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BUOYCRETE, A LIGHT-WEIGHT CONCRETE IN COMBINATION WITH A MEMBRANE MOLD

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Figure 1: the underwater application of bouycrete in a membrane mould for the restauration of key walls

Key words: Buoycrete, floating concrete, neutrally buoyant concrete, light weight concrete, ductility, membrane moulding, freeform design, extrusion.

Summary. In this study, the authors present Buoycrete, a new material and work method invented by the company Boskalis. "Buoycrete" is a new cement mixture and work method. This mixture and the work method related to this material are developed by Boskalis and are patented in 2017[1]. The material is a lightweight concrete mixture that is 'neutrally buoyant' and non-dissolvable. The concrete is intended to be used under water. The neutral buoyancy makes that the concrete does not sink or float. In other words, within the cement mixture under water, right after application, there is no resultant vertical force apparent because of the neutral buoyancy. The cement slurry will be kept in place only by the internal cohesion of the Buoycrete slurry itself. This allows for fast and flexible adjusting of the concrete shape under water before the concrete cures. The unique cement-based grout opens up a wide array of possible application areas and markets, especially since application equipment, mixing equipment and curing characteristics are analogue to normal cement mixtures. Currently, there are no comparable light-weight cement mixtures available on the market. This paper

will start with an overview of concrete structures in combination with fabrics and will present the structural behavior, construction methods and applications of Buoycrete. It demonstrates that Buoycrete combined with fabric formwork creates new possibilities for the restauration of key walls but can also be used for the realization of façade elements, shell structures and other free forms.

1 INTRODUCTION

For the maintenance of water-related structures in civil engineering such as dikes, riverbanks, jetties and quays heavy equipment is needed. This results in long-lasting, complex and expensive projects. For this reason, maintenance of these structures is often postponed, which can lead to higher maintenance costs or even failure of the structure. Boskalis developed a new innovative, less complex and cost-effective alternative work method for maintenance of large concrete civil structures. This paper presents the properties of the Buoycrete mixture and a search to possible applications of Buoycrete for civil engineering and the built environment. In section 2 the mixture and material properties of Bouycrete will be discussed. Section 3. provides a description of how to process the material. In section 4 a summary of different application will be presented.

2 BUOYCRETE

"Buoycrete" is a new cement mixture. This mixture and the work method related to this material are developed by Boskalis and are patented in 2017[1]. The material is a lightweight concrete mixture with a weight of about 1000kg/M3. This makes this material 'neutrally buoyant' within water. Experiences with different water concentrations and intensive compaction procedures demonstrate that the Buoycrete mixture is very stable. No separation was experienced and the slurry viscosity can be tuned to very low values. The cement slurry will be kept in place by the internal cohesion of the Buoycrete slurry. With regard to viscosity, Figure 1 shows the low viscosity after intensive compacting with a poker vibrator.

Figure 2: Visual viscosity test after compacting [41] Figure 3 Fiber reinforcement [42]

This allows for fast and flexible adjusting of the concrete shape under water before the concrete cures. In stagnant water it is possible to extrude Bouycrete without a mold. In this case the surface of the mold will be irregular. Therefore it is not preferred to use this method for architectural applications. In situations with running water or with a more regular surface it is recommended to use a mold.

The unique cement-based grout opens up a wide array of possible application areas and markets, especially since application equipment, mixing equipment and curing characteristics are analogue to normal cement mixtures. Currently, there are no comparable light-weight cement mixtures available on the market.

The main ingredients are cement, puzzolans, colloidal additives, plasticizers, water, light-weight aggregates, sand, and other regular cement, concrete and grout additives. The particle sizes are very small, size range which makes the slurry pumpable through hoses with a minimal diameter of 5 mm. With an adjustable aggregate weight, the density and Uniaxial Compressive Strength (UCS) can be tuned to the desired level. For a density of about 1000 kg/m3, we achieved average compressive strengths between 30 and 40 MPa. It is assumed that the characteristic cylindrical compressive strength will be above 30 MPa, however we did not do enough sample tests for statistical evidence because the mixture is still in development. Indirect Tensile Strength (ITS) tests showed values of over 2 MPa. A side effect of our light-weight aggregate is the low elasticity modulus. Depending on the needed pressure strength the E-value is between 5-6 GPa.

