CHALMERS
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Towards Ultra-thin Façade Elements

Textile Reinforced Green Concrete with Vacuum Insulation Panels

Master's Thesis in the Master's Programme Structural Engineering and Building Technology

SANDRA BENTLAND

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Concrete Structures
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Cover:
Illustrative picture of the façade element of textile reinforced green concrete with vacuum insulation.

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ABSTRACT

This Master's thesis project was part of an ongoing research project that aims to develop a façade element for a Passive House standard that can help reduce the energy and material use, and emissions in the buildings sector, but at a smaller thickness than what is typical for Passive House walls. The research project focuses on three innovations in combination: green concrete, textile reinforcement and novel insulation materials. Green concrete is concrete with an industrial waste product as the binder which presumably makes it more environmentally friendly than Portland cement concrete. Textile reinforcement instead of conventional reinforcement may decrease the needed concrete volume of a construction element by 85%. Vacuum insulation have 2 to 9 times better thermal resistance than conventional insulations. A façade element developed from the three innovations will be installed in the research and demonstration arena HSB Living Lab and evaluated during real circumstances.

The aim of this Master's thesis project was to study shrinkage of green concrete and to model and simulate the temperature distribution and heat flux in the façade element when installed in HSB Living Lab. The aim was also to calculate the U-value of the façade element with two different frames, one of timber and one of steel, that was developed specifically for the installation in HSB Living Lab and to find the needed thickness of the façade element that makes it fulfil the Passive House standard.

A literature study was carried out to find possible solutions to reduce the shrinkage of green concrete and it was found that heat treatment and addition of quicklime, gypsum, fly ash, polypropylene glycol and light-burned dolomite, separately had shown to have a reducing effect. Casting and shrinkage measurements of samples with fly ash added to the green concrete binder was performed. The results were compared with results from earlier studies without fly ash, but the fly ash did not decrease the shrinkage. Numerical simulations showed that the frames used for the installation in HSB Living Lab need to be insulated and two insulated frame suggestions were developed in a cooperative project. Calculations of the U-values of the framed façade elements showed that with 100 mm vacuum insulation in the element, the U-value will be about 0.22 W/($m^2 \cdot K$) with the timber frame and 0.13 W/($m^2 \cdot K$) with the steel frame. The total thickness of the unframed façade element was found to be 130 mm at U=0.10 W/($m^2 \cdot K$) and 104 mm at U=0.15 W/($m^2 \cdot K$).

Key words: Textile reinforcement, facade elements, vacuum insulation, green concrete, ground granulated blast furnace slag, alkali-activated slag, water glass, shrinkage.

Contents

Preface

The Master's thesis project presented in this report was performed from January to June 2015 at the Department of Civil and Environmental Engineering, Chalmers University of Technology, Sweden. It was part of an ongoing research project called *Ultra-thin Envelopes* that, as the name indicates, aims to develop ultra-thin exterior walls for low energy houses. The research project is one of five sub-projects in the project *Next Generation Building Envelope Systems* at the Department of Civil and Environmental Engineering, which in turn belongs to the Climate-KIC flagship program *Building Technologies Accelerator*. Climate-KIC is an innovation partnership that is working against the climate-change.

This Master's thesis project has been carried out with support of the examiner and supervisor Assistant Professor Filip Nilenius, and the supervisors Associate Professor Angela Sasic Kalagasidis and Assistant Proffessor Helén Jansson. In different ways they have provided helpful guidance throughout the project and I would like to thank them for that! I would also like to thank PhD student Shuping Wang for her help with the experimental work in my project and all other members at the Department of Civil and Environmental Engineering that has helped me when needed. They are all doing a great job for our climate and I am glad to have got to be a part of that!

Göteborg June 2015

Sandra Bentland

1 Introduction

1.1 Background

One of the major concerns of the society today is how the world is affected by people's way of living. Measurements of temperature and precipitation show that the climate is changing and the intensification of extreme events such as floods, storms and droughts are probably consequences of the global warming. The awareness of the greenhouse effect and that some of the world's resources are limited has increased during the last years. This has resulted in a global fight towards a sustainable society where a reduction of greenhouse gas emissions and a decrease in the use of materials and energy are main priorities.

The buildings sector contributes with approximately 30% of the global greenhouse gas emissions and accounts for as much as 40% of the global material use (Roodman & Lenssen, 1995; UNEP, 2009). The sector is the largest user of energy with an energy use that represent about 40% of the global energy consumption (International Energy Agency, 2013). During the lifecycle of a building about 15% of the total energy used is consumed during production of materials and during construction and demolition of the building. As much as 85% of the energy is hence consumed during a building's operational phase (Petersson, 2009) and to construct buildings that use as little energy as possible, for heating and cooling it, is therefore very important. A concept that has been created to make this possible is the Passive House concept which was created in Germany in the 1990s. The Passive House concept regulates for example the U-value, which is a measure of the heat loss, of buildings and building parts. The simplest way to affect the U-value of a building is by extra insulation in the building envelope and experts have determined the optimized insulation thickness, from an energy economic point of view, to about 300 mm to 500 mm for conventional insulation materials (International Energy Agency, 2010). As comparison, the buildings built in end of the 1900s had exterior wall thicknesses of between 200 mm to 300 mm, both load-bearing and non-load-bearing (Björk et al., 2009; Björk et al., 2013). A quadratic house of 100m^2 livable area would gain another 10m^2 in livable area if the exterior walls were decreased from 500 mm to 250 mm thickness. In other words, the livable area would increase from 100m^2 to 110m^2 which corresponds to for example an extra bed room. Thinner walls would also result in other benefits such as lighter structures, more daylight and less consumed material, which in turn may lead to less transports to the building site.

1.2 Problem discussion

To reach the energy demands of a Passive House, walls insulated with conventional insulation materials often have an insulation thickness of about 500 mm. Today there are newly developed insulation materials, such as vacuum insulations, which have about 2 to 9 times better thermal conductivity than conventional insulations. This means that exterior walls insulated with vacuum insulation can have the same thermal resistance as walls insulated with conventional materials, but at smaller thickness.

In both load-bearing and non-load-bearing exterior walls, concrete is one of the most used materials but a disadvantage with concrete as a building material is that reinforcement is needed to give the material sufficient tensile strength. Conventional reinforcement is made of steel that may corrode and therefore needs to be protected by a thick layer of concrete, ranging from 20 mm to 75 mm (Swedish Standards Institute, 2008). Due to the needed concrete cover construction elements, in most cases, are cast with more concrete than what is needed to ensure the load-bearing capacity of the element. A construction element with conventional reinforcement has shown to need up to 7 times more concrete than a construction element with textile reinforcement (Tomoscheit et al., 2012). Hence, concrete with textile reinforcement instead of steel reinforcement is a solution that can decrease the exterior wall thickness and thereby gain more livable area.

Another disadvantage with concrete is that the manufacture of cement, which is the usual binder in concrete, produce about 5% of the global carbon dioxide emissions. That is 1/6 of the total amount of greenhouse gas emissions that the buildings sector contributes to globally. By 2050 the amount of produced cement per year is expected to be between 44% to 73% larger than it was in 2006 (International Energy Agency, 2009) and consequently, environmental benefits can be gained by an exchange of binder material. Possible binders are other cementitious materials such as the industrial waste product ground granulated blast furnace slag which is produced from a by-product in the production of iron. The exchange of Portland cement to slag is a concept that in this report is referred to as green concrete. However, concrete cast with slag has shown higher shrinkage than concrete cast with Portland cement. The shrinkage of slag concrete is in fact severe and possible solutions to reduce shrinkage have been found in the literature study in this Master's thesis project.

1.3 Purpose

This Master's thesis project was part of an ongoing research project called *Ultra-thin Envelopes* which is one of five sub-projects in the project *Next Generation Building Envelope Systems* at the Department of Civil and Environmental Engineering, Chalmers University of Technology. The project is sponsored by Climate-KIC and thereby belongs to the Climate-KIC flagship program *Building Technologies Accelerator*. The research project *Next Generation Building Envelope Systems* aims to develop a façade element for a Passive House standard that can help reduce the energy and material use, and the emissions in the buildings sector, but at a smaller wall thickness than what is typical for Passive House walls. Separate studies are made in the research project to evaluate the shrinkage, thermal properties and mechanical properties of green concrete and of green concrete reinforced with carbon and basalt textile reinforcements. Also a combination of the three innovations green concrete, textile reinforcement and vacuum insulation is examined.

1.4 Aim

The aim of this Master's thesis project was to find possible solutions to decrease the shrinkage of green concrete and to model and simulate the temperature distribution and heat flux in the façade element when installed in HSB Living Lab. The aim was also to calculate the U-value of the façade element with two different frames that had been developed specifically for the installation in HSB Living Lab and to find the needed thickness of a façade element of vacuum insulated textile reinforced green concrete that has a U-value below the value required by the Passive House standard.

1.5 Limitations

In this Master's thesis project the only insulation material chosen for comparison with vacuum insulation was mineral wool. Laboratory tests were limited to shrinkage measurements of different concrete mixes and the time interval of the measurements was limited 28 days. The difference between the concrete mixes was in particular different ratios between the contents of the binder. No other additives than fly ash were tested for their ability to reduce the shrinkage of green concrete during the project. Minimum slag content was half of the binder. However, no sample with slag as the only binder was cast during the project. The sandwich element design was the only design studied for the façade solution in the project. Numerical simulations were performed in the finite element modelling program COMSOL Multiphysics 5.0.

2 Presentation of the Façade Element

2.1 Prefabricated construction elements

In recent years the use of prefabricated construction elements has increased in the construction industry. Prefabricated construction elements are wall, roof and floor structures which are assembled indoors in a factory and delivered finished to the building site. At the building site, the elements only need to be mounted in the right places which means that the envelope of a building can be completed faster than if it is completely built on site. Thus, two of the advantages with prefabricated construction elements are that the building process will be faster and that the sensitive building materials will be exposed to possible bad weather conditions during a shorter time. The construction elements may consist of the entire cross-section of a wall, roof or floor, or of a part of the cross-section. An example of the latter is, as in this project, a non-load-bearing façade element which has to be supplemented with a load-bearing structure.

A popular type of prefabricated construction element is the sandwich element which typically is constructed of two reinforced concrete layers with an intermediate insulating layer, see Figure 2.1 (Strandberg, 2014). Today there are many types of sandwich elements on the market. They can have external layers of for example plywood or steel sheets instead of concrete, and they can either be load-bearing or non-load-bearing.

