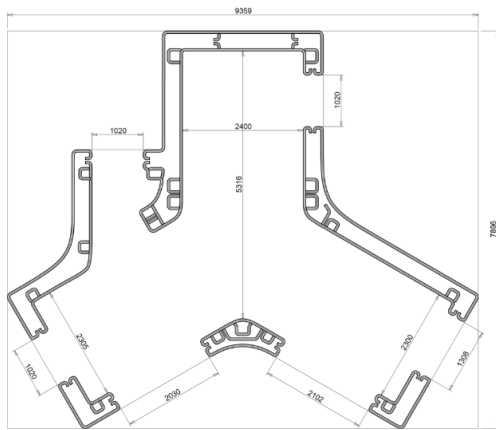


Fig. 10. Floor plan of the demo house in Holstebro, Denmark.

The wall design consisted of double cavity walls with columns as the load bearing elements. The walls were printed with 50 mm width and a layer height of 40 mm. The building is 5,1 m high. A total of 12 m³ of materials was used for the project.

The printing crew consisted of local operators from 3DCP Group (a newly formed company), assisted by COBOD employees and one employee from CEMEX for a week. Printing took place over 3 weeks, as all day rain and other factors delayed the project.

After printing, the house was not completed (see Figure 11) as it will be taken down in the months to follow, since the site will be used to make space for 44 similar small houses. Through the demo house, the 3DCP Group paved the way for the following 44 units to be 3D printed – a successful proof-of-concept.



Fig. 11. The printed 37 m² tiny house in Holstebro, Denmark. The second 3D printed building with the D.fab concrete solution.

Even if the base recipe had been developed in Denmark, adjustments to the recipe was still necessary as the temperature at the time of printing was significantly higher than in the warehouse. Also, the humidity during the summer season was quite high.

The Middle East: Muscat, Oman

The third location where the D.fab solution was implemented was in Muscat, Oman. The German University of Technology in Oman (GU Tech), wished to print a building to prove that the technology could be a viable solution for social housing in Oman.

Social housing in Oman is, compared to standards found in other countries, a quite large unit, and consequently the one floor house occupies an area of 195 m². It consisted of two parts, a private family as well as public units. Given that the printer, with a printable area of 12,5 m X 10 m per floor, was not large enough to print the whole building

in one go, the building was printed in two parts and the printer moved between the printing of the first and second part – Figure 12.



Fig. 12. A COBOD printer set up in Muscat, Oman around the second part of the social housing building after having completed the first part.

As can be seen below in Figure 13, the design allowed for the movement of the printer along the north/south axis where the two entrances of the house are found.

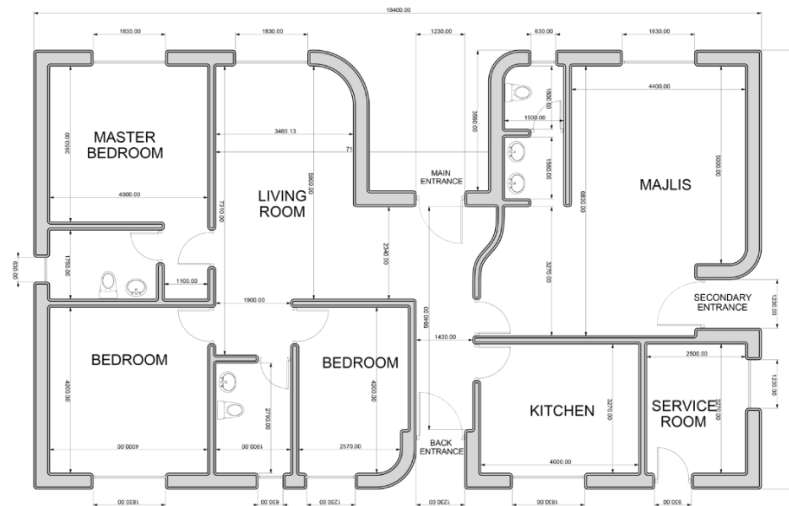


Fig. 13. 2D floor plan of the 195 m2 social housing demonstration unit in Muscat, Oman.

The wall design consisted of double cavity walls as loadbearing. The walls were printed with a 50 mm width and a layer height of 40 mm. The building is 3,4 m high. A total of 35 m³ of materials was used for the project.

The printing crew consisted of local operators from GU Tech, assisted by 1-2 COBOD employees and one employee from CEMEX for a week. Printing took place over 3 weeks. During the first two weeks the printer was set up and the recipe adjusted to the conditions in Oman. Also one week of training was provided to the GU Tech crew by COBOD during which the first part of the house was printed. Following the previous two weeks, the GU Tech operators, on their own, skillfully moved the printer and finished the second part of the house, which was completed in just 5 days.

After printing, the house was not plastered as GU Tech wanted to show clearly that it had been 3D printed, but the first part of the house was painted and finished inside, while the second part was left just with the raw printed appearance for the inauguration. Just a little more than a month after that the printer had arrived on site, the building was inaugurated by the finance minister of Oman at a Grand Opening event which also hosted several other ministers.

GU Tech wanted to pay special attention to and celebrate that this house now is the world's largest on-site 3D printed building with real concrete.



Fig. 14. Inauguration of the building in Muscat, Oman. The third and with the 195 m², the largest 3D printed building made with the D.fab concrete solution so far.

