24 Zero Waste Free-Form Formwork

S Oesterle[1], A Vansteenkiste[1] and A Mirjan[1]

[1] *Professorship for Architecture and Digital Fabrication, ETH Zurich*

This paper introduces a completely waste-free fabrication method of formwork for free-form, cast-on-site, non-repetitive concrete structures. The characteristics of concrete, to be cast into any shape, make it an ideal material for complex, double-curved large scale projects. However, the state of the art in free-form formwork fabrication for on-site use still requires labor intensive or wasteful processes. The method presented here, consists of wax formwork elements, poured on a flexible actuated mold that after curing can be assembled on-site, on standard scaffolding, ready for concrete casting. After striking the formwork, the wax elements can be fully re-used by re-melting and moulding them into new shapes. .

1 Introduction

The question of constructing free-form concrete structures has challenged many architects, designers, engineers and fabricators, especially since the 20th century. The challenges included bending and placement of the reinforcement, developing appropriate concrete formulations and finally the construction of free-form formwork and its re-use.

Figure 1: Ponte sul Basento, Potenza, 1969, Sergio Musmeci, in universale di architettura.

Concrete is well suited for large scale, load-bearing free-form structures (Figure 1). It has demonstrated its potential in this field in many applications such as for the large span roofs of Pier Luigi Nervi or the shells of Felix Candela that are particularly interesting with respect to formwork. Candela limited his structural designs to shapes derived from hyperbolic paraboloids in order to allow the formwork being fabricated from straight members, thus drastically simplifying the construction process and making it possible to re-use the formwork parts (Tom van Mele & Philippe Block 2010).

In recent decades, computer-aided design, engineering and fabrication have opened up new approaches to building free-form geometry (Bechthold 2008), but an economic and sustainable construction still poses great challenges to the industry.

An important part in building free-form concrete architecture is the fabrication and construction of the formwork, since it accounts for 35% - 60% of the total concrete work's cost (David W. Johnston 2008). Particularly challenging regarding cost are, load bearing concrete structures that require monolithic on-site casting. The state of the art for on-site formwork is milling of expanded polystyrene blocks into formwork inlays for high curvature solutions (Nedcam 2010) or the use of custom cut and flexed sheet materials such as plywood for low curvature applications (Weilandt *et al*. 2009). When looking at industry standards, both technologies are waste intensive, since they allow only for a single use of the formwork element.

A wide field of academic studies is also concerned with flexible formwork solutions. The state of research includes approaches such as fabric formwork for pre-cast and cast-in-place building elements (Mark West & Ronnie Arya 2009), pneumatic formwork (Werner Sobek 1986) and flexible formwork moulds for the prefabrication of concrete panels (Christian Raun *et al*. 2010). Prefabricated panels are mainly used as façade cladding or lost formwork (Schipper & Janssen 2011). Several concrete moulding technologies exist. The two most widely use ones are a densely packed array of pins that are leveled by a flexible top layer (Walczyk & Munro 2007) and the combination of wider spaced actuators with an interpolating sheet material layer that is bent into shape (Pronk *et al*. 2009).

In summary the formwork technologies accessible today are either limited due to cost factors, precision or in size.

The purpose of this research is to develop a novel free-form formwork technology that is economically and ecologically sustainable and delivers on-site construction feasibility comparable to state of the art solutions. The research aims at establishing a precise and waste-free formwork system, specifically targeting large scale and structural applications that consist of non-repetitive shapes.

2 Methods

This paper details a formwork process cycle that applies off-site prefabrication of formwork elements for on-site concrete casting.

It continues with describing the development of wax as a re-usable on-site formwork material.

Furthermore it presents a forming method for wax formwork elements based on a robotically actuated mold. The industrial robot used for actuation is available as part of a larger fabrication cell at our lab. The robot is capable of managing multiple operations in the production process of the wax formwork elements.

The paper concludes with the constructive detailing and on-site handling procedures for wax formwork elements.

2.1 Wax Formwork Process Cycle

The Zero Waste Free-Form Formwork combines a new type of wax-based formwork element (Figure 2) with standard scaffolding for on-site application. The wax elements are inexpensive in comparison to other free-form formwork inlays and the wax material is fully re-usable.

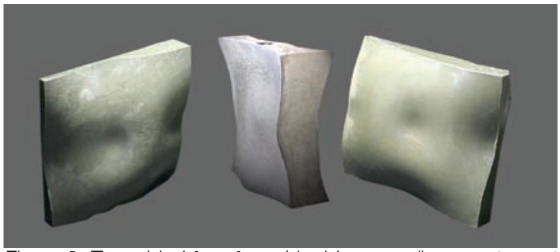

Figure 2: Two-sided free-form (double-curved) concrete cast with corresponding wax formwork.

