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Performance of insulation materials for historic buildings

Case studies comparing a super insulation material and hemp-lime

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Abstract – There is a challenge to reduce the energy use of historic buildings while preserving their cultural values. New materials and solutions are being developed that could contribute to improving the energy performance of historic buildings without altering their character defining elements. The aim of this paper is to technically evaluate and compare a 'high-tech' material (VIP) with a 'low-tech' material (hemp-lime) for adding insulation to historical façades. This comparison was made with respect to thermal properties and moisture performance, as well as available environmental impact data. The VIPs are characterised by reaching a high level of insulation although they are thin, which means they do not alter the proportions of the building the way thick layers of insulation do. Hemp-lime on the other hand has the advantage of being in line with the traditional materials already present in historic buildings.

Keywords – historic building; energy efficiency; super insulation material; VIP; hemp-lime

1. INTRODUCTION

Historic buildings from before 1941 account for 25 percent of the energy use for heating in the Swedish building sector [1]. At the same time there are physical factors and legislation that regulate the measures that can be implemented in these buildings. The challenge is to reduce the energy use of historic buildings while preserving their cultural values. New, technically advanced materials and solutions – either 'high-tech' such as vacuum insulation panels or 'low-tech' such as hemp-lime – are being developed that could contribute to improving the energy performance without altering the character defining elements of historic buildings. These materials can be used in different cases and with different results on the overall building performance.

Conventional thermal insulation materials, such as mineral wool and expanded polystyrene (EPS), require a relatively thick layer of insulation to meet today's energy requirements. For example, an insulation thickness of more than 22 cm is required using mineral wool (λ=0.040 W/(m•K)) to reach a U-value of 0.18 W/m^{2}K, which is recommended by the Swedish building regulations for renovated buildings [2]. Often, the physical space for adding insulation is limited in the building envelope where character defining elements should be kept, thereby limiting the achievable energy reduction.

Super insulation materials (SIMs) are 'high tech' materials and components with a substantially higher thermal resistance than conventional insulation materials. The thermal transmittance of the building envelope can therefore be substantially reduced with a limited insulation thickness, thus preserving the building's proportions. One type of SIM is vacuum insulation panels (VIP) [3]. A material which is more compatible with traditional construction methods is hemp-lime. This is a 'low-tech' building material that consists of hemp shiv (the woody core part of the hemp stem) and building lime. It is different from conventional insulation materials as it has a relatively high thermal mass. The material properties of hemp-lime resemble those of historic materials, such as timber and lime.

The aim of this study is to technically evaluate and compare a 'high-tech' material (VIP) with a 'low-tech' material (hemp-lime) when additionally insulating historical façades. This comparison was made with respect to thermal properties and moisture performance, as well as available environmental impact data. Four Swedish case studies are presented in which the above-mentioned materials were tested to demonstrate how they could be used for improving the energy efficiency of historic buildings. Two case studies are located in Gothenburg, one is located in the historic town of Visby and the last one is a laboratory study at Lund University.

2. MATERIAL PROPERTIES

The materials used in this research were hemp-lime and VIP. Figure 1 shows hemp-lime after mixing and a VIP with the core material and air tight barrier visible.

A B

Figure 1. A) Hemp-lime mix, B) VIP with fumed silica core material and metalized film envelope. Photos: Paulien Strandberg, Pär Johansson.

VIPs were first tested in buildings in the early 1990s followed by several case studies both in laboratory and in the field [4]. They have different core materials (fumed silica, glass fibre, polyurethane, expanded polystyrene and others) and different envelopes (metalized film, aluminium laminate, stainless steel, glass, or combinations). VIPs are rigid panels which cannot be cut on site and are sensitive to puncturing. Therefore, attention must be paid to the design of details and envelope components. They are wrapped in an air- and moisture-tight metallized multi-layered polymer laminate which gives a vapour and liquid water transfer only at the edges between the VIPs.

