Vacuumatic Concrete: From Boats to Architecture

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Abstract

With the invention of ferro-cement by Jean Louis Lambot around 1848, a new material and corresponding manufacturing technique had been introduced for producing structural objects with beneficial material properties (light-weight, strong, ductile and watertight), great formability potential and ease of construction. Although this ‘new’ material had first been applied to relatively small-scale structural objects, such as rowing boats, the technology got successfully adopted in the field of architecture. Pier Luigi Nervi, amongst others, is worldly renowned for using ferro-cement as a permanent formwork for realising appealing, yet structurally efficient (ribbed) floor and structures.

In the same tradition as the early applications of ferro-cement, this paper introduces a ‘new’ material and corresponding manufacturing technique, referred to as ‘Vacuumatic Concrete’, of which its potential is demonstrated by producing a small boat (or rather canoe). Further developments are mainly focussed on architectural applications.

Research on Vacuumatic 3D Formwork Systems by the first author has put forward the idea of effectively using vacuum pressure to draw a concrete mortar with low viscosity through a porous material, analogue to the resin-infusion process that is used for producing light-weight composite structures (not-surprisingly also boat hulls). Instead of applying the technique to an aggregate core, the intention of this study has been to use a sheet of spacer material, which is intended not only to function as a flow medium for the concrete mortar, but also as the reinforcement of the concrete object when fully cured. Ideally, the vacuum-infusion process facilitates the casting process of the concrete mortar as it does not require the use of (potentially) complex, double-faced, rigid formworks.

Keywords: Vacuematics, vacuum-infusion, concrete canoe, free-form concrete.
1. Introduction

Research on Vacuumatics 3D Formwork Systems by the first author (Huijben [1]) has put forward the idea of effectively using vacuum pressure (or rather an internal underpressure) for drawing a concrete mortar with a low viscosity through a porous material, such as (initially unbound, yet vacuumatically stabilised) granulate (Figure 1). The end product of this new technique is referred to as Vacuum-Infused Concrete.

![Vacuum-infusion principle with vacuumatics](Image source: Huijben [1])

The underlying technique of Vacuum-Infused Concrete is considered similar (in principle) to Vacuum-Assisted Resin Transfer Moulding (VARTM), also known as vacuum-infusion moulding, or vacuum-injection moulding. Instead of using a resin, however, a concrete mortar with low viscosity is used.

In various industries, VARTM is regarded as a successful closed mould technology for producing large, complex-shaped composite products in small series. Examples are amongst other things rotor blades of wind turbines, sports equipment, customised parts for the aerospace and automotive industries and boat hulls. With VARTM, dry sheets of reinforcement (such as glass fibre) are placed onto a rigid mould, after which the mould is closed by means of the flexible film and a liquid (resin) is drawn into the mould to effectively impregnate the reinforcement. The driving force for the flow of the liquid is a difference in pressure (Brouwer et al. [2]).

With Vacuum-Infused Concrete, it is assumed that the vacuum-infusion process facilitates the ‘casting’ process of concrete mortar as it does not require the use of (potentially) complex, double-faced, rigid formworks. The benefit of applying the vacuum-infusion technique to a vacuumatic structure with an aggregate core, is that these structures do not require an additional rigid mould or support structure for support during the vacuum-infusion process, since vacuumatic structures are typically relatively rigid (and thus stable) on their own. Self-evidently, various aspects determine the actual need for additional supports, such as the overall dimensions of the structure, the weight of the aggregate core, the weight of the concrete mortar and the level of vacuum pressure.

To the knowledge of the authors, Vacuum-Infused Concrete has not yet been researched or applied in practice before, apart from the research on Vacuumatics 3D Formwork Systems. Preliminary experiments have illustrated the technical feasibility of vacuum-infusion of a non-resin liquid, such as cement water (Figure 2) (Huijben [1], Slotboom et al. [3]). It has been proven to be rather difficult, however, to design a suitable concrete mortar (with sufficiently low viscosity) that can be drawn into the pores of an aggregate core or even through the feed lines.
Instead of applying the technique to an aggregate core, the intention of this study has been to use a (flexible) sheet of spacer material, such as a 3D spacer fabric, as the core. When applied with vacuum-infused concrete, the fabric is intended not only to function as a flow medium, but also as the reinforcement of the concrete object when fully cured. The end product is then referred to as ‘Vacuum-Infused Textile-Reinforced Concrete’. Furthermore, with this study the practical feasibility of shaping and curing concrete mortar that is subjected to a vacuum pressure has been explored. For referring to the end product of this specific approach (not necessarily obtained by means of a vacuum-infusion process), the term ‘Vacuumatic Concrete’ is used.