Table 1: characteristics Buoycrete [41]

Table 2: Preliminary characteristics of glass fibre and polyvinyl alcohol [41]

Buoycrete characterics		
Volumetric weight	1000-1200	kg/m3
Compressive strength	> 35	Mpa
Tensile strength	> 2	MPa
Young's modulus	5<E<6	Gpa
Superior workability (pumpable)		
No separation/wash-out		
Good adhesion		
Lower building costs (time)		
Enhanced form freedom		
Normal strength Portland cement concrete characteristics		
Volumetric weight	2240-2400	kg/m3
Compressive strength	20-40	Mpa
Tensile strength	2-mei	MPa
Young's modulus	14-41	Gpa

Glass fibres		
Tensile strength	1300-1700	MPa
Youn's modulus	72 - 74	Gpa
Length	10'-40	
No corrosion		
Better chemical adhesion to concrete		
Cheap		
Polyvinyl Alcohol (PVA) fibres		
Tensile strength	1600	MPa
Youn's modulus	40-45	Gpa
Length	<10	mm

For tensile forces Buoycrete needs reinforcement. This can be done with traditional reinforcement with rebars to be assembled before printing. The steel structure could be placed underwater and a robot will print the Buoycrete around the reinforcement in layers to endure all compressive forces.

When standard reinforcement is not possible, fibers with different size, shape and material could be added to the Buoycrete mixture fig. 3. It is preferred to use smaller fibers and add them gradually to the mixture to avoid clogging at the end of the nozzle.

3 PROCESSING

Buoycrete gives many opportunities in architectural design and civil engineering. With Buoycrete it is possible to realize innovative and non-standard shapes in a cost-effective way. This gives a large possibility to make all kind of different shapes that cannot be realized with conventional printing. Concerning the processing, the following items will be discussed: Extrusion in water, 3D printing, Inflatable mold, Mold with distance fabric, Restauration and Pipe supports.

3.1 Extrusion in water

The neutral buoyant and adhesive behavior of the material ensures that the concrete slurry stays in place when it is poured in water. The benefit for 3D printing with Buoycrete is that we need no formwork and due to the neutral buoyancy printing can be done in all directions, even horizontal and downwards, like zero gravity printing in space.

Figure 4 Application of a thick Buoycrete layer at a vertical concrete surface [41]

Figure 4 is an example of the underwater application of a thick layer of Buoycrete at a vertical concrete wall. The good adhesion of the contact surface between the Buoycrete slab and concrete wall prevents the Buoycrete slab form being pushed away by the “printing” force of the pump extrusion and application force of the Buoycrete hose.

3.2 3D printing

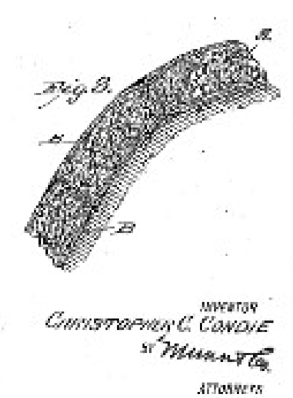
Figure 5 3D printing of instable concrete [42]

Figure 5 shows what happens when the eccentricity becomes too big during conventional 3D printing with concrete. The stiffness of the fresh concrete is too low and in combination with the gravity the structure will fail. [2]

The structure can be generated with software and can be converted to a robot. This robot can print the structure as programmed. This will save time and material compared to conventional methods.

3.3 Inflatable mold

A wide range of molds can be used from stiff molds up to membrane molds. It is also possible to pump Buoycrete inside an inflatable mold. In 1911 Christopher Condie submitted a patent concerning a Revetment-Mattress[3]. In 1916 A.C. Chenoweht patented the Protective Reinforced Concrete Construction [4]. J. Store patented in 1922 his Method of Constructing Subaqueous Concrete Structures [5]. These patents used permeable fabrics (geotextiles) padded with soil or concrete and were developed for civil engineering applications for the protection of dams, dunes, canals, etc. The textile is brought in tension to strengthen (reinforce) the soil or concrete. These techniques are still explored.



