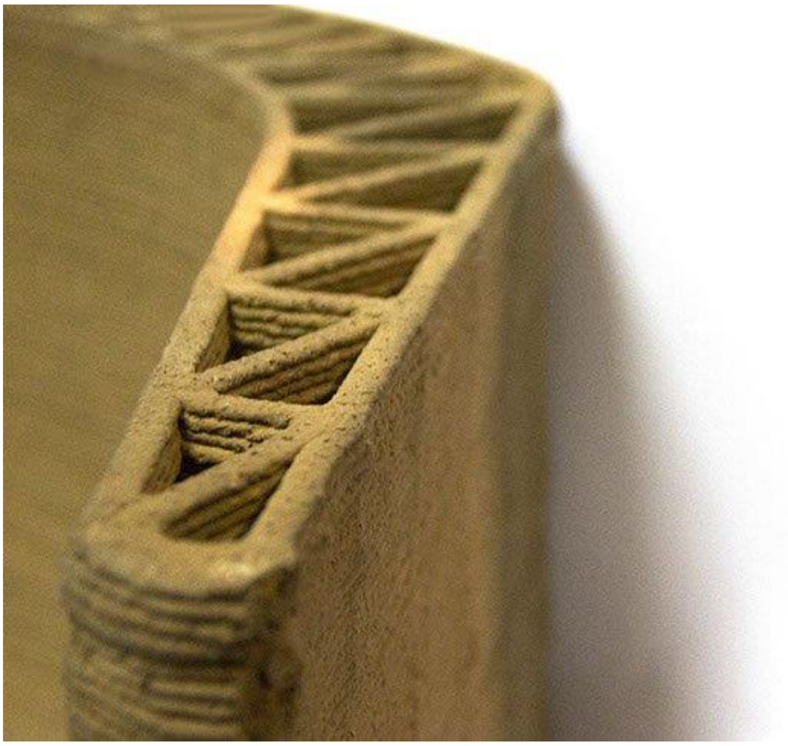
# PLYOS PROJECT - REPORT



Another project emerging from the Institute for advanced architecture of Catalonia (IaaC) and exploring the possibilities of us using soil in architecture and construction. Pylos focuses on studying beautiful and curvy geometric shapes that are stable, and a material that is sustainable, affordable and durable at the same time.

**Institution:** IaaC
**Technology/Project:** Pylos
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## 1. Technology overview

Pylos is a project based on a layered material extrusion process. It is essentially a fused material that is pushed through a nozzle and deposited on a printable surface. The nozzle moves around the printable surface and deposits a continuous line of material in several layers, until the whole height of the object has been printed. With a technology that is very typical and well established both in 3D Printing in general (known as Fused Deposition Modeling or FDM), as well as in its construction-scale variants, this process focuses mostly on the research on the material, in this case soil, and the various stable geometrical shapes that can be achieved.

The project aims at experimenting with a material that is affordable and sustainable at the same time, while also focusing on its mechanical properties.

*The Pylos 3D Printer extruding wet soil*

## 2. Institution and development

### 2.1 Institution's overview

The Pylos project is under the supervision of the Institute for advanced architecture of Catalonia (IaaC). This educational and research center based in Barcelona sets its main focus on developing architecture to meet the worldwide challenges of the 21st century. It boasts a large digital production laboratory comprised of 3D printers, laser cutters, milling machines, robotic arms, chips manufacturing platforms, and many more. The institute has also various collaborations with other highly recognized institutions, such as the Media Lab of the Massachusetts Institute of Technology (MIT).

This has allowed for a wide array of highly technological ideas and projects to emerge in the last decade. With a special focus on additive manufacturing and 3d printing on the large architectural scale, it is home to some promising projects on the 3D Construction Printing scene, which helped pave the road for many others. There is a strong collaboration with D-Shape and its founder Enrico Dini, who collaborated in various workshops and projects, and the institute has also designed the first 3D printed bridge printed with the D-Shape technology. Needless to say, Iaac is intended to stay an important player in this emerging field, and has already established itself as one of its early developers.

The Iaac 3d printing projects include Mataerial, FabClay, Pylos, Minibuilders, On Site Robotics, and TerraPerforma. They all share the same knowledge and experiences, tackling various aspects of a 3d printed construction, such as materials, movement of the printer, or the thermal efficiency of a printed geometry. They are essentially all part of a greater picture that is trying to bring 3d printing closer to architecture and construction.