Hemp-lime was first used in France in the 1990s. Hemp shiv was initially used to make concrete mixes lighter but it turned out to work very well in combination with building limes [5]. It has since been used both to cover masonry walls and to fill timber frame structures in new construction as well as in renovation. There are several projects in France and the United Kingdom where hemp-lime has been used in renovations of historic buildings [5, 6]. Hemp-lime has been considered suitable as an internal insulation material in historic buildings. Studies have shown that it had a higher thermal mass than most other insulation materials, which can reduce the effects of fluctuations in the outdoor climate on the indoor temperature [7]. The thermal conductivity of hemp-lime varies with the mixing ratio and with the application technique, where a denser material has higher thermal mass and higher thermal conductivity.

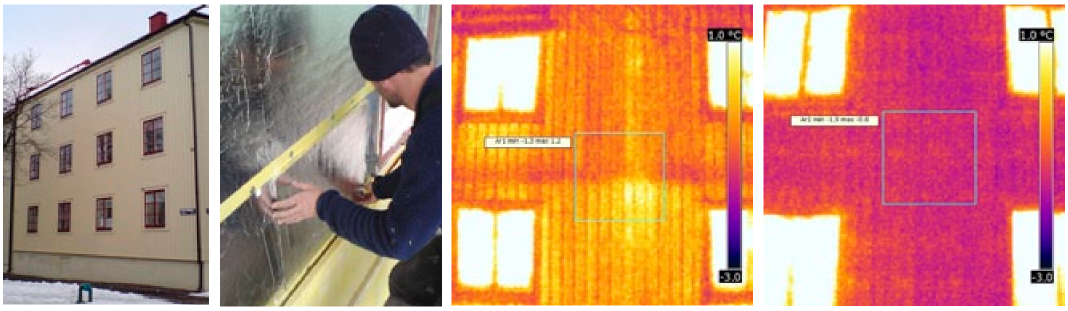
Among the important material properties for building materials are thermal conductivity, heat capacity and moisture diffusivity. The hygrothermal properties for hemp-lime and VIP differ subtantially. The material properties of hemp-lime varies with the mixing ratio and application technique. The thermal conductivity is 0.06-0.19 W/(m•K) for hemp-lime [8–11] and 0.002-0.008 W/(m•K) for VIPs [3]. The specific heat capacity of hemp-lime is 300–470 J/(kg•K) [11], while it is 850 J/(kg•K) for VIPs [12]. For VIPs, a recent study has shown that the embodied emission are 28.5 $kgCO_2eq/kg$ [13]. Hemp-lime is considered a carbon negative material [14, 15]. The cost for hemp-lime in Sweden is approximately 147–269 €/m^3 [16], while the cost for VIPs is approximately 2 755 €/m^3 [13].

3. CASE STUDIES

Four case studies are presented to demonstrate how VIPs and hemp-lime, respectively, can be used for improving the energy efficiency of historic buildings. VIPs are tested in two case studies; one as exterior insulation in a brick and wooden building (case 1) and one as interior insulation in a brick building (case 2). The case studies with hemp-lime are exterior insulation of a single family house in the historic Hanseatic town of Visby on the island of Gotland, Sweden, (case 3) and the last one exterior insulation of a wall in the laboratory of Lund University (case 4).

3.1 CASE STUDY 1: VIP ON EXTERIOR OF A MULTI-FAMILY BUILDING

Johansson, et al. [17] studied a multi-family building from 1930 in Gothenburg which was renovated in August 2010, see Figure 2. The building has a load-bearing structure of brick on the ground floor (340 mm) and the walls in two upper floors have wooden planks (80 mm) covered with straw and plaster on the interior. On the exterior, a 22 mm thick vertical wooden cover boarding with rib flanges was mounted on top of a wind and waterproof tar paper. The building was non-insulated before the renovation. The original wall has a U-value of around 1.1 W/m^{2}K both in the brick and wooden parts. Since the building is listed, the walls must not be changed too much to preserve the building's architectural characteristics. An additional insulation thickness of 80 mm was allowed. After renovation, the load-bearing construction was (from inside out) covered by a vapour barrier, 20 mm VIP, 30 mm mineral wool to protect the VIPs from damage, a 28 mm air space and a new wooden cover boarding with the same design as the original wall. This solution required that the windows were moved 80 mm to be in line with the new façade.