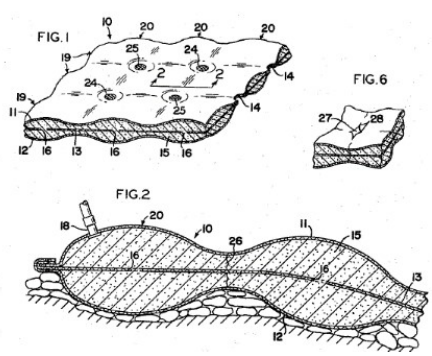


Figure 6. Patent 984,121 by C.C. Condie (1911)[43] Figure 7 Patent by Lamberton [43]

The improvement of materials in the 1950s provided a new impetus to the ideas on civil engineering with geotextiles. It led to new and better applications. The technique is still used by the Fabriform Company[6] Patents were developed invented and developed by B.A. Lamberton: Method and Arrangements for Protecting Shorelines [7] and Fabric Forms for Concrete Structures [8]. R.L. Mora: Inflatable Construction Panels and Method of Making Same [9]. H.F.J. Hillen: Form for Constructing a Slab for Talus or Bottom Protection [10].

Due to the fine partials, reduction in weight and neutral buoyancy of Buoycrete, the injection of geotextiles with Buoycrete is cheaper and easier compared to conventional concrete. The advantage of using an inflatable mold is the smooth finishing of the concrete surface. For the injection of inflatables a low viscosity is beneficial to guarantee a good degree of filling and to be able to fill up thin-layered inflatable moulds with small-distance reinforcement wires inside. The design and construction of inflatables is much cheaper and easier compared to conventional formwork.

Figure 8 and 9 Buoycrete objects created with an inflatable mould [11,12]

3.4 Distance fabric mold

Distance fabric is a structural textile that was developed in the nineteen fifties and is characterized by two parallel skins of fabric, which are integrally connected by large numbers of threads [13]. Because of these characteristics, distance fabric is often used in inflatable boats manufactured by Zodiac. Concrete Canvas consists of a cement impregnated distance fabric developed in 2003 [14]. The concrete is held between the two layers of a distance fabric. Once the Concrete Canvas is hydrated it has a working time of 1-2 hours and will achieve 80% strength after 24 hours. After 10 days the compressive strength of the rigidized canvas is 40 MPa, and its bending strength 3.4 MPa. This concrete mix consists of high early strength concrete with a limited alkaline reserve. The synthetic fibre reinforcement prevents cracking of the concrete and absorbs energy from impacts, while the PVC coated fabric ensures that the material is water impermeable. Once the structure is rigidized, the Concrete Canvas structure is fire proof and does not contribute to the surface spread of flames.

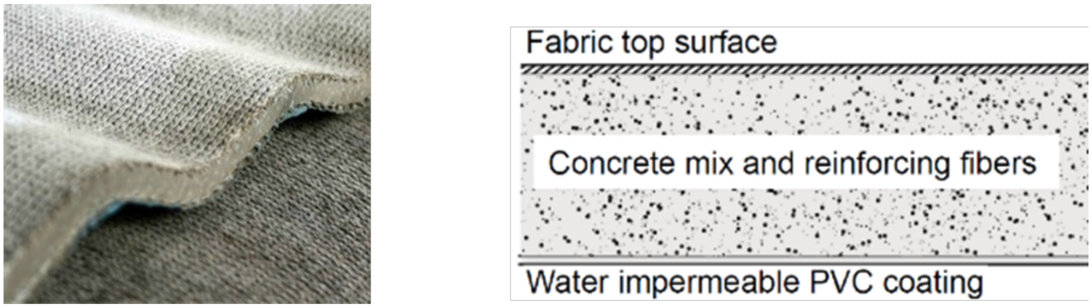


Figure 10 Cement impregnated concrete canvas. [23] and section view Concrete Canvas [16]

The concrete canvas mould is stabilized by inflation of air, and after the building has reached its actual size only water is required for impregnation to cure the surface into a thin and rigidized concrete shell structure fig 11 and 12. The application of these structures is mainly used for humanitarian aid and military applications. Once a Concrete Canvas Shelter is constructed it has a design life of approximately ten years [15].