The complete wax formwork process cycle can be summarized as follows (Figure 3):

1) The wax based formwork elements are formed off-site by a flexible actuated mold, onto which the hot and liquid thermoplastic wax is poured.
2) After solidifying, the wax elements are taken from the mold and mounted onto a standard support structure on-site.
3) Reinforcement is placed on the wax formwork, concrete is cast and after curing the formwork is removed.
4) The wax formwork elements are ready to be re-used for producing a new element.

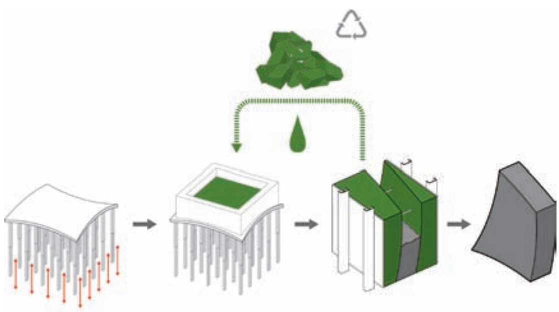

Figure 3: Waste-free wax formwork process cycle

2.2 Wax Material Development

Wax can be molded in to any form and subsequently re-used by melting and forming it into new shapes. At the same time wax can achieve the necessary strength and stiffness required for concrete casting when hardened. Previous research tested wax for prefabrication of concrete panels (Ralph K. Scott 1971).

2.2.1 Wax as a Transfer Material

In the process cycle presented here wax is used to transfer the macro geometry from the mold surface (positive) to the wax element surface (negative) and subsequently to the concrete surface (positive).

Tests also showed that a transfer of micro scale properties such as surface texture and surface shininess through the wax element is extremely accurate.

Several different wax formulations have been tested and in collaboration with a wax manufacturer a new wax blend has been specifically developed for concrete casting and subsequently assessed.

2.2.2 Wax Softening Point

When using wax as a formwork material on-site, its softening point at higher temperatures needs close attention.

The softening point must be sufficiently high to avoid deformation under load and low enough to allow for re-melting. Additionally, a higher softening point results in a harder surface, but it also leads to a more brittle wax and a higher degree of shrinkage during moulding due to the increased melting temperature and eventually increased volume.

To determine a good relation between surface hardness and shrinkage an array of ring shrinkage tests of several wax blends has been carried out. A selection of the results is presented in Figure 4.

For the on-site use of wax formwork elements there are two important heat sources to take into account: concrete hydration heat and solar insolation.

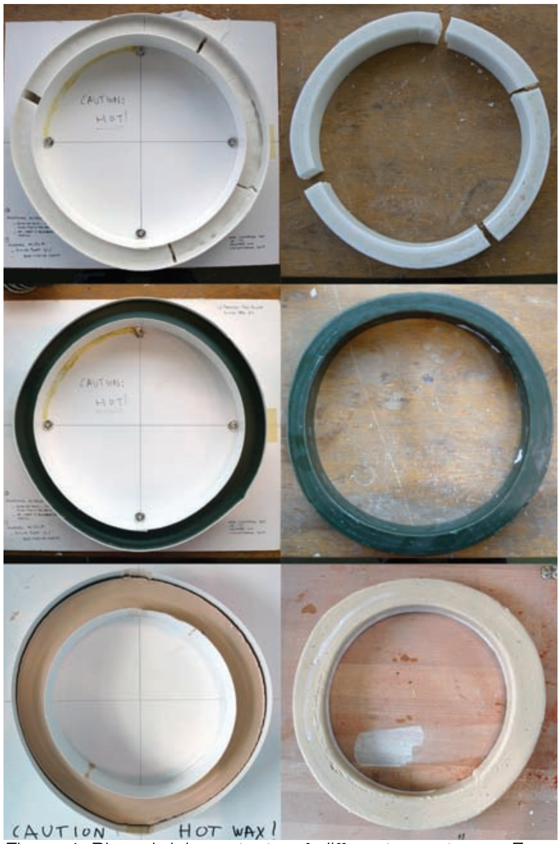

Figure 4: Ring shrinkage tests of different wax types. From top to bottom: High melting point polymer wax with shrinkage cracks, investment casting wax without shrinkage cracks, custom formulated concrete casting wax without shrinkage cracks.

