Buildwise

3D concrete printing

Technologies, challenges, opportunities and applications

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Innovation Paper

Foreword

This publication aims to survey the current knowledge available about 3D printing when used to make elements, structures and permanent formwork from mortar. It is a technology in which interest is constantly growing among manufacturers, architects, design and engineering consultancies and construction companies.

Both in the literature and on daily practice, the expression '3D concrete printing' is used to denote a broad range of projects implemented using cement-based 'cementitious' materials (concrete) as the 'ink'. From a technical perspective, it should be noted that these are actually mortar – given their maximum granular size distribution of between 2 and 4 mm. In the present document, the term '3D concrete printing' is used for practical reasons.

This process of 3D printing by extrusion, also known as additive manufacturing, involves depositing material (mortar) in successive layers using a printing machine (a motorised gantry or industrial robot) controlled using software. Many different 3D printing machines intended for the construction industry are gradually being adopted by off-site and on-site construction.

As an innovation centre, we at Buildwise are supporting the industry in adopting digital technologies such as 3D printing, cobots and drones, etc. In terms of 3D printing, many research and development projects are springing up in a quest to constantly improve efficiency. Achieving these advances will help the industry to stay ahead of the growing demand for a technology that no longer requires formwork and opens the way to designing and implementing complex geometry while reducing the use of materials. At Buildwise we are therefore launching both pilot projects to investigate the technology for printable mixtures – their composition, mechanical performance and durability – and demonstration activities in a hall equipped with a 3D printer (robotic arm) for mortar.

This document also aims to survey the main opportunities that 3D printing opens up to industry professionals, focusing on the most relevant applications and outlining the challenges ahead. Given that 3D printing for the construction industry is constantly evolving, there is always the possibility that information gathered for the present publication may become obsolete in the near future.

This document was drafted in consultation with C-Tech and the standards hub 'Béton, Mortier et Granulats'*.*

Author: Khadija El Cheikh

Other contributors to this document:
Angelo Buttafuoco, Laurent Clabots, Stefan Danschutter, Yves Grégoire, Niels Hulsbosch, Josse Jacobs, Laurent Lassoie, Yves Martin, Julie Piérard, Valérie Pollet, Gaëtan Wégria, Jörg Wijnants and Eric Winnepenninckx (Buildwise).
Damien Duvivier and Benoit Parmentier (formerly at Buildwise).

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1. What is 3D printing?

3D printing, also known as additive manufacturing, refers to the process of creating an object by layering material using a 3D printer. These machines operate according to the same basic principle. A three-dimensional digital model (3D file or model) is created by a design software. This model is then virtually cut up into successive layers using another software, known as a slicer. The instructions sent to the printer then allow the print head to move in such a way that it deposits the material in the right place. Figure 1 summarizes the main stages in additive manufacturing.

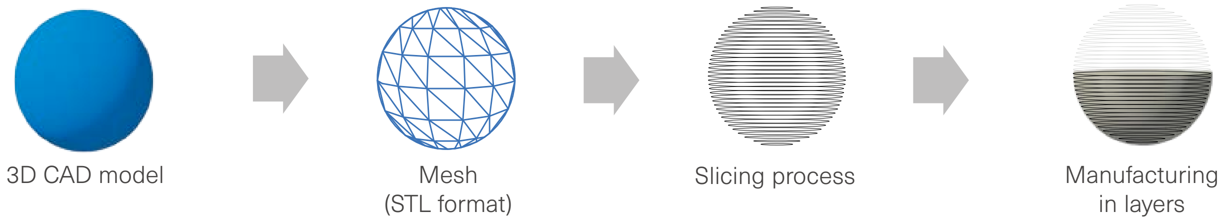

Fig. 1 Outline of additive manufacturing [B15].

In 2023, industrial additive manufacturing comprized seven standardized process categories for producing layers (see figure 2). It does not currently include 3D concrete printing technologies.

Liquid material	**Powdered material**	**Solid material**
1 – Material Jetting	3 – Binder Jetting	6 – Material Extrusion
MJM – Multi Jet Modelling	3DP – 3D printing	FDM – Fused Deposition Modelling
2 – Vat Photopolymerisation	4 – Powder Bed Fusion	7 – Sheet Lamination
SLA – Stereo Lithography Apparatus DLP – Digital Light Processing	SLM – Selective Laser Melting EBM – Electron Beam Melting	LOM – Laminated Object Manufac-turing
	5 – Directed Energy Deposition	
	DALM – Direct Additive Laser Manufacturing LMD – Laser Metal Deposition	

Fig. 2 The seven standardized categories of additive manufacturing techniques as defined in standard NBN EN ISO 17296-2 [B15].

For a long time, 3D printing was limited to conventional materials such as plastic. Today, it covers a wide range of materials including metal, wax, carbon fibre and – more recently – mortar. This technique has numerous applications in a wide range of fields: aeronautics, automotive, healthcare and civil engineering and more. Items produced by 3D printing may be endowed with particular properties, either physical – colour, shape – or mechanical – rigidity, heat resistance.

The construction industry also employs alternative terms like Large Scale Additive Manufacturing (LSAM) and Free Construction (FC).

2. A brief history of 3D printing in construction

First of all, despite the recent enthusiasm of the construction sector for 3D printing, this technology is not new. In 1941 William E. Urschel applied in the United States to patent a machine for building walls using concrete without formwork. This machine had a large hopper into which lean concrete, made with small aggregate size was poured (see figure 3). A rotating roller underneath fed and compacted the concrete. The machine had support from a trowel member that pressed the stream of concrete exiting the hopper forwards against the rotating roller.

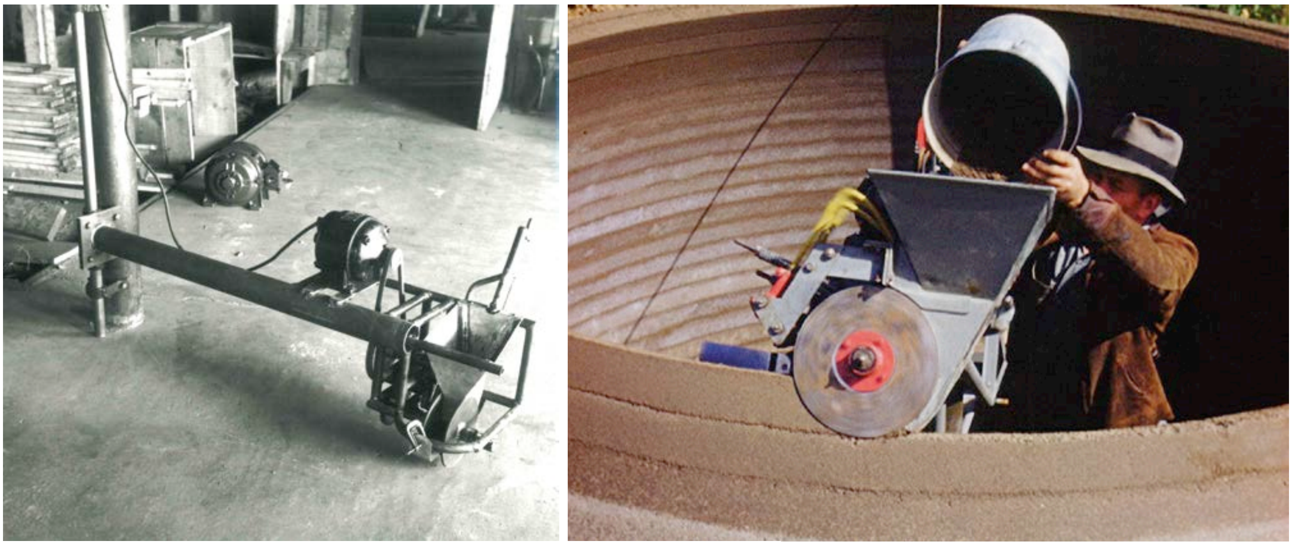

Fig. 3 Prototype machine for building walls by William E. Urschel.

Although 3D printing had existed for decades within manufacturing, it did not expand into the construction industry until the late 1990s. The first attempts at using 3D printing technology in automated construction employed two different methods. The first used steam to selectively bond the material into layers. The machine deposited a thin layer of silica (sand) followed by a layer of binding agent (Portland cement). Next, steam was projected onto it to harden the binder and produce the desired shape [P1]. The second method, Contour Crafting (CC), was developed at the University of Southern California (in the United States) and achieved significant popularity [K2]. This extrusion method used cement-based materials to print 3D parts [K1]. The system consisted of a crane and a computer-controlled gantry (see figure 4, p. 9). This technology only permitted the contour of an element to be printed, the interior cavity would then have to be filled with fluid concrete. The main aim of Contour Crafting is to avoid using conventional formwork.

From the 2000s onwards, there was further growth and development of 3D printing in the construction industry. The Freeform Construction Group at Loughborough University in the UK was established to adapt existing 3D printing techniques to mortar-based printable materials. Initial results showed that this technology had yet to meet the threshold for financial viability. The same team then built a large-scale 3D printer by combining components such as a pumping system, and a gantry concept with shotcrete. The printer they developed was able to print not only the contour but also entire parts. At the same time, D-Shape technology was introduced in Italy (see § 3.2, p. 13). This technology used adhesives as binding agents and was used in a variety of construction projects. The above advances marked the beginning of the construction industry's adoption of 3D printing.

Fig. 4 The process of Contour Crafting (left) and the principle of building on a large scale using this process (right) [K1].

Since 2010, 3D printing using concrete began to attract the interest of construction companies and several projects relating to this technology were launched around the world. In recent years, this innovative technique has grown somewhat with the support of research into this topic. Since the concept of 3D printed mortar was introduced over 20 years ago, research into and applications of it have been gradually evolving. Nevertheless, the number of relevant projects is limited and they are mainly demonstration sites linked to research.

3D printing technology has today reached a certain level of maturity, given the numerous 3D printers for mortar available on the market (see chapter 7, p. 45). It is possible to print in a factory and assemble the printed parts on-site, or print directly *in situ*. Although the existing materials and technologies have many benefits, there are also challenges and limitations. In terms of the market, companies appear to be competing to automate the extrusion process as far as possible, so they can supply the most practical, the most reliable or even the cheapest building method. In addition, it is still necessary to more precisely target the applications for which 3D concrete printing offers real added value over conventional methods (see chapter 4, p. 16, and chapter 8, p. 50, for some examples).

The global market for 3D concrete printing is segmented according to supply, technology and end users. Increasing investment in research and development activities and the emergence of new technologies are the main factors driving market growth. Companies are investing in research and development of more advanced 3D printers capable of producing large structures. The printing system's ability to implement more sophisticated designs and the growth of construction in emerging economies, particularly in China, are some of the factors behind the expansion of the international market for 3D concrete printing. Soaring urbanization has further boosted interest in 3D printing for residential building. Market actors are also contributing considerably to its growth, adopting various strategies including partnerships, collaborations, financing and launching new products to ensure they remain competitive. However, the high cost of buying and maintaining a certain range of 3D printers, their operating software and the lack of qualified operators are some examples constraining growth in the global 3D concrete printing market. Other obstacles both to market growth and technological developments worldwide are limitations on the area and height of printing.

The market is segmented geographically into North America, Europe and Asia Pacific. Asia Pacific is expected to see the fastest growth on the global market for 3D concrete printing. Governments and regulatory bodies in emerging economies such as India and China are increasingly focusing on environmental construction, as well as handling rapid industrialization and urbanization. These are some of the main factors behind growth in the 3D concrete printing market in that part of the world.

Growing experience in computer-assisted manufacturing, and especially in building information modelling (BIM), has facilitated the evolution of 3D printing. Overall, experiments and research projects in the 3D printing of concrete structures have demonstrated its special potential, expanded the experience base in this area and highlighted multiple technological challenges. In order to 3D print mortar, the material, 3D printing system and specific software all need to be appropriate. These aspects are discussed below.

3. 3D printing processes in the construction industry

To date, a number of 3D printing processes have been demonstrated, notably on-site and off-site manufacturing of construction parts or entire buildings, using industrial robots and gantry systems. Several different 3D printing processes can be used for construction-scale work. The main ones are:

- extrusion (see § 3.1)
- powder bonding or adhesion (see § 3.2, p. 13)
- wire and arc additive manufacturing (see § 3.3, p. 15).

Extrusion is the technique most readily associated with 3D concrete printing. Wire and arc additive manufacturing may be beneficial for producing reinforcements.

A slipform process, also known as slip forming or smart dynamic casting, is sometimes also listed in the process categories for 3D concrete printing. In this automated process, dynamic formwork is continually moved and filled with concrete at a speed that allows the material to be shaped during its crucial hardening phase (for instance when forming columns). However, unlike other 3D printing processes, slipform is a continuous process that is not based on the extrusion of layers. It cannot therefore be classified as an extrusion-based 3D printing process.

3D concrete printing by extrusion in layers is the most widely used method for on-site construction using large-scale 3D printers. In the remainder of this document, we will look in more detail at this extrusion-based 3D concrete printing technique (see chapter 4, p. 16).

3.1 Extrusion

The extrusion process consists in pumping a prepared mixture through a hose and delivering it to a print head with a nozzle at its end (see the left-hand side of figure 5, p. 12). After the material has been extruded through the nozzle, layers will be deposited on a printing platform to form the final object (see the right-hand side of figure 5, p. 12). Each layer is usually between five millimetres and several centimetres thick. The print head moves in different directions following a 3D model. The (lateral) finished surface of the printed element will be relatively rough due to the visible layer patterns. The extrusion nozzle may be equipped with a trowel-type tool that flattens the 3D printed layers and covers the grooves at the interfaces between the layers, by means of which a smooth surface can be obtained (see also § 5.4, p. 33).

The quality of the printed element depends on specific properties of the material: rheology[1] and thixotropy[2] (workability, consistency, etc.) as well as preprogrammed machine parameters (print speed, flow rate, layer thickness, nozzle shape). The material must possess specific properties at each stage of printing, as these will allow it to flow during pumping and then stabilize after it has been deposited.

3D printing by extrusion is the most popular approach in additive construction, given that it is compatible with a wide range of construction materials including mortar and clay. The waste of material generated by this process can be considerably limited if its printability[3] has been tested in advance.

(1) Rheology is the study of the flow of deformable materials. It covers plasticity, elasticity, viscosity and fluidity.

(2) Thixotropy is described as structural build-up (flocculation) when the cementitious material is at rest.

(3) The printability of cementitious materials covers the following aspects: pumpability (workability), extrudability (capacity for being extruded) and buildability (capacity for being deposited into stable layers).

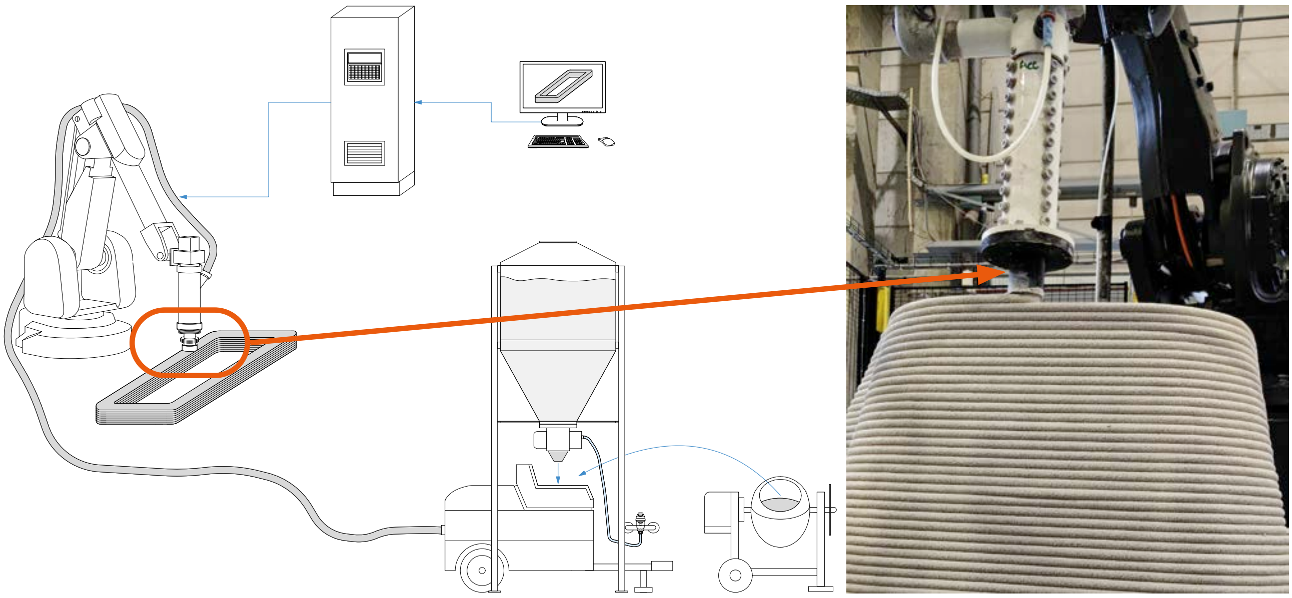

Fig. 5 The principle of 3D concrete printing by extrusion (left) and the superposition of layers by extrusion (right).

There are three conventional categories for 3D printing machines using extrusion (see also chapter 7, p. 45):

- gantry system machines
- lever machines
- robotic arm machines.

Gantry system machines consist of a print head attached to a mobile frame. The gantry moves along rails according to a Cartesian coordinates system (along x, y and z axes). This type of printer is mainly used for large-scale projects (such as a small house) due to its size, its limited portability and above all the complexity of assembling and disassembling it. These systems can be used to print sections or whole items. Lever machines comprize a print head suspended from levers, like a crane. These can usually move along six axes (six degrees of freedom), allowing for more complex shapes and a better surface finish than with a gantry. Finally, robotic arm machines feature a print head attached to the end of a robotic arm that can move along six axes, imitating the movement of a human arm. However, these printers remain more expensive than gantry system printers. Some companies, such as Twente Additive Manufacturing (TAM) in the Netherlands, have combined gantry and robotic arm systems to build a printer that can move along nine axes (the six standard axes and three for raising and withdrawing the gantry; see figure 6, p. 13).

Despite some similarities, these printers are designed for different, specific applications and have their own strengths and weaknesses as described in table 1. The main point of difference is the robotic arm, as this is normally difficult to program and its reach is limited, which limits the printable area. This restricts its use on-site and only allows single elements to be printed, although these can be more complex and detailed in

Table 1 Comparing the three categories of machines.

	Gantry	Levers	Robotic arm
Preferred placement	On-site (construction)	On-site (construction)	Off-site (prefabrication or laboratory)
Printing volume and applications	To print an entire building on-site, high productivity	To print small houses, complex geometries	Limited volume (depends on the arm length), possibility to extend the working area (e.g. robot on rails) To print one-off items, very agile, complex geometries

Fig. 6 Gantry system printer (A), lever printer (B), six-axis robotic arm printer (C) and nine-axis printer with robotic arm, mounted on a gantry (D).

shape. A robotic arm machine has the advantage of being more mobile than a gantry printer if placed on rails or equipped with wheels. It is more suited to manufacturing components in a factory. These components may be assembled before being installed on-site. On the other hand, the gantry system printer covers greater distances and can facilitate on-site production of higher volume printing, such as for houses with a small surface area.

The range of 3D printing machines using extrusion available on the market is given in chapter 7 (p. 45).

3.2 Adhesion or binding using powder

In Europe, Italian engineer Enrico Dini unveiled a process that emerged from developing a four-metre cube shaped gantry 3D printer, named D-Shape. The frame is formed from a square base which moves vertically along four columns (see figure 7 left, p. 14).