Figure 2.1 Typical construction of a sandwich element. Prefabricated wall element in the factory of the concrete supplier AB Strängbetong. (Photo: Angela Sasic Kalagasidis).

In the research project *Next Generation Building Envelope Systems* efforts are being made to further develop the standard sandwich element mentioned above. Sandwich elements with a vacuum insulation panel as the core material have already been developed and façade elements with textile reinforced concrete have been investigated. However, the combination of vacuum insulation, textile reinforcement and environmental friendly concrete has not yet been studied.

2.2 Performance demands

One of the requirements that the research group of the project *Next Generation Building Envelope Systems* impose on the façade element is that it shall perform and be able to be classified as a Passive House element. A Passive House is a building that is heated primarily by internal heat gains from people, the sun and household appliances such as refrigerators and computers. The Swedish Passive House standard is based on the international definition of a Passive House but adjusted to fit the Swedish climate and building regulations. Simply stated, the Swedish Passive House standard limits the yearly energy used for heating of a building, the overall heat transfer coefficient and the U-value of glazed sections (Sveriges Centrum för Nollenergihus, 2012). By the Swedish Passive House standard it is not possible to certify a façade element, but internationally a certification of building components is possible to attain from the Passive House Institute (Passive House Institute, 2012). The international recommended U-value of a wall is less than 0.15 $W/(m^2 \cdot K)$ and was consequently used as the limit for the façade element in this Master's thesis project (BRE, 2011). The target U-value, in the research project, is 0.10 $W/(m^2 \cdot K)$.

Another demand that the research group impose on the element is that the thickness of the wall, even though it performs a Passive House element, shall be smaller than what is typical for Passive House walls. No specific thickness was required, only an evaluation of the possibilities was requested.

2.3 Demo site

The research group of the project *Next Generation Building Envelope Systems* will have the opportunity to install and observe two façade elements of vacuum insulated textile reinforced green concrete at the demo site HSB Living Lab. *HSB Living Lab* is a project that HSB runs with the main partners Chalmers University of Technology and Johanneberg Science Park. It is one of the five sub-projects in the project *Next Generation Building Envelope Systems*. HSB Living Lab is going to be a research and demonstration arena which will accommodate both residential and social spaces, and the idea is that new innovations created for a sustainable living in the future will be examined under real circumstances. During the autumn of 2015 it is planned for the residents to move in, and from then and about ten years forwards researchers will have the possibility to collect all sorts of data from both short and long-term research projects in the Living Lab (HSB, 2014).

Figure 2.2 The first rendering of the research arena HSB Living Lab (HSB, 2014).

2.4 Construction of the façade element

The construction of the façade element is of two layers of textile reinforced green concrete with an intermediate layer of a vacuum insulation panel, see the principle sketch in Figure 2.3. Since no extra concrete cover is needed to protect the reinforcement from corroding the concrete panels can be made thinner than if the reinforcement had been of steel. The research group of the project *Ultra-thin Envelopes* has suggested a maximum thickness of 30 mm of the concrete panels and in the Master's thesis project the concrete layers were assumed to be 25 mm thick which is equal to the thickness of the concrete panels cast in the laboratory, see Figure 4.4 in Chapter 4.2. The needed thickness of the vacuum insulation panel, with regard to the demand of the U-value of the element, can be found in Chapter 5.3.

For the installation of the façade element in the research arena HSB Living Lab the element needs to be exchangeable. Therefore two possible frames were designed by Mohammad Sadegh Khani, master student, and Shea Hagy, MSc and project manager of the *HSB Living Lab* project at Chalmers University of Technology. One of the frames was designed completely in cross-laminated timber and consists of three aerogel insulated parts, see Figure 2.4. The two parts marked with a darker color in the figure are intended to be permanently mounted to the existing structure of HSB Living Lab. To these two parts the third removable part, marked with a lighter color, is supposed to be assembled and in turn act as the frame for the façade element. The second suggested frame was designed with a load-bearing structure of rectangular steel profiles, see Figure 2.4. The steel frame is meant to be removable and connected to the existing structure via additional permanently mounted steel profiles. The steel alternative is further equipped with aerogel insulation and a covering layer of timber. The exposed parts of both frames are to be covered with galvanized steel plates.

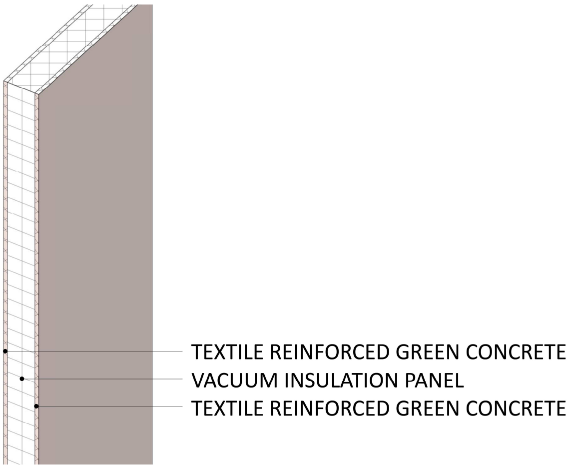

Figure 2.3 Principle sketch of the textile reinforced green concrete façade element.

Figure 2.4 Left: The cross-laminated timber frame, here without galvanized steel covers. Middle: The load-bearing structure of the steel frame. Right: The steel frame equipped with insulation (in yellow), covering timber and galvanized steel covers.

2.5 Materials of the façade element

2.5.1 Green concrete

Concrete with an industrial waste product as the binder can have a significantly lower impact on the environment during its lifetime than concrete containing ordinary Portland cement (Jiang et al., 2014) and this exchange of binder concept is therefore called green concrete. The green concrete consists of a binder referred to as ground granulated blast furnace slag produced from a by-product in the production of iron. The by-product is called blast furnace slag which is found together with iron in a liquid state in the blast furnace. To become ground granulated blast furnace slag, a substance suitable as binder material, the by-product has to be rapidly cooled down with water to solid form and then ground into powder, see Figure 2.5 (Cervantes & Roesler, 2007).

When ordinary Portland cement is used in concrete a gel (C-S-H) is produced from the hydration process that binds the components of concrete together. The formation of the gel is very important since it gives the concrete its strength (Cervantes & Roesler, 2007). To make the C-S-H gel form in the green concrete mix the ground granulated blast furnace slag needs an alkaline environment, i.e. it needs to be activated with an alkaline solution (Jiang et al., 2014). In this study a solution of liquid sodium silicates, also known as water glass, is used as activator of the slag in which the silicates contribute to the strength. Different activators give different properties to the slag concrete and alkali-activated ground granulated blast furnace slag concrete has shown to have better compressive strength than concrete with ordinary Portland cement as the binder (Chi et al., 2012).

Figure 2.5 Ground granulated blast furnace slag. (Photo: Sandra Bentland)

2.5.2 Textile reinforcement

Fabrics used as reinforcement in concrete can be manufactured in a variety of ways. Different materials such as carbon, aramid, alkali-resistant glass and basalt fibers can be used and the yarns made from the material fibers can be arranged in several manners (Brameshuber, 2006). In the research project *Ultra-thin Envelopes* the studied textile reinforcements are of carbon and basalt, see Figure 2.6. When a textile reinforcement is manufactured, yarns composed of up to thousands of thin threads are woven or knitted into different patterns. The reinforcement can be made two or three dimensional and the yarns can be arranged in different directions, whatever fits the application area of the concrete (Brameshuber, 2006).

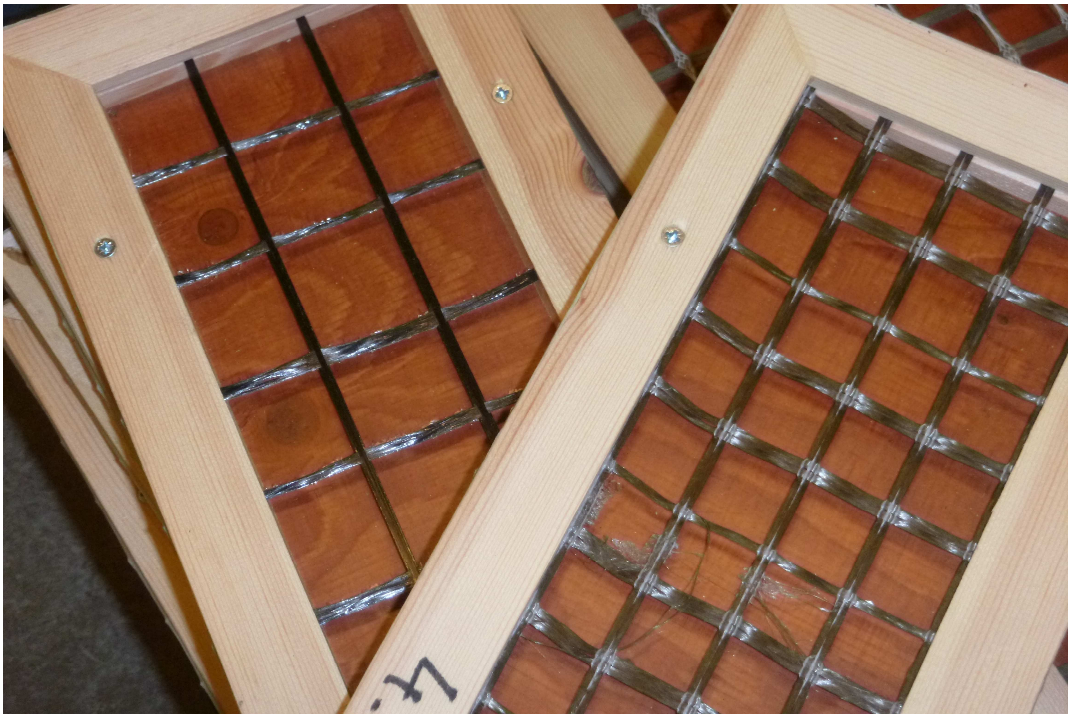

Figure 2.6 Left: A concrete mold reinforced with a carbon textile. Right: A concrete mold reinforced with a basalt textile. (Photo: Helén Jansson)

2.5.3 Vacuum insulation

Vacuum insulation is usually in the form of a panel, which consequently is called vacuum insulation panel. A vacuum insulation panel is constructed of a core surrounded by a multi-layered metalized polymer film or a foil of aluminum that acts as a sealant. The core material is usually of fumed silica, precipitated silica, glass fibers, polyurethane foam or polystyrene foam from which the air has been removed. The thermal conductivity, λ, which depends on the core material of the insulation panel, has been measured to approximately 0.004 W/(m·K) and to about 0.020 W/(m·K) if the panel becomes punctured (Simmler et al., 2005; Berge & Johansson, 2012). In comparison mineral wool, which is one of the most used conventional insulation materials, has a thermal conductivity of about 0.036 W/(m·K) (Petersson, 2009). Due to the early aging of vacuum insulation panels a thermal conductivity of 0.006 W/(m·K) should be used in design purposes when the core is wrapped with an aluminum foil film, and 0.008 W/(m·K) when the core is surrounded by a metalized polymer film (International Energy Agency, 2010). The design values are based on the thermal conductivity of a panel at an age of about 25 years.