2.2.3 Concrete Hydration Heat

The concrete hydration process generates heat that will increase the temperature of the concrete in contact with the wax formwork.

As shown in Figure 5, the temperature rise in a 0.4m thick concrete element in wooden formwork is approximately 30°C at the formwork surface. However, this peak in hydration heat happens when the concrete has already hardened to an extent where the pressure on the formwork is decreasing.

Tests with a concrete column demonstrator (see: 2.6 Demonstrator: Mechanical Wax Properties and Handling) showed that no visible deformation of wax occurs despite the hydration heat. Further quantitative tests are necessary to verify these results.

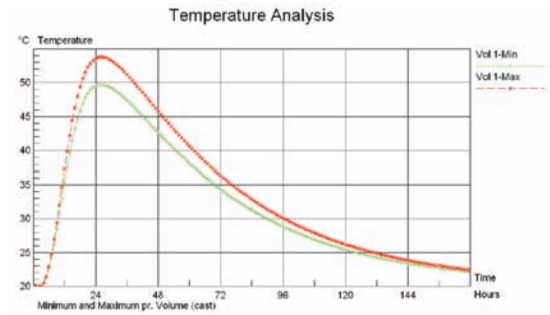

Figure 5: Simulation of temperature progression during the hydration phase of a 0.4m thick concrete wall in wooden formwork. Source: Danish Technological Institute.

2.2.4 Solar Insolation

Another heat source that can influence the mechanical wax properties to a critical extent is solar insolation. Especially if combined with high ambient temperatures, this can lead to an unsustainable rise of wax formwork element temperature.

In order to reduce the temperature rise in the wax formwork elements, several measures have been tested: covering the dark wax elements with white fabric, shading the wax elements, treating them with a white coating and changing the color of the bare wax.

Several samples were tested, exposing solid wax blocks to the sun for one day with clear sky and air temperatures up to 33°C. Results showed that exposed dark wax can reach surface temperatures above 60°C. By protecting the dark wax with a white cloth, the exposed surface temperature is reduced to 50°C. Using a white color coated dark wax, the surface temperature is reduced to 40°C; a similar result was achieved with a bare white colored wax element resulting in a maximum surface temperature of 46°C.

The temperature rise over one day for bare dark colored wax and bare white colored wax is shown in Figure 6.

In order to address the unsustainable temperature rise of the wax elements, a specific wax blend for concrete casting with a higher melting point and white color was developed in collaboration with the wax manufacturer. This wax blend has a good ratio of hardness/toughness and brittleness/shrinkage. It has unimpaired mechanical properties at higher temperatures up to 50°C. This allows for on-site applications with ambient temperatures up to 30°C and direct sun exposure.

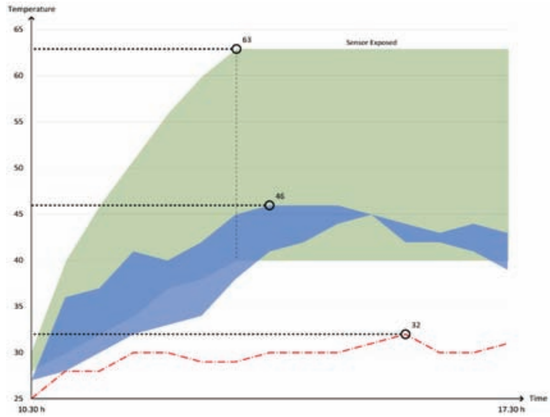

Figure 6: Temperature rise of a dark color wax block (green) and a white wax block (gray), during 7 hours, on a hot sunny day (Zurich, 17. Aug. 2011).The bands on the graph show temperature at the bottom and top surface of each wax block and the ambient temperature (yellow).

2.2.5 Re-use of Wax

The re-usability of the wax is crucial to the waste-free nature of this formwork technology.

After being used for one application, the wax elements can be either broken up or directly re-melted without any further processing. No cleaning is necessary since dirt can easily be separated from the liquid wax, due to the difference in density. Furthermore, tests showed that small dirt particles do not negatively affect the surface quality of the wax elements.

From an ecological perspective, the amount of energy needed for re-melting has to be considered. Although wax has a relatively high embodied energy (Geoff Hammond & Craig Jones 2008), it can be re-used until the embodied energy can be neglected in the overall energy evaluation. Due to the single, one time investment in material embodied energy, this process compares well to processes where the material cannot be re-used (e.g. custom cut wood formwork or EPS milled blocks).