***Institute for advanced architecture of Catalonia - headquarters and workshop***

## 2.2 Project overview, size and development

The Pylos project is one of the many at Iaac, and it is mostly focused on the research of the material, as it aims to bring soil into 3D Construction printing. The projects is led mainly by researcher Sofoklis Giannakopoulos, with the supervision of Areti Markopoulou and external support from Enrico Dini (D-Shape). The hardware and software are handled by Alexandre Dubor (robotic expert) and Rodrigo Aguirre (computational expert). Apart from some general material properties and experiences from test prints, there is no official data on the development of the project. However, it is known that the success of this project has led to some additional research with the same material in the following projects.

*A cylindrical shape being printed*

### 2.3 Targeted market

Since this is only a research project, there is no specifically target market for the moment, apart from construction and architecture in general.

### 2.4 Past, current & future projects

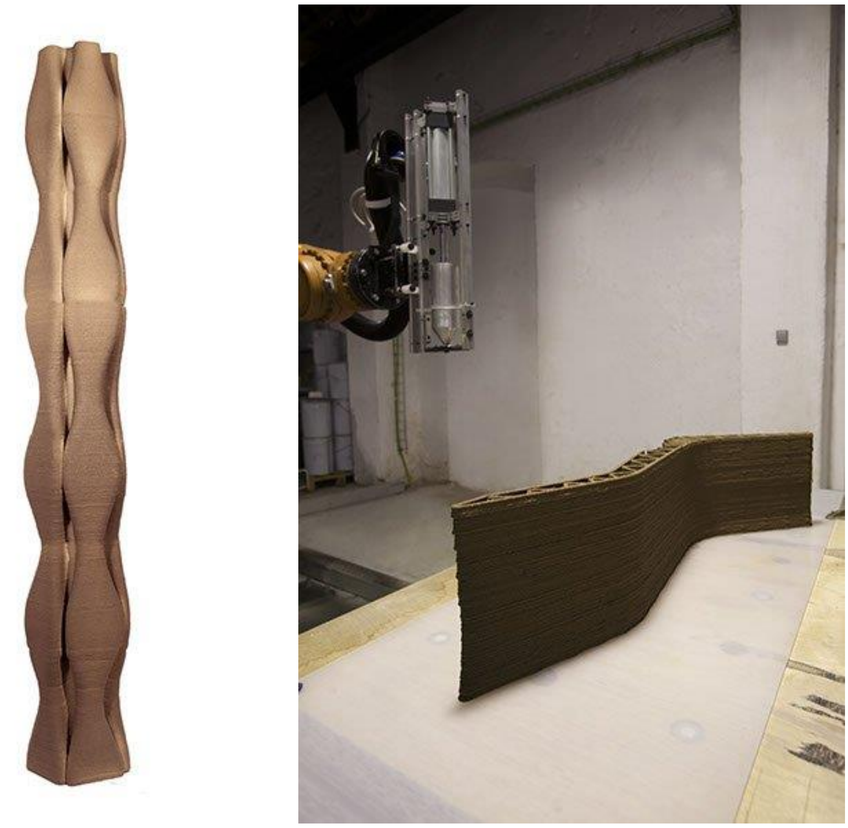
The Pylos project is a direct successor of the FabClay project, led by Sasa Jovic, which is the first project of Iaac dealing with an extruded soil-based material. The On Site Robotics and TerraPerforma projects are its successors, dealing with the same material and using the experiences gained from it as their starting point.

### 2.5 Development stage of printers

The Pylos project is not focused on the development of the printer. There is no specific focus on developing the printer further than to obtain a system that allows for testing the materials. The project uses a robotic arm equipped with a mechanical displacement extruder. The latter is a variation of the extruder introduced in the FabClay project.

### 2.6 Development stage of printed materials and largest print to date

A part of the project was the production of various organically shaped columns. These columns or piles, where the name Pylos has its origin, are used to study the various geometrical shapes as well as show the potential of the technology. The printed piles range from around 1 meter to up to 2 meters in height. Apart from these, there have also been several other test prints, one of which a curved surface segment, that is approximately 3 meters in length and 1 meter in height, with a thickness of 20 centimeters, Both of these could be considered the largest prints of the project.