Figure 11 Concrete Canvas Shelter [16] Figure 12 Internal view of shelter [16]

Concrete Canvas can also be applied in an artificially shaped element, like the stitching concrete shapes of fig. 13, made by German designer Florian Schmid[17]. In his designs, the softness of cloth, together with the stability of concrete, are both represented in an artificially shaped stool: There is the illusion of cloth, stitched together with colored thread, that would not provide enough strength to sit on. However, because of the concrete inside the fabric the stool is strong enough to use it like any other stool.

Figure 13 Stitching concrete, made by Florian Schmid [17]

Concrete Canvas is also applied in various other civil applications to strengthen the soil of dikes, benches, retaining walls and dam reinforcements, and therefore provide erosion control (fig.14). Concrete Canvas can also be used for the construction of canals or pipeline protection against impact damage and chemicals. Depending on the application of the Concrete Canvas, there are several options to secure the fabric together, such as screwing or using hog rings. In a dry, un-hydrated state an adhesive sealant can also be applied on the flap of the fabrics. In an already hydrated state mortar is used. The most watertight connection can be achieved by welding the fabric thermally together by heating the PVC coated fabric with hot air and then pressing them against each other. Depending on the ground conditions, Concrete Canvas can be secured to the ground using drilled bolts or nails with a washer to ensure that the head of the nail does not penetrate through the surface of the Concrete Canvas (fig.16). For ground surfacing applications such as ditch lining, slope stabilisation or erosion control, pegs are used or the edges of the Concrete Canvas are buried with soil or aggregates [18].

Figure 14 Concrete Canvas applied for slope protection with a spreader beam [16]
Figure 15 Nail with washer and Stitching [16]

For small and irregular curvatures with distance fabric a model was made by combining two surfaces of PVC polyester membrane strips. After the surfaces of the distance fabric were stitched together to create a doubly curved shape, the polyurethane in between the two surfaces was removed with acetone. The inner surface was closed and inflated. The distance fabric was filled with concrete. Figure 16, 17 and 18 shows the result.

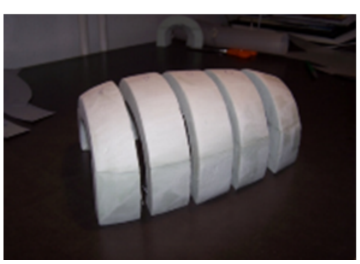


Figure 16 3D pur mould for weaving of distance fabric. Figure 17 sinclastic 3D fabric concrete[12]
Figure 18 sinclastic 3D fabric [12]

The second model is of a hyperboloid distance fabric as a mechanically stressed membrane fig 20. The two surfaces were connected by stitching in a flat position and were moved into position afterwards. The space between the membrane was filled with concrete and reinforced with straight bars fig 21. In this prototype the elasticity of the membrane allows the deformation that occurs when it is made into a doubly curved surface. The pretension in the membrane combined with a dense matrix of connection threads provokes a smooth surface of the concrete shell.

Figure 19 hyperboloid 3D fabric [12] Figure 20 s hyperboloid 3D fabric concrete [12]

To research the structural behavior of the concrete in the distance fabric 5 material experiments were done with different reinforcements: (1) plain concrete beam without distance fabric and reinforcement, (2) polyester fiber without additional reinforcement, (3) with glass fibers, (4) with aramid fibers and (5) with steel bars. The purpose of the test was to get an indication of the possibilities and outcome of the combinations. The membrane used is Hey-tex 2586 and the concrete BEAMIX 104

Table 3 Properties of concrete [12]

· Kind of concrete:	· Cement:
· 2250 - 2400 kg/m³	CEM III / B 42,5 N LH HS
· B 35	NEN EN 197-1 / NEN 3550
· Strength: 35 N/mm²	· fractures: NEN 5905
· Classification: 1, 2, 5a	· maximum gains size ± 4 mm
· *Water-concrete factor*: < 0,55 m/m	· super plasticizer NEN 3532