From an economical perspective, the re-use of wax means that the material cost can be considered as an investment cost, rather than a consumable cost.

2.2.6 Wax Surface Resistance

Reinforcement handling on site can damage the wax surface and heavy reinforcement loads can leave marks from the reinforcement spacers. Penetration tests showed that this can be a serious challenge when working with a softer type of wax. This was addressed during the development of the new concrete casting wax, which resulted in an increased wax surface hardness.

No precise figures from penetration test are available yet but qualitative tests showed that the combined use of rounded reinforcement spacers with the new concrete casting wax can reduce indentation marks to acceptable levels, comparable to spacer indentation marks in PU coated OSB wood plates.

2.2.7 Prototype: Wax Material Properties

After producing several smaller samples, a first prototype was manually fabricated. This 1:1 scale prototype of a wax formwork element served to analyze the feasibility of using wax as a formwork material. It was tested:

1) The shrinkage behaviour of wax material when moulding larger elements,
2) The fabrication handling of heated, liquid wax,
3) The casting of concrete on wax
4) And the wax from concrete release properties.

A 1.0m x 1.0m wax element with a hollow back was molded on a positive test shape made from MDF. The geometry consisted of a double-curved surface with minimal principal curvature radii down to 1.5m, a conservative estimate of targeted geometry (Figure 7).

The wax did not show any shrinkage cracks and both the wax and concrete surface accurately replicated the original MDF mold surface. The wax element was released from the concrete without leaving traces on the concrete surface. Although a vacuum suction effect was firmly holding the wax element to the concrete surface.

Figure 7: Prototype for testing of the wax material properties. Wax formwork (left), concrete cast positive (right).

2.3 Wax Forming Mold

For a time efficient moulding of wax formwork elements a machine is required that can fabricate such elements according to their digital geometric delineation.

A custom flexible mold was developed specifically for the pouring of re-useable wax formwork elements. It consists of a square top surface with a side length of 1m. The top surface rests on 5x5 CNC actuated rods that allow bringing it into a defined shape.

2.3.1 Step by Step Moulding Procedure

Figure 8: Step 1, melting re-used wax.

Figure 9: Step 2, adjustable mold actuation.

Figure 10: Step 3, casting hot wax in mold.

Figure 11: Step 4, formed wax element on mold.

Figure 12: Step 5, wax formwork on-site.

2.3.2 Wax Mold Surface Layer

The mold surface layer interpolates between the CNC actuated rods. It is the contact surface onto which wax is poured. In order to allow for high curvature the surface needs to be flexible, but at the same time it needs to be rigid enough to not show any deformation in between the actuated supports under melted wax load.

An empirical test series of different surface solutions has been carried out, to find the best stiffness to flexibility ratio for wax moulding. Options such as slotted plates (Schipper & Janssen 2011) or wire supported stretchable sheet materials similar to (Christian Raun *et al*. 2010) have been tested.

The best results were achieved with a composite of two materials, addressing two different requirements in the wax forming process.

A sheet of closed-cell plastic foam allows for a continuous double-curved elastic deformation, while still being stiff enough to carry the weight of the wax.

The contact surface to the wax is made from a 2mm silicone layer that is applied on top of the foam sheet. This allows easily removing the finished wax element from the mold after hardening without leaving traces. Since the wax is an almost perfect transfer material it is possible to achieve a wide range of concrete surface qualities, from matte to glossy, by adjusting the surface properties of the silicone layer.

Due to the low weight of wax, a relatively thin foam sheet can be chosen that allows higher curvature than with direct concrete casting moulds. Currently the mold surface allows for double curvature radii down to 0.6m in minimal principal curvature direction.

2.3.3 Wax Mold Surface Actuation

According to a digital geometry model, the mold's actuators are positioned (Figure 9). For a continuous surface from one wax panel to another, the precision of the location of the supports and eventually the accuracy of the shaped surface in comparison with the digital model is crucial.

The mold described in this paper uses our lab's industrial robot to push telescopic rods in place before blocking them with an electromagnetic locking system (Figure 13).

Figure 13: Experimental robotic mold.

2.3.4 Wax Mold Enclosing Edges

The wax formwork elements have to be assembled flush onto the standard support structure. This requires the formwork edges to be vertically aligned and eventually a vertical mold enclosure that can adapt to the deformation of the moulding surface without bulging.

A frame of coated soft foam is pressed vertically on the curved top surface of the mold. This frame makes a watertight connection with the top surface while keeping the edges vertical (Figure 10).