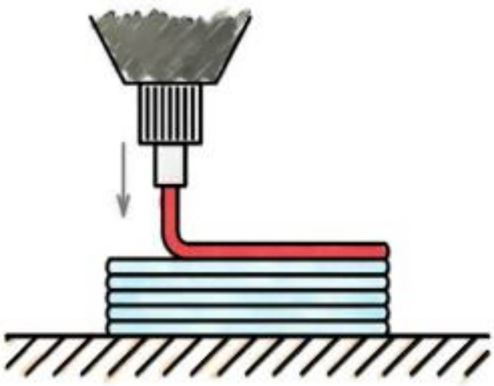


*The largest prints of the Pylos project, an organic pile (left) and a curved surface segment (right)*

# 3. Technology

## 3.1 Additive manufacturing technology

The Pylos additive manufacturing technology is a Layered Material Extrusion process. This is an construction-scaled *Fused Deposition Modeling (FDM)* process, a very known desktop printer process where a material in fluid form is extruded through a small nozzle as a continuous stream or filament. The material is then solidified on the printing surface, ready for the next layer to printed on top. Its desktop counterpart uses molten plastic, that melts when going through a hot nozzle and then solidifies by cooling down once deposited on the surface. In this construction scale process a soil-based material is mixed with water to create semi-fluid paste of mud, which is then fed into the extrusion machine. The fluid paste material is extruded through a simple nozzle and deposited on a printable surface. The deposited material then slowly starts to dry through evaporation at room temperature, and becomes a solid.



