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Analysis of on-site construction processes for effective external thermal insulation composite system (ETICS) installation

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Abstract

Developing a more energy efficient building stock is the focus of the European energy policies. Much of the required reduction in energy consumption needs to be achieved through the renovation of existing buildings. The External Thermal Insulation Composite System (ETICS) is widely used for the reconstruction of apartment building facades to improve thermal performance. However, the impact of the building technology and the construction process management on the quality of these reconstructed facades has received relatively little attention. In this paper, the defects in facades reconstructed using the ETICS are identified and classified, relating them to the corresponding deficiencies in the on-site technology and management. The focus is on the identification of the factors that influence facade durability in order to outline an assessment methodology for on-site monitoring.

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Keywords: Construction norms; construction process; External Thermal Insulation Composite System; nearly zero-energy buildings; sustainable building

1. Introduction

Improving the energy efficiency of the European building stock is essential in order to meet both the medium- and long-term targets of the European climate strategy. In terms of new buildings, the European Commission has directed that all new builds are to be Nearly Zero-Energy Buildings (NZEBs) by 2020. However, much of the required energy use reduction needs to be achieved through the renovation of existing buildings. In order to improve

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the thermal performance of buildings, the External Thermal Insulation Composite System (ETICS) is widely used for the reconstruction of apartment building facades in the Nordic countries. The effectiveness of these reconstructed facades depends on a wide variety of factors and, while it is essential to understand the importance of each factor, the previous research has indicated that the impact of the building technology and the on-site construction process management have received relatively little attention. On-site construction process variables relating to kneading water, mixing time, weather conditions, external agents, insulation fixation, material moisture level, etc. can influence micro cracking, the cracking of exterior layers, stratification, biological growth and ice formation and, thus, lead to reduced energy efficiency. While analysing durability aspects, it is important to investigate specific mechanisms for deterioration arising from deficiencies in installation processes and on-site management. The focus is on the identification of the factors influencing durability and the outlining of an assessment methodology for on-site monitoring.

2. Energy efficiency of the building stocks in Europe and Estonia

According to the statistics – 70% of the housing stock in the countries of the European Union were built before 1980 and 23% before 1945 (Feder*casa, 2006).* Due to the beginning of industrialisation of the construction market in Estonia, the large scale increase of dwellings began 1960s. The apartment buildings which were built from 1961 to 1990 cover 79% of today's dwellings and 46% of them are located in Tallinn and in the northern part of Estonia – Harju County (Kalamees et al., 2009*).* Due to the rapid industrialisation of the construction market at that time, precast concrete panels were used mostly to erect new apartment buildings in the accelerated method. As the life span of these apartment buildings is around 50 to 70 years, the structures themselves and also the building services are or will be out-dated in the near future and will need renovation to meet today's requirements. The European Parliament and the European Council have published a directive in 2002 with the aim to increase energy performance of the buildings *(*European *Union, 2002).* Furthermore, in 2020 all new buildings have to meet nearly zero energy requirements and the countries need to have long-term renovation strategies *(*European Union, 2010*,* 2012*).*

The installation of the External Thermal Insulation Composite Systems (ETICS) is one of the recognised reconstruction options to extend the service life of buildings. It has been noted that the use of ETICS has increased during the last decades in Europe (Amaro et al., 2014, Künzel et al., 2006*).* Due to the Nordic climate conditions and the high thermal inertia of the ETICS, this system is also suitable and widely used in Estonia. Based on ETAG 004, the service life of the composite system is considered to be 25 years at least (EOTA, 2013). However, the past 10 years of the ETICS experience in the renovation of the Estonian housing stock reveals that the first signs of deterioration might occur less than one year after installation.

3. Visual inspection

The aim of the visual inspection was to map the scope of degradation signs on existing facades and to provide necessary information for the classification of an on-site survey framework. All the visual defects in the lower area of the buildings (up to 2 meters from the ground) are reachable and were photographed separately. For the higher areas, a high quality camera (24Mpix, 300dpi) was used to ensure visibility of the defects during digital image analysis. The inspection was conducted in March (2014) thus ensuring that the field of view was not covered with snow or leaves. The observed defects were coded and classified according to their characteristics and the specific area on the facade in which they appeared.

Based on the Estonian construction situation, the parameters of sample buildings have been selected so that their properties represent a large proportion of the typical housing stock, keeping in mind the representativeness of chosen sample buildings. Therefore the selection of visual defect identification is limited to apartment buildings, built before or in 1990. A total of 51 apartment buildings were randomly selected from the list of reconstructed apartment houses which have received a reconstruction grant established by the Kredex Fund which was founded by the Ministry of Economic Affairs and Communications with the purpose of enabling people to build or renovate their homes and develop energy-efficient ways of thinking (Kredex, 2013). The main variable characteristics are the construction year, renovation year, number of floors and the initial material of exterior walls.

3.1 Categorisation of areas and defects

Every visual defect was identified with the two main parameters as follows:

- Area of a defect; and
- Defect class.