Tests showed that minimal bulging of the foam enclosure occurs, depending on the shape of the mold surface.

2.4 Construction Details

2.4.1 Hollow Back, Wax Formwork Elements

In order to save weight and material, the wax formwork elements are conceived with a hollow back with ribs in two directions (Figure 14). The dimensioning of this structure was calculated using mechanical properties, derived from three point bending tests on wax samples.

The structural integrity of this concept was confirmed by the use of hollow back wax formwork elements for a 3m high self-compacting concrete column prototype (see: 2.6 Demonstrator: Mechanical Wax Properties and Handling) that exerts a pressure of 70 kN/m^2 on the formwork elements at the base of the column. The wax elements did not break or visibly deform.

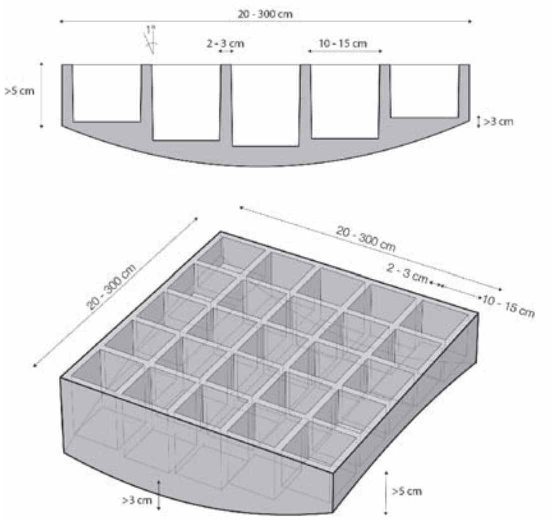

Figure 14: Dimensioning of hollow back of formwork elements, based on mechanical properties.

2.4.2 Release

The wax formwork elements can be released from the concrete without leaving traces on the concrete surface, even without the use of release agent on the formwork. However, some force is needed to release the wax element, to overcome a vacuum holding it against the concrete. For this reason, as well as to reduce air holes in the concrete surface, the use of a release agent is still recommended.

2.4.3 Wax Elements Joints

The application of wax formwork offers the possibility of using a hot wax joint filler to achieve quasi seamless concrete surfaces. Hot wax paste can be applied on the joint between two adjacent wax elements and evened out to close the gap between elements (Figure 15). This method results in a continuous formwork surface, although a difference in surface texture at the joint is still visible.

Figure 15: Joint of adjacent wax elements sealed with hot wax (left). Concrete surface cast against wax surface with sealed joint (right).

2.4.4 Form-ties

Since the wax formwork technology is developed for double-curved free-form geometry, a form-tie solution that is always normal to the surface is required. A special form-tie cone for this situation has been developed by Robusta-Gaukel (Robusta-Gaukel GMBH & CO.KG 2007).

Throughout several tests the suitability of this form-tie for the wax formwork element has been verified. The applicable curvature ranges have been tested as well as nailed connections of the form-tie to the wax formwork.

2.5 On-Site Assembly and Handling

The wax formwork elements were designed to be compatible with existing formwork systems, assembly procedures and on site working methods (Paschal-Werk G. Maier GmbH 2009).

The following steps describe an exemplary assembly procedure for two-sided formwork. After erecting one side of a support structure, the wax elements are fixed to it. Rebar and form ties are placed. After fixing a second side of wax elements to a second support structure, this is lifted in place and the form ties are closed (Figure 16).

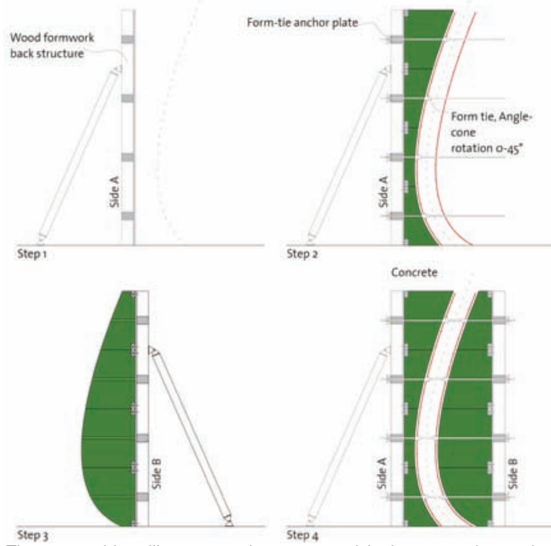

Figure 16: Handling procedures for 2-sided formwork on-site: 1. placement of the support structure side a; 2. attaching of wax elements, tie rods and form ties; 3. assembly of side b; 4. attaching side a and b.