A B C D

Figure 2. A) Multi-family building from 1930s, B) Installation of VIPs on the exterior, C) Thermography images from 7 February, 2018, non- insulated reference wall, D) VIP insulated wall, average temperature in the square at the intermediate floor between ground floor and first floor is –1.4 °C and -0.2 °C, respectively. Photos: Pär Johansson.

Inside the wall and inside some of the apartments of the buildings, temperature and RH sensors were installed to evaluate the performance of the VIP and wall. The measurements were compared to a nearby non-insulated reference façade. The calculated energy use before retrofitting was 158.7 kWh/m^2/year for heating and domestic hot water. Calculations show that the total energy use was reduced with more than 25 % for the case with a continuous VIP layer and without any thermal bridges. With regard to the thermal bridges in the façade, the final reduction of the total energy use became 20 %. As a comparison, changing the old windows (U-value 3 W/m^{2}K) to windows with a U-value of 1 W/m^{2}K reduced the energy use by 15 %. The hygrothermal performance of the wall was improved after the renovation since the temperature in the load-bearing structure was increased. During seven years, the VIP layer was monitored by comparing the temperature drop over this layer. The evaluation showed that no visible degradation could be seen [18]. Infrared thermography was also used to evaluate the wall performance. Images from 7 February, 2018, showed that the exterior wall surface temperature was 1.2 °C higher on the non-insulated wall than on the wall with VIP, see Figure 2. The evaluation showed no visible degradation (i.e. elevated temperatures) of the VIPs.

3.2 CASE STUDY 2: VIP ON INTERIOR OF AN INDUSTRIAL BRICK BUILDING

An old industrial brick building, see Figure 3, south of Gothenburg is planned to be equipped with VIP on the interior of the wall during 2018. The walls are made of 500 mm thick non-insulated homogenous brick masonry which gives a calculated U-value of 1.0 W/m^{2}K. The building was constructed in 1896 and has been reconstructed several times since then.

A B C

Figure 3. A) Industrial building from 1896 south of Gothenburg to be insulated on the interior with VIP, B) The test room inside the industrial building, C) Sensors in the external brick wall. Photos: Pär Johansson.

There are several challenges to renovate the building where the thermal performance of the walls is one example. The cultural values of the building have been evaluated and one of the features that is considered important is the brick façade. Therefore, interior insulation is considered to be a possible solution to reach sufficient energy performance [19]. Inside a part of the deserted building, a small room (2.1 x 2.6 x 4.0 m) has been constructed which consist of floor, walls and roof insulated with 170 mm mineral wool, and the exposed brick wall, see Figure 3. The room is heated to around 22 °C and ventilated by natural ventilation with 0.5 h^{-1} air exchange rate. The air in the room is circulated by a fan to create homogenous temperature and moisture conditions in the entire room. The exterior wall is divided in three parts where VIP will be tested and compared to a non-insulated reference. The wall is equipped with hygrothermal sensors that every hour registers the temperature and relative humidity in the middle of the wall and at the interior surface. A weather station monitors the outdoor temperature, relative humidity, wind speed and rain intensity.

3.3 CASE STUDY 3: HEMP-LIME ON EXTERIOR OF A SINGLE FAMILY HOUSE

One gable section of a detached single family house in Visby's historic centre was renovated with hemp-lime render in September 2017, see Figure 4. The house was built in the mid-1800s and rebuilt to a large extent in the 1930's. It is built with a mix of construction techniques; the gable section of the eastern wall is built with wooden planks and the lower part of the same wall is built with lime stone. All façades are covered with lime rough-cast. The preservation of the buildings in the historic town centre is safeguarded in building regulations which apply when making any renovations. According to the building regulations the original and existing lime renders in Visby should be preserved as far as possible [20]. Choosing materials and techniques that do not damage the underlying timber construction is crucial.