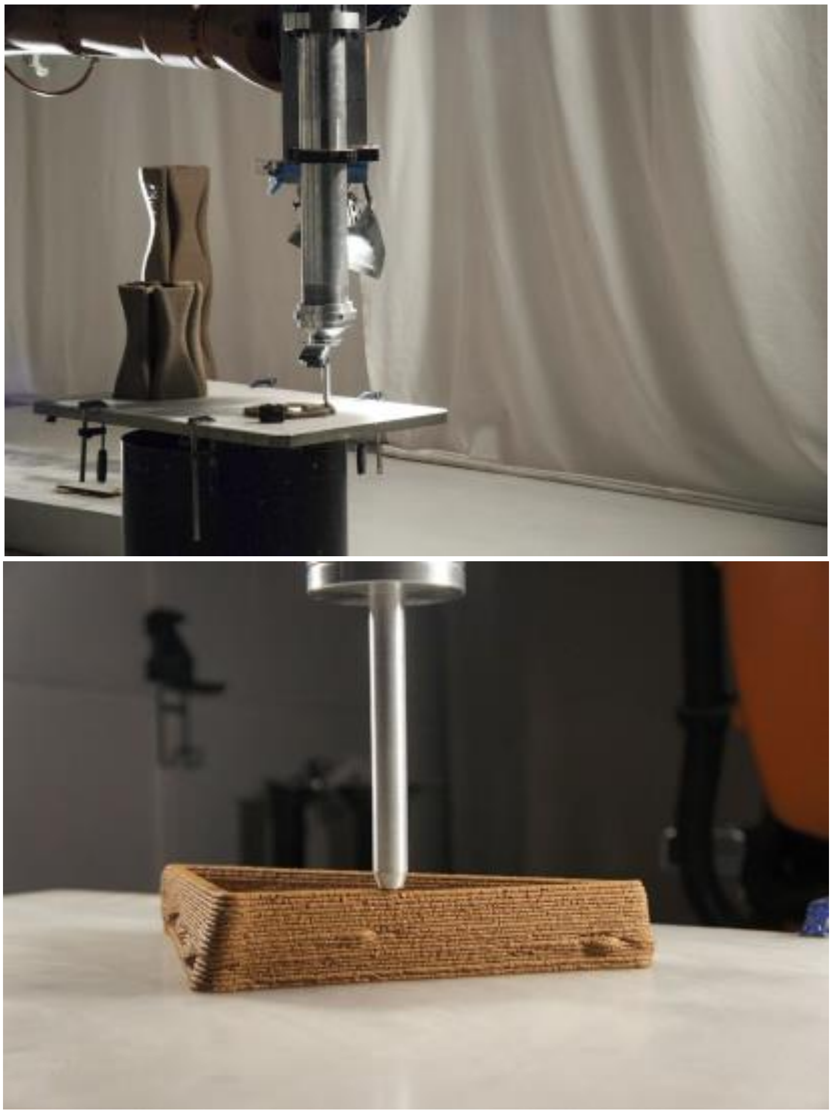
*Materiale Extrusion (layered)*

## 3.2 Printing procedure

The printing procedure starts with a 3D model being sliced into layers by a layering software, such as Simplify3D, Slic3r or similar. The thickness of the layers depends also on the type of material used, since all materials behave differently under the weight of all the layers printed on top. In the case of Pylos the layers are of approximately 5mm. The software then translates each layer into the movement of the nozzle around the printable area.. Depending on the needs of the print, the machine can be instructed to:

- **Print only the outlines of the object:** This approach is the most typical and the most suitable one for formwork and walls, since it allows to print the outer walls of the object, and then fill in manually the space in between.
- **Fill the object completely as a solid:** this mostly done when a part needs to be heavy or structural (a solid is usually more resistant than a hollow material)
- **Partially fill by creating a specific pattern/geometry:** this type of filling is used mostly to reduce the quantity of material, the weight of the object, to reduce deformations that are induced from the material warping (less material, less warping usually), or similar reasons. It is usually done as a square mesh, but it can also be done in various specific shapes, if necessary.

Once the software has prepared a file with all the necessary machine instructions, the printing process can start. The soil is mixed with water in smaller batches, and fed into the cylindrical feeder. Inside the feeder there is a piston that pushes the material through the nozzle and deposits it on a flat surface. Once the first layer has been printed, the next one can be printed on top. Once the last layer of the object has been printed, the process is finished. The printed object is then left to dry completely and become solid.

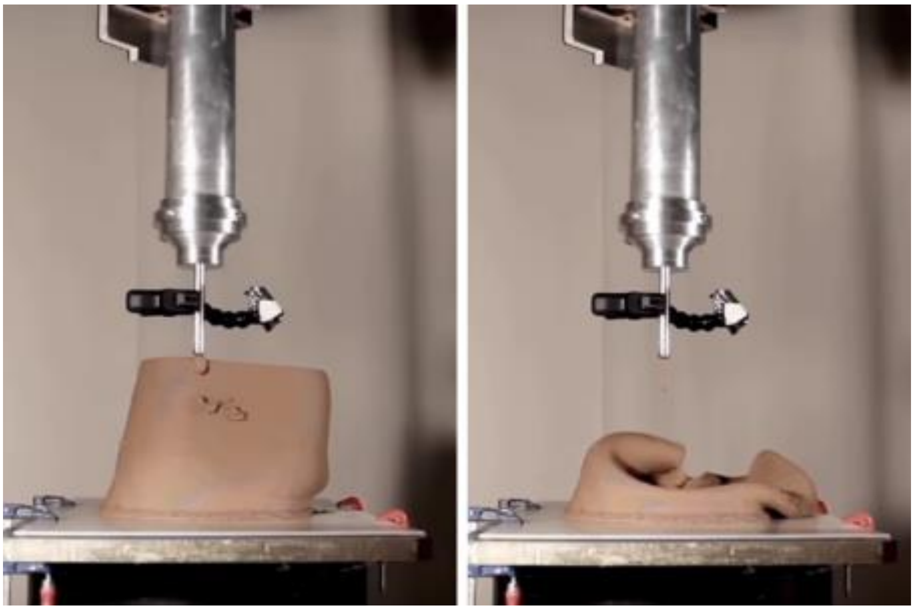


***The Pylos printing process***

## 3.3 Form freedom

Since each layer needs to be printed on top of the previous one, the freedom of this additive manufacturing technology is more limited than others. The printer can create any shape in the horizontal plane, but once that shape has been chosen, it can safely create only vertical extrusions of this shape on top of it, something contained within the shape itself, since it is impossible to start a next layer in the midair. This type of printing freedom is not considered three dimensional, and it is often referred to as 2.5D freedom.