In the project *Next Generation Building Envelope Systems* vacuum insulation panels with a core of fumed silica wrapped with a polymer film are studied, see Figure 2.7. Hence, the design value of 0.008 W/(m·K) was used as input value for the numerical simulations in this project.

Figure 2.7 *A vacuum insulation panel with a core of fumed silica. The layer closest to the silica core is a core protection and the outermost layer is a multi-layered metalized polymer film. (Photo: Axel Berge, PhD student at Chalmers University of Technology)*

3 Methodologies Used in the Project

3.1 Literature study

In the Master's thesis project a literature study was performed to find possible solutions to reduce the shrinkage of green concrete, see Chapter 4.1. A systematic research was performed of all articles published between the years 1980-2015 using the database Web of Science. The strategy for the initial search was using keywords in different combinations and to sort the results by relevance. The keywords used were *concrete, slag, ground granulated blast furnace slag, alkali-activated, shrink, shrinkage, sodium silicate, water glass, activator* and also the acronyms of ground granulated blast furnace slag and alkali-activated slag which are *ggbs* and *aas*, respectively. The titles of the articles were read and only the ones that could possibly include solutions to the shrinkage problem of concrete containing ground granulated blast furnace slag activated with sodium silicate were sorted out for further reading of the abstracts. The abstracts could more specifically tell if the articles were relevant or not.

The initial search resulted in a few interesting articles where in particular two articles were of great interest and the continued literature review therefore emanated from them. The articles were read through to learn from the studies and to find sources in the texts that could be interesting as well. Also the titles of articles that had cited the two selected articles were read in case they had carried out similar studies. New keywords were chosen based on keywords in the interesting articles and a second search was performed in the same way as the first. A flowchart of the process can be seen in Figure 4.1. When source articles were not found in the database Web of Science the database Google Scholar was used as a complement.

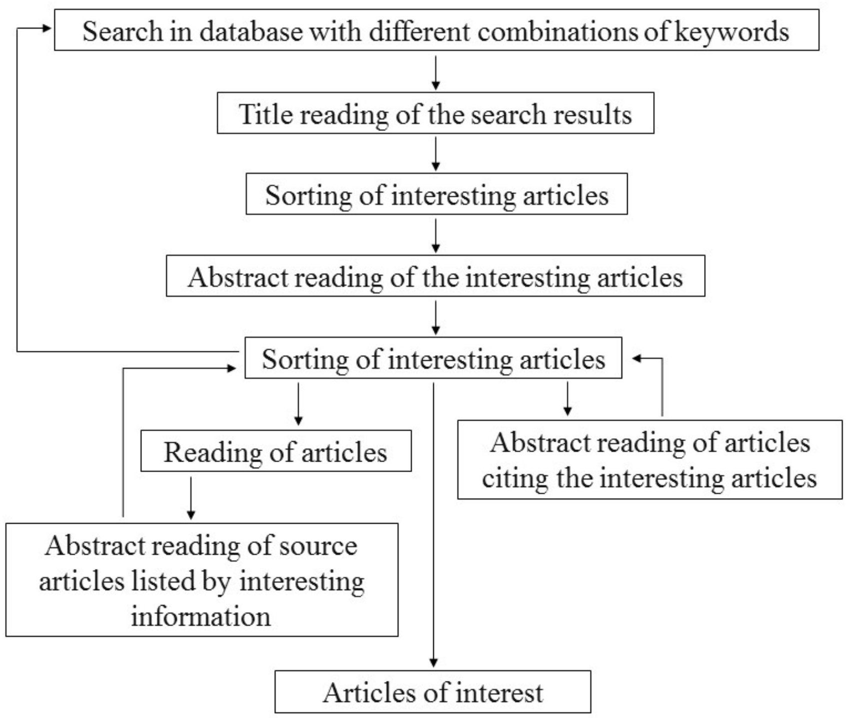

Figure 3.1 A flowchart showing the methodology used in the literature review.

3.2 Experimental studies

Casting of different concrete mixes in the laboratory was carried out in the Master's thesis project to evaluate the effect of fly ash in slag concrete with regard to shrinkage. The difference between the concrete mixes that were cast in the project was in particular difference in the ratios between the contents of the binder. In the concrete mixes without fly ash, that had been casted earlier, the binder consisted of ground granulated blast furnace slag and Portland cement. In the concrete mixes with fly ash casted in the Master's thesis project the binder consisted of ground granulated blast furnace slag, Portland cement and fly ash. The mixes contained different ratios of slag-cement and slag-cement-fly ash to evaluate the effect of an increased fraction of slag in the concrete. Minimum slag content was half of the binder. The procedure of the experimental studies is presented in Chapter 4.2 and the results and conclusions can be found in Chapter 4.3.

3.3 Numerical simulations

Stationary numerical simulations were performed in the finite element analysis software COMSOL Multiphysics 5.0 to simulate temperature distribution and heat flux in the façade element and to calculate the U-value of the element, see Chapter 5. The U-value was calculated by surface integration of the heat flux through the façade element with three different frames; one uninsulated steel frame and the two insulated frames, of steel and cross-laminated timber, developed specifically for the installation in HSB Living Lab. In addition, the needed thickness of a façade element of vacuum insulated textile reinforced green concrete was calculated with regard to the target U-value of 0.10 $W/(m^2 \cdot K)$ that the research group of the project *Next Generation Building Envelope Systems* has demanded.

4 Study of Green Concrete

4.1 Excessive shrinkage of green concrete

Green concrete made of alkali-activated slag has in many studies shown high drying shrinkage. An example is in the study presented by Duran Atiş et al. (2009) who found that slag concrete activated with water glass shrinks up to six times more than concrete containing Portland cement. Also in previous experiments made in the *Next Generation Building Envelope Systems* project at the Department of Civil and Environmental Engineering, Chalmers University of Technology, it was found that the green concrete pulverized very easy as a result of the drying shrinkage and therefore gave no good test results. To solve this problem a literature study was performed according to the methodology presented in Chapter 3.1.

Most of the relevant articles presented different additives that had shown to reduce the shrinkage of alkali-activated slag concrete. Yuan et al. (2014) found that an expanding admixture made from anhydrite and quicklime reduces the drying shrinkage of alkali-activated slag concrete since portlandite is formed and compensates for the shrinkage. The idea of adding quicklime as the expanding agent they refer to Nagataki & Gomi (1998) who used it to compensate for shrinkage of ordinary concrete.

Bakharev et al. (2000) found that adding gypsum to the alkali-activated slag concrete lowered the shrinkage. The reason was found to be the formation of two expansive phases, one of them ettringite. Palacios & Puertas (2007) used an admixture based on polypropylene glycol which made it possible to reduce the shrinkage of alkali-activated slag concrete with 50% at a relative humidity of 50% and with 85% at a relative humidity of 99%. With a reduction of 85% the shrinkage of alkali-activated slag concrete is comparable with the shrinkage of Portland cement concrete. The reason for the reduction of shrinkage in this case was found mainly to depend on the surface tension of the pore water which decreased when the admixture was added.

By adding light-burned dolomite, which contains reactive magnesium oxide, Shen et al. (2011) lowered the shrinkage of alkali-activated slag concrete. The reduction of shrinkage was due to the reactive magnesium oxide which expands when it reacts with water and becomes magnesium hydroxide.

Another solution to the severe shrinkage of alkali-activated slag concrete was found by Bakharev et al. (1999). They investigated heat treatment of alkali-activated slag concrete and found that it reduces the shrinkage with such an amount that the shrinkage becomes similar to that of Portland cement concrete. A pre-treatment at room temperature for two hours was found to decrease the shrinkage of the alkali-activated slag concrete even more. The reason for the lowered shrinkage is unsure, but Bakharev et al. mention a possible reason to be the lower water content in the C-S-H structure which is an effect of the heat treatment.

As a result of the literature review it was decided by the research group to make an experimental study in the laboratory based on the studies that used magnesium oxide and polypropylene glycol as shrinkage reducers. In addition it was also decided to try other polymers than just polypropylene glycol and to study the effect of fly ash as part of the binder since the research group had found that alkali-activated fly ash has shown less drying shrinkage than alkali-activated slag. The experimental studies will be performed during the autumn in 2015, except for the study of fly ash which was started when this Master's thesis project was carried out.

4.2 Procedure of the experimental studies

The experimental studies that were performed to evaluate the effect of fly ash in slag concrete with regard to shrinkage included casting of different concrete mixes:

- Water-activated blends that contained water, sand, slag, cement and fly ash.
- Alkali-activated blends that contained water glass, sand, slag, cement and fly ash.

To be able to evaluate the effect of the fly ash the results from the shrinkage study of the concrete mixes mentioned above had to be compared with studies of mixes without fly ash. Therefore results from earlier studies performed by PhD student Shuping Wang at the Department of Civil and Environmental Engineering, Chalmers University of Technology, were used for comparison. The results were obtained from shrinkage studies performed at:

- Water-activated blends that contained water, sand, slag and cement.
- Alkali-activated blends that contained water glass, sand, slag and cement.

As can be seen in the lists of concrete mixes above some of the mixes were activated with water which activates the hardening process of cement. Slag, however, needs an alkaline environment to be activated which can be generated by an alkaline solution such as water glass. An alkaline environment is also created when cement reacts with water and hence the hardening process in a slag-cement concrete can be activated without an alkaline solution. However, when the slag to cement ratio increases in a water-activated concrete the rate of the hardening process slows down. In the end the objective is to totally exchange the binder in concrete from cement to slag and alkali-activation may then be preferred since an alkaline solution increases the setting rate, and hence decreases the setting time, of slag concrete. In all the mixes minimum slag content was half of the binder.