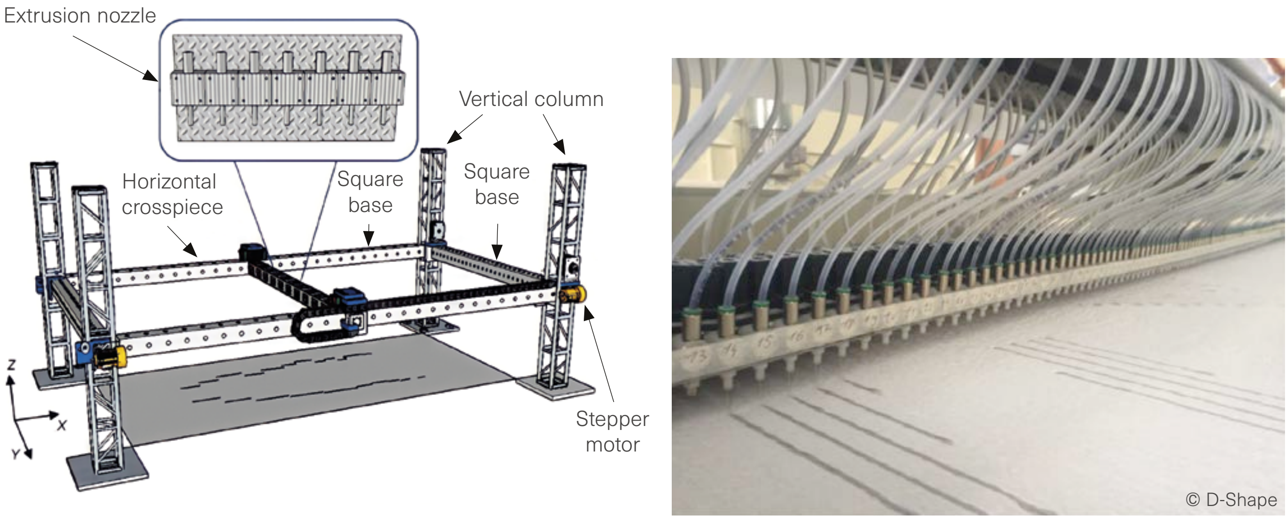

Fig. 7 Powder fusion 3D printing process using a D-Shape printer (left) and a print head with multiple nozzles (right).

The principle of the D-Shape technique is based on two actions. First a layer of granular matter like sand or aggregate of the desired thickness is paved. Then drops of specially formulated ink binder are locally injected to adhere the grains together into a solid shape. This is done using a print head made up of hundreds of small nozzles (see figure 7 right). These two steps are repeated for each layer. Once finished, the excess sand that has not been bound is removed to reveal the printed structure. This technique was originally developed to work with a binding system using epoxy resin. It was subsequently adapted so it could use inorganic binding agents and thus print larger volumes. Figure 8 shows the Radiolaria Pavilion, printed in 2007 using D-Shape technique on an industrial printer with sides measuring six metres.

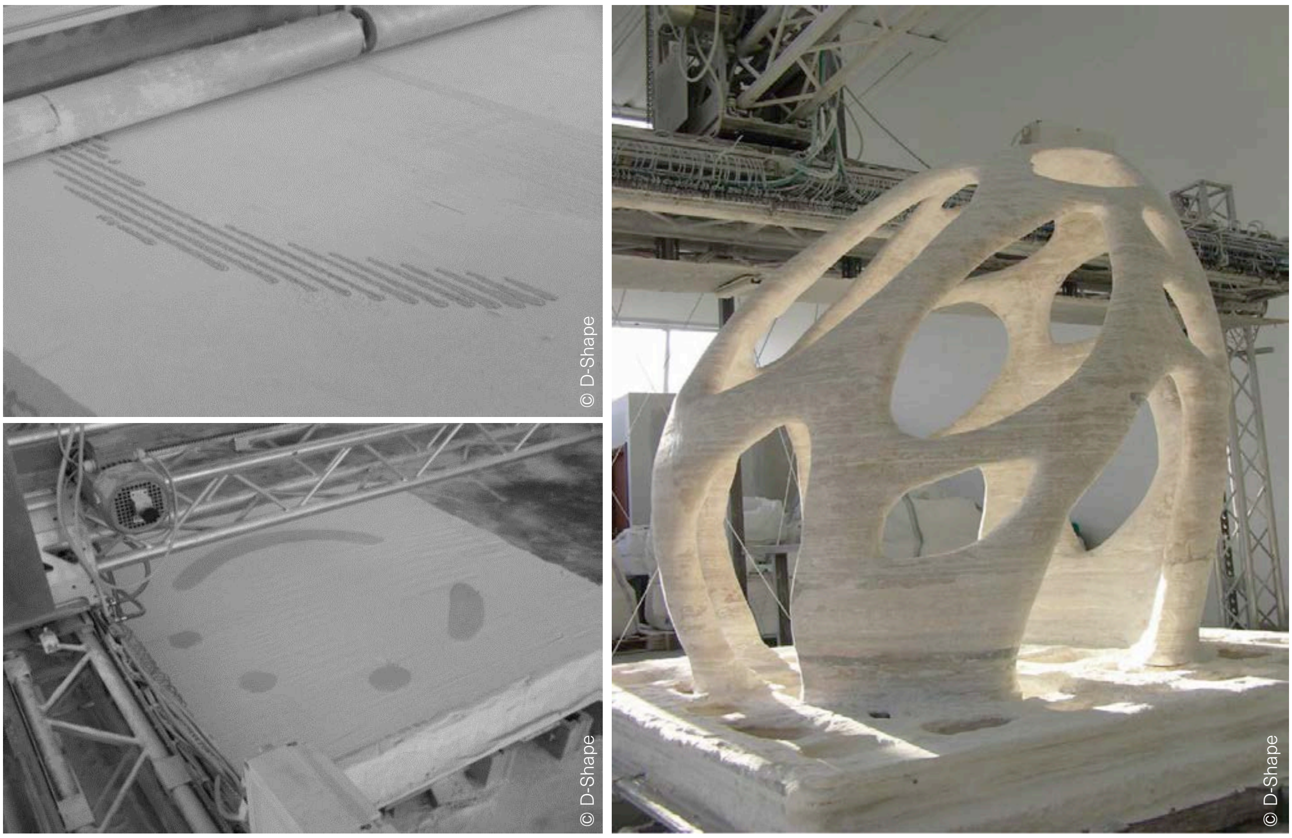

Fig. 8 The Radiolaria Pavilion, built using the D-Shape technique.

3.3 Wire and arc additive manufacturing

WAAM (Wire and Arc Additive Manufacturing, also known as Wire Arc Additive Manufacturing) is mainly intended for metal components. It uses welding wire as an additive metal. This process is based on arc welding and also produces metal items by layering welding seams on top of one another. Although WAAM is restricted to metal structures, it can achieve complex, solid structures. Figure 9 shows a stainless steel pedestrian bridge in Amsterdam printed by Dutch company MX3D. This technology is also used on a smaller scale to print reinforcements for concrete elements.

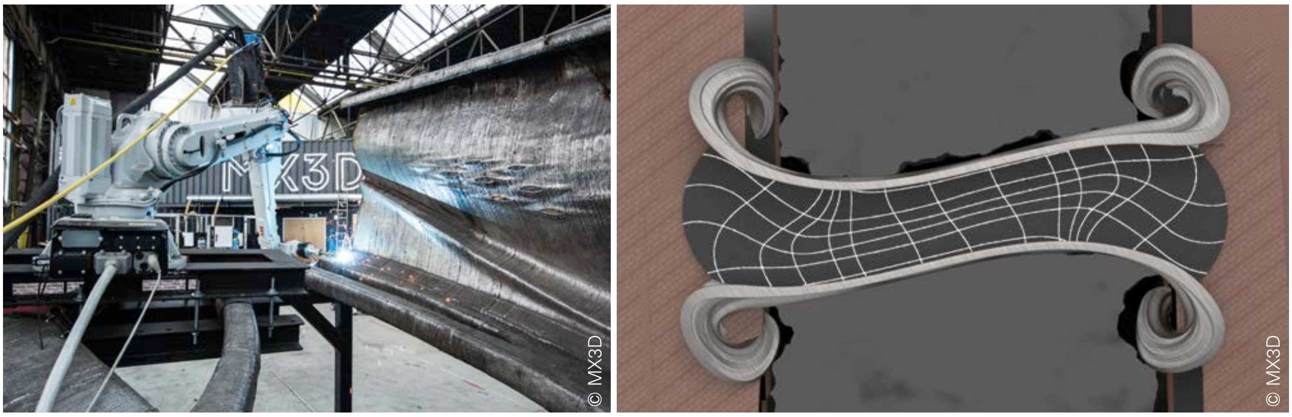

Fig. 9 3D printing a steel bridge using the WAAM process.

4. The potential of 3D printing in the construction sector

Multiple projects involving 3D printing by extrusion have demonstrated the benefits of this process over other, conventional construction methods. Interaction with the industry has shown that Buildwise's works have eased the adoption of automation and robotics, enabling companies to benefit from the potential gains these technologies bring. Some architects are showing great interest in this new construction process. Indeed 3D printing does open up new opportunities and allows complex shapes to be created, some of which would be impossible to achieve using traditional methods.

3D printing offers many benefits, of which the main ones are:

- construction time
- creation of complex forms
- potential reduction in costs and waste
- reduction in strenuous labour and accidents at work, and in human errors.

4.1 Construction time and architectural design freedom

'Time is money' is a phrase often used on-site – the speed of construction has obvious benefits for contractors. In the context of 3D printing, several factors shorten construction times: use of fast-setting mortars which require no formwork, continuous printing, and implementation of auxiliary works during the printing process. Conventional construction methods require several days of curing before the formwork can be removed. If there is no need for formwork, time is saved and the associated costs reduced. Depending on the project's complexity, these costs normally cover between 25 and 75 % of the total cost of concrete works. 3D printers also enable elements to be built continuously, reducing waiting times although printing speed – the speed with which the printer head moves – does vary depending on the printer (see chapter 7, p. 45). Construction times are also reduced thanks to auxiliary works implemented during printing, including installing and insulating ducts, and placing electrical junction boxes. Conventionally, these works would only be undertaken after the structural work has been completed. This shows how 3D printing can save time, and this, all the more when comparing to conventional methods instead of prefabrication in a factory.

A number of real-world demonstrations in a variety of countries have confirmed the speed with which 3D printers can produce buildings. For example, a two-storey house with an area of 90m^2 was built by Kamp C (Belgium) in three weeks using 3D printing (see figure 10, p. 17). Yet, this project is currently only a prototype. Some press articles mention houses built in only 24 hours, but this timescale is not always realistic and usually excludes the foundations, external joinery, plumbing, etc.

With conventional construction methods, the choice of formwork depends on the structure and its use, on the complexity of the shape and the degree of reuse. Wherever possible, shapes that would require complex, costly, labour-intensive and non-reusable formwork are usually avoided. Often, the industry cannot afford this type of unprofitable custom-made formwork. Yet, architects are currently tending to give concrete unexpected shapes so they can offer their structures a particular visual effect. These, however, are difficult to implement. Faced with this issue, initiatives such as textile formwork have sprung up to allow complex concrete shapes. Although they do allow many architectural opportunities, the forms that can be realized remain limited. Thanks to 3D printing, it is now possible to produce complex parts without the need for formwork. This is a major advantage for designers and architects who want to incorporate innovative, unusual geometries – such as organic forms – into their projects.

Figure 11 illustrates a complex-shaped column. This 4 m-tall column was printed by the French company XtreeE to support the new awning over a small commercial complex in Aix-en-Provence (France). In order

Fig. 10 Two-storey printed house at Kamp C in Westerlo.

to create the column, a 3D printed permanent formwork was printed and then filled with ultra-high performance fibre-reinforced concrete (UHPFRC).

3D printing hollow parts of street furniture can replace the production process using moulds. The Belgian company Urbastyle which specializes in this field has launched its new range of benches that were made by 3D printing (see figure 12). This shows how 3D printing concrete can save time, not only for building houses but also for producing any non-linear component.

© Métropole d'Aix Marseille, Territoire du Pays d'Aix, Marc Dalibard, EZCT Architecture & Design Research (Philippe Morel and Felix Agid), XtreeE, Artelia, Fehr Architectural, LafargeHolcim, AD Concept, Lisa Ricciotti.

Fig. 11 3D printed column by XtreeE.

Fig. 12 Bench, partly printed, by Urbastyle.

4.2 Economic impacts

In some cases, 3D printing provides a less costly construction compared to conventional methods. The reduction in costs includes the elimination of formwork costs, as well as lower transportation costs between the logistics hub and the site (if printing is done on-site e.g. house scale printing). Costs are also lower due to the reduced quantity of material used thanks to the design optimization (see § 4.3, p. 20) and to savings in labour resources. Unlike traditional methods that rely on formwork and are labour-intensive, 3D printing uses no formwork. This saves labour and reduces the costs for the used materials. However, the initial investment remains costly (see § 5.1, p. 24).

In some press articles on this subject, an inconsistency has been identified in the costs quoted for house building using 3D printing. Given that houses built using this process are still at an experimental stage, it is difficult to obtain convincing data on the total cost of a printed house. Costs may vary according to the raw materials used, the complexity of the design, the printing time, the country or even region where the project is located, the type of printer and other factors. A few house printing projects have been examined to estimate the average cost of printing a house. In some cases, the advertized price excludes the cost of foundations, roof, internal and external finishings, wall insulation, external joinery, suspended ceiling or floor.

The 3D printed house built by the company SQ4D in the United States was listed on sale for half the cost of newly constructed houses in the same region using conventional methods (see figure 13). The entire frame of the house and some of the furniture was 3D printed.

The Milestone project in the Meerhoven district of Eindhoven in the Netherlands was funded by the local authority and various academic and commercial partners. This comprizes social housing: five houses in different shapes, designed to be built using 3D printing (see figure 14).

Fig. 13 House printed by SQ4D.

Fig. 14 The five houses of the Milestone project.

The first, simplest house with an area of 95 m² has already been built and rented since April 2021 (see figure 15). The walls were printed at Eindhoven University of Technology (TU/e) in the Netherlands using recycled concrete, then assembled and erected on the foundations. The roof, framework and finishings were then installed. The total cost of the build has not yet been announced.

The Italian company WASP (World's Advanced Saving Project) has printed an environmentally friendly house named Gaïa, using the new Crane WASP technology and local materials (see also § 4.3, p. 20) which considerably reduced construction costs (see figure 16, p. 20). Printing took 10 days and the total cost of the raw materials used for the walls was € 900.

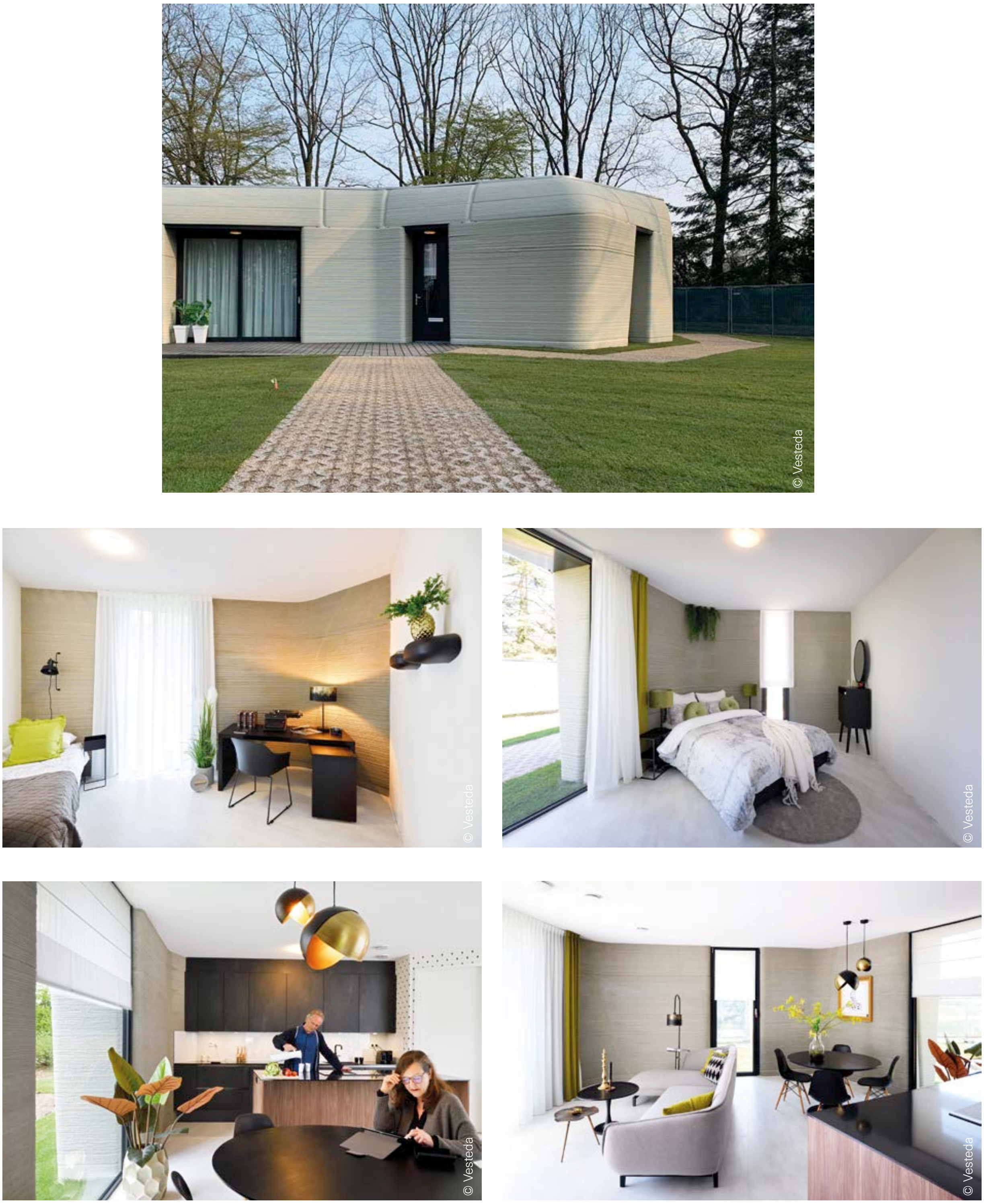

Fig. 15 House printed and rented out as part of the Milestone project.

Fig. 16 Gaïa house printed using the Crane WASP printer.

Ultimately, the above scenarios show that the use of 3D printing technology for construction is still in its infancy, and this explains the relatively high cost of 3D printed items. Although several prototypes exist, few actual houses built using 3D printing are currently on the market. It still seems difficult to compare the prices of printed houses to those built using conventional methods. Indeed, most 3D printed houses to date have not been built using concrete as defined in the standard NBN EN 206 [B14], but rather mortar: aggregates with a maximum size of around 4 mm and a high cement content (typically between 500 and 800 kg/m^3). To date, no 3D printing project has been carried out using ordinary concrete. Using ordinary concrete would allow substantial savings compared to ready-to-use mortars (ready-mixed). The lack of regulations and standards for 3D printed houses is slowing the adoption of this technique in the construction sector. However, given the number of companies taking the leap into 3D printing and the large-scale industrialization of this process, prices may start falling.

4.3 Environmental impacts

Concrete is the world's most-consumed manufactured material. It is therefore essential to use concrete in the most appropriate way according to needs. With 3D printing, the exact quantity of material required to design a complex element could be better estimated and controlled. Shapes can also be optimized using conventional prefabrication, but this requires complex formwork to be produced. 3D printing might also bring savings in materials as these can be distributed optimally within a volume so less waste is produced. This resource-saving benefit is further reinforced by a method called topology optimization. It is a method that deploys optimization software to identify areas with low and high stress by creating a 3D model to which loads are applied. Users can then select the essential parts and remove those that are unnecessary, thus the quantity of the used material can be reduced. For organic and complex shapes, topology optimization can have significant repercussions for the cost of the item and the production time. This allows optimized shapes to be printed with greater geometric control, while limiting the quantity of material used.

Examples of 3D printing have been publicized to show the potential for topology optimization in 3D construction: these include the column printed by XtreeE (see figure 11, p. 17) and the footbridge printed by the Dutch company Vertico in the Netherlands, in cooperation with Ghent University (see figure 17, p. 21). The partners designed the footbridge using topology optimization to remove unnecessary material. For both projects, the designers 3D printed permanent formwork which was then filled: with ultra-high performance fibre)reinforced concrete (UHPFRC) for the column, and self-compacting concrete (SCC) for the footbridge[(4)].

Although 3D concrete printing is often described as an economical process, it is important to emphasize the material waste generated while determining the optimal printing parameters – flow rate, speed of printing, waiting time between layers – especially in the manipulating phase of the printer (first trials). These parameters mainly depend on the rheological properties of the materials used and the volume of the element to be printed.