There is however a possibility to print each layer slightly leaning towards the outside compared to the previous one, slightly hanging over the edge. This allows to create mildly arched structures or shapes that have gradual and small changes in geometry through the height of the object. While this approach is very common in desktop 3D Printing, where the sizes are very small and the materials are very light, it is much more complicated to achieve the same with a heavy and fluid materials, especially on a construction scale. It has a very unpredictable behaviour that depends a lot on the quantities that have been mixed, how long has the material been drying, and many other external factors, such as wind as an example.. There is a high risk of the whole structure collapsing after many layers have been printed, losing a day's work. Pylos has experimented with many structures that have a gradual change in geometry through their height, mainly complex and curvy columns. They have also shown footage of structures collapsing in this process after reaching a certain limit point, due to the insufficient strength of the material to support these overhanging weights.

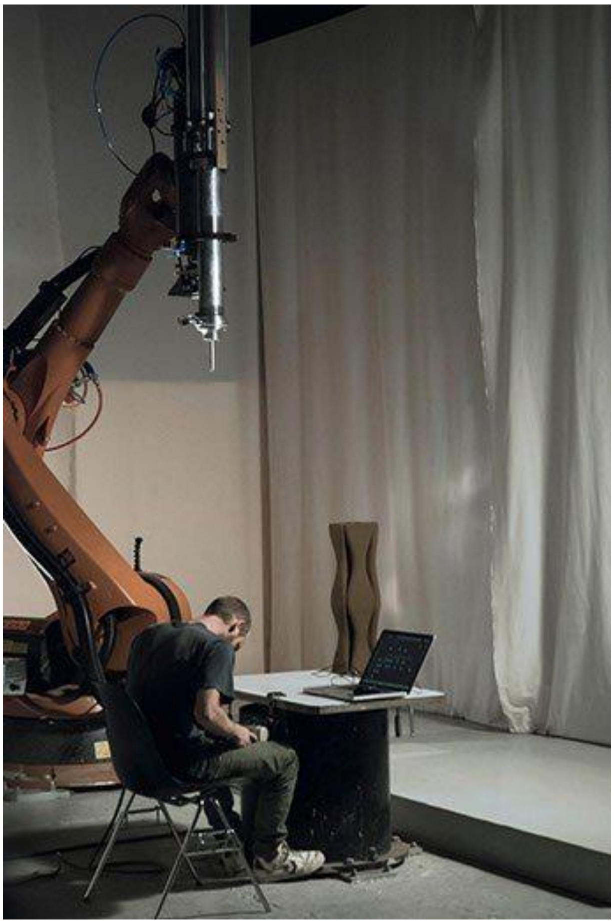


***A collapsed print***

## 3.4 Fabrication location and approach

The printer for the Pylos project is a robotic arm. It has a fixed support structure within the workshop of the institute, and it allows to print on any adjacent surface within the reach of the machine. The Pylos printer uses a flat table for its prints. With layered material extrusion technologies there is also a possibility to print on curved surfaces, making all the layers follow the curvature. This approach has not been used on the Pylos project.

The printing process can be compromised with some considerable atmospheric agents, such as heavy wind or rain. Optimally, the printer should be in a covered environment. During the Pylos project the printer has only been used indoors.



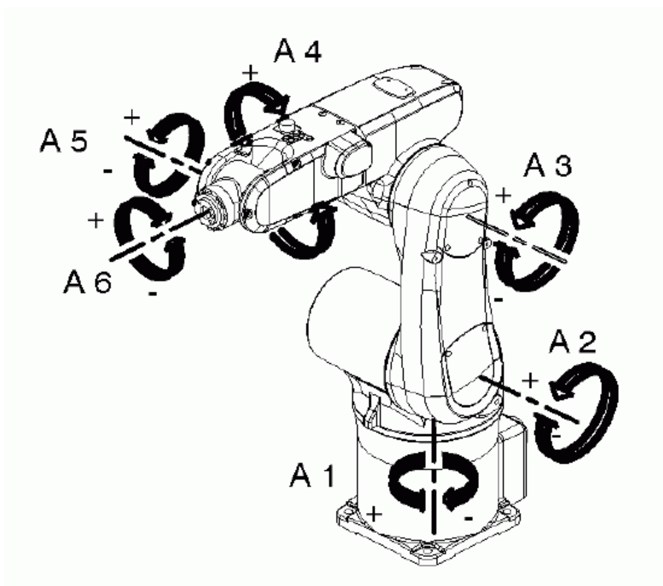
***The printer and the printable surface in indoor conditions***

# 4. Printer

The Pylos project is mainly focused on the material and the various geometries that can be obtained, not the printer itself. The only goal of the printer is to allow for a material to be extruded repeatedly and within an acceptable accuracy. The assembled printer is very similar to the FabClay project (also from Iaac), and is probably a modified version of the same.