For all the blends the same manufacturing process was followed. Sand was first dry mixed with ground granulated blast furnace slag, Portland cement and fly ash. Water or water glass was added to the dry mix and the mix was blended to the right consistency. The concrete paste was then put into molds, see Figure 4.2, which were vibrated. When the casted prisms had cured under plastic for 48 hours they were weighted and their lengths were measured, see Figure 4.3. After the first measurement, which hence was performed before shrinkage had started, the prisms were put to dry in a climate room that has a temperature of 20˚C and a relative humidity of 50%. After some time the prisms will adjust to the temperature and relative humidity in the room which makes the shrinkage stop. Normally, the rate of shrinkage slows down within 28 days which means that the trend of the shrinkage is visible quite early after casting, and the difference in weight and length was consequently measured by PhD student Shuping Wang at 1, 3, 5, 7, 11, 14, 21 and 28 days after the first measurement. Measurements of the further shrinkage will be continued by the research group in the sub-project *Low-carbon Materials*. In Figure 4.4 textile reinforced green concrete test panels, cast in the research project, can be seen.

Figure 4.1 *Dry ingredients of the concrete mixes. 1: Sand. 2: Fly ash. 3: Cement. 4: Ground granulated blast furnace slag. (Photo: Sandra Bentland)*

Figure 4.2 *The molds, each for casting of three prisms of the sizes 160x40x40 mm^3. (Photo: Sandra Bentland)*

Figure 4.3 *Left: The prisms after 48 hours of curing. The small steel bars were casted into the prisms so that they would fit into the measurement equipment. (Photo: Sandra Bentland) Right: The measurement equipment that tells the difference in length compared to the wood prism. (Photo: Helén Jansson)*

Figure 4.4 *Prisms and textile reinforced concrete panels cast in the project Next Generation Building Envelope Systems. (Photo: Helén Jansson)*

4.3 Results and conclusions of the experimental study

The results from the shrinkage studies are shown in Figures 4.5 to 4.8, of which Figures 4.5 and 4.7 are results from earlier studies performed by PhD student Shuping Wang. The plotted lines in the figures correspond to concrete mixes with different slag-cement and slag-cement-fly ash ratios in the binder. However, no data about the different ratios can be seen in the figures and the reason to that is that the information needs to be kept secret for an upcoming publication of the results by PhD student Shuping Wang.

In the figures it can be seen that the blends that are alkali-activated generally shrink more than the blends that are water-activated, up to about 2.3 times more. The difference of the shrinkage between the two activators generally increase with the increased fraction of slag. The water-activated samples has a shrinkage close to the shrinkage of Portland cement concrete that in shrinkage tests has shown a shrinkage behavior very close to that of the water-activated sample in Figure 4.5 that has the smallest fraction of slag. The shrinkage of Portland cement concrete at 28 days after curing has hence been measured to about 1mm/m. However, as already mentioned in Chapter 4.2 alkali-activation may be preferred over water-activation since alkali-activation decreases the setting time of the concrete.

In Figures 4.5 and 4.7, which show the results from earlier studies, it can be seen that the shrinkage increase with the increased fraction of slag. In Figures 4.6 and 4.8, which show the results from the studies with fly ash, it can be seen that the shrinkage decrease with the increased fraction of slag and that the shrinkage increase with the increased fraction of fly ash.

In Figures 4.6 and 4.8 reference lines are plotted that correspond to the lines in Figures 4.5 and 4.7, respectively, that has the same color and symbol as the reference lines. The reference lines are plotted since the concrete mixes that they correspond to have a specific slag-cement ratio that represented the start value, to which fly ash was added, for all the concrete mixes plotted in Figures 4.6 and 4.8. This means that the effect of the fly ash on the shrinkage can be seen by comparing the results in Figures 4.6 and 4.8 by the respective reference lines. Consequently, it can be seen that for both the water-activated fly ash samples and the alkali-activated fly ash samples the shrinkages are larger than the shrinkages of the reference concrete mixes. This means that fly ash as part of the slag-cement binder actually increases the shrinkage of the concrete, which was not expected. More research is needed to examine the reason for this unexpected behavior.

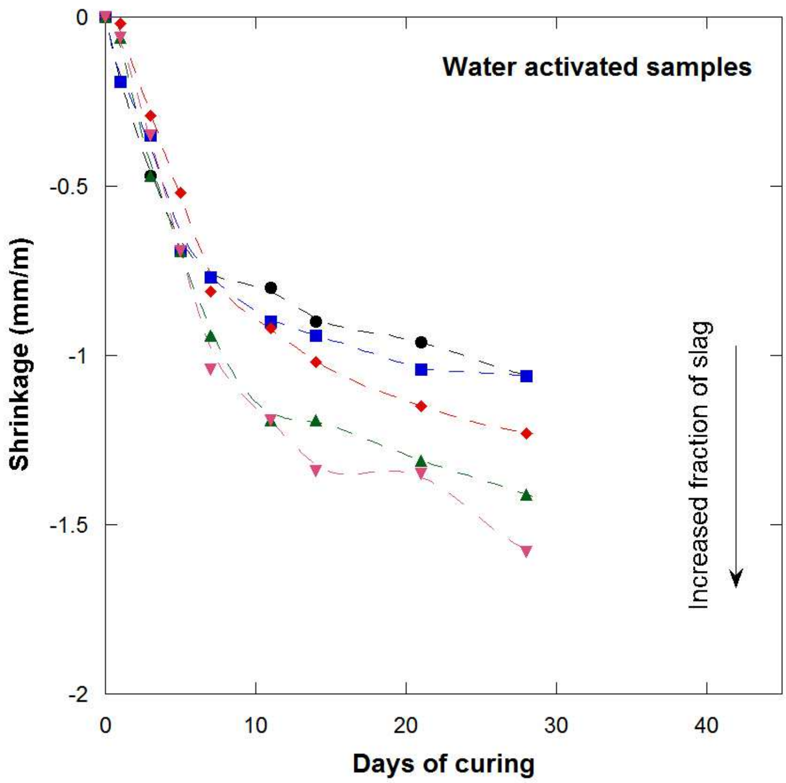

Figure 4.5 Water-activated samples that contained water, sand, slag and cement.

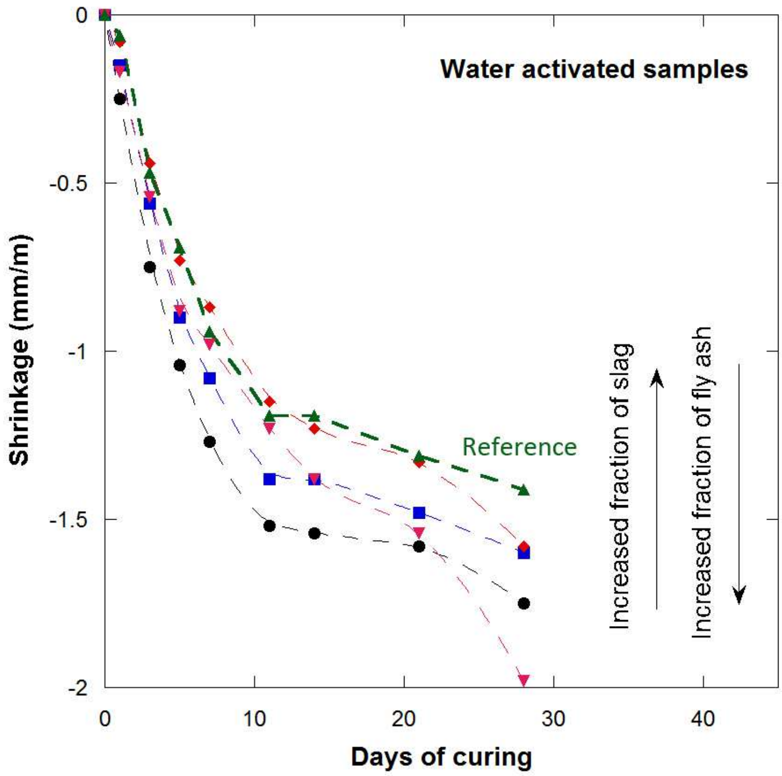

Figure 4.6 Water-activated samples that contained water, sand, slag, cement and fly ash.

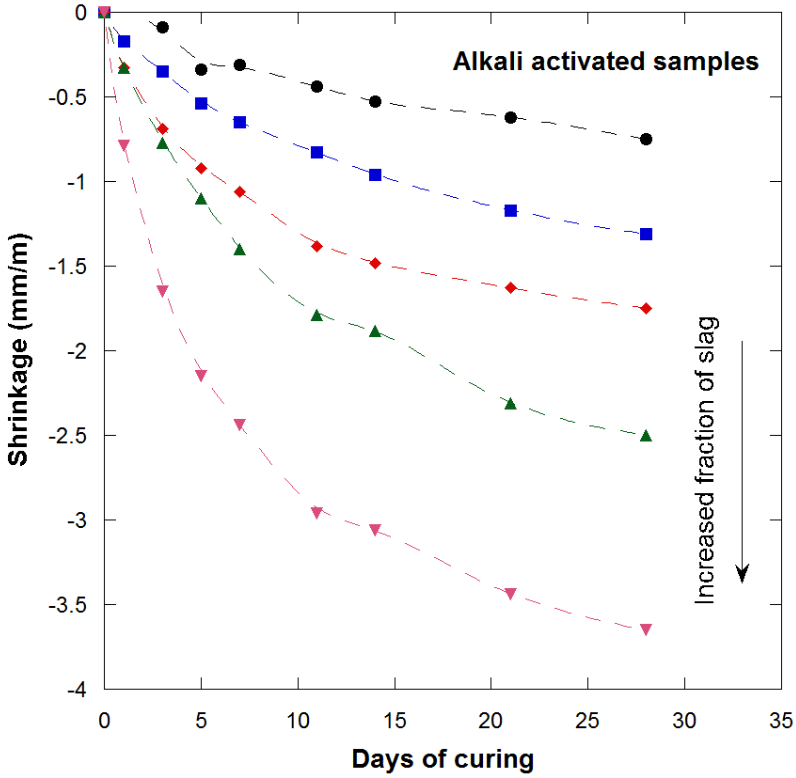

Figure 4.7 Alkali-activated samples that contained water glass, sand, slag and cement.