4.2 Mix Design Adaptations

As the above descriptions have clarified, the concrete mixes were adjusted (Table 2) in all projects compared to the initial base mix design as a consequence of the ambient conditions - primarily the temperature and humidity.

Table 2. Overview of the printing conditions in the various projects.

Location	Lab, warehouse Copenhagen	Luanda, Angola	Holstebro, Denmark	Muscat, Oman
Temperature	Low 5-10 C	Very high 25-35 C	Medium 10-20 C	High 20-30 C
Humidity/ Relative humidity	Medium 40-45%	Very high 70-90%	High 60-65%	High 60%

Figure 14 summarizes how the D.fab admixtures system was adjusted depending on the weather conditions. Note, the main component that was adapted to the conditions was the accelerator.

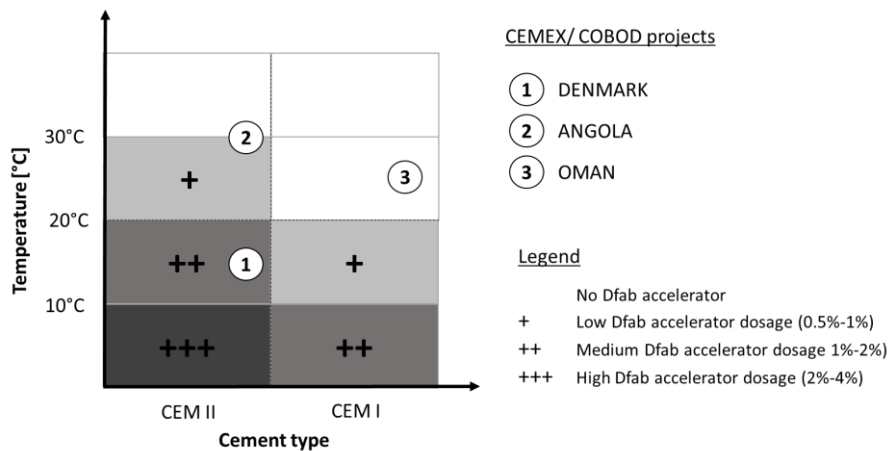


Fig. 14. Optimizations of the D.fab Admixtures Toolbox (primarily the accelerator) depending on the weather conditions of the selected printing sites.

The D.fab admixture system proved to be versatile in addressing extremely different weather conditions as well as dealing with local materials used to produce the ready-mix concrete.

4.3 Economic viability of the developed solution

In all three locations cement, sand and gravel was sourced locally. The final concrete solutions were tailor-designed as shown below in Table 3. For all locations the price of the D-fab concrete was confirmed to be comparable to truck-delivered conventional concrete from a ready-mix concrete batching plant.

Table 3. Overview of price of the D.fab concrete in the three locations.

Printing with real concrete to lower cost

3 Project examples



	Luanda, ANGOLA Power2Build	Muscat, OMAN German Technical University of Oman	Holstebro, DENMARK 3DCP Group
Floor area m2	53	195	37
Material used m3	17	35	12
Total material cost	<900€	<1600€	<1200€



Total materials costs incorporating the D.fab concrete ranged from 900-1,600 EUR, and already from this result it can be seen that with the D.fab concrete solution combined with the relative fast execution time even in these first pilots, 3D printing is becoming very competitive.

The economic advantage of printing with the D.fab concrete instead of a dry mix mortar becomes even more evident when the concrete solution prices are compared to prices of dry mix mortars for 3D printing - the same houses that above had materials costs of 900-1,600 EUR would have had a materials cost of 10,000-40,000 EUR had they been printed with dry mix mortars.

It is clear from the above economic analysis that using a real concrete (D.fab concrete), the cost of fabrication of buildings with 3D printing will be much lower than when printed with dry mix mortars. In fact, the costs become so low, that 3D printing with this solution combined with the fast execution time keeps the promise of being able to disrupt the construction sector, initially especially for low rise housing, but as the technology matures and grows further other sectors are likely to be disrupted too.

5 Conclusions

A novel 3D Printing material has been developed – a true ready-mix concrete, an alternative solution is offered to the typically consumed pre-packaged / dry mortar mixes. The concrete technology was adopted in three 3D Printing projects located at sites with different weather conditions and materials, demonstrating the versatility to deal and adapt to local conditions

The key factors underlying the development are a) the CEMEX admixture Toolbox for digital (D) fabrication (f) – D.fab coupled with b) COBOD's development of a special dosing unit at the printhead just before the concrete extrusion resulting in precise admixture dosing and mixing.

The D.fab concrete performance was evaluated showing mechanical properties matching those of an equivalent conventional concrete, and the D.fab accelerators can speed up hardening resulting in very early age strength developments that can speed up 3D Printing construction in a significant manner and optimize material consumption.

Durability of the D.fab concrete was assessed through shrinkage measurements, freeze-thaw resistance, and water impermeability. All test results indicated that the D.fab concrete preformed very well with respect to the conventional concrete as well as the mortars typically used in 3D Printing.

The proposed material and technological solutions provide a highly industrialized 3D Printing construction process which has demonstrated to be highly economically viable - the houses showcased and printed with D.fab concrete had materials costs in the range 900-1,600 EUR and would have had a materials cost of 10,000-40,000 EUR if printed with dry mix mortars.

A key solution (concrete technology + machine development) is being introduced to the 3D Printing Construction sector that will make it more accessible because of the important reduction in construction costs, industrialization, versatility, and robustness. A disruption is on its way in the 3D Printing Construction sector.

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