## 4.1 Movement

The printer uses a six-axis robotic arm from Kuka KR-16 for its movement. The machine is capable of moving in every direction with its reach, by a combination of movements of its six different rotational joints. These complex joint movements are coordinated through a specific programming software, in this case the proprietary KUKA Robot Language (KRL).




*A kuka robot (left) and a sketch of the the six-axis of rotation (right)*

## 4.2 Material deposition system

The deposition system is made of a cylindrical container that has a piston on one side, and a thin nozzle on the other. The piston is pushed into the cylinder to create pressure on the material, which is then extruded through the nozzle on the other end.


*The Pylos deposition with piston on top, cylindric container in the middle, and nozzle in the bottom*

## 4.3 Material feeding

There is no specific feeding mechanism for this printer. The material is fed directly into the cylinder by unscrewing the nozzle and filling it. Once the whole length of the cylinder has been extruded, the cylinder has to be refilled. The quantities are very small (less than 0,05$m^3$). This kind of system is suitable for a research project, but would be detrimental within a construction environment, where larger quantities of material are necessary. Cleaning and preparing the printer after each batch would make the process way too long.

*The procedure for feeding the material: nozzle unscrewing (left) and material filling (right)*

## 4.4 Printer electronics and software

There are no specific details disclosed regarding the printer electronics and software. The robotic arm is probably operated through proprietary software from Kuka, while the material deposition mechanism is open source. The whole machine operation is very similar to the FabClay printer, which has only a slightly different nozzle. Therefore, the electronics involved are also similar.

## 4.5 Printer speed

The printing speeds used during the projects were various, and a standard printer speed is hard to define at this point. As a guideline the printer speed is approximately 5-10 centimeters of a layer of material per second. That translates to a theoretical speed of not more than 0,03$m^3$/hour. When considering a realistic speed taken from the printed sample columns, the values are even lower, down to 0,01$m^3$/hour for some of the faster printed ones.

The current speed is not suitable for construction use.

## 4.6 Printer accuracy

Similar to the speed, the accuracy of the printer is hard to define, since there are no official values given by the project. Judging by what has been seen in operation, the accuracy can be safely estimated to less than 30mm.

## 4.7 Printer operation, handling and assembly

There is no disclosed information regarding the printer operation. The printers seems suitable to be handled by a single person.

## 4.8 Printer specifications

**Printer size (assembled):** Not available

**Printer size (stored):** Not available

**Print volume:** Not available

**Printing speed (estimated):** Approx. 0.01-00.3m3/hour

**Layer thickness (estimated):** approx 5-10mm

**Accuracy (estimated):** <30mm

**Deposition head:** Single nozzle (mechanical extrusion)

**Structure:** Robotic arm

**Movement:** Six-axis robotic arm

**Shape freedom:** 2.5D

**Weight:** Not available

**Energy consumption:** Not available

**Required personnel:** 1 person

**Price per unit:** Not for sale / Not specified

# 5. Material

## 5.1 General description

The Pylos approach is to use a widely known and traditional construction material, that is sustainable, locally-sourced and extremely affordable. Soil is mixed with water to create a mud paste that can be extruded and used within a 3DPrinting framework, reinventing the process, but keeping essentially the same material.

## 5.2 Earth as a construction material - properties

Earth or soil is one of the oldest and most used materials in construction, and has been used for thousands of years. It has been widely used in Mesopotamia for large constructions such as palaces, temples and ziggurats, and it is still a very common material in poor and rural parts of the developing world.

Earth within construction comes in various forms, like rammed earth, mud bricks, compressed earth blocks, earthbags, fired clay bricks, and many other. Rammed earth is essentially layers of damp soil that are manually compressed (or rammed) in a formwork until bonding into a stable mass. Compressed earth blocks (CEB) are a modern reinterpretation of the latter, but with soil placed in brick moulds under high pressure. The fired clay bricks are a much stronger version of bricks made out of mud, but they need a lot of thermal energy when being produced (they need to be baked). The earthbags are filled with soil and stacked on top of each other to create barriers or walls (same as sandbags).