2.1. Architectural Context

With the invention of ferro-cement by Jean Louis Lambot around 1848, a new material and corresponding construction technique had been introduced for producing structural objects with beneficial material properties (light-weight, strong, yet ductile and watertight), great formability potential and ease of construction (Lavache [4]). Ferro-cement (or ‘ferciment’) typically consists of two layers of iron or steel reinforcement bars with a mesh of fine wires, which is plastered with cement mortar (Pemberton [5]). Although Lambot demonstrated this new material by producing relatively small-scale non-architectural objects, such as rowing boats (Figure 3), the technology got successfully adopted in the field of architecture. Several quite different examples of (free-form) concrete structures that have been produced throughout the years by effectively applying the ferro-cement technique are amongst others the Pallazzetto dello Sports in Rome by Pier Luigi Nervi in 1959 (Kato et al. [6]), the Truss Wall House in Tokyo by Ushida Findlay Architects in 1993 (Findlay et al. [7]) and the large aardvark sculpture (‘Feestaardvarken’) in Arnhem by Florentijn Hofman in collaboration with ABT Consulting Engineers in 2013 (ABT [8]).
Nervi’s ‘re-invention’ of ferro-cement in the 1940’s (which he patented in 1943) and its novel application as pre-fabricated (permanent) formwork for realising aesthetically appealing, yet structurally efficient (ribbed) floor and shell structures can be regarded as one of the biggest contributions to the development of concrete shell structures and their construction technique of the 20th century. What is interesting, is that, similar to Lambot in the mid 1800’s, Nervi experimented with ‘his’ ferro-cement technique by building small boats (Figure 4). In 1967, he was commissioned by the Food and Agriculture Organisation (FAO) to begin hull construction experimentation as they wanted to promote the construction of the inexpensive ferro-cement hulls in developing countries (Lavache [4]). In the years to follow, the technique evolved into a successful production technique, which has resulted in a long period of concrete hull construction.

Figure 4: Ferro-cement fishing boat ‘La Giuseppa’, designed by Nervi, 1967
Image source: ericafirpo.com

In the same tradition as the early applications of ferro-cement (by both Louis Lambot and Pier Luigi Nervi), the potential of Vacuumatic Concrete is illustrated in this study by designing and constructing a concrete boat (or rather canoe). The main objective of the overall experimental approach has been to gain practical knowledge on the manufacturing technique, intending to adopt it effectively in the field of architecture for the production of free-formed, potentially thin-walled, concrete objects. Examples of envisaged applications are free-form cladding, furniture and permanent formwork for producing large-scale, structurally-efficient, ribbed shells or floor structures, analogue to the work of Nervi.

2. Methodology
Although spacer materials are common items in the world of composite manufacturing (flow medium for VARTM), it needs to be determined whether a concrete mortar with low viscosity can be used instead of a resin. Therefore, first a few series of small experiments have been conducted on samples with various spacer materials. Apart from these preliminary tests, a variety of shaping experiments have been carried out to illustrate the shaping potential of concrete mortar, while subjected to a vacuum pressure. Lastly, a concrete canoe has been designed and build to participate in the annual Concrete Canoe Race (“BetonKanoRace”), which has been held in Rotterdam in May of 2015.

3. Spacer Material Testing
To explore the potential of using spacer materials to create Vacuum-Infused Textile-Reinforced Concrete, two different types of spacer material have been considered: a woven 3D spacer fabric and a non-woven spacer material ‘Colbond Enkadrain’ (Figure 5).
A 3D spacer fabric is a three-dimensionally-knitted fabric that consists of two separate layers of fabric, which are joined together by threads of nylon spacer yarn. Spacer fabrics are widely used for their properties in terms of cushioning, breathability, insulation and vapour transport in items such as car seats, back packs and mattresses. The Colbond spacer material, on the other hand, consists of more rigid threads and has therefore a relatively higher resistance to compression. Colbond products are commonly used in drainage applications, but also in VARTM for their beneficial properties as a flow medium.