Table 4 Properties of distance fabric [12]

Product	HEY-TEX 2586 (Zweiwandgewebe)
Material distance fabric	Polyester
Length distance fabric	67 mm
Coating	PVC
weight of fabric	780 g/m^2
Weight of total	1900 g/m^2
Tensile strength	± 3.700 N/50 mm
Elasticity modulus	± 12.000 N/mm^2
Elongation at fracture	± 14 %
Fracture stress	± 1.200 N/mm^2

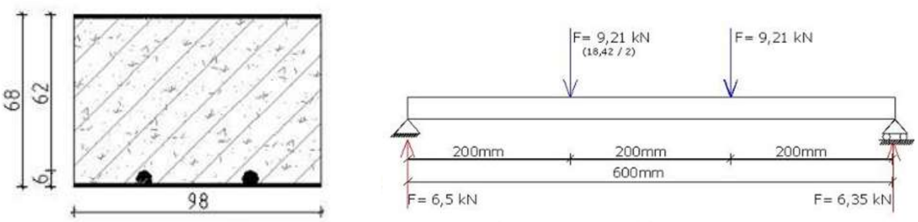


Figure 21 testing of 3D concrete fabric beam with steel bars [12]

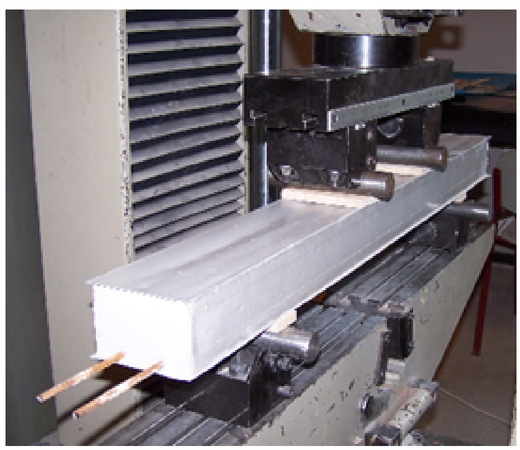


Figure 22 testing of 3D concrete fabric beam with steel bars [12]

The young's modulus of steel is 200 GPa Two 6 mm steel bars ruptured at 29.4 kN. The stress capacity of the two steel bars is 24.6 kN. The rupture occurred at 115% of the theoretical capacity of the steel bars.

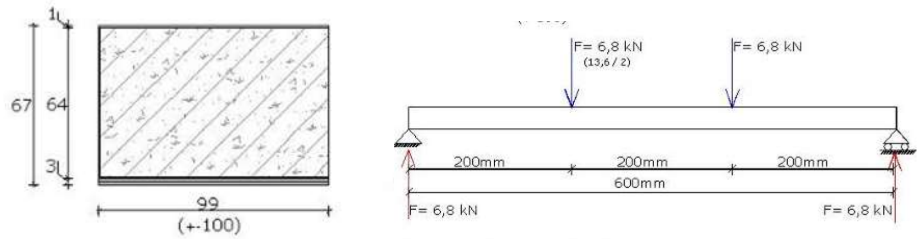


Figure 23 testing of 3D concrete fabric beam [12]

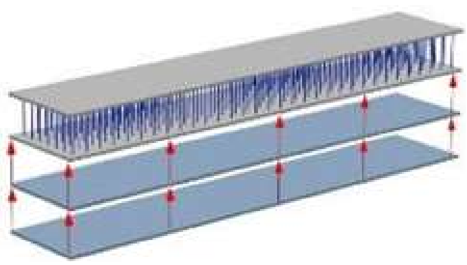


Figure 24 Beam with aramid [12] Figure 25 Failure of beam with aramid [12]

The young's modulus of aramid is 70-112 GPa. Aramid beam ruptured at 24.6 kN. The stress capacity of aramid is 41.0 kN . The rupture occurred at 60% of capacity of the aramid fibre.