*A mosque in Djenne, Mali - the largest mud brick structure in the world*

The Pylos project is probably closest to mud bricks. This technology, also known as adobe (Spanish for mud brick), has been known for thousands of years, and has been widely used in Mesopotamia and other great civilizations in the past. These mud bricks are usually made by filling wooden moulds with a wet mud paste and letting them dry in the sun. When dry, the moulds are stricken down and the bricks are ready to be used. The paste can also be mixed with various other materials, such as sand or stray, to improve its properties, such as reduce cracking or improve strength. The bricks are then stacked in a staggered manner, as in a common masonry wall, and connected with a mortar that is made of the same mud material.

***Making of mud bricks with moulds***

The advantages of mud bricks are many, but are mostly revolving around sustainability, affordability and abundance. Mud is essentially a material that is temporarily “borrowed” from the surroundings, and can easily be brought back into its original state. There is almost no processing involved, and all the energy is given by the sun. Its environmental impact is almost zero. Mud is also as cheap as a material can get, and it is found pretty much everywhere. It can be used and reused an infinite amount of times. Apart from that, mud has also good sound and thermal insulation properties, and can store a lot of thermal energy, preventing the building from overheating. Mud makes also naturally fireproof and ventilating structures.

***A mud brick wall***

The main disadvantage of mud structures is  its vulnerability and deterioration with time. If exposed to constant rain or humidity, mud structures can easily collapse back into its original shapes. They need attentive care and maintenance to be able to resist the stand of time, such as the use of protective layers. The bricks can also be partially waterproofed with various additives. Same as other brick structures, mud is also a very brittle material, so it has a very poor resistance to earthquakes, if not properly reinforced. Finally, the making of mud bricks is a very manual process, which makes it harder to automate and align with current industrial processes.

Generally speaking, earth structures are best suited for warm and dry regions, with very low precipitations.

In these areas its thermal mass can have a great benefit when cooling down the buildings during warm days, and the structure can have a longer lifespan without the presence of humidity or rain. Mud structures are currenlty most widely spread in this type of areas.

*A deteriorating earth wall*

## 5.3 Pylos material properties

The material is essentially a mud structure, 96% made of soil, and it is not far different from the traditional mud structures. However, the project is mentioning an outstanding outcome for the research with the use of an ingredient that improves the mechanical properties of the material. The finally obtained material is claimed to have 3 times higher tensile strength than industrial hard clay. However, no other details have been disclosed regarding the specific properties of the 3D printed material, such as the bonding between the layers, shrinkage, or others.

There are currently no pre-treatments or post-treatment that were introduced to the process.

## 5.4 3D printed soil - material possibilities

Soil mixed with water is a very good candidate for a 3D printed material. It has a long working time, since it needs to lose a large quantity of water to become solid. It can also be easily melted back into a 3D Printable material, as many times as necessary. By 3D printing a soil material, the traditional process gains an added value in the shapes that can be created. The material can have more resistance and stability simply by printing specific geometries that supports itself better. This is a very promising combination for the future, that has a lot of potential especially for solving housing issues in the developing world in a sustainable way. However, the current printer would need to be heavily modified to live up to construction requirements, such as speed or quantity, among others. There is also a need for a more extensive research on the properties of the 3d printed material. The Pylos project is certainly a step in the right direction.

# 6. Useful links and sources

Official website:
http://pylos.iaac.net/

Iaac Youtube channel:
https://www.youtube.com/channel/UCM_pHL0Txd32ZE56EZcjqbQ

Media articles on the technology:
https://3dprintingindustry.com/news/houses-printed-soil-83229/
https://3dprintingindustry.com/news/sofoklis-giannakopoulos-pylos-project-sustainable-house-3d-printing-grows-taller-59691/
http://www.archdaily.com/776261/iaac-researchers-pylos-3d-prints-with-soil

Further reading on mud brick technology:
http://www.yourhome.gov.au/materials/mud-brick
http://www.builditbackgreen.org/bushfires/interactive-green-building-guide/building-materials/mudbrick.aspx