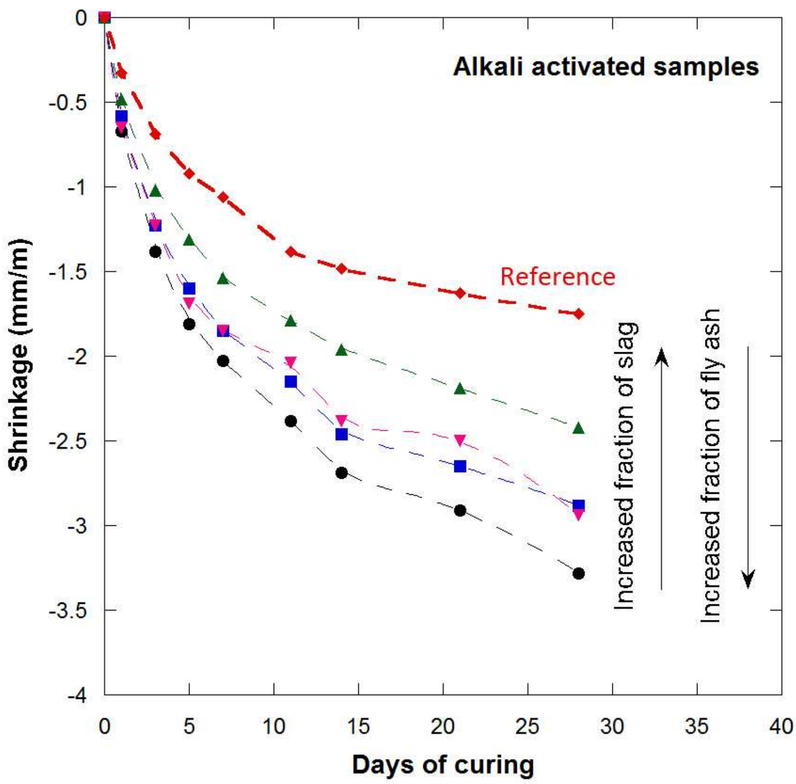

Figure 4.8 Alkali-activated samples that contained water glass, sand, slag, cement and fly ash.

5 Modelling of the Façade Element

5.1 Design input

Numerical simulations were performed in the finite element analysis software COMSOL Multiphysics 5.0 to simulate temperature distribution and heat flux and to calculate the U-value of the façade element. As already mentioned in Chapter 2.3 the research group of the project *Next Generation Building Envelope Systems* will have the opportunity to install the façade element at the demo site HSB Living Lab. Some of the numerical analyses were hence performed to evaluate the possible performance of the façade element when installed. The façade elements, including the frames, will cover an area of 1.2x3.6 m^2 each and will be installed in between two ordinary wall and two ordinary floor elements in HSB Living Lab. To model this situation a drawing of HSB Living Lab was used as a basis, see Figure 5.1. Drawings for the modelling of the two frames were provided from the designers.

The material properties used in the modelling, i.e. the thermal conductivities of the materials, can be found in Table 5.1. The thermal conductivity of textile reinforced green concrete was found from testing by the research group *Building Physics* at the Department of Civil and Environmental Engineering.

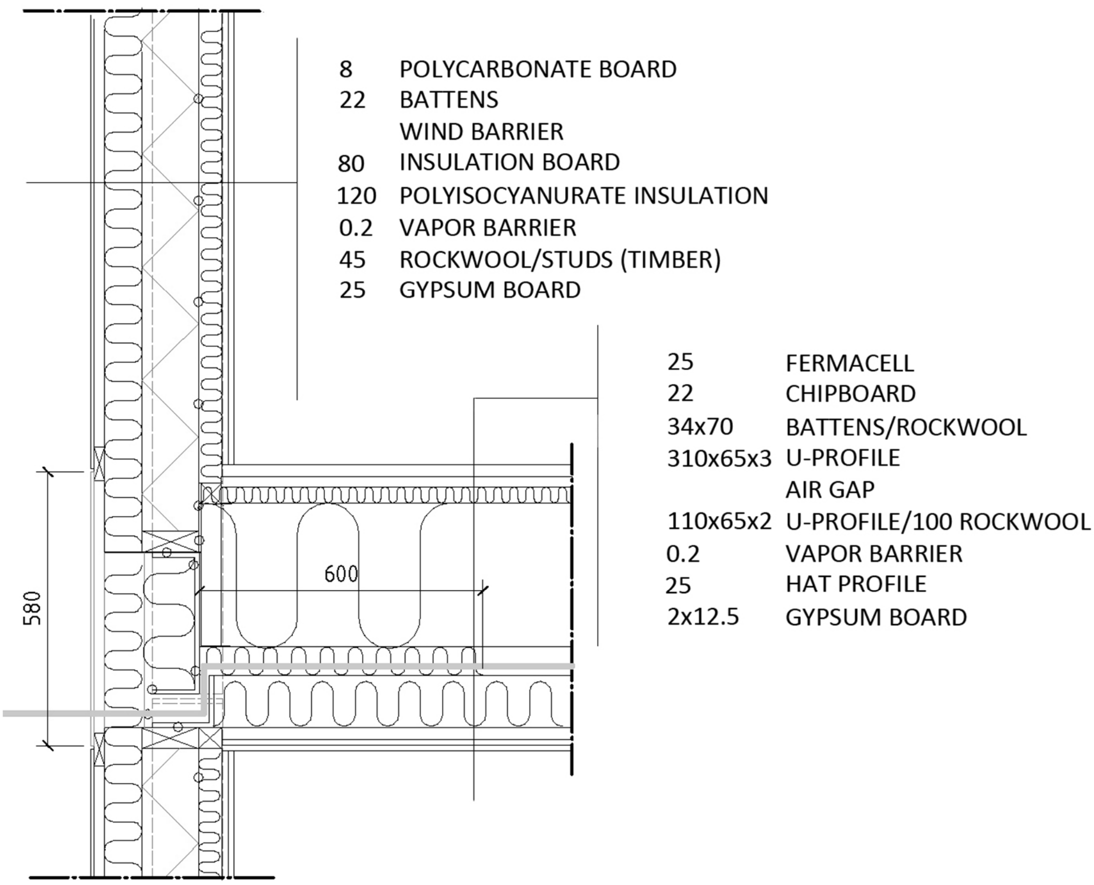

Figure 5.1 Section of the ordinary walls and floors in HSB Living Lab.

Table 5.1 Thermal conductivity of the materials used in the modelling.

Material	**Thermal conductivity, λ [W/(m·K)]**
HSB Living Lab, ordinary walls and floors	
Polycarbonate board	0.210
Battens	0.140
Insulation board	0.035
Polyisocyanurate insulation	0.024
Rockwool	0.036
Gypsum board	0.220
Fermacell	0.32
Chipboard	0.140
Façade element frames	
Steel	60
Timber	0.140
Aerogel insulation	0.020
Façade element	
Vacuum insulation panel	0.008
Textile reinforced green concrete	1.27

5.2 Preliminary modelling

5.2.1 Aim

The preliminary analyses were mainly performed to evaluate the effect of an uninsulated frame on the U-value of the façade element. As mentioned in Chapter 2.2 the façade element shall be able to be classified as a Passive House element and therefore needs to have a U-value of less than 0.15 $W/(m^2 \cdot K)$. However, it is also mentioned that the target value is 0.10 $W/(m^2 \cdot K)$.

The analyses were also performed to determine at what minimum distance, from the façade element edges, the measurement equipment has to be positioned in HSB Living Lab to measure a one-dimensional heat flow. To perform measurements where the heat flow is one-dimensional is important if the results are to be compared with results from numerical simulations of the façade element.

5.2.2 Models

During the preliminary modelling of the façade element the design process of the element frames had not yet been initiated. Therefore a simple uninsulated steel frame was modelled to evaluate the need of insulation in the frame. Two models were created: one of the façade element without frame and one of the façade element with the uninsulated steel frame. In this way the effect of the uninsulated steel frame could be evaluated with regard to the difference in U-values between the models.

The façade element was modelled with two layers of 25 mm textile reinforced green concrete and an intermediate layer of vacuum insulation, which was modelled as 100 mm thick which was assumed to be a suitable start value. The frame was modelled as a 50 mm high rectangular steel profile with a medium inside with a thermal conductivity ten times higher than that of still air. The reason for this is that the air inside the frame will not be still due to the temperature difference between indoor and outdoor climate.

In a third model the façade element with the simple steel frame was modelled as installed in HSB Living Lab, see Figure 5.2. As can be seen, the connecting walls and floors are not fully modelled. Instead they are modelled so that they extend about one meter from the connections. This is a simplification that is further explained in Chapter 5.2.3.

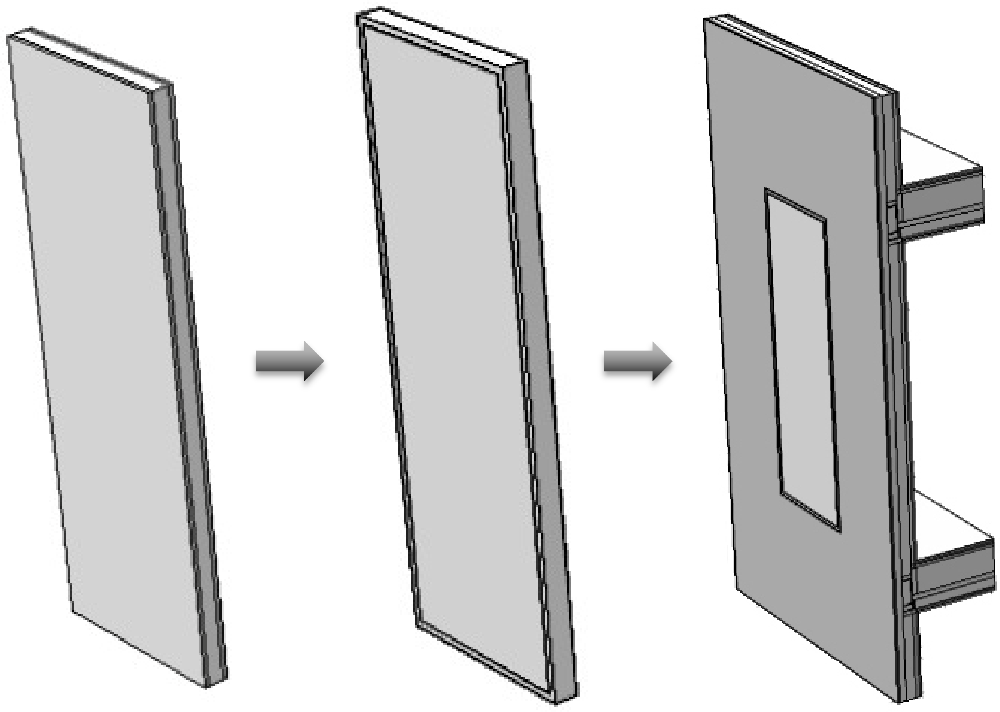

Figure 5.2 3D models of the façade element. Left: The façade element. Middle: The façade element with an uninsulated steel frame. Right: The framed façade element as installed in between two wall and two floor elements in HSB Living Lab.