(4) Ultra-fluid concrete that settles itself with no need to be compacted.

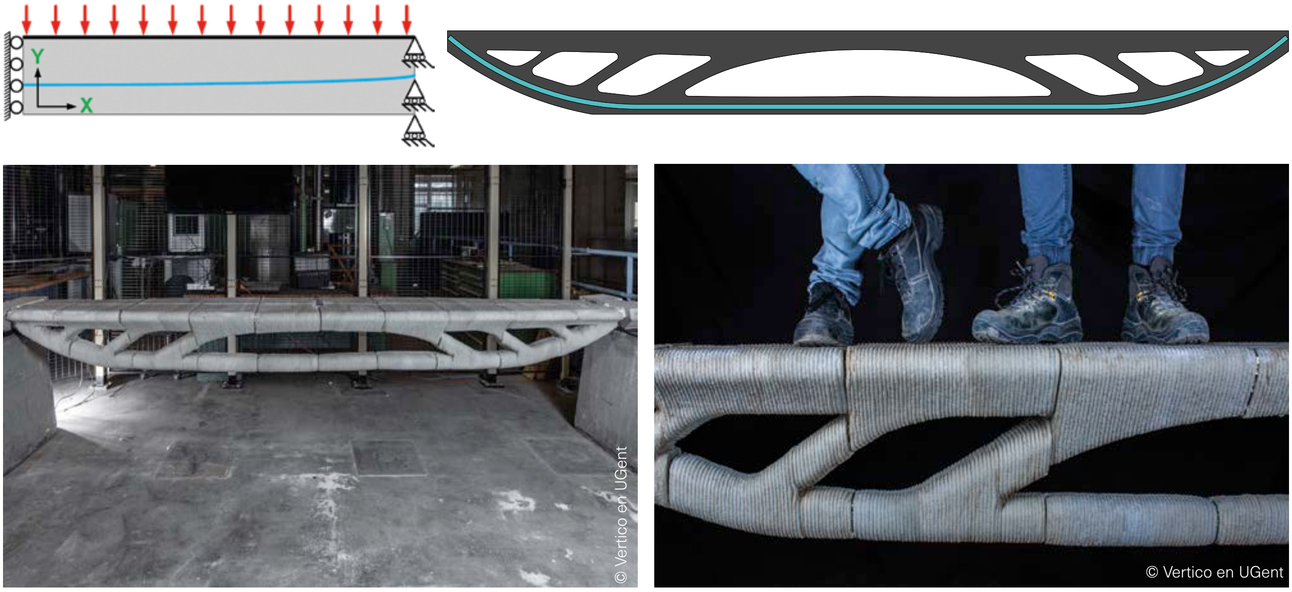

Fig. 17 Results of topology optimisation on a one-off, single-span girder under uniform load (top, [O1]) and 3D printing for the optimal footbridge (bottom).

The environmental impact can be reduced by minimizing the quantity of the material, but also by using environmentally friendly materials. The GCCA (Global Cement and Concrete Association) states that the production of cement, the most widely-used material in the construction sector, is highly polluting and represents around 7 % of greenhouse gas emissions worldwide.

Most 3D printed elements are produced using cement-rich mortars (Portland cement) which have a higher carbon footprint than ordinary concrete. In fact, it is essential to use a high proportion of fast-setting cement so layers can be superimposed (see § 6.1, p. 37). Reducing the proportion of Portland cement in printable mixtures is the current priority for making 3D construction more environmentally friendly. Initiatives aimed at developing printable mixtures based on local raw materials or even industrial by-products have been carried out. These reduce the environmental impact of 3D printing without lowering the surface quality of the finished elements.

Fast-setting cement is commonly used for 3D printing, and its carbon footprint can be reduced by using alternative binders that are more environmentally friendly, such as alkali-activated binders or other cementitious industrial byproducts. As an example, the startup Renca, part of the Dubai Future Accelerators collaborative programme, has commercialized its Geopolymer 3D ink, a 3D printing material made from industrial residues. It is important to note that geopolymers and other alkali-activated cementitious materials constitute a very diverse group of binding agents whose environmental impact indicators are quite variable.

Furthermore, initiatives aimed at environmentally friendly and recyclable additive construction have been launched to tackle shortages of natural resources. As part of the European project CIRMAP, research has been conducted by several partners including the University of Liège (ULiège) on using recycled sand obtained from demolished buildings in formulations designed for printable mortars (see figure 18, p. 22). CIRMAP is just one of several cooperative research projects, including SeRaMCo (Interreg region North-West Europe) and MATRICE (FEDER region Hauts de France).

3D printing is already opening up new opportunities for the use of natural local materials. As a part of the eco-housing project TECLA led by the architectural office Mario Cucinella Architects and the Italian firm WASP, dome-shaped structures (e.g. single-family dwellings) were printed using a printable mixture prepared from recycled and low-cost local materials (see figure 19, p. 22). WASP aims to build sustainable housing using additive manufacturing. The company has therefore developed a special printer called the Crane WASP which can run on solar, wind or hydraulic energy. This means regions affected by electricity shortages can build environmentally sustainable structures using local raw materials.

As with many others, this project shows that 3D printing technology is certainly compatible with the use of alternative materials (such as clay), which are likely to be abundantly available at the printing site (see § 6.1, p. 37).

Fig. 18 Printed mortar based on recycled sand from Belgium supplied by the RECYMEX non-hazardous waste recycling centre (experiment conducted at Buildwise in collaboration with ULiège).

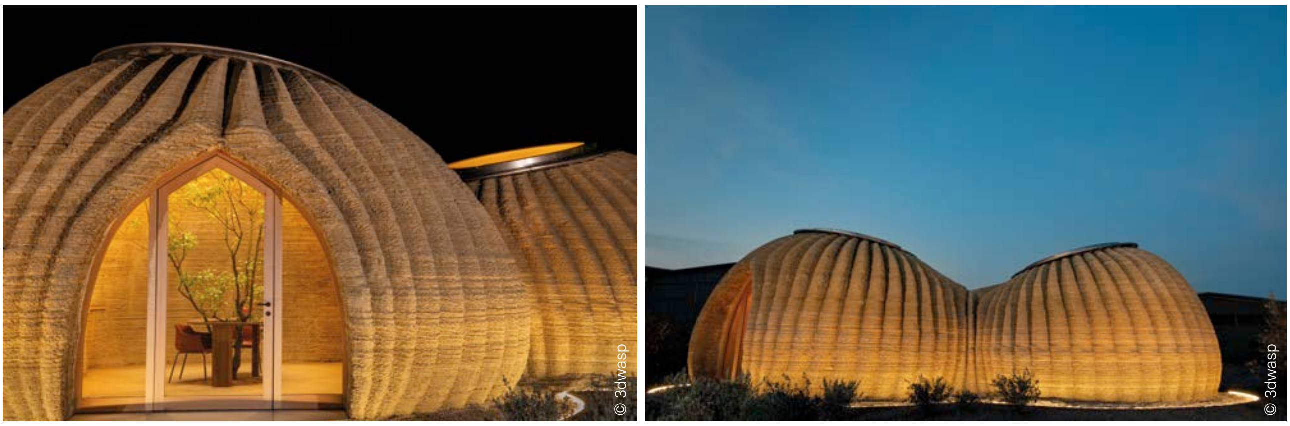

Fig. 19 Domes printed using material based on raw earth as part of the TECLA project.

4.4 Reducing risk and human errors on-site

Construction is one of the riskiest industries: construction sites are known for accidents at work and for the strenuous work that contributes to these risks. In 2021, the Belgian construction sector reported over 8,300 work-related accidents that caused at least one day's incapacity. Working conditions and risk prevention have been central to ergonomic studies and interventions undertaken in the construction industry and on public works sites.

Reducing the human intervention required and the time spent on-site by scheduling and automating construction will in turn reduce risks and strenuous work. Although human intervention is required to install, feed, control and program the 3D printer and to monitor the various stages of printing, the printing process is entirely automated and most operations do not need human input. Automating the construction of concrete structures will mean fewer workers are needed for fewer strenuous tasks, whether these relate to 3D printing or carrying heavy loads.

Automating construction requires standardized, thorough and complete information. As a result, 3D printing is more accurate and human error is greatly limited.

However, some fears have been expressed about this, especially surrounding the replacement of qualified building professionals by robots and the massive job losses that could result. Robots should mainly be used for strenuous and dangerous tasks. This is the case with 3D printing by extrusion. It goes without saying that 3D construction will create new job roles, given the specific skills needed to control, programme and maintain 3D printers. So it is not a question of replacing qualified workers, but rather of re-orienting them according to the different skills required. The printing system – comprizing mixing, pumping and robot printing – must be supervized and monitored to ensure that tasks run smoothly and the material behaves as expected. The new job roles will allow construction workers to gain new skills and construction companies to diversify their activities.

To sum up, it is currently possible to print small houses, items of street furniture and foot or cycle bridges. One of the great advantages of 3D printing is design freedom. This makes it possible to build complex forms that were previously impossible using conventional methods. Mastery of 3D printing technology and topology optimization should allow for reductions in waste, material consumption and construction costs. The use of 3D printing could also reduce the risk of work-related accidents. The majority of printing projects are carried out using mortar with a high Portland cement content. This fast-setting cement not only increases the carbon footprint of the printable mixtures, but it also favours the appearance of shrinkage cracks. These can affect the durability performance of the printed elements. In terms of printable mixtures, the priority must be to use other, more durable materials made from industrial waste or recycled concrete. Despite the many benefits of 3D printing, this construction process is still a real challenge for our sector and raises a number of questions.

5. Challenges associated with the adoption of 3D printing in the construction industry

The construction sector is increasingly adopting 3D printing, motivated by the flexibility this technology offers over conventional methods. Yet, certain obstacles and challenges are slowing its adoption. These include the initial investment, on-site installation, development of printable mixtures (see chapter 6, p. 37), structural reinforcement, surface finish, climatic conditions and lack of codes and regulations.

5.1 High cost of initial investment

Despite the savings to be made in manufacturing specific components using 3D printing, this technology first requires major upfront investment, especially in machinery, consumables, software and sometimes post-processing. Among the various factors affecting the cost of 3D construction, the printer represents the most significant initial investment. This may certainly be profitable in the medium term, but it remains a major expense. The financial viability calculation for 3D printing has yet to be fine-tuned in terms of factors such as the quantity of material and the aesthetic value it adds. The target market also comes into the equation because 3D printing is not yet deployed to print multi-storey buildings. Nevertheless, it is an attractive choice over traditional methods for niche applications such as realizing elements with a complex shape.

The price range for printers still varies greatly depending on factors such as the volume of printing, precision and performance required. A large-scale printer is normally priced at between 75,000 and several million euros (see chapter 7, p. 45, for the range of printers available on the market). The price of a printer is also affected by its compatibility with materials. Indeed some printers are only compatible with materials that have specific properties and were developed by the printer manufacturer. Yet, the printer is not the only cost relating to printing machinery. A printing system also requires a mixer and a pump to deliver material to the printer itself, and this can add up to tens of thousands of euros. Maintaining all the machinery also costs up to several thousand, or even tens of thousands of euros annually. Recruiting the specialist production operators, training them in the relevant software and paying them are other examples of costs to be added to the initial bill.

A 3D printed part originates from a model created using modelling software. Novice contractors can use a wide range of free software packages, including open source software, that are constantly being updated and improved: these include 3D modelling and slicing (see chapter 1, p. 7). Before purchasing any printer, it is strongly recommended to check the files compatible with each printing machine. The choice of software depends on the complexity of the element to be printed. Platforms are also available from which several models that have already been developed can be downloaded free of charge. Once a model has been installed, a slicer will be needed to launch the printing process. Each modelling and slicing software has its own particular features and peculiarities. Paid-for software usually provides additional functionality such as precise settings for extruders and preprint simulations that can help establish weak points which could lead to the process failing. If the user opts to pay for software, annual subscriptions can amount to several thousand euros. One can also resort to other, optional tools, such as topology optimization software that allows to save on materials (see § 4.3, p. 20) and workflow automation software that allows to send information and execute actions within a given timeframe. Such softwares are particularly expensive.

Besides the machinery, 3D construction materials also increase costs, especially where printable mixtures are based on Portland cement. Ready-to-print mixtures are available on the market such as those offered by Weber, Vicat, Sika and Cantillana. Although these are generally more expensive than mixtures developed on the basis of local raw materials, they basically guarantee that the mixture is compatible with most printers and ensure that the printed element has the desired mechanical properties.

The price of a printing system and the necessary technical expertise to employ it can limit its use in the construction industry. Yet 3D printing for construction could bring great added value, justifying the higher initial investment than for other, conventional construction methods.

5.2 Partially automated construction

Although 3D printers can reduce time and material consumption, they can only print houses with a small surface area. Nor are these machines able to print all the components of a house. This means 3D printing can only meet part of the challenge of automating the sector. It is often restricted to structural works and sometimes includes some insulation and furniture. Other elements such as the roof, finishes (floor coverings, paint, etc.), interior and exterior joinery, plumbing, electrics and reinforcement bars are installed separately – either by interrupting the printing process or after the structure has been printed.

Several factors can be considered during the design phase to make particular techniques easier to use. For example, a hollow printed wall requires less material and can incorporate insulation and water pipes. The print head may also be customized to automatically reinforce the concrete (see also § 5.3.1, p. 26).

Ultimately, researchers and designers hope to extend 3D printing into other parts of construction: for this, further research and development will be required.

As part of its evolution, the French company ERB has developed a house concept as a collaborative innovation involving more than 20 partners: SMEs and start-ups from the Pays de la Loire region of France. It aims to digitize all stages of the construction process, from augmented reality to construction using 3D printing. All the technologies and materials are selected from a very precise specification that combines the circular economy with energy and environmental performance criteria. Instead of inserting insulation into an element that has been printed from mortar, two walls are 3D printed in recycled polyurethane foam, and concrete is poured between them as the printing progresses. The idea behind this is to produce permanent, insulating formwork. The foam acts both as a mould and as thermal insulation between the building's interior and exterior. This was the method used to print a house called '*Empreinte*' in Beaucouzé, France (see figure 20).

Fig. 20 Two 3D printed polyurethane foam walls between which concrete is poured (left); and the house called '*Empreinte*' (right).

The Swedish company BLB Industries has developed a machine capable of printing doors and window frames 2.5 m high and 1.5 m wide from granules of polymer or resin material. This project and other initiatives are important milestones towards more widespread automation of the construction process.

5.3 Structural reinforcement

Since the placement of reinforcement cannot easily be integrated into the 3D printing process, arch shapes are preferred as they limit traction stresses. Although non-reinforced concrete can bear significant compression loads, it is much weaker when subjected to traction such as tension or flexion. It is not currently possible to print cantilevered components such as floors. 3D printing is therefore limited to small structures such as pavilions or walls.

For 3D printing to be adopted more broadly in practice, the printed elements must be reinforced to improve their traction strength and thus grant them sufficient mechanical properties. In contrast to conventional reinforcement methods such as pouring concrete into and around steel reinforcement cages, reinforcing 3D printed mortar requires a flexible technique that can be controlled very precisely.

Recent research has focused on improving the structural performance of printed elements. Several reinforcement strategies have been proposed and studied. These include:
- use of fibres
- continuous automated reinforcement
- adding reinforcement bars (internal or external)
- inserting cables (during extrusion or, if these are prestressing cables, afterwards).

Although many opportunities have been explored in laboratory and on a few pilot projects, these methods are not yet widespread.

5.3.1 Reinforcement during 3D printing

Fibres of various sizes and origins have been considered for use as reinforcement, including steel, synthetic and glass. These fibres are added either when the printable mixture is mixed, or in the print head to remove the risk of damaging the pumping system.

Adding fibres can improve the mechanical flexion properties of the printed element and reduce its plastic shrinkage. This can in turn reduce cracks and thus improve the quality of the mortar. Yet, adding fibres does reduce the workability of the mixture, which is essential for pumping it. Fibres also give mortar anisotropic behaviour, as its properties depend on the direction of the fibres. This direction is in turn affected by the orientation induced by extrusion (see figure 21). If significant traction loads arize, adding fibres may prove insufficient.

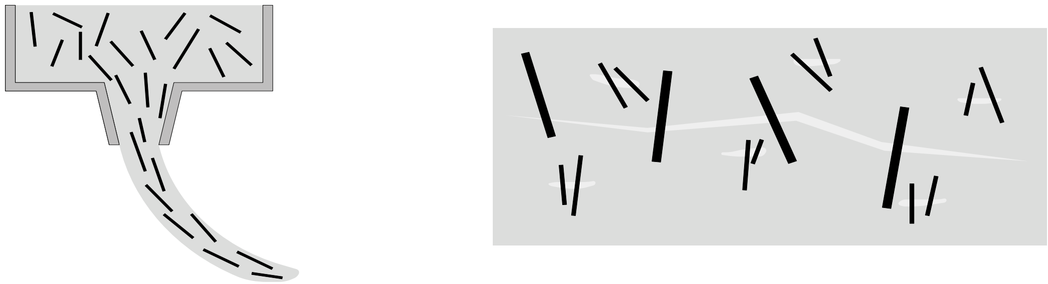

Fig. 21 Schematic diagram for 3D printing fibre-reinforced concrete. Fibres oriented in the direction of printing (left) and an illustration of the importance of distributing fibres in different directions, to limit cracks (right).

Reinforcement may also be manually inserted between layers. Reinforcement bars can be deposited horizontally after printing the layer, as illustrated in figure 22.

A method for continuous reinforcement by inserting steel micro-cables into the extruded mortar layers was proposed by Eindhoven University of Technology in the Netherlands. Although this method requires an additional mechanism to insert the micro-cables during printing, this is a first step towards automating continuous reinforcement (see figure 23). The feed speed can be regulated to synchronize concrete printing with steel micro-cable insertion. One important aspect of this method is cable slippage when the element is subjected to loads.

Fig. 22 Manually adding reinforcement between printed layers (element printed at Buildwise in collaboration with KU Leuven).

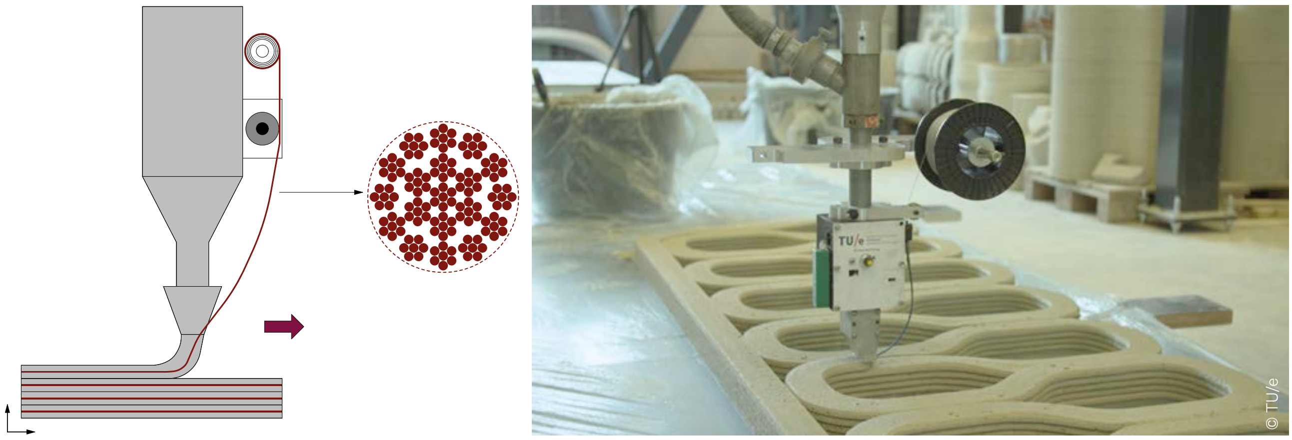

Fig. 23 Continuous reinforcement during printing. Schematic diagram (left, [M1]) and reinforcement with metal cables (right).

Researchers at Eindhoven University of Technology in the Netherlands are also exploring the possibility of using a second robot that is programmed to insert reinforcement rods into a mortar-printed element in multiple directions. This technique has been used to reinforce the steps in a spiral staircase (see figure 24A, p. 28). The robot was also used to insert screws so the various constituent components of the steps could be assembled (see figures 24B and 24C, p. 28).