Based on the above test it can be concluded that the adhesion between concrete and distance fabric is sufficient but it ruptures at 60% of the capacity of the aramid fibers. Material with a higher young modules like carbon or dyneema would give a better result and higher efficiency. Another option to improve the results would be a hybrid mix of steel bars and fiber reinforced concrete in combination with the distance fabric. In case of hyperbolic surfaces the steel bars can be straight in two directions while the fabric would make a doubly curved surface. In this research a distance fabric is combined with a local grid of beams. By leaving out the connectors the membrane surfaces will bulge out and form ribs to make the structure stiffer.

Due to the fine particles, reduction in weight and the neutral buoyancy of Buoycrete, the injection of distance fabric with Buoycrete is cheaper and easier compared to injection with conventional concrete. The invention of Membrane Concrete Grid Shells combines the advantages of these traditional technologies, like membrane formwork with the new material Buoycrete. This leads to a fast buildable, economic and ecological structure. Removing some fibers within the distance fabric will lead to an inflatable grid shell fig 26 and 27. Injection of the inflatable grid shell with Buoycrete will give interesting opportunities for realizing grid shells with more form freedom and will increase the freedom of complex shell structures.

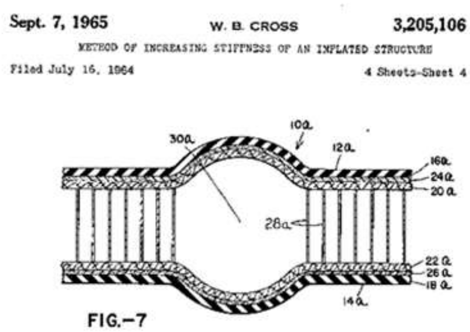


Figure 26 Patent 3205106 W.B. Cross (1965) [18]
Figure 27 Distance fabric mold combined with Buoycrete grid shell. [12]

3.5 Pipe support

Due to erosion, oil/gas pipes resting on the seabed can locally lack a proper support. This might result in high bending moments and broken pipes. To solve this problem, so-called grout bags are used to reduce the unsupported length of the pipes. A grout bag is a pyramid-shaped inflatable fabric formwork which is first placed underneath the oil pipe and then filled with a low-quality grout. In the offshore industry this work method is called a 'free span correction'. The desired shape is depicted in Figure 8. Filling these grout bags is a challenge, because they need to be filled layer by layer, avoiding high pressures to prevent the fabric from bursting. This method requires several dives, which are extremely costly at remote locations. The use of Buoycrete inside the grout bag or printing the pipe-support will lower the diving time and costs significantly. Thereby the load bearing capacity of the Buoycrete filled grout bag is much higher, because the submerged weight of the filled grout bag itself is zero.

Figure 28 and 29: Pyramid pipe support shape [11]

Figure 30 - Un-controlled Buoycrete application around steel pipe [11]

During the first actual test, the Buoycrete grout pump and mixer stopped working and the printing went very uncontrolled. Two piles of Buoycrete were wrapped around the pipe and the desired solid pyramid could not be formed. However, the final result without the brick supports demonstrates the high strength and quality of the cured Buoycrete mixture. With a very limited amount of Buoycrete and a far from optimal placing of the Buoycrete, the heavy steel pipe stayed perfectly in place after all water had been drained from the basin.

3.6 Restauration of key walls

The most interesting and feasible method is the restauration of key walls. Quay wall stabilization

With Buoycrete Boskalis developed a disruptive work method for (emergency) quay wall stabilization and renovation. It allows for quick repairs as well as much less extensive restauration work processes. Compared to traditional methods this does not require drainage of the quay wall nor does it require one to add extra weight to the already overloaded foundation. This reduces the risk of damage for the surrounding historic structures and minimizes the interruption of local accessibility. Meanwhile, the original quay wall structure can be maintained and used as much as possible to minimize the use of new raw materials.

Figure 31 – Old key-wall Figure 32 – Restauration of key-wall with inflatable mould

Figure 33 – Key-wall after restauration with Buoycrete with an inflatable mould.