5.2.3 Simplifications

The temperature distribution and the heat flux was evaluated due to a temperature difference of one unit, i.e. the boundary conditions in the models were chosen as 0 °C on the exterior surfaces and 1 °C on the interior surfaces. The surfaces at the edges were assigned an adiabatic boundary condition which corresponds to total thermal insulation. Since the consequence is that no heat can pass through these surfaces, which is not the reality, this is a simplification used in the modelling.

Most of the simplifications in the preliminary modelling concern the modelling of the ordinary walls and floors in HSB Living Lab.

- In the floor the 34x70 mm^2 battens were not taken into account. Instead the floor layer was modelled as a homogenous insulation layer.
- The UPE-profiles of 110 mm height were not taken into consideration.
- The hat profile in the floor was modelled as a solid layer of steel.
- In the walls no battens were modelled in the air gap and no vertical studs were modelled in the insulation layers.
- The wind and vapor barriers were not modelled.
- The connecting walls and floors were not fully modelled, see Chapter 5.2.2.

The simplifications were considered acceptable since the battens, studs and UPE-profiles are located relatively far away from the façade element and since the effects of the wind and vapor barriers will be unnoticeable. The connecting walls and floors were not fully modelled since only a short extension of them is needed to make sure that the adiabatic boundary condition at the edges does not affect the temperature distribution and heat flow in the simulations of the façade element. However, the joint between wall and floor has been modelled as accurately as possible, but without consideration of the fasteners. Some of the simplifications can be seen when Figure 5.3 is compared with Figure 5.1.

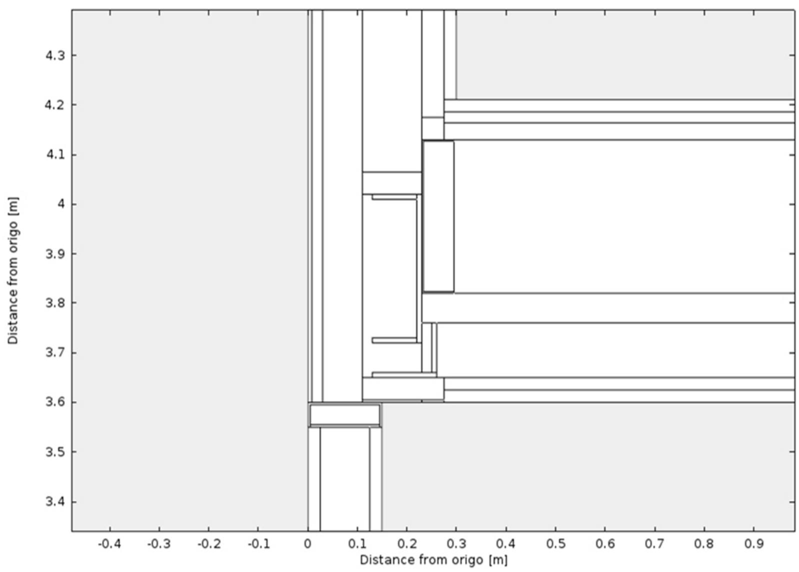

Figure 5.3 Section of the 3D model. Vertical section of the upper joint between floor and the framed façade element.

5.2.4 Heat simulations

To evaluate if there is a need of insulation in the façade element frame the U-value was calculated for the façade element with and without frame. The U-values were calculated by surface integration of the total heat flux magnitude in Watt which was further divided by the surface area in m^2. Since the heat flux was evaluated due to a temperature difference of 1 °C, or 1 Kelvin, the ratio becomes $W/(m^2 \cdot K)$ which is the unit of the U-value.

The U-value of the façade element without frame was calculated to be 0.08 $W/(m^2 \cdot K)$ and the façade element with an uninsulated steel frame was calculated to have a U-value of 8.76 $W/(m^2 \cdot K)$ which shows there is a need of insulation in the frame. To further substantiate that insulation is needed the insulation thickness was increased to 250 mm which only lowered the U-value to 4.28 $W/(m^2 \cdot K)$.

The influence of the frame on the temperature distribution and heat flow in the façade element was analyzed by vertical sections taken in the middle of the element. The sections can be seen in Figures 5.4 to 5.6, in which the isotherms show the temperature distribution and the normalized arrows show the direction of the heat flow. As can be seen in Figure 5.4, when the insulation thickness is 100 mm, the heat flow is one-dimensional 150 mm from the element edge. In Figure 5.5, where the insulation thickness has been decreased to 25 mm, the distance from the element edge to the one-dimensional heat flow is further validated.

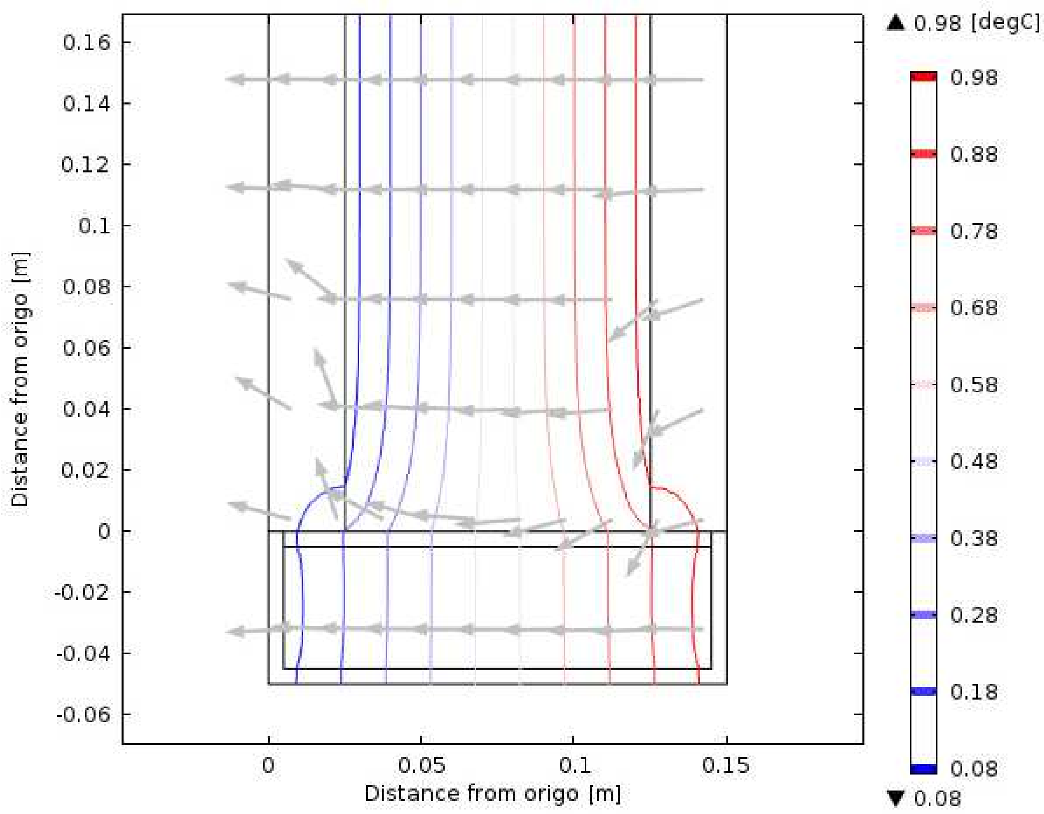

Figure 5.4 Temperature distribution and heat flow direction. Vertical section in the middle of the façade element showing the bottom end of the element with a frame of a rectangular steel profile. The insulation thickness is 100 mm.

The credibility of the results can also be confirmed by the vertical section in Figure 5.6 where the element is modelled as installed in HSB Living Lab. In Figures 5.4 to 5.5 there was a possibility that the temperature distribution and heat flow was affected by the adiabatic boundary conditions at the element edges. Due to the extended walls and floors, in the model of the installation in HSB Living Lab, the temperature distribution and heat flow in the façade element is not affected by the adiabatic boundary conditions and the result is therefore more realistic. Still, it can be seen from Figure 5.6 that even in this case the one-dimensional heat flow is found 150 mm from the façade element edge.

Summarizing the preliminary modelling it was concluded that the frame needs to be insulated if the façade element shall have the opportunity to be classified internationally as a Passive House element. It was also concluded that the measurement equipment in HSB Living Lab needs to be positioned at a minimum distance of 150 mm from the façade element edge.

