AMA - Additive Merged Appliance

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The production of concrete structure components is often a backbreaking process due to the inconvenient and time-consuming process of producing the formwork. Depending on the geometry, this can be a very time-consuming activity. A trial will be made to solve these problems within the manufacturing process using adapted binder jetting technology. First of all, the research will deal with the behavior of concrete as well as the bond between the cement paste and the aggregate. Various additives and grain sizes will be determined to find an appropriate result. On the other hand, different spray and drop systems will be analyzed to compare the new method and the common binder jetting setup. After fabricating some geometrical shapes manually the study is going to be continued using computer-aided manufacturing.

Keywords: 3D Print, Binder Jetting, Concrete, Robotics, Additive Fabrication

INTRODUCTION

3D printing or additive manufacturing is a process of making three-dimensional solid objects from a digital file. Usually they are created by laying down successive layers of material until the object is entirely assembled. Each of these layers can be seen as a thinly sliced horizontal cross-section of the final geometry. This technology is presently being used for a number of different materials. At the moment, a lot of research is being carried out in the area of 3D concrete printing. The main questions that need to be investigated, deal with the process, the materials and the scale. There are already several documented projects about the progression of 3D printing technology. (Bogue 2013)

The main focus of "Concrete Printing" (Lim et al. 2011) is the construction of buildings. One major topic is how to include reinforcement into the printing process. Once this is possible, it opens the door to 3D printed, self-supporting, sustainable, free form architecture.

The founder of "D-Shape" (Dini 2010), Enrico Dini, implemented a methodology to create structures and sculptures in a big scale. He developed a strategy to produce a monolithic, seamless geometry.

Two scientific works from the ETH Zurich show that the scope for designing digitally developed walls is almost limitless. "Digital Grotesque" combines technology and nature in a very novel way (Mayer 2013). The commonly recurring problem is the fragility of the material that the structures are made of. They can only bear their own weight and no additional loads.

The aim of "AMA - Additive Merged Appliance", a modified version of the binder jetting process, is to bind the cement paste with the aggregates and in this way to produce load-bearing architectural components. Due to the application of a binder and support material it is an economic and ecological manufacturing process (Figure 1).
EXPECTATIONS
The trials are going to look at the bond between the cement, the water and the aggregate. Tools for the robot need to be developed for the computer-aided manufacturing. One tool needs to be developed for each material. The computerized control system should enable adjustable layer height as well as targeted application of cement paste.
AMA fabrication should be able to adjust the aggregate grain size meaning that the problems of scaling will then be irrelevant. Also, the process should allow for the accurate placement of cement paste. This means that the process will be more precise.

METHODS AND RESULTS
A series of experiments were performed to get first impressions of how binder jetting works.

Water Spray Attempts
The first trials were based on the basic concrete ingredients such as water, cement and sand.

1. Rapid-hardening cement was spread over a small area to testing the method. Water was sprayed onto the thin layer of cement using a nebulizer. A second layer of cement was spread over the first sprayed with water. This was repeated several times. After the fifth layer, a roller was used to compact the layers. In comparison to binder jetting process, the quick cement substitutes the powder, and the fluid binder is substituted with water.
2. The main components of the second step were rapid-hardening cement, water and sand. Sand was used in the cement mixture. The water was then sprinkled onto the cement mixture to create a 3D shape.
3. Thick layers of rapid-hardening cement were spread before spraying water on them. This achieved a smoother surface and enabled the liquid to fill the small voids between the sand particles.
4. Plain cement and sand, in a 1:1 ratio, were mixed and spread before moistening it.

The first experiment showed that it is impossible to achieve an effective combination of cement and water when the water is being sprayed onto the layers of cement.
The results of the different methods showed that nothing had been produced that would be usable. The samples were fragile and horizontally stratified. The second and third experiments were dissected and it could be seen that internally the layers were not totally connected.

Cement Paste
The previous test showed, water is not an effective binder on its own. A different binder had to be used. Different combinations of cements with water were tested to achieve an appropriate cement paste (Figure 2).