A hybrid process for 3D printing reinforced structures is under development at KU Leuven, in collaboration with RWTH Aachen University, Germany. This is called Additive Manufacturing of Reinforced Concrete, or AMoRC for short. Hybrid AMoRC works by means of an intermittent stud welding and an extrusion process (see figure 25, p. 28). Segments of steel reinforcement are assembled to form a three-dimensional mesh using the welding process and are simultaneously enveloped with extruded mortar. Compared with the above

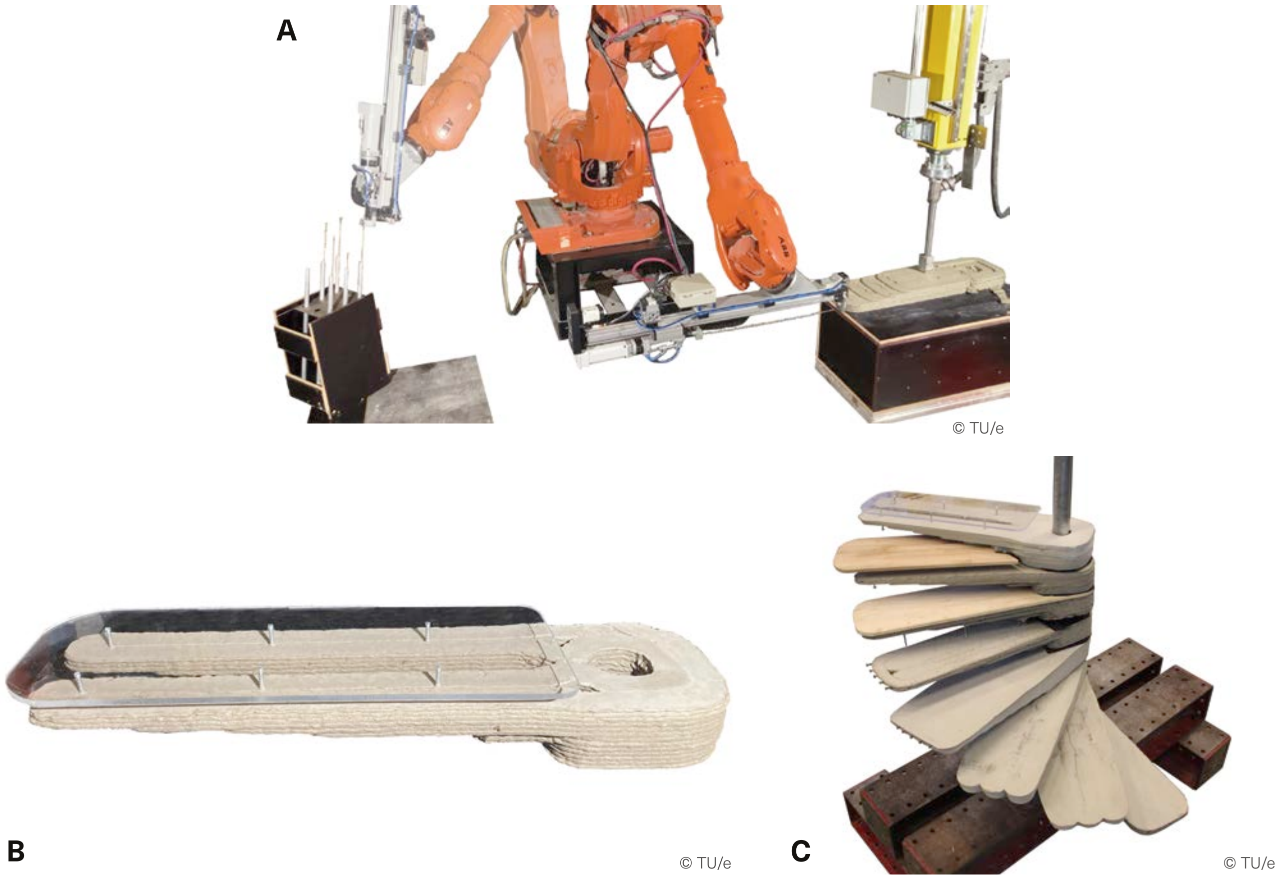

Fig. 24 Using a second robot to insert reinforcement or screws into a printed element [H1].

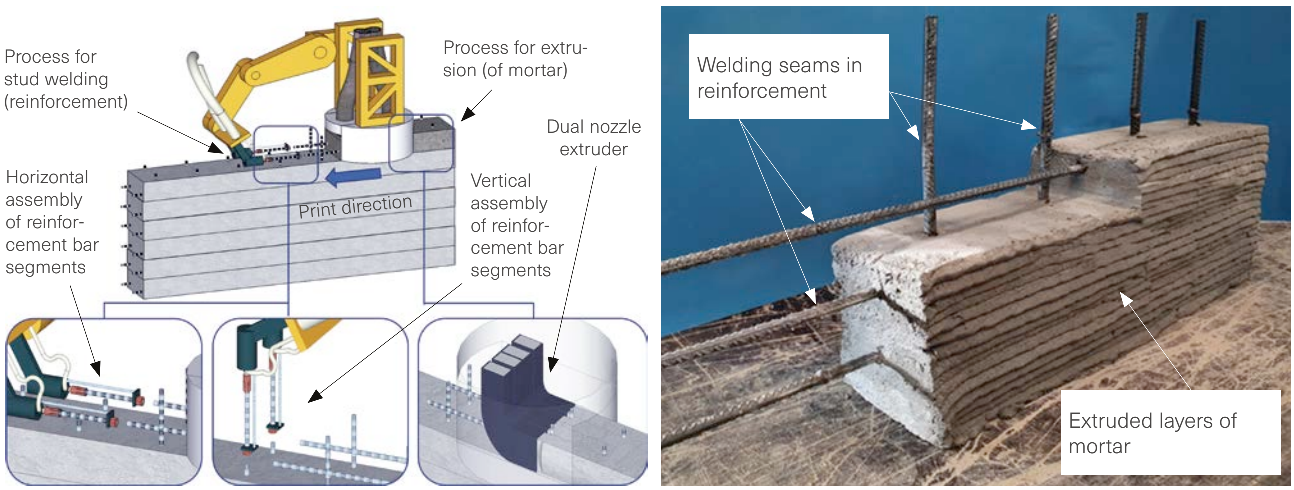

Fig. 25 Principle behind the AMoRC process and prototype printed using this process [C1].

approaches, the main advantage of this reinforcement technique is that the welding and extrusion processes can be adjusted so they work at identical feed rates. Synchronizing the two processes allows them to be combined in a single, hybrid print head to produce a reinforced printed element. Further research will however be necessary into the structural performance of this type of element.

The process for automated reinforcement proposed by Swinburne University of Technology, Australia, is similar to the AMoRC process. It comprizes reinforcing layers with mesh added during extrusion. The mesh is inserted perpendicular to the layers, and overlaps to simulate continuous reinforcement (see figure 26, p. 29).

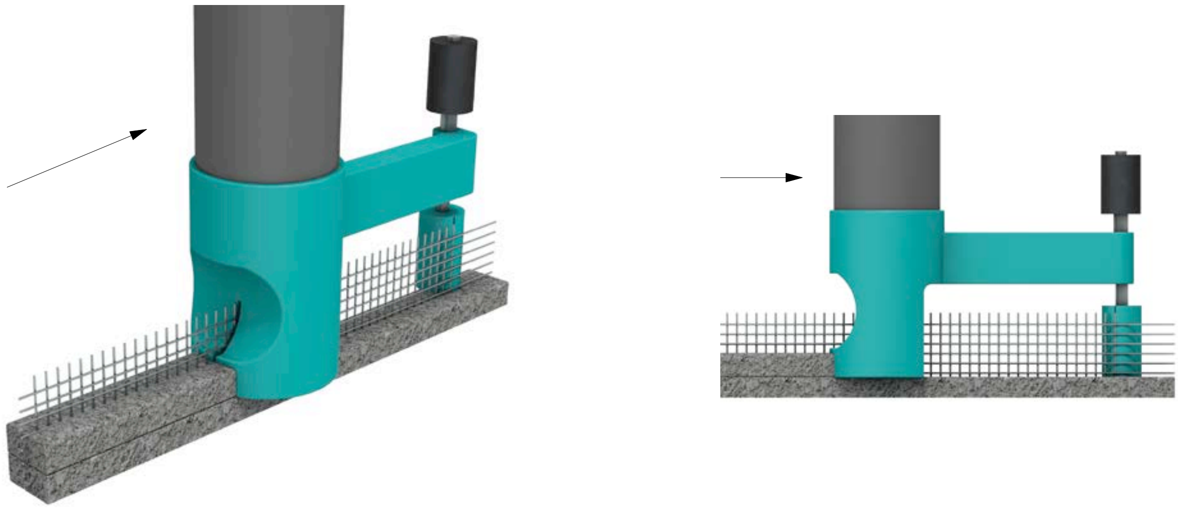

Fig. 26 Insertion and covering of mesh using a custom-designed nozzle [M2].

5.3.2 Preinstalled reinforcement

Printing hollow elements is another reinforcement strategy. One advantage of printing permanent formwork is the option to insert conventional reinforcement bars or reinforcement cages manually. Self-compacting concrete is then poured into the designated cavities (see figure 27). In this case, the printed element can be considered as permanent formwork and not as a load-bearing element. The second benefit is the ability to pass pipes and electricity cables through the cavities.

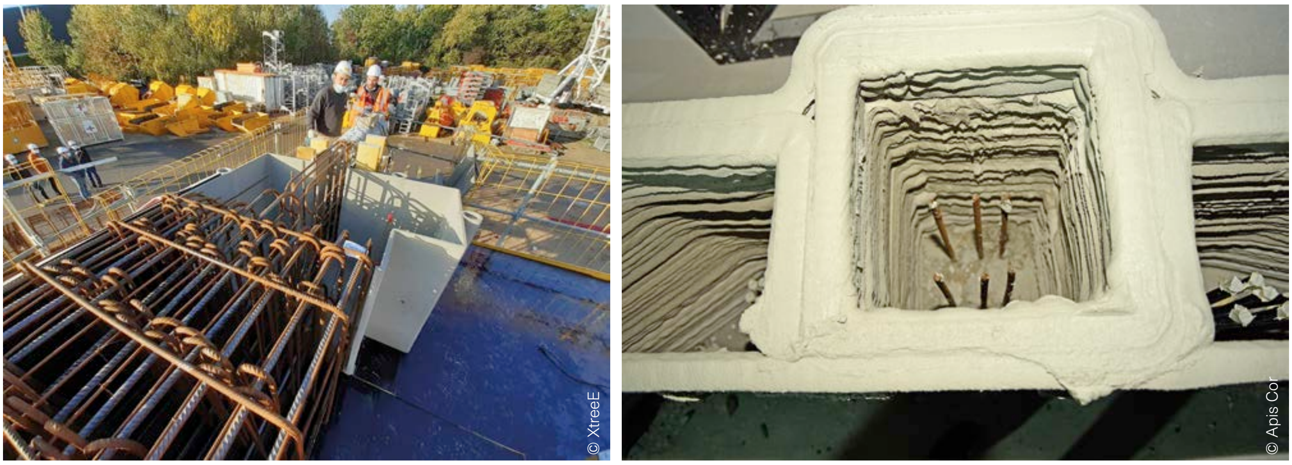

Fig. 27 3D printed beam node acting as permanent formwork (left) and concrete poured into a printed column acting as permanent formwork (right).

A new method for printing reinforced concrete was developed by the Chinese company HuaShang Tengda. Their approach uses vertical and horizontal steel bars that are held in place before a customized dual print head deposits layers of mortar on either side of the mesh (see figure 28, p. 30). This method is mainly used to construct items wholly reinforced using 3D printing, and has already been used in several projects. It does, however, restrict the freedom of shape design.

A process called Mesh Mould was developed at ETH Zurich in Switzerland. Mesh Mould uses an industrial robot equipped with a special mechanism designed to produce a dense reinforcement cage automatically by cutting, bending and welding steel bars. Once the mesh has been made, fresh concrete is poured and

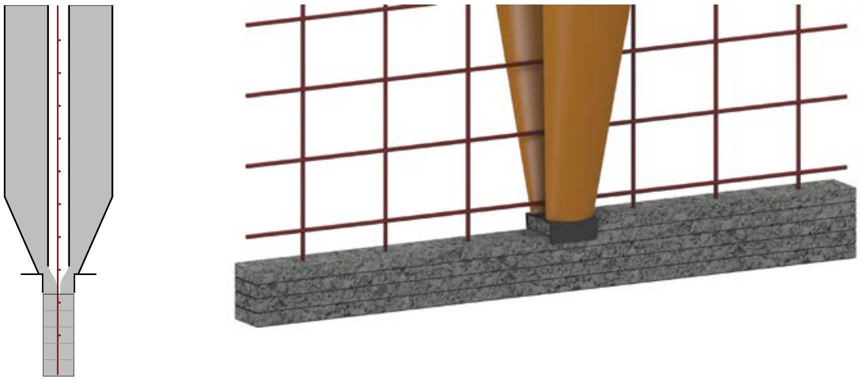

Fig. 28 Schematic diagrams for the method developed by Chinese company HuaShang Tengda, comprising printing layers of mortar on either side of a preinstalled mesh.

a covering layer can then be added. By spraying mortar in one go, the problems with layering inherent in other digital manufacturing processes can be minimized or eliminated. The mesh also plays the role of functional formwork that remains in place. Shotcrete 3D Printing (SC3DP) was developed by Technische Universität Braunschweig in Germany (TU Braunschweig). A robot assembles the reinforcement cage onto which mortar will be sprayed to produce the element. This procedure is illustrated by a reinforced column (see figure 29).

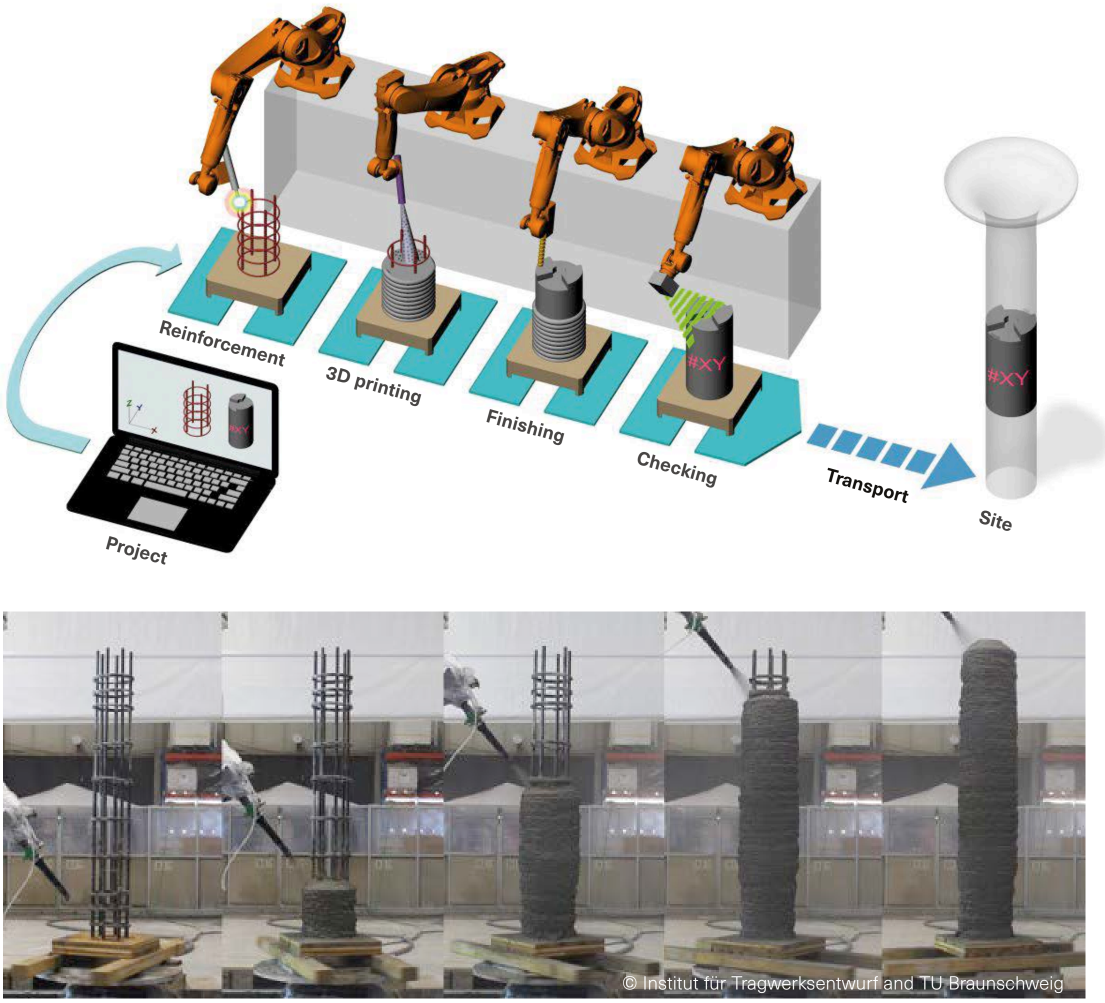

Fig. 29 Stages in building a reinforced column using the SC3DP method.

5.3.3 Reinforcement after 3D printing

It is possible to manually add reinforcement on the outside of the printed component. Figure 30 shows a beam made up of segments assembled using external bars. Sealing is used to anchor the bars in the segments. It is important to emphasize that this type of external reinforcement requires the use of corrosion-resistant reinforcement bars (for example stainless steel, galvanized or coated with a layer of epoxy resin). This is more expensive than the steel for use in conventional concrete.

Fig. 30 Beam reinforced through assembly by external reinforcement.

Another solution lies in reinforcing printed elements using the prestressing method. This technique involves creating cavities in printed elements that will ultimately be used as conduits for prestressing cables. This method has been applied to a bridge printed in mortar by Eindhoven University of Technology in the Netherlands. The bridge is eight metres long, intended for use by cyclists and installed in Gemert in the Netherlands. It was reinforced by inserting micro-cables in the direction of printing. The bridge is also prestressed lengthways (see figure 31) using steel cables anchored to the abutments. It forms part of a major road construction project (the Noord-Om project) led by the company BAM Infra and commissioned by the Province of Noord-Brabant in the Netherlands.

Fig. 31 Mortar 3D printed bridge in Gemert, the Netherlands.

At Ghent University, a laboratory-scale footbridge was designed using topology optimization (see also § 4.3, p. 20). The various components for this footbridge were 3D printed in collaboration with Vertico, a company from the Netherlands that made a mobile 3D printer, and Technion from Israel. The shape of the bridge and the trajectory of the steel cable at the foot of the bridge were optimized with a view to minimizing constraints (see figure 32, p. 32).

Fig. 32 Stages in reinforcing a printed bridge using prestressing cables.

Table 2 summarizes the advantages and disadvantages of the various methods of reinforcing printed elements.

Table 2 Advantages and disadvantages of different methods to reinforce printed elements.

	Reinforcement method	Particular features	Downsides
Reinforcement during printing	Discontinuous reinforcement (e.g. steel fibres)	Improves mechanical performance and limits cracks	Insufficient reinforcement for elements subject to high stresses, preferred orientation of fibres
	Continuous reinforcement (e.g. metal cables)	Improves mechanical performance and ductility, limits cracks	Needs a personalised print head
	Reinforcement bars inserted manually between layers	Improves mechanical performance	Needs labour during printing, risk of human error
Preinstalled reinforcement	Prefabricated steel structure (e.g. Mesh Mould)	Improves mechanical performance and stability	Application is restricted to sprayed mortar
Reinforcement after printing	Reinforcement cage placed into a hollow printed element	Improves the structure's mechanical performance	The printed element is used as permanent formwork
	Prestressing by post-tensioning	Improves mechanical performance	Needs cable placements in the design
	External reinforcement	Improves mechanical performance	Corrosion-resistant reinforcements required

5.4 Surface finish and reproducibility

The additive nature of 3D printing means that, due to the layering effect the lateral surfaces of printed elements are not as smooth as the surfaces of those produced conventionally using moulds. The surface finish of a printed part depends mainly on the thickness of the layer and the shape of the nozzle. The thickness of layers is a key parameter that influences printing time, the visual aspect and the physical and mechanical properties of the printed element.