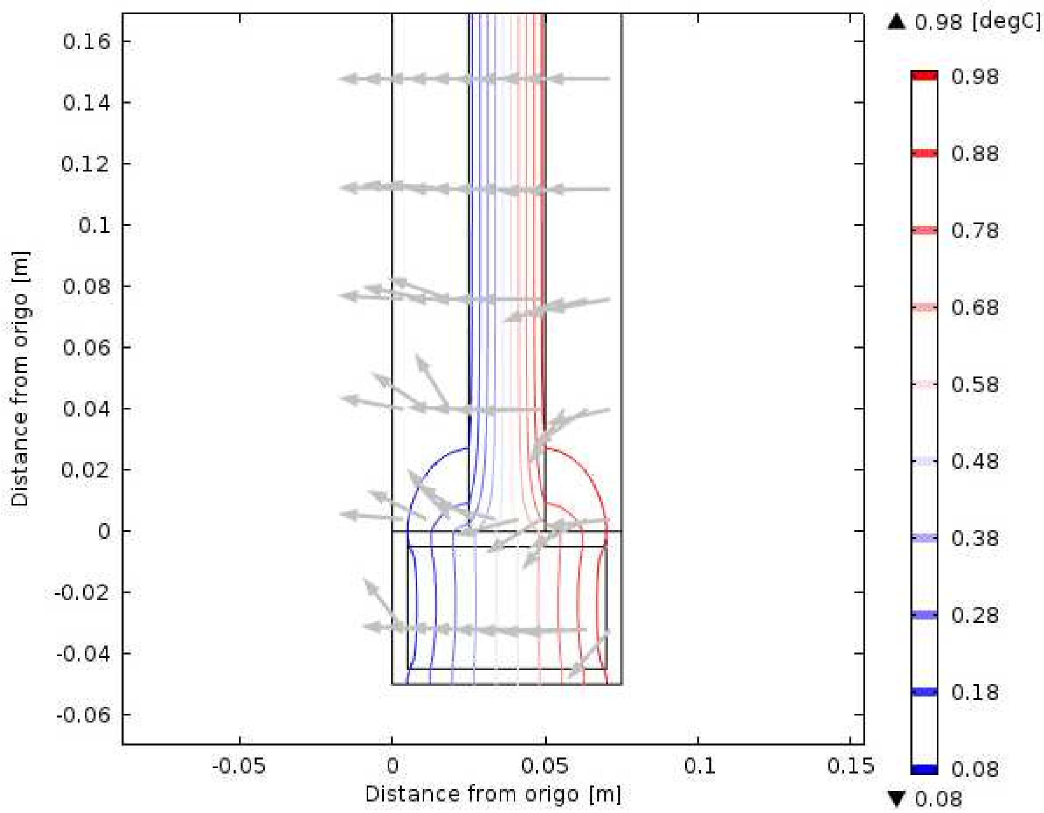

Figure 5.5 Temperature distribution and heat flow direction. Vertical section in the middle of the façade element showing the bottom end of the element with a frame of a rectangular steel profile. The insulation thickness is 25 mm.

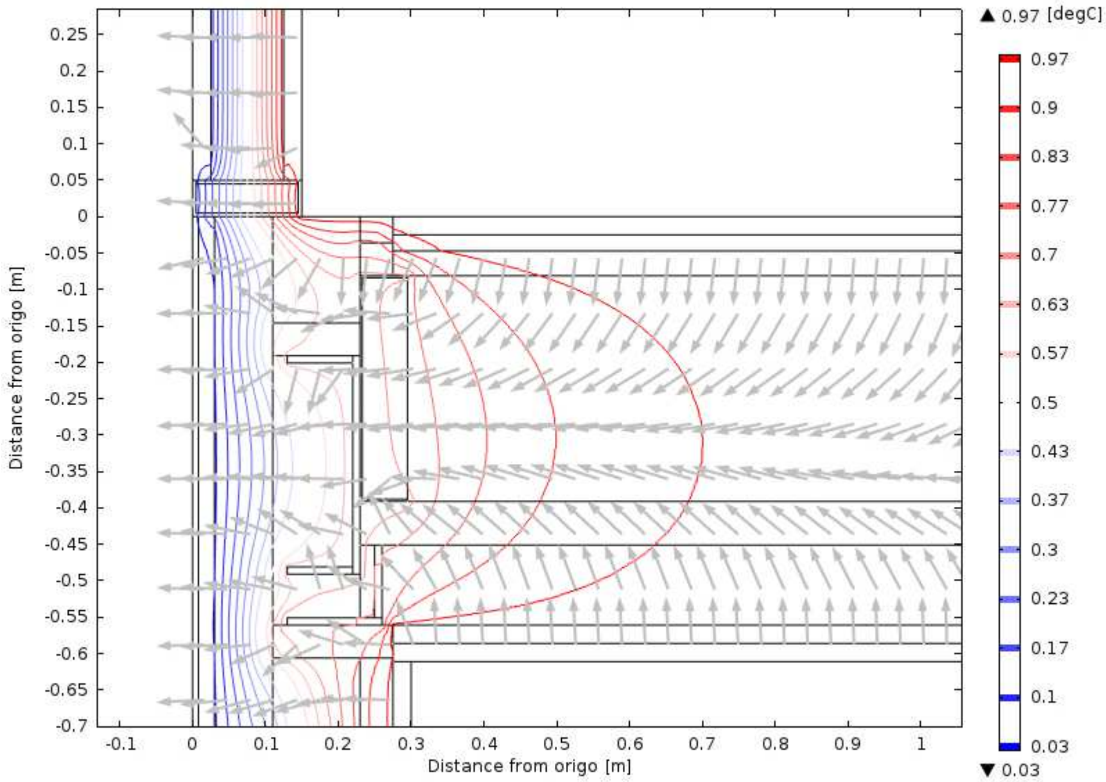

Figure 5.6 *Temperature distribution and heat flow direction. Vertical section in the middle of the façade element showing the lower connection between the element and the floor in HSB Living Lab. The insulation thickness is 100 mm and the frame is of a rectangular steel profile.*

5.2.5 Convergence study

To ensure that the results of the simulations have a good accuracy a convergence study was performed. The temperature in the point located a quarter into the wall in the corner between the frame and the façade element, see Figure 5.7, was calculated with five different mesh sizes. In Table 5.2 the different meshes are presented with names and element size ranges. They are pre-defined in COMSOL and possible to use instead of custom-made meshes.

From the table it can be seen that the temperature in the chosen point converges to 0.28102 °C. It can be seen that the *Normal* and *Fine* meshes give the same results as the *Finer* mesh, and due to this is sufficiently accurate to use. The heat simulations of the façade element were performed with the *Finer* mesh, which from this convergence study has shown to be sufficient.

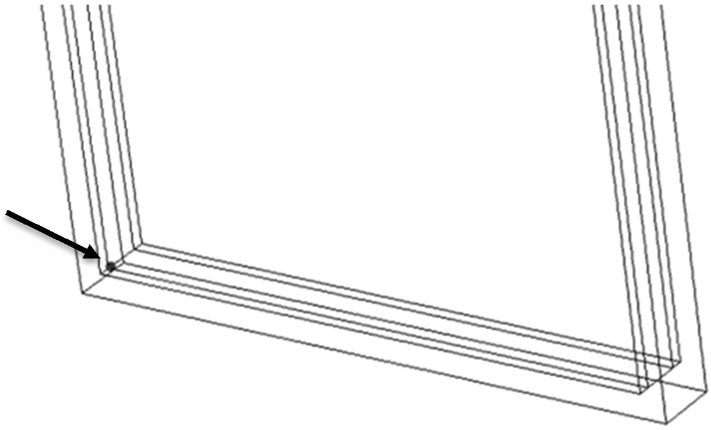

Figure 5.7 Point in the façade element from which results for the convergence study were obtained.

Table 5.2 Results from the convergence study of the façade element based on the mesh size.

Mesh	**Mesh size [mm]**	**Temperature [°C]**
Extremely coarse	252-1800	0.28045
Coarser	144-684	0.28090
Normal	64.8-360	0.28102
Fine	36-288	0.28103
Finer	14.4-198	0.28102

5.3 Final modelling

5.3.1 Aim

The final analyses were performed to determine the U-value of the façade element when it is framed with the two frame alternatives suggested specifically for the installation in HSB Living Lab. The aim was also to determine the total thickness of the façade element, i.e. without frame, if it is to reach the target U-value of 0.10 W/($m^2 \cdot$K) claimed in the project *Next Generation Building Envelope Systems*.

5.3.2 Models

The models created in the preliminary modelling were reused for the calculation of some of the U-values. Also, two new models were created during the final modelling; a model of the cross-laminated timber framed façade element and a model of the steel framed façade element. The models of the frames were based on drawings obtained from the designers of the frames.

5.3.3 Simplifications

In the frame models no steel covers, fasteners or air tightens were taken into account. The steel covers and air tightens were neglected since they have a small impact on the heat flux due to their small thickness and the fasteners were judged to take too much modelling effort compared with their expected effect on the heat flux. Also, some minor simplifications of difficult geometries were made.

As in the preliminary modelling the heat flux was determined due to a temperature difference of one unit, with the boundary conditions chosen to 0 °C on the exterior surfaces and 1 °C on the interior surfaces. Again, the surfaces at the edges were assigned total thermal insulation.

5.3.4 Heat simulations

As in the preliminary modelling the U-values in the final modelling were calculated by surface integration of the total heat flux magnitude in Watt which was divided by the surface area in m^2 and the temperature difference in K to obtain a ratio of $W/(m^2 \cdot K)$, i.e. the unit of the U-value.

For the cross-laminated timber framed element insulated with a 100 mm vacuum insulation panel the U-value was determined to be 0.22 $W/(m^2 \cdot K)$. For the steel framed element insulated with a 100 mm vacuum insulation panel the U-value became 0.13 $W/(m^2 \cdot K)$. It should be noted again though that the calculations were performed with simplifications in the modelling and that the U-values therefore are expected to be somewhat higher in reality.

For future use of the façade element in buildings, which then may be unframed and permanently installed, the U-value at different element thicknesses was calculated. The U-value dependent on the insulation thickness of mineral wool and vacuum insulation, respectively, can be seen in Figure 5.8. The relation between U-value and thickness of the vacuum insulation is plotted both with regard to the design value of the thermal conductivity and with regard to the true thermal conductivity, see Chapter 2.5.3. The U-value at different sandwich element thicknesses can be seen in Figure 5.9, where two 70 mm thick conventionally reinforced concrete layers were added to the mineral wool and two 25 mm thick textile reinforced concrete layers were added to the vacuum insulation panel. The conventionally reinforced concrete layers will be at least 70 mm each due to needed concrete cover. It can be seen in the figures that to reach the target U-value of 0.10 $W/(m^2 \cdot K)$ the façade element needs to be 130 mm in total, of which 80 mm is the vacuum insulation thickness. 360 mm of mineral wool is needed to reach the target U-value which results in a total sandwich element thickness of at least 500 mm. The limit value in the international Passive House standard of 0.15 $W/(m^2 \cdot K)$ is reached by 54 mm vacuum insulation or 240 mm mineral wool. The sandwich element thicknesses hence become 104 mm and about 380 mm respectively.