Figure 2
Cement paste tests using different aggregates. Sand, fine aggregate and coarse gravel aggregate.
1. In the first tests quartz sand and cement paste were layered alternately.
2. In the second test, fine gravel aggregate was mixed with sand and covered with cement paste.
3. Thirdly, coarse gravel was used in combination with the cement paste.

The results were much improved now that cement paste was being used as the binder. It was difficult to bind the sand using the cement paste as the pores between the grains of sand were too small and the paste could not permeate the first layer of sand. The second test with fine gravel and sand showed a similar result. The most successful test was the coarse gravel. The cement paste could pass through the spaces between the grains of the gravel. Substituting rapid-hardening cement with normal cement made no difference to the final appearance. It only speed up the drying time and changed the color of the object.

**Cement Paste Spray**
Tests were then carried out to investigate the necessary features of the nozzle. It showed how accurate the nozzle was and what pressure was needed and the size possible spraying radii of the deposited cement. A wooden box was produced for the experiments. This made sure the grit was laterally restrained during the drying phase. The tests were as follows:

1. Using an air brush and a compressor to spray the cement paste.
2. The second system was a spray painting system from a company called Wagner. This had a small nozzle and a large spraying radius.

These steps delivered important results. The airbrush compressor was deemed unusable as the pressure was far to high. The spray painting system was the more appropriate. One disadvantage is the time factor (Figure 3). The size of the spray radius also needed to be reduced as the application area of the cement paste was large and uncontrollable.

**Workability of the Cement Paste**
The experiments with the nozzle did not provide satisfying results. This meant the process needed to be changed. The next investigation involved dropping the paste through a funnel that was placed in the correct position.

Therefor investigations were carried out into the workability of the cement paste. Three different compositions were tested by dropping them on the gravel by hand. The different mixtures effected the appearance of the surfaces. The flow and drop behavior were taken into account and the most appropriate water cement ratio was selected based on the appearance of the test objects.

**Binder Jetting by Hand**
The next step involved testing a possible binder jetting setup for usability. A device consisting of two wooded boxed, one on top of the other, was used (Figure 4).

The two boxes were separated by two horizontal di-
aphragms. One is perforated so that the aggregate can pass through and the second is not.

The new printing process, performed by hand, consisted of 3 steps:

1. First, the aggregate was spread on the base of the top box in a layer which had a defined thickness.
2. Second, a mold was placed in the box and filled with cement paste.
3. Finally the mold was removed and the process started again.

This process was repeated 10 times. The mold was a little different for each layer. The opening increased in each layer. This meant that a self supporting object would be produced upside-down.

Once the cement paste had dried, the solid diaphragm without perforations was removed. This allowed all of the loose aggregate to fall down through the perforated diaphragm. The upper box was a casing for the printing process and the lower box was now used to contain the loose aggregate.

Different aggregates were tested to see how effectively they worked. The first aggregate was a coarse angular gravel with a grit size of 5-8 mm. The next was crystal quartz sand with a grain size of 3 mm was tested. Another material used was expanded clay.

The crystal quartz sand provided for a top quality surface but due to a small particle size which condense the layers, the cement paste could not flow through it. Both the crystal quartz sand and expanded clay samples presented a separated appearance in layers. The test with the chunky grit showed the best results: The layers were perfectly connected and not visible. The sample appeared to be homogeneous (Figure 5).

To optimize the surfaces, two different materials were then used. The coarse gravel was bonded and the sand was loose.

These steps were repeated for each of the molds.

1. The mold was placed in the retaining box.
2. The mold was filled with gravel.
3. The mold was removed.
4. The void from removing the mold was filled with sand.
5. The mold was put back in the box onto of the sand layer and cement paste poured into the mold.
6. The mold was removed.

The test with sand as supporter and angular gravel as aggregate was successful. The inside of the pyramid was homogeneous mixture of the cement paste and gravel and the surface was clearly defined by the sand particles (Figure 6).

Producing a self supporting object by hand
To test the possibilities of binder jetting a shape which had large overhangs was printed (Figure 7). For the first samples crystal quartz sand was used as both supporting and binding bind material. As before, a layer of aggregate was spears and then the cement paste poured.

The cement paste did not seep through from the...
most recently printed layer into the lower layers. The aggregate which was not bonded acted as a support material for the next layer.