Printed elements may also have residual porosity that, although it cannot be detected by the naked eye, can lead to failure. In addition, the interface between two layers can provide a privileged way for water and aggressive agents. It is therefore essential to ensure a good adhesion between the layers to give the materials good mechanical properties and durability. More heavily textured surfaces are also more likely to become dirty more quickly in an outdoor environment (dust, moss, etc).

Post-processing surfaces using conventional finishing techniques is one way to make surfaces smoother. Another approach of smoothing out the lateral surface of the printed layers is to attach trowels to the sides of the nozzle as illustrated in figure 33. The crenelated shape of this nozzle also creates some roughness in the upper surface of the printed layer, which increases adherence between layers.

Fig. 33 Lateral layered surface (left) and using lateral trowels for smoothing the surface (right).

For concrete elements produced by the conventional method, geometric, production and installation tolerances are defined in the European standard NBN EN 13670 [B8], and its Belgian national supplement: standard NBN B 15-400 [B5]. The European standard NBN EN 13369 [B7] establishes common rules for precast concrete products. The aspect, shade and texture of the concrete depend mainly on its composition, the nature of the formwork (whether it is smooth or textured i.e. its topography), and any processing after the formwork has been removed (such as washing or bush hammering). The specific features of exposed concrete (site-cast) that must comply with aesthetic requirements are described in the Belgian standard NBN B 15-007 [B4] and the Technical Information Note (TIN) 268 'Le béton apparent' [B2]. For architectural concrete (pre-fabricated), the Technical Specifications PTV 21-601 apply [P3].

In 3D printing, 'tolerance' describes the observed difference between the theoretical dimensions (stated on a technical drawing or CAD model) and the real dimensions of an item as built. There is currently no standard to define the aesthetic requirements or geometric tolerances for 3D printed construction.

And finally, there remains the difficulty of reproducing 3D printed houses or other objects. The materials may react differently from one build to another, depending on external parameters, and their properties may therefore vary. Each layer brings a risk of inaccuracy. It is therefore difficult to guarantee the regularity of the printed layers throughout the printing process. The 3D printer specifications and the materials used are the main parameters in determining the final precision of the printed element.

In time, research will be carried out to meet expectations in terms of precision and repeatability in 3D concrete printing.

5.5 Climatic conditions

Climatic conditions influence 3D construction significantly. Examples include the very hot, dry weather in the Middle East and the very cold, wet weather in Northern Europe. The parameters for 3D printing must therefore be adjusted to the relevant climate. This brings a variety of challenges. Research and development work is needed upstream so the technology, the equipment and especially the mixtures can be adapted to tricky climate conditions (heat, cold, wind and precipitation). 3D printing projects undertaken in extreme climates show that the process can be adapted if precautions are taken.

In some site-printed projects, the print zone has been covered with a tent to ensure a suitable temperature. This was the case when an office was printed in Copenhagen by the Danish company COBOD (see figure 34, left). In Saudi Arabia, the whole process took place in an area without any cover, where temperatures reached over 40 degrees Celsius (see figure 34, right). The mixture was designed to be appropriate for these higher temperatures.

Fig. 34 3D construction projects undertaken using COBOD printers. Office printed under a tent in Denmark (left). Three-storey house 3D printed out in the open air in Saudi Arabia (right).

Where the weather is unfavorable to construction, for example if it rains constantly, installing a tent is the most effective solution for on-site printing. However, it is not always necessary to erect a tent: this depends on the weather. PERI, manufacturer and supplier of formwork, shoring and scaffolding systems, took the initiative to print a small house during the Bauma exhibition which was held over seven days in Munich, Germany (see figure 35). Printing was done outdoors, without a tent, even while it was raining.

Fig. 35 3D printing the walls of a small house, outdoors, during the Bauma exhibition in Germany.

5.6 Lack of codes and regulations

It is important to emphasize that standards are not laws, but collections of good practice: the people concerned apply them voluntarily (these include manufacturers, suppliers and clients). They are not mandatory in nature. However, a standard may become mandatory in order to obtain a CE marking, or where laws or regulations (such as those on EPB) and contracts (such as special specifications) refer to it. The standards are always considered to be the preferred set of rules for reference where there are disputes, or claims are made for damages.

Concrete is governed by a set of standards and regulations designed to optimize its quality and the durability of the structures. For concrete used in buildings and civil engineering structures, the specifications are defined in the European standard NBN EN 206 [B14] and the Belgian national supplement NBN B 15-001 [B3]. These standards contain precise rules concerning the specification, performance, production and conformity control of concrete. They apply to concrete for structures cast *in situ* and precast structures for buildings. Additional requirements or tests with different operational methods can be established for specific types of concrete and applications, especially for concrete with a maximum aggregate diameter (D_{max}) less than or equal to four millimetres (mortar). For precast products, additional requirements are provided in the European standard NBN EN 13369 [B7] as well as in the particular product standards for each type of component.

The codes for the dimensioning of concrete structures (Eurocodes in general and NBN EN 1992 [B12] or Eurocode 2 in particular) as well as standards for the execution of concrete structures (standards NBN EN 13670 [B8] and NBN B 15-400 [B5]) require compliance with the standards NBN EN 206 [B14] and NBN B 15-001 [B3] (see figure 36). The structural Eurocodes and related standards (execution, materials and test methods) therefore act as a basis for designing and implementing structures.

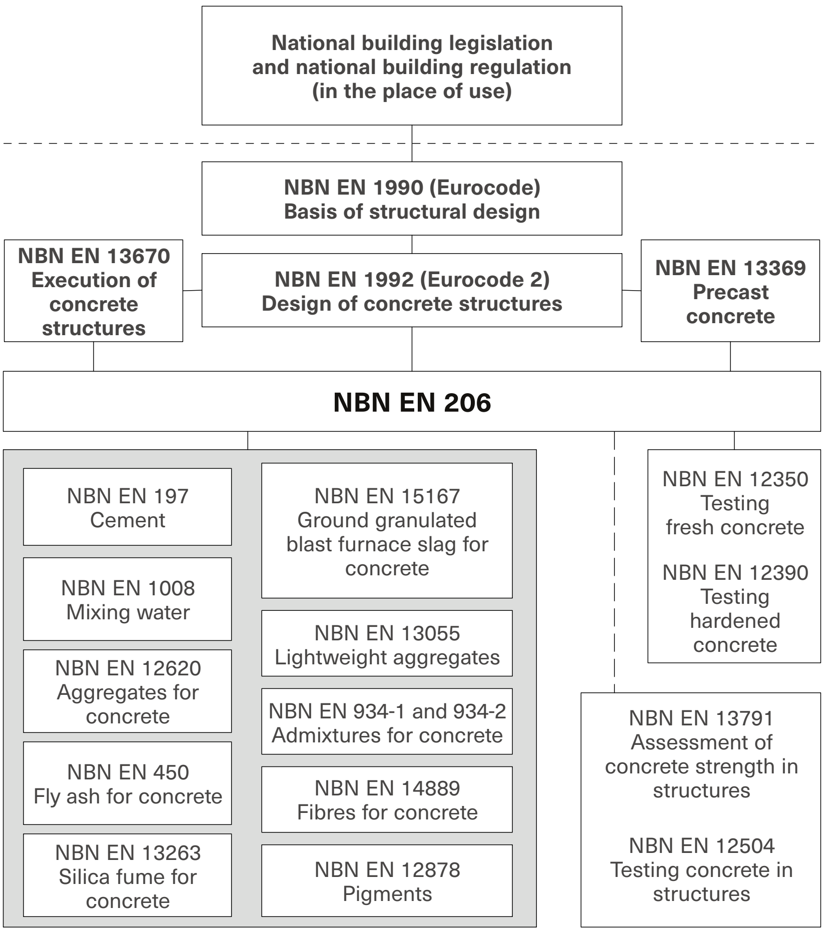

Fig. 36 Relationships between NBN EN 206 [B14] and standards for design and execution, standards for constituents and test standards, Europe-wide.

One of the most important roles that these standards play is as a tool to ensure the durability and performance of civil structures and buildings. Today, it is technically possible to print houses. However, some question marks and ambiguities remain with regard to the standardization framework for 3D printing in building.

The lack of standards is slowing down the adoption of 3D printing in the sector. In fact, the performance criteria for printable construction materials are not covered by any technical standards or recommendations: this shows that the printing process has yet to be recognized as a construction technique. Printed structures also differ from conventional structures, which makes it difficult to conduct strength and resistance calculations over time. Technical assessment is therefore essential (Technical Approval or ATG) as a way to promote innovation in Belgium and elsewhere (see also § 9.1, p. 59).

The lack of standards for 3D printing has led some projects to print formwork or hollow walls. Conventional concrete is then poured inside the printed element and mesh is added to certain cavities so that they meet the current standards (see also § 5.3.2, p. 29). For example, Batiprint 3D chose to 3D print the walls for its Yhnova student residence units using polyurethane (as an insulating material), and to pour conventional concrete between these. With this certified technology, Batiprint 3D is looking into ways to add multiple storeys to its residences.

In several countries including France and the Netherlands, some designers have opted to obtain not only planning permission, but also certification to implement 3D printing projects such as houses. In these cases, the local municipality grants planning permission, and the project is therefore managed locally. Intensive collaboration is required in order to ensure safety and obtain permission. It is often the contractor who handles the technical implementation and sends details to the relevant authorities, who use a number of assessment criteria to examine the choice of structure and supporting arguments submitted. Ensuring safety relies mainly on tests and test methods, at least some of which have only recently been developed. This is often an expensive step, as it requires additional, intensive testing. It is within the local authority's remit to ascertain whether the project is sufficiently safe. Once the works meet all the planning and construction requirements in force, permission will be granted. With the French project Viliaprint, a new 3D concrete printing method was certified by the CSTB (*Centre Scientifique et Technique du Bâtiment*) through the ATEx procedure (*Attestation Technique d'Expérimentation*). This proves that it complies with specific functionality taken from the intended application: this includes insulation, safety, waterproofing, durability and mechanical strength. In 2022, Plurial Novilia inaugurated the first five houses made with a combination of concrete walls 3D printed off-site and conventional prefabricated elements. These were not permanent formwork: they were load-bearing walls.

Acknowledging the need to provide innovations with a possible route onto the construction market, Eurocode 0 [B11] provides the option to develop structural designs based partially on experiments specific to the project, rather than general tests. Annex D 'Design assisted by testing' details the type of experiments that can be carried out and the regulations for statistically evaluating the results. Thus a test protocol may be drawn up using the options supplied by the Eurocode to deviate from generalized calculation rules. This was the case for the 3D printed cycle bridge in the Netherlands. An initial series of mechanical tests was performed to establish the relevant properties of the structural material (Annex D, Category b) including compressive strength, flexural strength and modulus of elasticity. The mechanical properties of the material applied – a printable mortar marketed by Weber – were established through an extensive testing programme. The data was used to define the final dimensions and the required level of prestressing of the cables. The ultimate limit state (ULS) was calculated on the basis of common load factors taken from the standard NBN EN 1992-1-1 [B13] and mechanical properties.

The development of standards for mortar or concrete printed elements, and the associated software for calculating and analyzing future printed structures, is proving to be indispensable for professionals dealing with designing and printing structures. Very recently, some committees and working groups have begun to examine this issue so they can gradually cover the current gaps as identified above. These groups include RILEM (International Union of Laboratories and Experts in Construction Materials, Systems and Structures) and ACI (American Concrete Institute).

6. Materials for 3D construction

6.1 Mix designs of printable mortars

Ready-to-use mortars have particular properties that depend on the type and proportion of raw materials and admixtures. These mortars are produced to meet specific requirements for specific use, such as the setting time, pumpability, workability, load-bearing capacity and durability required. Including large aggregates contributes to the mechanical strength of the mortar, improves its durability by reducing the overall shrinkage, and lowers its price due to the lower quantity of cement needed.

Ready-to-use concrete is intended for conventional use by pouring, so it does not meet the specific requirements for materials intended for 3D printing. The main reasons for the absence of large aggregates in printable mixtures are restrictions on nozzle size and the desired surface finish. A maximum particle size of 2 mm is a common choice for most 3D printing mixtures. Thus, the most fitting term for printable mixtures would therefore be 'printable mortar' or 'printable micro-concrete' rather than 'printable concrete'.

To meet the specific rheological properties required, printable mixtures use a large proportion of fast-setting cement. This ensures that the material is sufficiently fluid to be pumped, and sufficiently rigid not to collapse under its own weight or that of subsequent layers (see § 6.2, p. 38). In some cases, it may be necessary to add setting accelerator at the print head to give the mixture the required rigidity.

This is why most demonstration projects are not currently printed with conventional concrete but with ready-to-use mortar, with or without admixtures. These only need water to be added – and possibly other admixtures to modify their viscosity and setting. Such mortars are specifically developed for this particular application, and most often have a very high cement content (especially Portland cement CEM I 52.5 R). It should however be noted that these mortars have a large carbon footprint and are more expensive than standard concrete. Some printable mortars are already available on the market but the supply is relatively limited at present. It is also worth bearing in mind that some printers are only compatible with the mixtures developed by their manufacturers, which further restricts the choice available.

The absence of large aggregates and the high proportion of fast-setting cement may worsen the issue of shrinkage and therefore affect the durability of the printed elements. Some ready-to-use mixtures contain fibres such as polypropylene to control cracking due to plastic shrinkage (see § 5.3.1 p. 26). To avoid or limit the drying (shrinkage) of the printed element, a curing compound can be used, the printed element can be covered by a plastic sheet throughout the hardening period, and the printing can be done in a temperature- and humidity-controlled environment. The use of shrinkage reducing admixtures is another option to limit the shrinking of the printed element. No study or experience has yet shown that printed houses perform as well as, or better than, houses built using conventional methods. Indeed, given the current stage of development in 3D printing, it is difficult to accurately estimate the lifetime of a 3D printed house.

The current priority for making 3D printing more environmentally friendly is to reduce the amount of Portland cement within printable mixtures. This will be replaced with other types of cement that have lower carbon footprint, such as binary or ternary cements containing less clinker, or alkali-activated cementitious materials. Although cementitious materials are still the main ones used for many 3D printed construction projects, it may be worthwhile turning to natural materials available locally. It is however important to check whether these are compatible with the printing machine.

Initiatives have been launched to make 3D printing more environmentally friendly. They aim to reduce the carbon footprint of printable mixtures and address the shortages of natural resources (see also § 4.3, p. 20). There are many difficulties associated with replacing the binder and the granular skeleton. Adding minerals can make the mortar more or less fluid than it was initially, and thus influence its extrudability and buildability. Mechanical strength and durability depend on the nature of the raw materials used and the level of cement substitution.

Within this perspective, research laboratories are currently working to optimize the incorporation of industrial byproducts and mineral additions in printable mortars, in combination with Portland cement. These include limestone filler, a byproduct of the aggregate and limestone industries, as well as blast furnace slag from the steel industry, and fly ash from burning pulverized coal in the boilers of thermal power plants. These last two are becoming increasingly rare. All the above materials have been used in mixtures for 3D printing to replace totally or partially the Portland cement. Although some composite cements are already on the Belgian market (like CEM III type blast furnace cement), this research opens the way for new types of 'low carbon' ternary cement defined in the NBN EN 197-5 [B10]. These are Portland-composite cement CEM II/C-M and composite cement CEM VI.

Substitute materials have also been considered for the mortar's granulate skeleton, usually made from natural sand. The European CIRMAP project aims to completely replace natural sand with recycled sand, prepared from crushed concrete obtained from demolished buildings (see figure 18, p. 22). Researchers at the University of Texas, United States, are proposing a new range of natural construction materials of earth-based origin, which are reconfigured into extrudable formulations compatible with the additive manufacturing of buildings [B1].

6.2 Desirable characteristics in the printable mixture

The choice of material remains a fundamental factor in the success of 3D printed construction, alongside 3D printer capacity and printing parameters. Several research projects have focused on the mix design and characterization of mixtures designed for 3D construction. Each of the materials has distinct properties that may affect the end result. Three factors need to be taken into account when developing 3D printing mixtures:

- rheology
- mechanical performance
- durability.

Rheology covers the behaviour of materials at fresh state: workability and hardening. Mechanical properties and durability are defined depending on the material's final application in the project. They include load-bearing, risk zones, exposure and environmental classifications.

Developing 3D printable micro-concrete or mortar is a real challenge. A printable mixture has a specific composition that ideally combines the benefits of shotcrete and self-compacting concrete. First and foremost, the mixture must have the right consistency – fluidity and stability under pressure – to be pumped through a pipe and extruded through a nozzle with a particular section without showing any signs of segregation or risking blockages. The geometry of the nozzle highly depends on the material parameters (the maximum aggregate diameter). Once it has been extruded through the nozzle, the mixture must be sufficiently stiff and rigid not to collapse under its own weight or be deformed by the weight of subsequent layers.

To sum up, the workability of the mixture must be adapted to the pumping process, the extrusion rate from the print head and the speed of printing. The mixture must also harden quickly to avoid the structure collapsing and allow a vertical structure to be printed continuously. A printable mixture is therefore pumpable, extrudable and buildable (see figure 37c, p. 39): it is a fast-setting, fluid mixture. These contradictory, complex characteristics – a mixture that is fluid prior to extrusion and stiff afterwards – have led to several consequences. Different print head designs have been developed (with or without mixer, static or dynamic, with the option of adding admixtures), the large aggregates in the composition of the mixture have been limited (a maximum diameter established for a given nozzle size), and admixtures and other additives have been used to adjust the consistency (e.g. superplasticizers, setting accelerators, viscosity modifying agents).

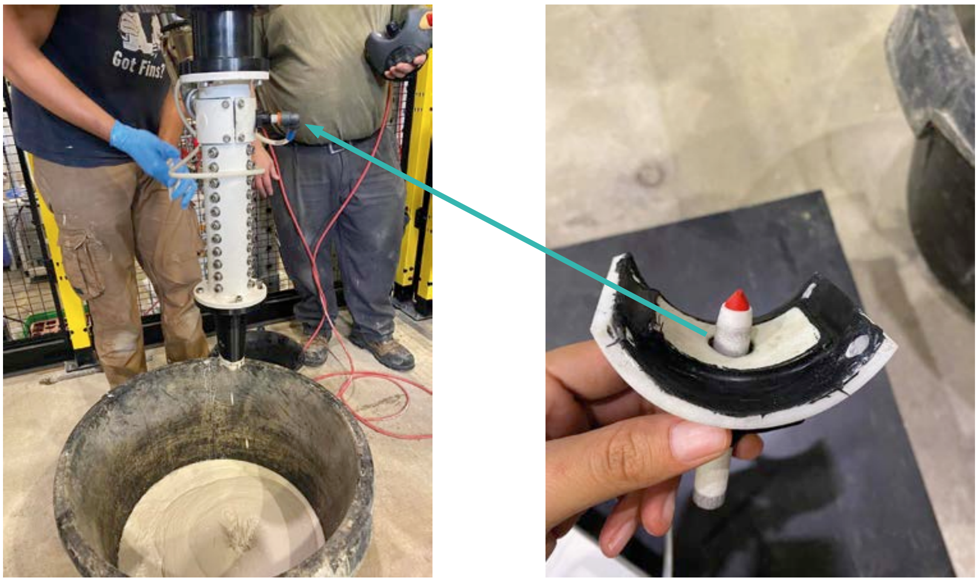

Fig. 37a 3D printing experiments conducted at Buildwise. Injecting setting accelerator into the print head equipped with a dynamic mixer.

Fig. 37b 3D printing experiments conducted at Buildwise. Mixture considered too fluid (high slump, non-buildable mixture).