Wax formwork elements can be mounted and fixed on a support structure by screwing in small wood blocks, embedded in the wax during fabrication. This fixation method is simple and allows for tolerance in on-site mounting (Figure 17).

The wax formwork elements can be handled on-site either manually or with a crane, depending on the size and weight of the element. For larger elements where handling by crane is necessary, anchors can be embedded in the wax during fabrication (Figure 17).

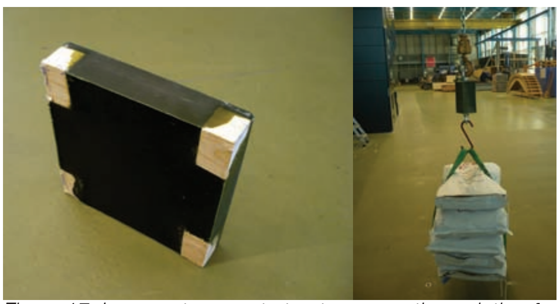

Figure 17: Low-cost support structure mounting solution for wax formwork elements and wax formwork anchor load test

2.6 Demonstrator: Mechanical Wax Properties and Handling

In order to test the mechanical properties of the wax material and handling procedures of the wax formwork elements in a 1:1 scale, on-site scenario, a 3m high concrete column was built.

The two-sided formwork of the double-curved column consisted of eight 0.75m x 0.75m wax elements in standard steel concrete formwork. Since the handling test was done before the development of the actuated wax mold, an experimental sand mold procedure was used to form the wax elements. The characteristic surface texture is a result of this forming process.

The concrete used for the column was a self-compacting concrete with a slump-flow of 0.65m. The 3m high formwork was filled completely within 5 minutes. This allowed a worst-case pressure test of the mechanical properties of the wax formwork elements.

The wax formwork was released from the concrete without traces.

Figure 18: Demonstrator: Mechanical Wax Properties and Handling - Assembly and casting of a 3m high concrete column on wax formwork with a steel support structure.

3 Conclusions

This paper has proposed a wax-based, re-useable, free-form formwork process for on-site concrete casting. The process provides:

1) A new type of a digitally controlled flexible mold for lightweight wax element casting;
2) An economically viable free-form formwork solution due to rapid moulding timing, low manual labor in the construction of the formwork elements and low formwork material cost;
3) An ecologically sustainable and waste-free free-form formwork process cycle due to the re-usability of the wax formwork; and
4) A precise transfer of design geometry to the build concrete structure.

Key features of the wax formwork elements are:

1) A melting point higher than the above average hydration temperatures of most concrete surfaces and higher than sun induced material temperatures for central European regions;
2) A weight saving element design with a hollow back for easy on-site handling;
3) Minimal principal curvature radii down to 0.6m.

The presented formwork system extends the advantages of rapid moulding of prefabricated panels to be transferred on-site and to be used for large scale applications. Wax as the material for the formwork elements has clear ecologic advantages over existing on-site free-form formwork solutions. In comparison to the approach of fabric based formwork or pneumatic formwork, we achieve a precise transfer of arbitrary geometry from model to build structure. The proposed process cycle will allow for an economically feasible construction process. It expands the proven and tested concept of formwork inlays by a low cost, easy to fabricate and easy to handle solution.

Currently, the process cycle is in a prototypical development stage regarding the moulding of the wax formwork elements. Future work includes going towards a fully automated robotic moulding process specifically regarding edge solutions. Furthermore wax surface hardness could be increased to avoid damage from reinforcement. The enhanced process will be applied for the construction of a large scale demonstration structure towards Autumn 2012.

4 Acknowledgements

This research has been made possible by funding from the EU-FP7 project TailorCrete. The authors would like to thank the project partners for their comments during the development. Project partners are: Bekaert, Chalmers, Czech Technical University, Danish Technological Institute, designtoproduction, Dragados, El Caleyo, Gibotech, Grace, Paschal, Superpool, Unicon, University of Southern Denmark. Without the amazing help from the team at the concrete laboratory of the Institute for Physical Chemistry of Building Materials, Prof. Robert Flatt, ETH Zurich, this research would have been impossible. Further the authors would like to thank the team at the Raplab, ETH Zurich. Wax material has provided by Paramelt who also developed a new wax blend specifically for this project.

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