Robotics

Figure 8
AMA setup: robots with linear print head (left) and cap for the cement paste (right).

Using a printing area that is surrounded by casing a multitude of different shapes are possible. Two industrial robots, ABB IRB 140s, with different print heads were applied (Figure 8). One tool was used for filling up the layer with coarse aggregate. It is a linear funnel, which leveled the surface of the aggregate. The second print head was a cone shaped funnel with a small round opening at the bottom. The cement paste was filled into the cone where it was stored until the locking bar opened and the cement paste could flow out of the tube onto the aggregate.

1. The exact amount of aggregate for one layer was filled into the casing and Robot 1 leveled the aggregate.
2. Robot 1 returned to its waiting position.
3. Robot 2 then moved to the correct position and opened the locking bar and placed the cement paste where it was needed.

The path of Robot 2 changed for every layer. The thickness of each layer was defined by the size of the aggregate. The workability was defined depending on the size of the aggregate grain so as to provide the perfect bond between the layers.

Hollow Cube

A shape was digitally modeled that could show the capabilities of the adapted binder jetting process. It was a simple shape with interesting surfaces. The shape focused on testing the limits of the process using overhanging parts.

The hollow cube was the divided into 8 equal parts. As the writing area was also limited in size. The digital model was then sliced using Repetier Host a computer slicing software. To be able to test overhangs the digital model was turned upside-down. It needed to be sliced in order to obtain the target points necessary to define the robots movements. (Figure 9).

Figure 9
Drawing of the hollow cube.

The next consideration of the computer-aided fabrication was the automatization of the cement paste supply. This was carried out using a sturdy printer head and a booster pump (Figure 10).

Figure 10
Tool path with an alternative printer head.

DISCUSSION

Although one suitable cement paste mixture has been found for the relationship between the aggregate size some parts of the manufacturing process still need to be fine tuned.

The modified binder jetting process is dependent on the aggregate size, the aggregate shape, the height of the layers and the workability of the cement
paste and all of these parameters have an effect on the internal bond between the lines of printed cement paste. Due to high variance in the chosen scale of the expanded clay and rounded shape of the crystal quartz sand as well as the expanded clay, the inner structure of the object was non-satisfying. To achieve a better quality using these materials it is possible to add aggregates with a larger grain size or more angular aggregate grain. Using the angular aggregate achieved the best results for the scale of the printing area that was tested.

The possibility of using different kinds of aggregate and several grain sizes makes it possible to produce smooth surfaces and therefore remove the necessity for post processing.

Further investigations should include the relationship between the grain size and the layer height, the mixture of water-cement with each grain to achieve a seamless bond between the layers.

The technique of removing the loose aggregate by establishing space below the printing area, demonstrates a promising approach to reduce the total fabrication time. However, the success of this procedure depends on the form of the object. Horizontal surfaces or enclosed regions prevent the aggregate support material from falling away from the object. When there is a horizontal surface or an enclosed region, additional automated processes would have to be developed. It could involve a lifting tool for the finished shapes. As previously known, the tool path is a continual path which does not have any breaks in it. To create spaces it is necessary for the locking bar of the nozzle to be mechanically operated. Also the process of forwarding the cement paste could be improved.

OUTLOOK

In comparison to other concrete 3D printing processes, "Additive Merged Appliance" has demonstrated great potential in fabricating complex geometry for use as an architectural solution.

For example, modular structures consisting of overhangs and unique parts can be produced with- out using conventional systems including form work. Because of the loose supporting materials it is possible to produce nested and twisted elements.

This technology can be used on and in any scale. The possibilities of using the technology in a prefabricated concrete plant could be a viable application. This method is not expected to replace traditional concrete production, it aims to offer more possibilities is regards to the design and realization of material efficient objects as well as speed up the production process.

REFERENCES

Bogue, R 2013, '3D printing: the dawn of a new era in manufacturing?', Assembly Automation, 33, pp. 307-311

Dini, E 2010 'Full-Size Stone 3d Printing', Smart Geometry Symposium, Barcelona


Mayer, H 2013, 'Aus Staub wird Gold', Archithese, 3, pp. 86-87