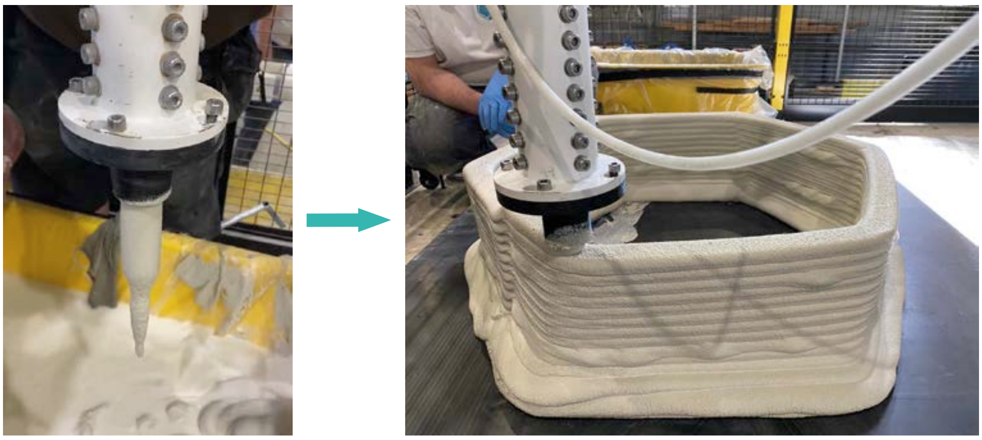

Fig. 37c 3D printing experiments conducted at Buildwise. Printable mixture considered acceptable (pumpable, extrudable and buildable).

Fig. 37d 3D printing experiments conducted at Buildwise. Mixture considered too stiff (not extrudable).

A mixture that is fluid, stable and low-friction during pumping can be achieved by incorporating mineral admixtures such as limestone filler or fly ash, by using a granular fraction of a limited size (usually with a D_{max} of 2 to 4 mm) and by incorporating admixtures like superplasticizers and viscosity modifying agents. It is also possible to use other minerals to obtain particular desired characteristics, like clay or bentonite to modify the thixotropy. However, the rapid hardening of the mixture after extrusion remains a major challenge for 3D printing. After the material has been extruded, it is not possible to achieve the desired stiffening purely by structuring[5] and hydrating the cement. Mortar needs to transition rapidly from a fluid state to a more solid state. In order to achieve this, a setting accelerator is often incorporated into the ready-to-use mixture (in its dried form) or injected and mixed with the fluid mortar in the print head (see figure 37a, p. 39). The choice of accelerator takes account of its compatibility with other ingredients. The quantity must be adjusted according to the type of cement, the shape and size of the element to be printed, the extrusion rate, the printing speed (speed at which the print head moves) and the time gap between printing two layers (which depends on the length of the printed path). For example, when printing small areas the delay between depositing two successive layers is reduced. Sometimes the layer of mortar deposited does not have enough time to harden sufficiently to bear the weight of the following layer (see figure 37b, p. 39). In such cases, the quantity of setting accelerator injected at the print head must be increased. If on the other hand there is more stiffening due to an excess of setting accelerator or a very long waiting time between layers, perhaps because the printer is temporarily out of service, then the print head may get blocked (see figure 37d, p. 40) and there may be problems with adhesion between layers. It is therefore required to tightly understand the rheology of fast-setting mortar.

Portland cement has been replaced – in particular with special and composite cements – to make cementitious products with high reactivity and rapid strength increase. For example, calcium aluminate-based cement accelerates the hardening of mortar layers, which increases the vertical construction speed. Special cements can also be used for 3D printing concrete if the printed element will be exposed to particular environmental conditions. Examples of cementitious mix designs used in 3D printing, patented by Vicat, and their rheological and mechanical properties, are presented in table 3 (p. 41).

To sum up, using fast-setting and fast-hardening cement and admixtures such as fly ash, silica fume or accelerators makes it possible to adjust the rheological behaviour of the material to be printed. However, there remain challenges to be overcome when considering undertaking a particularly high build in a short space of time, because the weight of successive layers adds considerable pressure on the layers below. 3D printing also requires a continuous supply of material. Stopping extrusion and consistency of the mixture affects

(5) This is due to a reversible physical phenomenon of colloidal origin – not to be confused with the setting of the material, which is an irreversible chemical phenomenon (for thixotropic behaviour, see § 3.1, p. 11).

the inter-layer adherence and may create weak porous zones. These can negatively influence the long-term durability of the printed element. There is also the issue of shrinkage occurring in the mortar if it dries too quickly. Avoiding this will in turn limit cracking (see also § 6.1, p. 37).

Table 3 Examples of cementitious mix designs patented by Vicat (international publication number for patents: WO2020/021202A1).

Mixture reference	Constituent		Proportion [% of mass]	Cone spreading without strokes according to NBN EN 1015- 3 [B6] [mm]	Compressive strength after 28 days [MPa]
E-1	Premix	Portland cement CEM I 52.5 R	28.1	175 (without setting accelerator)	92.1 (with setting accelerator)
		Limestone filler	33.2		
		Metakaolin	0.5		
		Sand	38.3		
	Liquid admixtures	Superplasticiser	1.6 (% binder weight)		
		Setting accelerator	variable		
	Water	W/C = 0.48			
E-2	Premix	Portland cement CEM I 52.5 R	17.5	152.5 (without setting accelerator)	86.2 (with setting accelerator)
		Sulfoaluminate cement (SAC)	7.5		
		Limestone filler	20		
		Metakaolin	5		
		Sand	50		
	Dry admixtures	Setting retarder	0.5 (% binder weight)		
		Setting accelerator	0.4 (% binder weight)		
	Liquid admixtures	Superplasticiser	1.5 (% binder weight)		
		Setting accelerator	variable		
	Water	W/C = 0.55			

6.3 Fresh-state characterization of printable mixtures

In the absence of standardized tests, many studies have been conducted to define and characterize printable mortar. It is essential to test the printability of the mixture first, to see if it is suitable and thus avoid blockages and/or collapse. Indeed, a blockage in the pumping hose may lead to considerable financial loss due to an unexpected stoppage in the printing process, the need to dismantle the hoses and the waste of materials. These studies are limited to specific, tested mixtures and machine parameters. The printing machine (printer), nozzle shape, extrusion rate and speed of printing have been shown to influence the quality of the printed layer. The studies conducted in laboratories proposed methods for checking the printability of the mixtures developed on a small scale. Each test method allows one or more characteristics of the printable mortar to be checked, including pumpability, extrudability and buildability.

The French laboratory Navier-Ecole des Ponts Paris Tech has developed a test for and the assessment of the printable materials yield stress. The test consists in determining the mixture's yield stress by weighing the drops exiting the nozzle before deposition (see figure 38). In fact, the drop flows and breaks up as a 'slug' when the stress induced by its own weight exceeds its yield stress. Thus, the higher the mass of the drop, the higher the material's yield stress. The calculated yield stress is then correlated to the printability of the material. This test is suited to adjusting the printing parameters according to the yield stress at the nozzle outlet, to ensure successful printing. Theoretical models based on the evolution of a material's yield stress have also been proposed by researchers attempting to predict the printability of a mixture [P2].

$$\tau_0 = mg/\sqrt{3}\pi r^2$$

where τ_0 is the yield stress (in Pa),
m is the mass of a drop (in kg) and
r is the radius of the nozzle (in m)

Fig. 38 The principle of the slugs test to determine the mortar's yield stress at the nozzle outlet.

A simple silicone gun could be used to manually test the extrudability of a mixture through a predefined size of nozzle, as illustrated in figure 39.

A penetration test (fall cone method, Vicat needle or similar) can be used to predict the buildability of a mixture. For example, the Vicat test is used to assess the setting time depending on the penetration depth of a needle into the mortar. The needle will penetrate less and less over time, reflecting the hydration kinetics of the cementitious mixture.

Fig. 39 Silicone gun used to test the extrudability of printable mixtures (left) and example of layers printed using this gun (right).

Some laboratories have developed small-scale printers (laboratory scale) to assess the extrudability and the buildability of a mixture prior to its large scale printing. Figure 40 illustrates the laboratory-scale printer used at Buildwise.

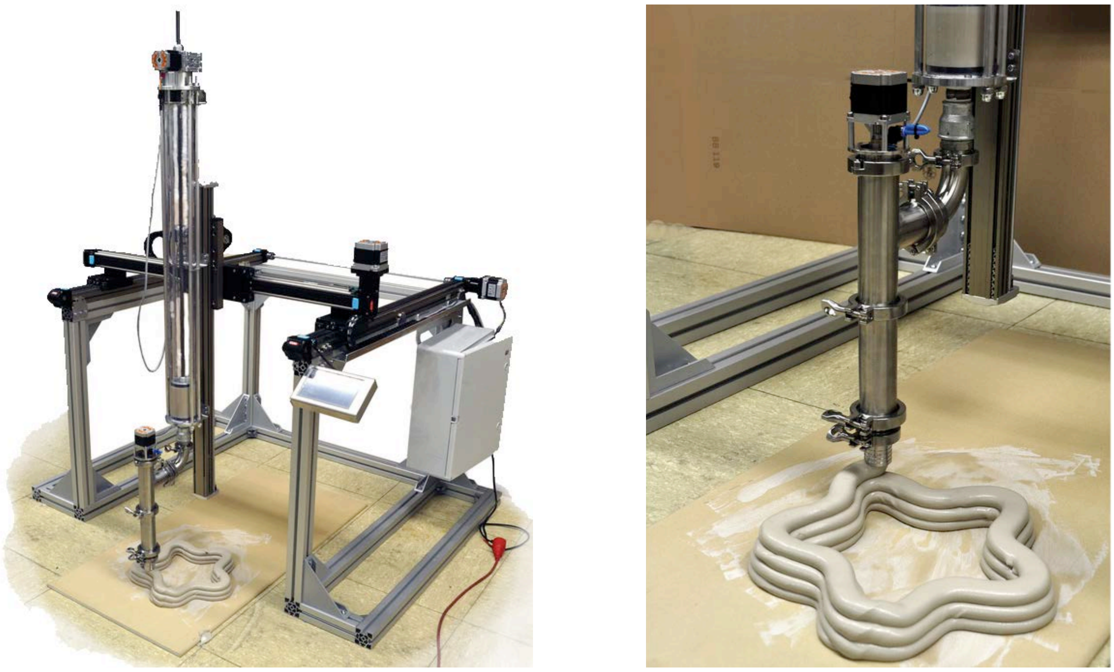

Fig. 40 Laboratory-scale printer used at Buildwise.

All the research undertaken has allowed two additional terms specific to mortar for 3D printing to be added: the printability limit and the blockage limit. The printability limit is the longest period for which a mixture can be printed at an acceptable print quality. The blockage limit is the longest period for which a mixture can remain in the nozzle before the mortar stiffens and thus prevents extrusion. These two limits should ideally be measured and reported for each specific mixture.

6.4 Mechanical performance of printed elements

In situ cast concrete has relatively isotropic mechanical behaviour[6]. In contrast, mortar-printed elements behave anisotropically, which means that their mechanical performance depends on the direction(s) in which loads are applied (in relation to the direction of printing). This anisotropy is due to heterogeneity caused by air pockets and adherence between successive layers. If the adherence between layers is of good quality, this could minimize anisotropy and generate quasi-isotropic behaviour. The mechanical performance of printed elements thus depends on machine parameters such as the speed at which the print head moves and the flow rate.

The stratification in the structure created by layer-by-layer deposition causes the mechanical performance to vary – in terms of compressive, flexural and traction strength – along three axes defined by the direction in which the material is deposited, the width of the layer and the height of the printed element (x, y and z in figure 41, p. 44). Properties within the deposited layer are different to properties between layers, which pro-

[6] Isotropy is where a material's physical properties remain the same regardless which direction they are measured in.

duces differences in mechanical performance between samples extracted from different places in a printed element and tested in different directions. Printed mortar therefore also behaves orthotropically[7].

The standardized test methods for conventional concrete and mortar are not necessarily suited to use on printed structures. It is necessary to revise the existing standards or adopt new regulations to assess the mechanical performance of printed mortar. The level of orthotropy in a printed structure is also an essential aspect in evaluating the overall mechanical behaviour. That is why it is necessary to extract, or take core samples, from different places and in different directions, and to test these in different orientations as illustrated in figure 41. The characteristics measured could thus be compared to those obtained from the same material poured into a mould (isotropic behaviour).

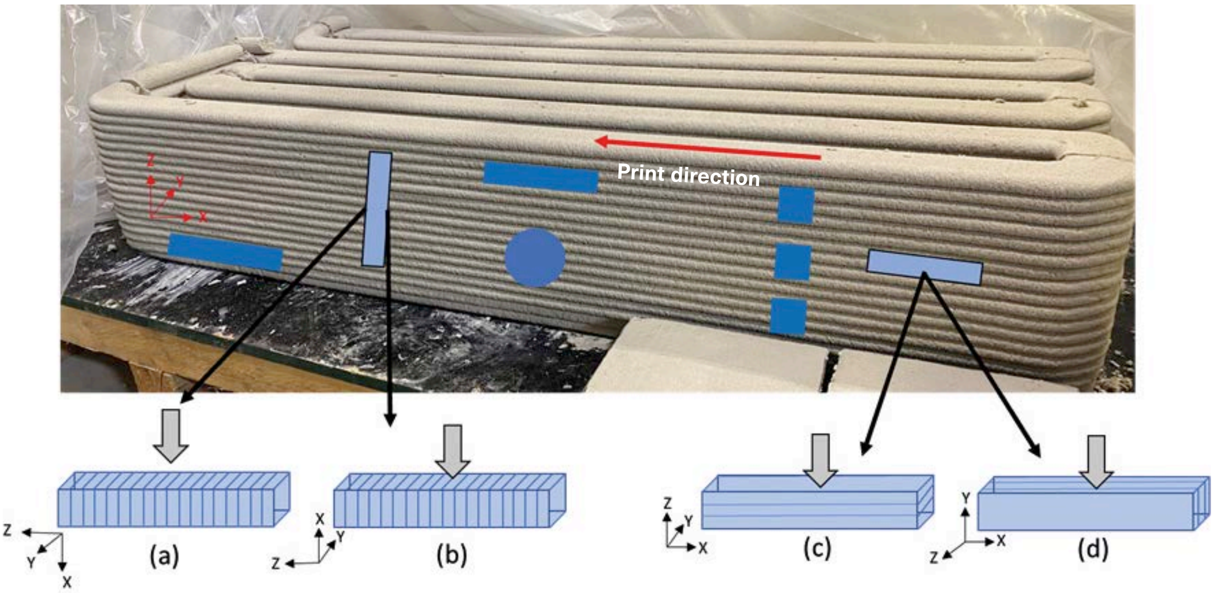

Fig. 41 Extracting samples from a printed element to assess its mechanical performance and durability.

Printed mortar could perform better mechanically than the same material cast in moulds. This can be explained by the beneficial effect of extrusion on the density of mortar (reduced total porosity).

Compressive strength usually shows the highest value when the load is applied perpendicular to the direction of printing in prisms extracted in the deposition direction (see figure 41 (c)). Indeed, the bonding area between two layers is more porous than the material inside the layer. In principle, elements printed using ready-to-use mortar have higher compressive strength (50-90 MPa) than elements made using conventional concrete (30-45 MPa). Flexural strength is around 10-15 % of compressive strength. Printed elements subjected to flexion or traction must therefore be strengthened using reinforcements that are difficult to integrate into the printing process (see § 5.3, p. 26).

(7) A particular case of anisotropy. A material is orthotropic if it has three planes of symmetry that are orthogonal with one another. Its mechanical properties are different and independent in three directions that are mutually perpendicular.

7. Printing machines used for 3D construction

A printing machine is mainly designed to guide the print head in accordance with the instructions programmed into control software that determines its trajectory, precision and print speed. It is in general accompanied by a silo filled with dry material and a mortar pump. It should be noted that there are three types of extrusion printing machines (see also § 3.1, p. 11): gantry, lever, and robotic arm printers.

Today, these printers come in different sizes:

- small printers, specially designed for work in laboratories (see figure 40, p. 43), can print elements measuring just a few centimetres and are mainly used for educational and scientific purposes, e.g. developing printable mix designs and testing some machine parameters
- large printers, dedicated to large-scale printing in factories or on-site. For on-site printing, the printer must be transportable and relatively easy to assemble and disassemble.

For printing on a large scale, a number of machines are available on the market. The choice of the adequate machine for a printing project depends on the application, mobility on-site, printing area and ability to print complex geometries.

Table 4 shows a selection of printers used for 3D construction. Besides these machines (manufactured by Concrenetics, CyBe Construction, Constructions-3D, WASP, COBOD and Apis Cor), other manufacturers such as BetAbram, Batiprint3D, MudBots 3D Concrete Printer, BAAM, AMT, XtreeE, Vertico and ICON offer machines for 3D printing concrete.

Table 4 Examples of 3D extrusion printing machines and their main features.

<table>
<tr><th>Company (country)</th><th>Printer</th><th>Type</th><th>Printing area (volume)</th><th>Compatible materials</th><th>Maximum speed with which the print head can move [mm/s]</th><th>Applications</th></tr>
<tr><td>Concrenetics (Belgium)</td><td>One-X</td><td>6-axis robotic arm</td><td>3.2 m reach and 2.4 x 2.4 x 3.0 m³ print volume</td><td>'Cantillana' printable premixture and other mortars</td><td>600</td><td>Prefabricated elements (e.g. street furniture)</td></tr>
<tr><td rowspan="6">CyBe Construction (Netherlands)</td><td>G</td><td>Gantry</td><td>7 (length) x 10 (width) x 4 (height) m³</td><td rowspan="6">Printable premixture from CyBe Construction (CyBe MORTAR) and other mortars</td><td>250</td><td>Prefabricated elements, relatively large (e.g. a house)</td></tr>
<tr><td>GR</td><td>Gantry</td><td>7 (length) x 10 (width) x 4 (height) m³</td><td rowspan="5">500</td><td>On-site printing of larger structures (e.g. a house)</td></tr>
<tr><td>R</td><td>6-axis robotic arm</td><td>2.65 m (circumference) x 3.2 m (height)</td><td>Relatively small prefabricated elements (e.g. street furniture)</td></tr>
<tr><td>RC</td><td>6-axis robotic arm</td><td>5 m (circumference) x 3.2 m (height)</td><td>On-site printing of smaller elements (e.g. street furniture or small buildings)</td></tr>
<tr><td>RT</td><td>6-axis robotic arm</td><td>5 (minimum length) x 2.5 (width) x 4 (height) m³</td><td>Relatively small prefabricated elements (e.g. street furniture)</td></tr>
<tr><td>Constructions-3D (France)</td><td>Maxi Printer</td><td>4-axis telescopic arm</td><td>10 m (height) and 9.5 m (length of arm/radius)</td><td>Mortar</td><td>300</td><td>Houses and structures in situ</td></tr>
<tr><td>WASP (Italy)</td><td>Big Delta</td><td>Delta</td><td>12 m (height) x 6 m (circumference)</td><td>Natural and cementitious materials</td><td>400</td><td>Houses and structures in situ</td></tr>
<tr><td>Cobod (Denmark)</td><td>BOD2</td><td>Gantry</td><td>49.4 (maximum length) x 14.6 (width) x 8.1 (height) m³</td><td>Cementitious materials: mortar and micro-concrete (D_{max} = 10 mm)</td><td>1000</td><td>Houses and structures in situ</td></tr>
<tr><td>Apis Cor (United States)</td><td>Frank</td><td>Crane</td><td>3.2 m (height) and 5.5 m (radius)</td><td>Mortar</td><td>333</td><td>Houses and structures in situ</td></tr>
</table>

Concrenetics: *One-X Industry*

The Belgian company Concrenetics has developed a machine that allows the printing of prefabricated elements, for example street furniture (see figure 42) in a factory. It consists of a six-axis robotic arm (ABB IRB6700) with a range of 3.2 metres, built into the *One-X* system. This comprizes a silo that can store up to 1,200 kilos of dry material (printable mixture) and can therefore produce up to 600 litres of printable mortar, a mortar pump, a robotic arm and a print head. The head is equipped with a dynamic mixer, and an admixture (setting accelerator) may be added immediately prior to extrusion. The system has an access control barrier so it can operate safely. Its print volume is 2.4 x 2.4 x 3.0 m^3. An optional rail extension is available to increase the system's capacity – giving a wider printing area.

Fig. 42 *One-X Industry* system (left) and an element printed using this system at Buildwise (right).