In a later stage , after 20+ years, the quay wall could be renovated for another 100+ years with the so-called ‘Schiedam Method’, executed in Schiedam in 2015

3.7 Architectural appellations

Architects, designers and builders of civil constructions, floating structures and architectural eyecatchers can enjoy enhanced form freedom with the inflatable technique. The feasibility of double curved surfaces, topological designs and zero-g printed structures is taken a step closer by the disruptive Bouycrete technique. Contact us if you want to brainstorm about your application, futuristic designs, or other ideas with our team of Buoycrete experts. We make the impossible possible! The construction of (architectural) design products with complex surfaces requires expensive moulding. Fabric formworks for reinforced concrete construction and architecture have the ability to transform concrete architecture and reinforced concrete structures because they are light, thin and easy to form and manipulate. The natural-tension geometries of flexible fabric membranes provide light and inexpensive formworks, using less material than conventional formworks, and thus less waste. The flexibility of a fabric formwork makes it possible to produce a multitude of architectural and structural designs from a single, reusable mould.

The pre-stress of the fabric and the qualities of the concrete determine the shape: strong tension in the membrane results in a flatter shape and less tension in a more curved shape containing more concrete. This principle can be applied to create efficient, structurally optimized curves, unprecedented sculptural forms, and extraordinary surface finishes. As mentioned before the reduction in weight and neutral buoyancy of Buoycrete gives more possibilities for the shaping and construction of complex surfaces.

Figure 31 and 32 Open cell structures with flexible moulding [12]

Figure 33 and 34 Open cell structures with flexible moulding [12]

Open cell structures are organic structures characterized by their low own weight and optimized load bearing capacity. The three main phases within this research are: modelling of a bone structure as a façade element, optimization of the structure and construction of models.

For the design of the open cell structures a grasshopper script was used [19]. The script was based on the Voronoi-algorithm and is capable of generating an open cell configuration, based on several parameters, such as density, the location of the voids and the location of the points. The Voronoi algorithm is transformed, so it works like a lattice algorithm. The objective of the script is to generate a continuous surface suitable for analysis and production. Application of the script allows the user to quickly generate a surface with an open cell structure and manipulate it.

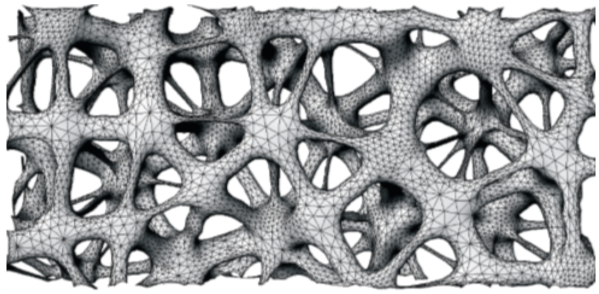


Figure 35 Simulating open cell structures in Grasshopper [19]

Figure 31 shows a model of a façade element in two parts, the inside bearing structure and outer façade. Both elements are connected with bolts. In-between both elements will be a transparent inflatable structure which will give a thermal break between both structures. The first bearing element will be placed during construction. The final element will be placed during the closing of the façade.

4 DISCUSSION

The natural buoyancy and adhesive properties of Buoycrete gives many advantages compared to conventional concrete. It increases the possibilities for 3D printing and manipulation of fabric formwork as described in the sections above. This new material and technique can provide many new opportunities in several areas such as architecture, civil engineering, offshore engineering, urban design and art.

5 CONCLUSION

Buoycrete is a relative new material and technique. This research has demonstrated that lightweight concrete with a mass equal to water could have almost the same mechanical properties as conventional concrete. The mechanical properties of the reinforcement of Buoycrete with fibers or rebars is not scientifically researched and will be one of the next research issues. The neutral buoyancy of Buoycrete makes it possible to create large cantilevers and shapes that could not be realized with conventional 3D printing. The combination of this material with fabric formwork makes it possible to realize large complex objects with a smooth surface. Up to now limited experimental projects and tests have been done. Therefore it is recommended to start with small-scaled experiments and prototypes and more research in the construction methods with this new material before realizing commercial applications.

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declare no conflict of interest.

8 PHOTO CREDITS

Permission was given for all figures that have been published elsewhere. The authors declare no conflict of interest.

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