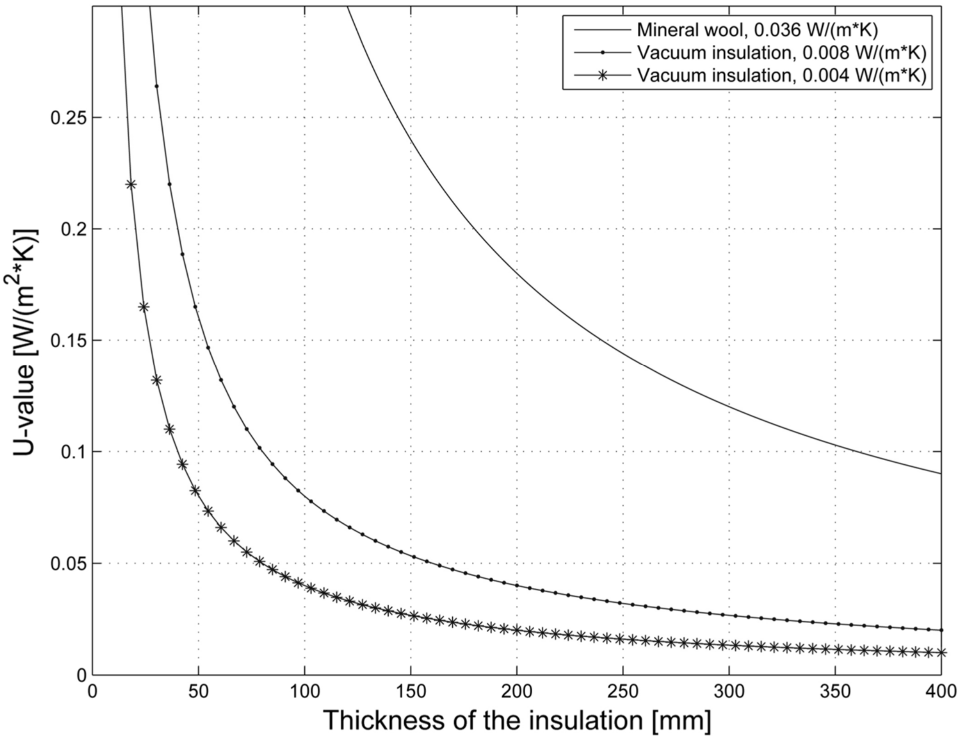

Figure 5.8 *The relation between thickness and U-value of mineral wool and vacuum insulation (0.008 W/(m·K)=design value of the thermal conductivity, 0.004 W/(m·K)=true value of the thermal conductivity).*

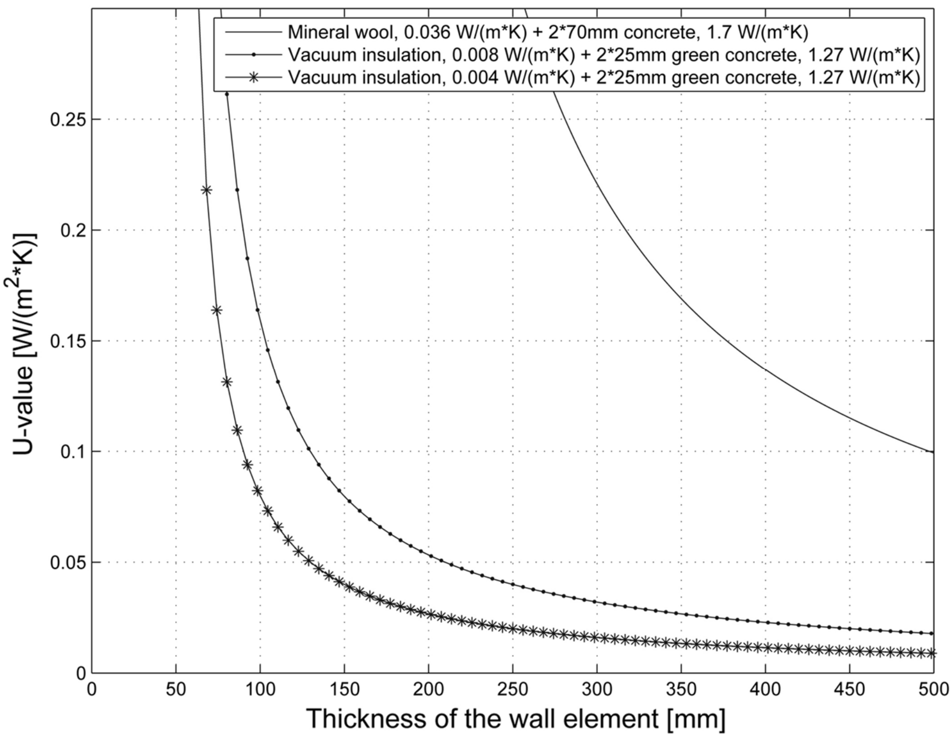

Figure 5.9 *The relation between thickness and U-value of three wall elements (0.008 W/(m·K)=design value of the thermal conductivity, 0.004 W/(m·K)=true value of the thermal conductivity).*

It can be noted that the difference in thickness, between the façade element and a sandwich element of mineral wool and conventional concrete, is big and that the façade element hence will result in more livable area, lighter structures, more daylight and less consumed material compared with the conventional sandwich element. Again, if the target U-value of 0.10 W/($m^2 \cdot$K) is to be reached the façade element needs to be 130 mm thick and the mineral wool element needs to be 500 mm thick. To revert to the example in Chapter 1.1; the livable area in a quadratic house of 100m^2 would increase to 115m^2 if the exterior wall thickness is decreased from 500 mm to 130 mm. The difference in thickness between the sandwich elements is illustrated in Figure 5.10.

Figure 5.10 Illustration of the needed thickness of a sandwich element of vacuum insulation and textile reinforced green concrete (left) and a sandwich element of mineral wool and conventionally reinforced concrete (right) if a U-value of 0.10 W/($m^2 \cdot$K) is to be reached.

6 Conclusions

This Master's thesis project was part of an ongoing research project at Chalmers University of Technology. The research project aims to develop a façade element for a Passive House standard that has great potential in reducing energy and material use, and emissions in the buildings sector, but at a smaller thickness than what is typical for Passive House walls. To reach the energy demands of a Passive House, a thickness of about 300 mm to 500 mm conventional insulation is needed in the building envelope. With decreased wall thicknesses more livable area can be gained, and there is also other benefits such as lighter structures, more daylight and less consumed material, which in turn may lead to less transports to the building site.

The research project focuses on three innovations in combination: green concrete, textile reinforcement and novel insulation materials. Green concrete, i.e. concrete cast with slag in the binder, has shown higher shrinkage than concrete cast with Portland cement, and one of the aims of this Master's thesis project was therefore to find possible solutions to the severe shrinkage. A literature study was hence carried out and it was found that heat treatment and addition of quicklime, gypsum, fly ash, polypropylene glycol and light-burned dolomite, separately had shown to have a reducing effect on the shrinkage. As a result of the literature study it was decided by the research group to make experimental studies to evaluate the additions of magnesium oxide and polypropylene glycol. In addition it was also decided to try other polymers than just polypropylene glycol and to study the effect of fly ash as part of the binder.

During the Master's thesis project the experimental study of fly ash was started. Samples that contained sand, slag, cement and fly ash, activated with either water or water glass, were casted and the shrinkage of the samples were measured during 28 days. To be able to evaluate the effect of the fly ash the results from the study were compared with earlier studies of samples without fly ash. From the comparative shrinkage study it was concluded that the samples activated with water shrink less than the samples activated with an alkaline solution and that the difference in shrinkage between the water-activated and the alkali-activated samples increase with the increased fraction of slag. However, water-activated slag concretes harden much slower than alkali-activated slag concretes and it is therefore preferred to use alkali-activation in many cases. From the comparative study it could also be seen that fly ash increased the shrinkage of the slag concrete. The expectation was that the fly ash would decrease the shrinkage since it had been found in the literature that alkali-activated fly ash shrink less than alkali-activated slag. More research is needed to examine the reason for the unexpected behavior.

Since the façade element of vacuum insulated textile reinforced green concrete developed in the research project will be installed and observed during real circumstances at the demo site HSB Living Lab, an aim of this Master's thesis project was to simulate the possible temperature distribution and heat flux in the façade element by a finite element analysis software. For the installation of the façade element in the research arena the element needs to be exchangeable and therefore needs to be mounted into a frame. The aims of the analyses regarding the installation in HSB Living Lab were to determine at what minimum distance from the façade element edges a measurement equipment needs to be positioned to measure a one-dimensional heat flow, to evaluate the effect of an uninsulated frame on the

U-value of the façade element and to determine the U-values of the façade element with two frames that had been developed specifically for the installation. It was found that the heat flow is one-dimensional 150 mm from the element edge. The U-value of the façade element without frame was calculated to be 0.08 W/($m^2 \cdot K$) with a vacuum insulation panel of 100 mm thickness, and the U-value of the façade element with an uninsulated steel frame was calculated to be 8.76 W/($m^2 \cdot K$). When the insulation thickness was increased to 250 mm the U-value only lowered to 4.28 W/($m^2 \cdot K$) which is 42.8 times more than the target U-value of 0.1 W/($m^2 \cdot K$) that was claimed by the research group. The numerical simulations hence showed that the frame used for the installation in HSB Living Lab needs to be insulated which affected the design of the two frame suggestions that were developed in a cooperative project.

The two frame suggestions were mainly of cross-laminated timber and steel, respectively. By numerical simulations the U-values of the framed façade elements were determined in the Master's thesis project. The U-value of the cross-laminated timber framed façade element was about 0.22 W/($m^2 \cdot K$) and the U-value of the steel framed façade element was about 0.13 W/($m^2 \cdot K$). These U-values were obtained with 100 mm vacuum insulation in the façade element. Since the calculations were performed with simplifications the U-values can be expected to be somewhat higher in reality.

The Master's thesis project also aimed to find the needed thickness of the vacuum insulated textile reinforced green concrete façade element that makes it fulfil the Passive House standard. The numerical simulations showed that the total thickness of the façade element needs to be 130 mm to result in a U-value of 0.10 W/($m^2 \cdot K$), of which 80 mm is the vacuum insulation thickness. To result in a U-value of 0.15 W/($m^2 \cdot K$) the façade element needs to be 104 mm, of which 54 mm is the vacuum insulation thickness. 360 mm of mineral wool is needed to reach the target U-value which results in a total sandwich element thickness of at least 500 mm since each conventionally reinforced concrete layer need to be at least 70 mm due to needed concrete cover. The limit value in the international Passive House standard of 0.15 W/($m^2 \cdot K$) is reached by 240 mm mineral wool and the sandwich element thickness hence becomes about 380 mm.

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