A B C

Figure 4. Detached historic single family house in Visby renovated with hemp-lime, A) Before renovation, B) During renovation, C) After renovation. Photos: Paulien Strandberg.

When the old render on the façade of the building was removed, the original wooden slats, placed diagonally on the timber for carrying the render, were exposed. These slats were kept for carrying the hemp-lime render. Since the space between the slats was only a few centimetres, some slats were removed to create some space between the slats for applying hemp-lime. A layer of hemp-lime of approximately 50 mm (the original thickness of the lime render) was put on the façade and finished with a 15 mm layer of traditional lime render on the outside. The hemp-lime was allowed to dry for a few weeks before a new lime render was applied. The mixing ratio of the hemp-lime was 1 part by volume air hardening lime for 2.5 parts by volume hemp shiv. Sensors to monitor temperature and relative humidity were placed in different locations and depths in the wall. Monitoring started in September 2017 and continues for one year. The results will give a better understanding of moisture levels and moisture flows in the walls. It will also give some indication regarding the temperature flows and insulating properties of the wall after renovation with hemp-lime.

3.4 CASE STUDY 4: HEMP-LIME ON EXTERIOR OF A LABORATORY WALL

At Lund University, two façades have been built at the laboratory of the Division of Energy and Building Design, see Figure 5. One façade resembles a traditional post-and-plank construction with a thick lime render about 80 mm. The other façade resembles a traditional post-and-plank construction that is renovated using hemp-lime (~100 mm) as additional external insulation. Behind each façade there is a room (3x3 m) that is insulated at all sides (floor, walls, ceiling). Therefore, the only heat loss that takes place will be through the façade. The energy use for heating the rooms behind the façades is monitored to evaluate the thermal performance of both façades. This way, a historic façade with a lime render can be directly compared to a façade that is renovated with hemp-lime. The façades were constructed in April/May 2017, monitoring started in September 2017 and continues for one year. The façades are exposed to the outdoor climate. Moisture conditions (RH and moisture content) and temperature are being monitored at four depths inside the wall. The aim of the study is to compare the walls with regards to their energy performance. Therefore, the energy use (kWh/m^2, year) is measured and recorded continuously.

A B C

Figure 5. Construction of two full-scale test walls at Lund University, A) Construction of post-and-plank walls, B) Timber planks mounted between the posts, C) Application of hemp-lime on the post-and-plank wall. Photos: Paulien Strandberg.

The preliminary results from the laboratory show a lower energy use for heating in the room behind the hemp-lime façade. The room behind the hemp-lime façade uses 60–70 % of the energy use that is required by the room with the lime façade. The temperature variations are also less apparent in the insulated room.

4. CONCLUSIONS

This paper presents studies on two very different insulation materials – VIP and hemp-lime – to show their potential for application in historic buildings, where the preservation of the buildings' character defining elements is of importance. Characteristics and preconditions of historic buildings vary a lot. A solution to improve energy efficiency can work well in one historic building but not in another. Compatibility needs to be evaluated from both the technical and the historic preservation point of view and the purpose of the renovation needs to be defined clearly before undertaking a renovation project. Therefore, it is important to be able to use materials with different characteristics and properties, and to evaluate these properties both in laboratory and in field studies.

'High-tech' materials such as VIPs are new types of materials which may have to be tested under different conditions and with other methods compared to conventional insulation materials. Further, they have a limited flexibility as they cannot be adapted on the construction site. Hemp-lime, on the other hand, allows for greater flexibility as it can be used both as prefabricated boards and cast in-situ. With the use of hemp-lime the underlying construction of wooden slats or pegs can be maintained; it is even advantageous to do so. It also requires only limited alteration of the original construction, which, in the Visby case study, is in line with the local building regulations.

VIPs are characterised by reaching a high level of insulation although they are thin, which means they do not alter the proportions of the building the way thick layers of insulation do. VIPs have higher thermal resistance than hemp-lime, while hemp-lime is more similar to historical materials than VIPs, and works well in combination with historical timber and limes.

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