Figure 5: Various spacer material: 3D spacer fabric (left) and Colbond Enkadrain (right)

For these preliminary tests, small samples have been placed inside a plastic membrane envelope and subjected to an internal underpressure. It has been found, however, that the 3D spacer fabric compresses too much locally (even when subjected to rather low levels of vacuum) for a low viscosity concrete mortar to be able to flow through the spacer fabric. The same conclusion has been drawn from the Colbond samples (Figure 6). In an attempt to even out the (externally acting) vacuum pressure, sheets of cardboard have been placed inside the membrane envelope. Although this approach levelled out the amount of compression, the viscosity of the concrete mortar (and potentially the capacity of the vacuum pump) appeared to be the limiting factor for the vacuum-infusion technique to be successful for this study.

It needs to be stated, nevertheless, that there are numerous types of spacer materials of which only two types have been tested in this study. Therefore, no definitive conclusions can be drawn here regarding the feasibility of the vacuum-infusion technique by using a low viscous concrete mortar and spacer materials.

Figure 6: Vacuum-infusion process applied to a sample of Colbond Enkadrain
For future developments, a detailed analysis of the concrete mortar and the spacer material will be desired to optimise the flow characteristics for vacuum-infusion purposes. Due to constraints in time and resources, the focus has been directed from the vacuum-infusion process towards the shaping and curing of the concrete mortar when subjected to a vacuum pressure.

4. Shaping and Curing Experiments

To explore the potential of shaping and curing concrete mortar when subjected to a vacuum pressure, various shaping experiments have been carried out. These experiments are illustrated below. From a practical point of view, with each experiment a layer of concrete mortar has been cast onto a flat surface, after which the mortar is vacuum-bagged and manipulated into its intended shape to cure. Consequently, the shaping process of concrete mortar can be explained analogue to the forming process of a piece of paper. This implies that the derived shapes are largely to be categorised as developable surfaces.

4.1. Experiment 1: From Strip to Arch

For this first shaping experiment, a strip of concrete mortar of approximately 850 x 190 mm$^2$ has been prepared on a flat surface, after which it has been vacuum-bagged and shaped (‘hung’ from elevated supports) to form a thin-walled arch that roughly represents the mid-cross-section of a typical canoe. For reinforcement, a sheet of fiberglass has been pressed into the freshly-cast concrete mortar prior to the vacuum-bagging process. The main aim of this first experiment has been to explore the feasibility of shaping concrete mortar in its uncured state, while being subjected to a vacuum pressure, in an attempt to retain its initial layer thickness. Typically, concrete mortar flows to the lowest point when placed in an inclined position, despite the thixotropic nature of cement-based materials. Nevertheless, it appears that particularly this resistance to segregation in combination with the vacuumatic prestressing of the concrete mortar enable a more or less consistent wall thickness of the object throughout the shaping and curing process.

With this first experiment, a concrete arch structure has been produced with a span of roughly 500 mm and a (slightly varying) wall thickness of approximately 6 mm (Figure 7). The surface finish of the object is considered relatively smooth in general, due to the use of an LDPE plastic membrane envelope. The slightly creased surface texture is caused by local deformations of the membrane envelope during the shaping process.

![Figure 7: Experiment 1: from strip to arch](image)

4.2. Experiment 2: From Strip to Arch

Although the first experiment has proven the feasibility of the shaping and curing of concrete mortar in vacuumatic state to obtain single-curved objects, a second experiment has been carried out with a number of potential improvements.
Due to the fact that an airtight connection is created between the wet concrete mortar and the membrane envelope, air pockets can occur inside the vacuum bag, which can result in an uneven distribution of the pressure along the surface area of the specimen when subjected to a vacuum pressure. With the first experiment, this has resulted in small variations in wall thickness of the final concrete object. In an attempt to resolve this issue, a net breather has been applied. In this case, a layer of Colbond spacer material has been used as breather, which is separated from the concrete mortar by means of a perforated sheet of plastic film. Additionally, the sheet of fibreglass reinforcement has been replaced with a sheet of carbon-fibre reinforcement for its higher stiffness. Furthermore, the specimen is only partly hung from elevated supports to form a flattened arch, which simulates the cross-section of a canoe hull more correctly (Figure 8).

The end result of this second experiment has been a flattened concrete arch structure with a wall thickness of approximately 9 mm (the wall thickness has been increased slightly, since the carbon-fibre reinforcement had some (unwanted) pre-curvature and sufficient covering with mortar was required). Furthermore, due to the non-uniform pattern of threats of the Colbond breather, the surface texture of the concrete object is slightly more wrinkled in comparison to the first experiment. A smoother breather will therefore be beneficial. The breather material did however result in a more or less uniform vacuum pressure along the surface of the specimen.