CyBe Construction: *G, GR, R, RC* and *RT* systems

CyBe Construction, from the Netherlands, manufactured different types of printers: gantry printers (*G* and *GR*) and robotic arm printers (*R*, *RC* and *RT*) (see figures 43a, 43b (p. 47) and 43c (p. 47)). Their gantry printers and the model *R* printer are in a fixed position. Their robotic printers have six-axis robotic arms (ABB). The models called *RC* and *RT* are mobile, as they are either crawlers (*RC*) or on a track (*RT*). This enables them to be moved from one construction site to another. CyBe Construction has also developed *CyBe MORTAR*, a special (compatible) mixture designed for their printers. Their printing machines are also compatible with other mortars.

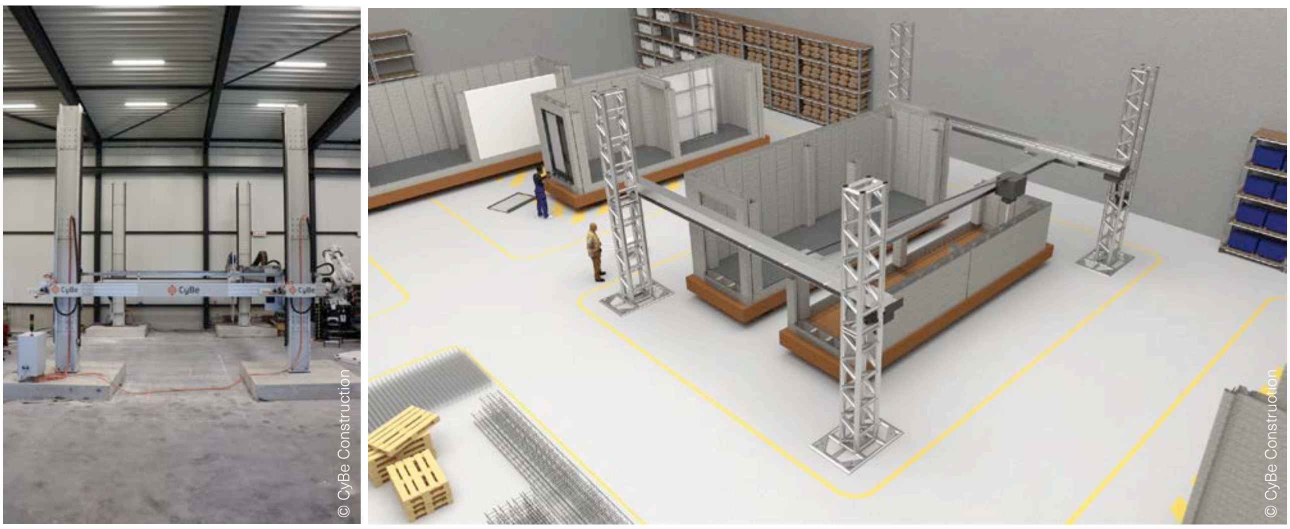

Fig. 43a Printers *CyBe G* (Gantry) and *CyBe GR* (Gantry Robot) from CyBe Construction – https://cybe.eu/.

Fig. 43b Printers *CyBe R* (Robot) et *CyBe RC* (Robot Crawler) from CyBe Construction – https://cybe.eu/.

Fig. 43c Printer *CyBe RT* (Robot Track) and example of a printed structure in the Netherlands made by robotic printer *Cybe RC* – https://cybe.eu/.

Constructions-3D: *Maxi Printer*

The 3D *Maxi Printer* was designed by the French company Constructions-3D (see figure 44). This is a large-scale printer comprizing a four-axis telescopic arm optimized for deployment on-site. For research and development, the company manufactured a smaller printer, named ‘*Mini Printer*’. It can print construction elements measuring up to 66 x 52 x 70 cm^3.

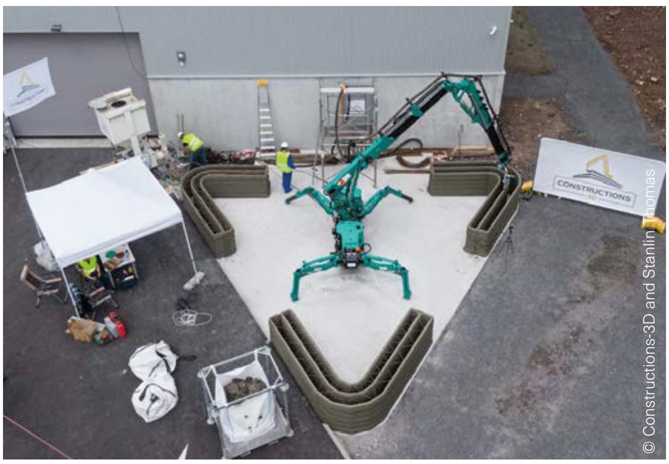

Fig. 44 *Maxi Printer* developed by Constructions-3D.

WASP: *Big Delta*

The Italian company WASP (World's Advanced Saving Project) offers two large-scale printing machines: *Crane* (see § 4.2, p. 18, and figure 16, p. 20) and *Big Delta*. *Big Delta* is a twelve-metre tall, six-metre circumference printing machine (see figure 45). It looks like a large scaffold from which a print head is suspended in the centre. The robot's mobile extremity is guided by three parallelograms and the motors are attached to the frame. This is a major difference compared to conventional serial robots, where the drive motors for each joint move along with it, which adds significant inertia to the motion. *Big Delta* has its motors attached to the frame, which makes the mobile part lighter. It can therefore move using less powerful motors. Although this printer was designed to print using locally-available natural resources such as clay and mud, it is also compatible with cementitious materials.

Fig. 45 3D printer *Big Delta*.

COBOD: *BOD2*

COBOD, a Danish company, recently unveiled the *BOD2* – an improved version of the *BOD1* printer. This is a gantry printer specially designed for on-site printing (see figure 46). The system can be extended in any direction using modules – for printed elements up to a maximum of 49.4 metres long, 14.6 metres wide and 8.1 metres high. Kamp C, the Centre for sustainability and innovation in construction in the Province of Antwerp, used this machine to print a two-storey house at Westerlo.

Fig. 46 *BOD2* printer (left) and house printed using *BOD2* at Kamp C (right).

Apis Cor: *Frank*

The American startup Apis Cor has developed a mobile printer called *Frank* which can print houses *in situ* (see figure 47). This is a portable printer that can be delivered to a construction site. It looks like a crane mounted on a mobile platform with a caterpillar track. The printer has a detachable arm that can reach up to 3.2 metres high, and a print range (radius) of 5.5 metres. To print taller buildings, the printer can be moved to an upper storey or installed on a elevated platform.

Fig. 47 *Frank* printer developed by Apis Cor.

8. Examples of 3D printing applications

Many projects and achievements have demonstrated the wide range of possible applications for 3D extrusion printing of cementitious materials in the construction sector. The development of large-scale 3D printers has facilitated the printing of full-scale structures. To date, with the exception of a few structural applications, 3D construction has been limited to non-structural applications. Some projects such as houses and offices on a small or medium scale can be printed on-site using transportable printers (see chapter 7, p. 45). Other projects such as street furniture, staircases and façade elements are printed in a controlled, factory environment – as prefabricated elements – before being installed or assembled on-site. In addition to the structure of the houses (external and internal walls), already highlighted in previous chapters, the present document also sets out a selection of other 3D printed elements and works to illustrate how this innovative technology is being used on a large scale. The examples can be divided into three categories:

- permanent formwork
- non-structural applications (such as underground structures, street furniture, façade elements and artificial reefs)
- structural applications (such as load-bearing walls, footbridges, staircases and wind turbine bases).

8.1 Permanent formwork

3D printed elements from mortar can be used as formwork to place steel reinforcement and pour concrete within. They therefore become permanent formwork, an integral part of the structure.

This technique can be applied to pylons, such as those supporting telecommunications antennae, which are usually made from steel. A tree-shaped, 12 m-high pylon was created by printing and assembling 6 x 2 m formwork segments (see figure 48). The segments will be planted so that they blend into the landscape as shown in the figure below. The overall structure was made by stacking the various factory-printed modules on top of one another. This was all held in place by steel cables run through ducts sealed with ultra-high performance fibre-reinforced concrete (UHPFRC) and tightened fully using jacks. The permanent formwork remained in place and acted as a protective layer for the concrete poured within.

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Fig. 48 12 m-high pylon produced by 3D printing and assembling of six formwork segments.

Figure 49 shows an example of outdoor column moulds, exposed on the façade of the YRYS house in Alençon, France. These were printed in a factory, transported to site and then filled with UHPFRC so they could perform as structural elements.

Fig. 49 Moulds for 3D printed outdoor columns.

8.2 Non-structural applications

In partnership with Point P Travaux Publics and Sade, XtreeE has printed underground works. These were a stormwater overflow (see figure 50) and manholes. The elements were printed in XtreeE's factory then transported to and installed on-site. In Rouen (France), in partnership with GTM Normandie Centre, XtreeE printed a starting bell for a tunnel boring machine (TBM) from mortar. These bells are conventionally made from metal (see figure 51, p. 52). Part of the bell was prefabricated in the factory, and part was cast *in situ*. A ring was printed with the precise geometry. It included cut-outs, or 'ears', into which reinforced concrete was poured. These allowed it to be anchored into a prefabricated shell. This shell was in turn placed in its final position, then concrete cast to adjust the unit to the walls of the excavation.

Fig. 50 Stormwater overflow installed in La Madeleine, Lille, France.

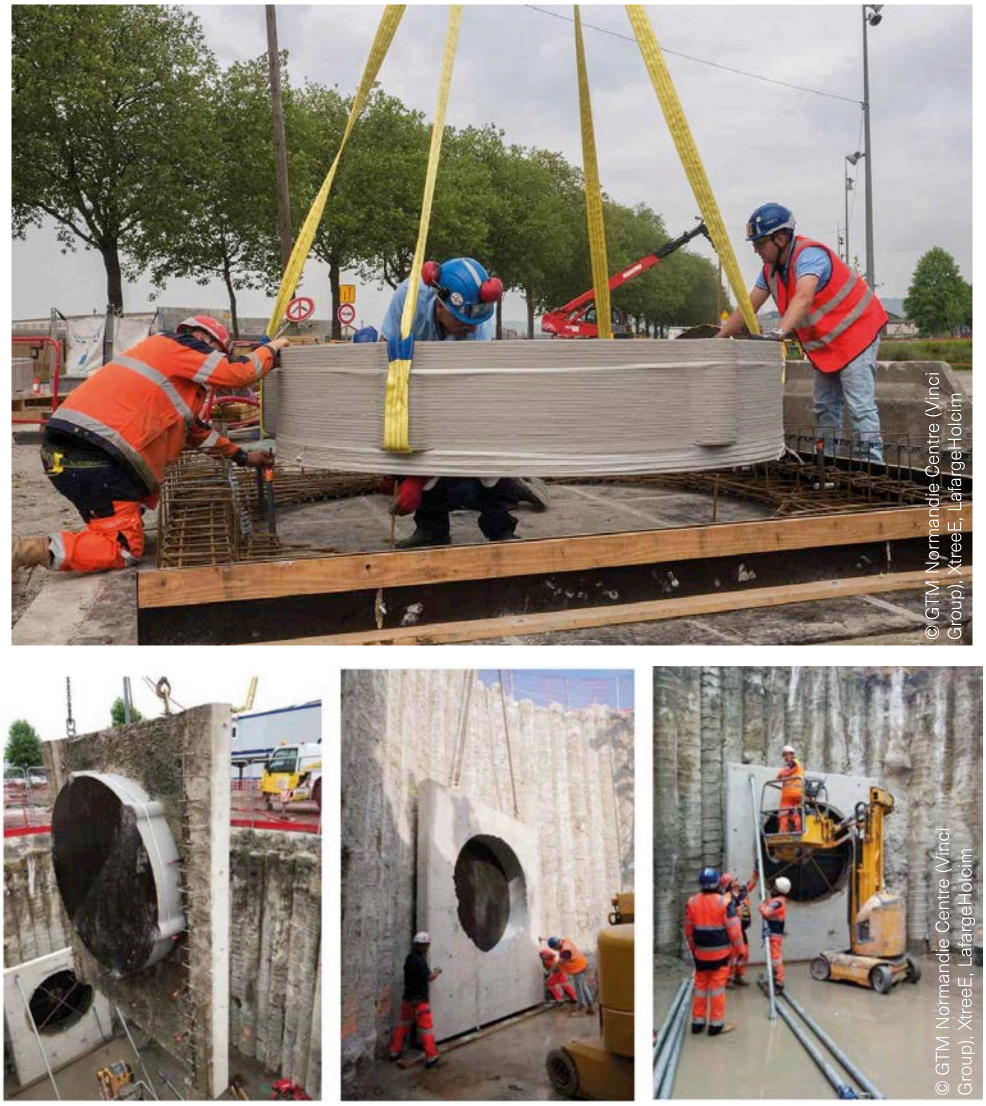


Fig. 51 Starting bell for a tunnel boring machine in Rouen, France.

Some of the most popular applications for 3D printing are the manufacturing of furniture, decorative elements in complex shapes, and street furniture. Examples of factory-printed elements placed inside buildings are given in figures 52a and 52b (p. 53).

Other examples of 3D printed elements placed outdoors and in public areas are given in figures 53a (p. 53) and 53b (p. 54).

Fig. 52a Reception counter.

Fig. 52b Elements printed by Buildwise and installed in its building at Zaventem.
1.1 m-diameter plant pot (left) and table base (right).

Fig. 53a Examples of 3D printed street furniture and decorative elements.
Urban plant pots (A), vegetable garden (B), planted areas and benches (C) and a picnic table (D).

Fig. 53b Examples of 3D printed street furniture and decorative elements.

For the surroundings of its new demonstration building dedicated to promoting the adoption of digital technologies in the construction industry, Buildwise sought to use modern organic forms to create spaces that allow an appreciation of nature through designed form. The building's outdoor staircase is surrounded by 16 mortar-printed blocks, some of which were printed at Buildwise and some at Concrenetics (see figure 54). The design was made by the architecture studio AAVA. The printed elements are hollow and serve as planters and benches.

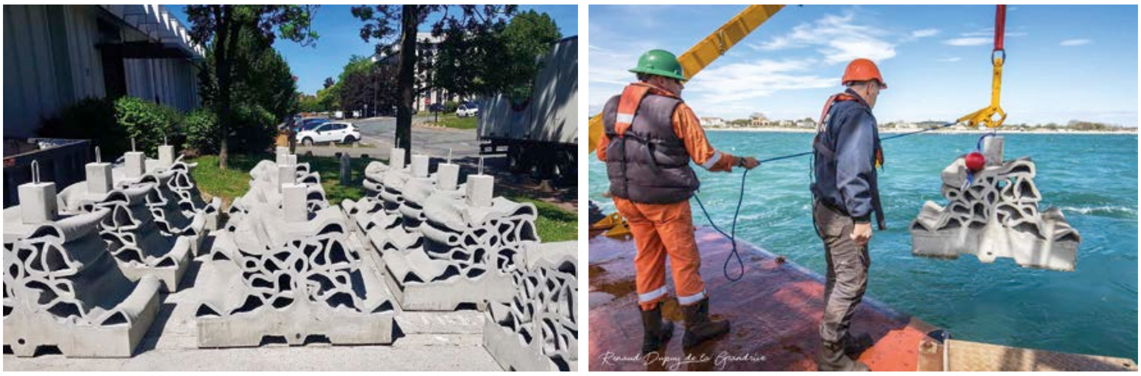
Fig. 54 Printed elements surrounding the outdoor staircase at the new building of Buildwise in Limelette.

Façade elements are another example of non-structural works that can be 3D printed. BESIX 3D used printing for the façade of the new Dubai headquarters. This façade is made up of 290 panels printed in a laboratory and assembled on-site (see figure 55).

Another pilot project was undertaken by Ifremer (the French Institute for Ocean Science), and aimed to supply artificial nurseries for fish in the port at Toulon (France). Artificial herbariums (imitation seagrass made from polypropylene) were placed on top of 3D printed mortar blocks by the French company Seaboost. These blocks offer cavities to shelter small fish and restore biodiversity in managed maritime zones. Besides these nurseries, Seaboost worked on the Récif'Lab project to create artificial biomimetic reefs by 3D printing. These were immersed in the sea off the *côte agathoise* (Cap d'Agde, France) to promote restoration of the ecology and recovery in marine biodiversity (see figure 56). This project was made reality thanks to Vicat's 3D mixture and XtreeE's 3D printing technology.

Finally, a research project that construction firm BESIX undertook with its partners Ghent University, the startup ResourceFull and engineering company Witteveen+Bos, focuses on the development of sustainable concrete mixes that can be adapted to print blocks for breakwaters. The main benefit of printing these blocks *in situ* was to reduce most of the costs associated with the logistics of transporting them from their place of production onto site. 3D printing can also be used to produce customized breakwaters of more complex designs, optimized according to the local wave patterns and ocean currents. The major challenge here lies in the durability performance of these blocks in a saltwater environment.

Fig. 55 3D printed mortar façade.



© Aire marine protégée du Cap d'Agde, Seaboost, XtreeE, Vicat

Fig. 56 Mortar reefs designed using 3D printing off Cap d'Agde, France.

8.3 Structural applications

In the context of the university research project Démocrite, which was initiated by the French company XtreeE, a 1.6 m-high load bearing wall and a generic element for structural and acoustic performance were printed using high-performance concrete (see figure 57, p. 56). The wall has an internal structure shaped like a double sine wave. The first transverse wave resembles a sandwich panel. The second vertical wave reduces thermal bridging by limiting its points of contact.

© Clément Gosselin: dissertation 2015 ENSAPM Digital Knowledge, in collaboration with Philippe Roux, Romain Duballet and Nadja Gaudillière. Philippe Morel and Jean-Pierre Shu. Projet Démocrite, EZCT Architecture & Design Research, Lafarge, PIMM, ENSAM, HAL, Nicolas Lecoq and XtreeE.

Fig. 57 3D printed high-performance concrete elements.

Retaining walls adjusted to fit the existing natural contours were printed in a factory by Twente Additive Manufacturing, a company from the Netherlands, then transported to site (see figure 58).

Fig. 58 3D printed retaining walls.

A pedestrian and cycle bridge was 3D printed and deployed in Nijmegen, the Netherlands (see figure 59, p. 57). This project emerged from collaboration between Witteveen+Bos, Eindhoven University of Technology in the Netherlands, the Netherlands' Ministry of Infrastructure and Water Management, and designer Michiel van der Kley. The bridge is 29 m long and is formed from 30 pieces printed at the Saint-Gobain Weber Beamix 3D printing centre. The pieces were then assembled on-site and held together using steel cables. The pieces are not full, uniform layers of material. They are mesh structures. The design relies on parametric design software that creates a model within which several parameters can be adjusted. This helps to optimize material use and printing time depending on the applied loads such as traffic and weight.

A trend is emerging, as with bridges, for staircases to be 3D printed. The layered surface texture inherent in the 3D printing process using extrusion provides a natural anti-slip mechanism and therefore limits the risk of falls. BAM Infra Nederland installed a 3D printed staircase in the Netherlands (see figure 60, p. 57). This project was a collaboration with Saint-Gobain Weber Beamix, Bekaert, and Witteveen+Bos, a construction engineering firm from the Netherlands. These stairs were placed onto an embankment, a location well suited to parametric design. The 3D printing business unit at Saint-Gobain Weber offers a new digital tool allowing its customers to design staircases. These can then be precisely reproduced and built into or onto any natural, sloping environment.

The use of parametric modelling here could help make adoption of this tool more widespread within additive manufacturing.

Figure 61 shows another example of staircase printed by Twente Additive Manufacturing from the Netherlands.

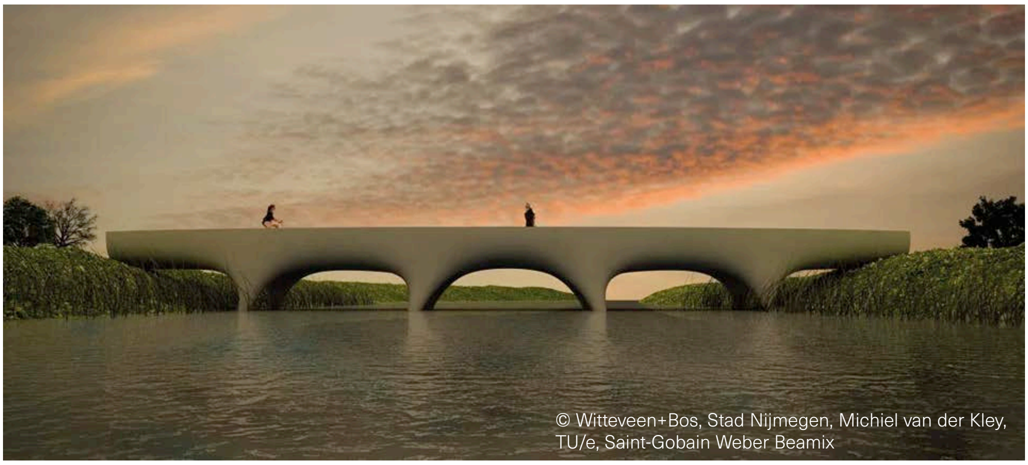


Fig. 59 3D printed footbridge in the Netherlands.