4.3. Experiment 3: From Trapezoid Surface to Pointed Object

For the third experiment, a trapezoid-shaped surface has been shaped to represent the pointed end of a canoe. Potential improvements in comparison to the second experiment have been amongst other things the use of a piece of cloth as the breather and the addition of a foam retaining strip along the perimeter of the specimen, which functions as a flow barrier for the concrete mortar. Furthermore, a spiral tube is placed behind the retaining strip along two sides of the specimen to achieve a continuous evacuation of air (Figure 9).
The end result of this third experiment has been a pointed (or folded) concrete object with a constant wall thickness of approximately 6 mm (Figure 10). This specific test has indicated both the technical as well as practical feasibility of producing freely-shaped Vacuumatic Concrete objects.

Figure 10: Experiment 3: from trapezoid surface to pointed object

With respect to the casting process of the concrete mortar, it is found to be beneficial to use a mortar with low viscosity for obtaining a uniform mortar thickness (on a flat surface). On the other hand, it is found to be beneficial to use a highly viscous mortar for guaranteeing a uniform wall thickness of the final object (due to the thixotropic behaviour of the mortar) during the shaping and curing process. For future developments, the initiation of the shaping process might therefore be determined in relation to the curing time of the concrete mortar. In other words, it should be possible to ‘postpone’ the actual shaping process up to the point where the concrete mortar has reached its optimal level of curing (and thus viscosity) for it to be manipulated into its desired shape.

5. Concrete Canoe

The final experiment has been the design and production of a concrete canoe for participating in the annual student Concrete Canoe Race (‘BetonKanoRace’). The construction process is comparable to the third experiment. The final shape of the canoe has been obtained by (partly) hanging the vacuum-bagged concrete mortar from a wooden frame that has the outline shape of a canoe. The parts of the canoe that are intended to be flat are resting on a flat surface underneath the framework (Figure 11).

Figure 11: Concrete canoe frame (left) and defining final shape by means of breather cloth (right)
For predetermining the exact dimensions of the canoe in its flat ‘unfolded’ shape, a piece of breather cloth is hung from the frame and cut to its desired dimensions. All further preparations have been carried out on a flat surface (Figure 12).

After the concrete mortar has been fully cured, the concrete canoe has been ‘demoulded’ by removing the vacuum-bagging equipment. For aesthetical purposes, the canoe has been painted (Figure 13), although any form of post-processing of the concrete surface is not strictly necessary. The quality of the final concrete surface finish is largely determined by the smoothness of the plastic membrane envelope, the accuracy with which the layer of concrete mortar is evenly laid onto the flat surface and by the handling of the specimen during the shaping process. It needs to be noted, that, in case of relatively rigid sheets of reinforcement, tight curvatures might cause this reinforcement to ‘push through’ the layer of concrete. The concrete canoe eventually has ‘wavy’ edges as a result of the way the vacuum-bagged concrete mortar has been ‘hung’ from its supporting framework. A smoother edge can be obtained by fixing the specimen in a more uniform manner to the supporting framework.
6. Conclusions & Discussion
With this study, the process of producing Vacuum-Infused (Textile-Reinforced) Concrete has not (yet) been proven technically feasible, largely due to the relatively high viscosity of the concrete mortar and potentially the rather limited capacity of the vacuum pump. Further study on the mixture of the concrete mortar (in particular its viscosity) is required. For successful implementation of the vacuum-infusion technique, Darcy’s Law can be considered, as it formulates (in an integrated form) a one-dimensional flow of liquid through a porous medium (Brouwer et al. [2]):

\[ t = \frac{\phi \cdot \mu \cdot l^2}{2 \cdot k \cdot \Delta P} \]  

(1)

In which \( t \) = injection time, \( \phi \) = porosity of the core material, \( k \) = permeability of the core material, \( \mu \) = viscosity of the infused fluid, \( l \) = flow distance, \( \Delta P \) = applied pressure difference.

On the other hand, the process of producing Vacuumatic Concrete by shaping and curing a liquid concrete mortar (from an initially flat surface) while it has been subjected to a vacuum pressure has been proven feasible both technically and practically. For future developments, the curing characteristics of the concrete mortar might be optimised for obtaining the optimal viscosity of the mortar for the casting process (low viscosity) as well as the shaping process (high viscosity).

In the same tradition as the early applications of ferro-cement, the potential of this new technique has been illustrated by designing and constructing a small boat (canoe). The concrete canoe has proven to be ‘seaworthy’ as it has entered (and survived) the annual Concrete Canoe Race and even won a price for the most innovative canoe. This holds the promise for the further development of vacuumatic concrete for architectural and structural purposes.

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References