Fig. 60 Staircase printed in mortar.

Fig. 61 Staircase printed in mortar.

Malawi has long suffered from a severe lack of educational facilities. As part of a joint project with 14Trees, a joint venture between Holcim and the CDC Group, Danish company COBOD printed the structure for a school *in situ* using its 3D printer BOD2 (see figure 62). The final building has an area of 56 m^2.

As a final example, wind turbine bases are generally transported by road and therefore cannot exceed 4.5 m in width, which limits the height of turbine towers to under 100 m. Printing optimized turbine bases on-site could allow towers of between 150 and 200 m high to be built. These would harness stronger winds and thus increase their efficiency. A five-megawatt turbine 80 m high currently generates 15.1 GWh annually. A 160 m-high turbine could generate 20.2 GWh a year, thus increasing its production by 33 %. The prototype for a 10 m-high base was printed in Copenhagen, Denmark (see figure 63).

Fig. 62 School in Malawi built using 3D printing.

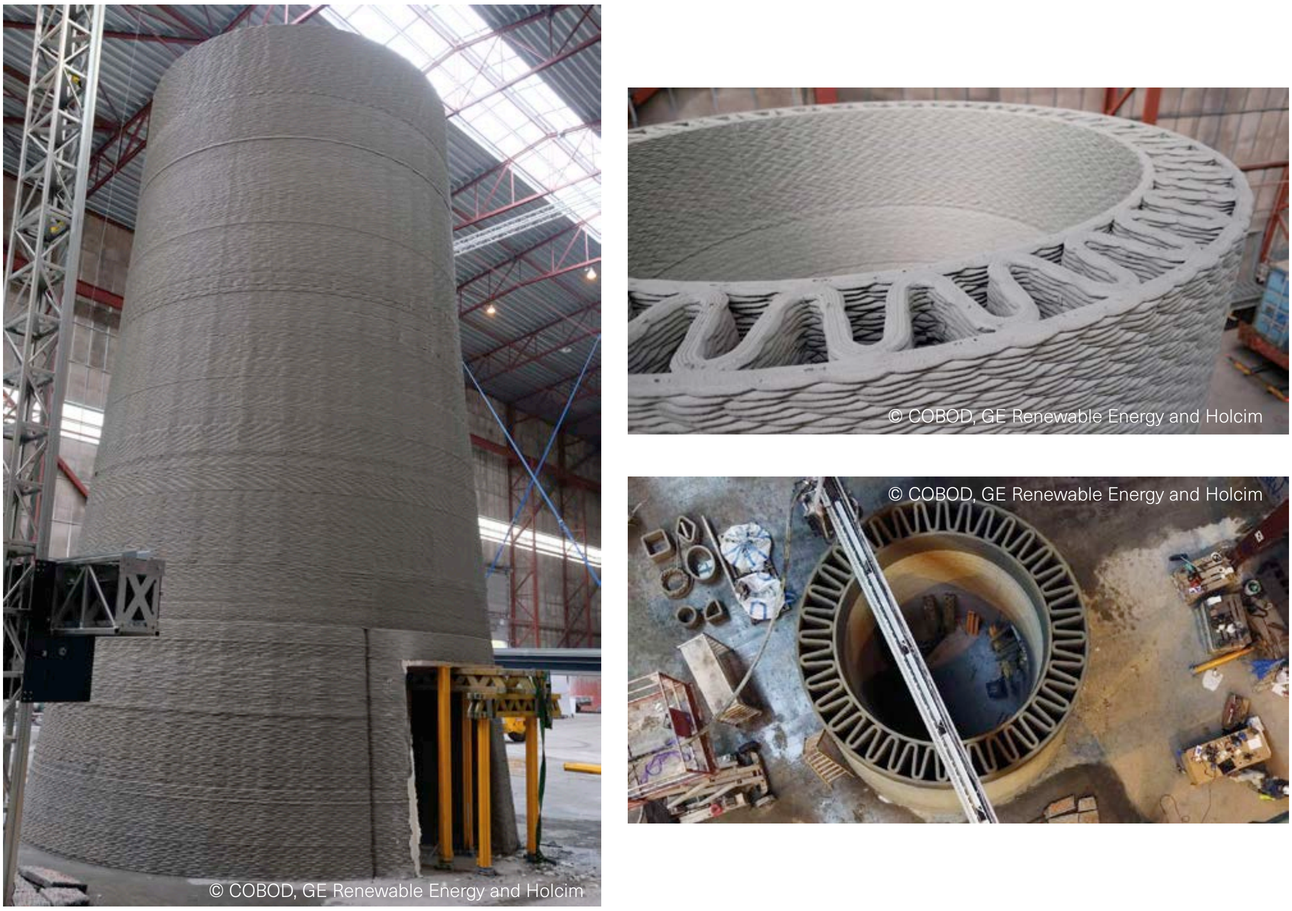


Fig. 63 3D printed wind turbine base.

9. Compliance and intellectual property in 3D printing

9.1 Marketing and compliance

CE markings on products indicate that these have been assessed and that the manufacturer has produced a Declaration of Performance. This allows EU member states to establish that the product's performance meets the regulatory criteria they require of construction works. The CE marking is compulsory for the marketing and free circulation of construction products within the European Union. Technical rules relating to these products were drawn up and this in turn led harmonized standards to be brought in, with an Annex ZA that relates to the CE marking (see the CEN website). For all products either not covered by or diverging from harmonized standards, which includes most innovative, unique or complex products and kits, manufacturers can request a European technical assessment (see the websites for EOTA, the European Organisation for Technical Assessment, and UBAtc, the Belgian Union for Technical Approval in Construction).

Indeed all manufactured products already covered by a harmonized standard (such as NBN EN 197-1 [B9] for cement) must display the CE marking when they are placed on the market. However, this rarely applies to innovative products that have not yet had time to prove themselves. Given that these differ from conventional products, there is not usually any documentation on their use in construction systems. For example, printable premix is not covered by a standard. If the manufacturers want to market their material(s) in one or more European Union member states, they can take measures to obtain a European Technical Assessment (ETA)[8]. An ETA issued by a technical assessment body allows innovative products to obtain a CE marking. It covers the product's performance in relation to the essential characteristics agreed between the manufacturer and the technical assessment body for the specified use, as well as the necessary technical details to implement the assessment and verification of constancy of performance. The essential characteristics feature on a Declaration of Performance (DoP) and allow the CE marking to be placed on the product.

Prefabricated products covered by a harmonized European standard must display the CE marking. As regards prefabricated concrete products, the first to bear that mark were concrete fences. For this product, the CE marking is based on a manufacturer's declaration, without any intervention from a notified body. The European standard NBN EN 13369, 'Common rules for precast concrete products', specifies the requirements for concrete and its components. It also states the general conditions in which the Eurocodes apply to establishing the dimensions of prefabricated concrete products. These common requirements also act as a reference text for products not covered by European standards or technical approvals. However, this standard does not apply to elements prefabricated in a factory using 3D printing, because the mixture does not comply with the NBN EN 206 [B14].

In Belgium, the BENOR label is a voluntary quality marking granted to construction materials that comply with the requirements of our national standards and technical requirements (PTV). For example, a ready-mix concrete that complies with the standards NBN EN 206 [B14] and NBN B 15-001 [B3] is eligible for the BENOR label. In the construction sector, this marking is managed by grouped certification bodies BUCP (Belgian Union of Certification and Attestation Bodies for Construction Products). Regarding 3D printing, the printable material is not covered by the standard NBN B 15-001 [B3]. Therefore the BENOR label may not be applied to this product. In this case, Technical Approval (the ATG label) is a possible alternative. It indicates that an innovative product, or one that diverges from standards, complies with a technical approval. ATG approval is managed by the Belgian Union for Technical Approval in Construction (UBAtc). It is important to note that ATG approval only applies to a very specific construction product, from a very specific manufacturer, for a very specific period.

[8] In Belgium, the abbreviation ETA (European Technical Assessment) is usually employed in place of the acronym for the French or Dutch terms, ETE (*Évaluation Technique Européenne*) or ETB (*Europese Technische Beoordeling*).

France has a procedure for Technical Experimentation Assessment (*Appréciation Technique d'Expérimentation* - ATEx). This is a rapid technical assessment process by a group of experts for any innovative product or process. However, an ATEx only applies to one (or several) specific experimental site(s). One recent example of this is the ATEx which the CSTB (*Centre Scientifique et Technique du Bâtiment*) issued to the Viliaprint project in Reims, France. This is a project to build five houses combining 3D printing concrete off-site with prefabricated products (see also § 5.6, p. 35). Belgium does not have an equivalent to the ATEx system.

In conclusion, the CE marking covers placing construction products on the market. It is the tool which manufacturers use to guarantee their products in dealings with other EU member states. The ATG and BENOR labels, and ATEx, deal with market acceptance. They do not influence placing products on the market. In other words, these are tools intended to convince the actors in the sector – such as architects, specifiers, companies and investors – that products are suitable for their intended use, are reliable and have properties and performance that will meet their requirements.

9.2 Patents

A patent grants its holder (a company or inventor) exclusive rights to their invention, meaning the holder can prevent others from using, manufacturing or selling it without their authorization. Analysing patent applications made in relation to 3D printing can give an overview of how this technology has developed. There are classification systems for patents. Finding patents for particular technological developments in 3D printing involves selecting and combining the classifications that will return the most relevant results (https://worldwide.espacenet.com). For instance, analysis of materials for additive manufacturing in the construction sector can be achieved by combining the classifications CPC B33Y70/00 ***Materials specially adapted for additive manufacturing*** and E04 ***General building constructions***. Other classifications can be applied to find other innovations such as cement mixtures specially adapted for 3D printing, or admixtures.

A wider search performed by Buildwise's patent unit (OCBC) combining both classifications CPC B33Y ***Additive manufacturing technologies*** and E04 ***General building constructions*** returned 385 results between 2002 and 2020 (see figure 64). Analysis of the years in which the selected patent applications were made in the field of 3D construction reveals that the number of patents in the 3D construction sector has grown continuously since 2013. Following this logic, the next few years will be marked by an increase in patent applications. It is also worth noting that the patent application process takes 18 months, which explains why the graph does not include the years 2021 and 2022.

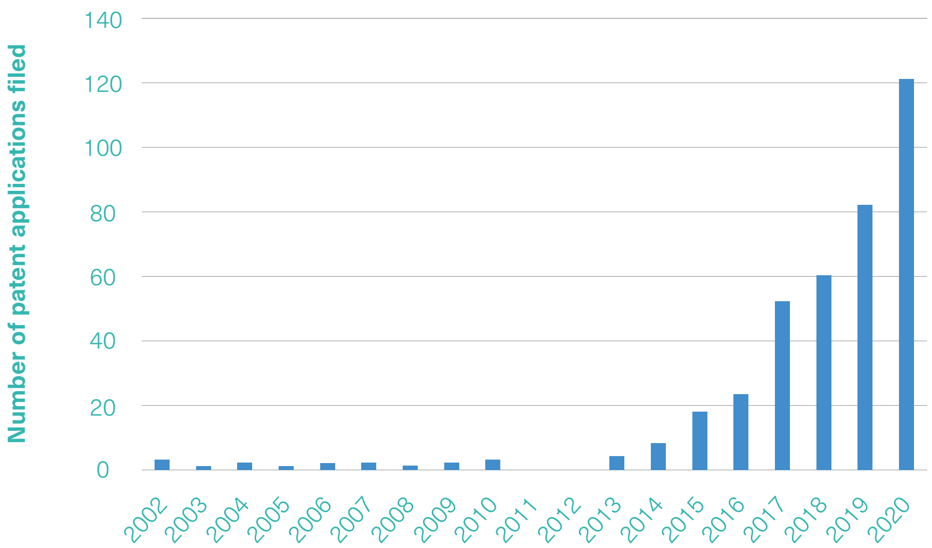
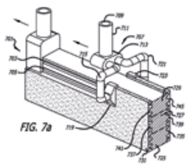
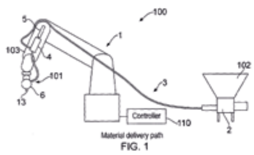
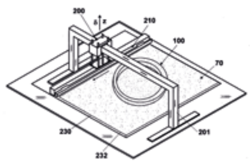
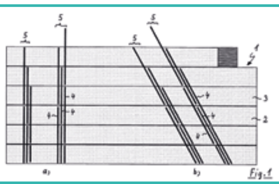


Fig. 64 Number of patent applications filed between 2002 and 2020 in the field of 3D construction.

Patents in the field of 3D printing in the construction sector can generally be categorized as relating to:
- material
- 3D printing technique
- reinforcement.

Some examples of patents, selected randomly from the above list, are shown in table 5.

Table 5 Examples of patent applications in the field of 3D printing.

Patent number	Description	
	MATERIAL	
EP4151409 A1	Mix designs of printable mixtures are included in this patent application submitted by Holcim Technology Ltd.	
WO 2020/021202 A1	Novel cement composition for 3D printing patented by Vicat (see § 6.2, p. 38)	
EP3738941 A1	Composite construction element produced using an extrusion-based additive manufacturing technique (ETH Zurich)	
	PRINTING TECHNIQUE	
US 2010/0257792 A1		Contour crafting (see chapter 2, p. 8)
EP 2773492 B1		An apparatus for performing a multi-layer construction method using cementitious material with a delivery nozzle for extrusion
WO 2011/021080 A2		A method and an apparatus to provide a building structure in conglomerate material. It deposits granular material and spreads binding agent, then presses the granular material with rollers (selective binding) (see § 3.2, p. 13)
EP 3501769 A1		An automated manufacturing method for a concrete structure utilizing a slipform (slip forming, see chapter 3, p. 11)
	REINFORCEMENT	
WO 2021/175580 A1		Print head equipped with a system for depositing steel reinforcement elements during printing (see § 5.3.1, p. 26).
WO 2019/092178 A1		Reinforcement of 3D printed concrete bodies using multiple similar reinforcing elements through different layers of concrete (see § 5.3.3, p. 31)

10. Conclusions and perspectives

In recent years, 3D printing projects using concrete have sprung up around the world. Many projects produced detached houses, some of which are now occupied. A pilot project launched in Belgium in 2020 was carried out by Kamp C in collaboration with Buildwise. The entire frame for the house, comprizing ground and first floors, as well as some of the furniture were 3D printed in mortar. This provides a fine example of the technology's current potential.

There is growing interest in 3D printing, from architects, manufacturers and contractors. In fact this technology has the potential to overcome some of the sector's current challenges: the economical production of complex-shaped structures, a gain in implementation time, a reduction in raw material consumption, improved waste management and less strenuous work. 3D printing currently allows construction processes to be better rationalized. For structural works, they are fully automated thanks to digitization, production control – managed using a digital model – and robotics.

3D printing could soon overtake more conventional methods for some applications, including street furniture, balconies, staircases, curved walls, footbridge segments, some underground works and even permanent formwork. The technology is not however fully ready for on-site production subjected to the vagaries of the weather. Yet, it should be noted that elements can be factory-printed in a controlled environment before being assembled on-site.

3D printers are increasingly technologically advanced, and could ultimately limit the need for repetitive, strenuous labour on building sites, while opening up new economically viable, architecturally innovative projects. This could give our industry a renewed audacity!

Yet, although prototypes have been made, the industrialization process is still a long way off. The main concern is to find out if 3D printed structures are strong throughout and durable when deployed outdoors. There are still many challenges to overcome before the technology can be used to manufacture structural elements. The main challenge lies in reinforcing printed elements, especially for multi-storey buildings. Elements printed in mortar have shown high compressive strength, but elements subjected to flexion or traction need to be strengthened using reinforcements that are difficult to integrate into the printing process. Many approaches are the subject for further research, including manual and automated reinforcement.

Few reliable, independent studies address the issue of costs. However, it seems clear that 3D printed elements are not always more economical than elements produced using a conventional method (*in situ* or with prefabrication). In some cases, as for straight walls that can be built using masonry, it remains more costly to build them using 3D printing than traditional methods – due to the investment and raw materials, among other things. For other applications such as a custom staircase placed onto an embankment, or curved walls, 3D printing could be an innovative, more economical solution. Indeed it is certainly more cost-efficient to 3D print any formwork – or even an entire element – that has complex geometry.

Regarding carbon footprint, to date most industrial-scale projects have used a mortar rich in Portland cement, despite initiatives to build with materials that have a lower environmental impact. This cement emits a high quantity of CO_2 during its production, and can lead to durability problems if steps are not taken to control shrinkage. Particular attention must therefore be paid to the curing of 3D printed elements.

Finally, standards do not yet allow to consider 3D printing as a method for building concrete structures. There are however increasing numbers of initiatives in Europe and around the world to study the many facets of this breakthrough technology and thus ease its inclusion in the relevant standards for concrete and concrete structures.

In the meantime, voluntary quality labels could offer a solution to reassure the various actors that these innovative materials and methods are reliable.

Although 3D printing in the construction sector is only in its infancy, with many challenges yet to overcome, it is worthy of our attention. It is disruptive at the level of architectural design, materials technology and the construction process. 3D printing is unlikely to replace conventional approaches in the near future, but it will find applications in certain niche markets. Scaling up the technology for wider markets will depend on how research responds to the various challenges stated and illustrated throughout the present document. However, the advances in robotics and automation are so rapid that their potential in the next few years cannot be ignored.

The numerous demonstration projects will help us to assess, in terms of full-scale applications, the true value added by a technology which some people present as one of the past decade's major innovations.

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B6 NBN EN 1015-3 Methods of test for mortar for masonry. Part 3: determination of consistence of fresh mortar (by flow table).
B7 NBN EN 13369 Common rules for precast concrete products.
B8 NBN EN 13670 Execution of concrete structures.
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Buildwise

After more than half a century, the Belgian Building Research Institute (BBRI) has changed its name to Buildwise. This new name also entails a new direction, with a greater focus on innovation, collaboration and a more integrated multidisciplinary approach. Since Buildwise is primarily financed by the membership fees of some 100,000 construction companies, these also help determine our activities, e.g. through their involvement in setting priorities and steering actions via the Technical Committees.

From research centre to innovation centre

Thanks to its knowledge acquired over the years, Buildwise has become the key reference for construction expertise. Buildwise is there to support all actors in the value chain. Our goal? To pass on all knowledge set to improve quality, productivity and sustainability and to pave the way for innovation on building sites and in construction companies.

A catalyst for sharing knowledge and connecting

The construction process is very complex and fragmented. Therefore, Buildwise wants to strengthen its connecting role. We can only overcome the sectoral and societal challenges by getting the whole sector to change tack, rethinking the way we work together.

From multidisciplinary to transdisciplinary expertise

Buildwise stands apart through its pragmatic and multidisciplinary approach. Finding robust solutions requires a comprehensive, integrated approach. Our ambitions are therefore built around three pillars: digital technology, sustainability and craftsmanship (represented by the contractors within the Technical Committees).

Buildwise Zaventem
Corporate headquarters and offices
Kleine Kloosterstraat 23
B-1932 Zaventem
Tel. +32 (0)2 716 42 11
Email: info@buildwise.be
Website: buildwise.be
- Technical advice – Publications
- Management – Quality – Information technology
- Development – Valorization
- Technical approval – Standardization

Buildwise Limelette
Avenue Pierre Holoffe 21
B-1342 Limelette
Tel. +32 (0)2 655 77 11
- Research and innovation
- Training
- Library

Buildwise Brussels
Rue Dieudonné Lefèvre 17
B-1020 Brussels
Tel. +32 (0)2 233 81 00