The main classes were separately divided into the sub-categories to conduct a detailed analysis if necessary. As the sub-class deviation is trivial to the framework of the on-site survey, the results are not presented in this paper. The area of the facade has 10 main classes, as shown in Table 1. The separation enables the study of the links between the visual survey and the on-site construction process.

Table 1. Classification by defected area.

Code of area	Area classification
C	Continuous wall
W	Window openings
P	Parapets
G	Ground
F	Bottom area of façade
D	Entry/door area
B	Balconies
S	Soffits
O	Fixed elements
E	Corners and edges

The defects are divided into five main categories identified as shown in Table 2. The primary defect classes which are probably the result of the poor on-site construction quality are the Classes T, M and B. By Class R it is recognised that the repairs have been done, but the reason is not visible. Class A is a subjective opinion and has no effect on the lifetime of the facade.

Table 2. Classification by degradation defect.

Code of defect	Defect classification
M	Materials rupture anomalies
T	Technological deficiencies
B	Biological growth, moisture damage, corrosion
A	Aesthetic defects
R	Visually identifiable repairs

3.2 Main results of visual inspections

Overall, 886 defects were reported on 51 sample buildings. The distribution of the results from the visual inspection by main area classes showed that the most defected areas were:

- Continuous walls (class C) – 38%,
- Bottom area (class F) – 19%,
- Corners and edges (class E) – 9%,
- Ground area (class G) – 8% and
- Windows and openings (class W) – 8%.

By degradation defects the foremost shortcomings were caused by:

- Technological deficiencies (class T) – 28%,
- Materials (class M) – 26% and
- Biological growth, corrosion and moisture damage (class B) – 14%.

The stated defects cover 64% of all the facade defects and can be linked directly to the on-site construction technology.

4. Necessity for on-site survey

There is a large number of documents regulating the design and installation of the ETICS in Estonia which have been described and analysed in our previous paper (Sulakatko et al., 2014*)*. The most detailed documents, which are comparable between European countries, are the product manufacturer guidelines, but their use on construction sites is not compulsory. Based on these recommendations, the data of the on-site construction survey was classified into four main categories: construction site assessment and adaption to external factors; construction material properties; on-site construction technology and measurable parameters of application. The results of the previously conducted visual assessment indicate that, in the distinct areas, the different degradation signs dominate. Therefore, the data is sub-categorised by area type.

4.1 Construction site assessment and external factors

The assessment of construction site conditions involves a clear understanding of what kind of data we should gather and analyse. In the first stage, these on-site conditions which can influence the quality of the ETICS facades have to be identified. The monitoring of pilot sites has to confirm the selection and reveal the dataset that is influential from the facade quality viewpoint. Finally, the checklist of data to be gathered during monitoring is created in order to make the observation results on different construction sites comparable.

For example, the pilot-monitoring of construction sites revealed that renovation of the apartment buildings is often carried out on scaffolds without the requisite protection tent (see Fig. 1). As a result, the thermal insulation boards or the ETICS layers are exposed to direct climate influences during the installation process: absorbing moisture, wind-driven rain, humid conditions expressed as a frozen layer on the surface of the thermal insulation material at negative temperatures, etc. According to previous research on the moisture content of the thermal insulation material of the ETICS, it was found that wool materials (glass and stone wool) have a serious decreasing effect on adhesive strength with rendering mortar at higher relative humidity conditions (>95%). On the contrary, expanded polystyrene materials (EPS) showed an increasing effect on adhesive strength with rendering mortar in low (<60%) relative humidity conditions (Liisma et al., 2014). When direct rain or additional freezing effect on the surface of thermal insulation material is present, a significant decrease in the adhesion strength is noticeable. Therefore, it is important to mention that the need for a protection tent is unavoidable to prevent direct rain or its freezing process on the surface of insulation board during the ETICS installation process.

Fig.1. (a) Partly covered scaffolds; (b) Scaffolds without any protection net; (c) Material storage (Liisma et al., 2014).

In addition to the protective tent, the ETICS material storage should be organised and covered with a protective layer to avoid direct rain or other exterior climate influence. The drying of installed materials will be problematic if the exterior, water repellent layer is attached. This leads to a higher mould growth rate and increases the risk of moisture damage (Salonvaara & Karagiozis, 1999).

4.2 Construction material properties

The holistic design and construction material compatibility with the system are determined in the design phase and it might seem that there is not much left for the constructor except to follow the documents. Unfortunately, in practice, it is not this simple. The properties of materials depend on various factors and not all of them are presented in the design documents. The main types of regulations which cover the area of construction works are: legal acts, national, EU and harmonised standards, commonly used descriptive instructions and producer's certificates and manuals. From these, only legal acts and harmonised standards are compulsory. In principle there are too many requirements and guidelines in different documents which are difficult to follow and it is up to the project manager to decide if and how to follow them if there is nothing mentioned in the contract. The overview of documents which regulate ETICS applications in Estonia have been analysed in our previous paper (Sulakatko et al., 2014).

The first outcomes of on-site monitoring indicate that the abovementioned recommended guidelines are not really followed in the working process and very often construction materials are replaced following on-site decisions. Although the replacement may have a beneficial economic effect, the properties can compromise the system (Böhmer & Simon, 2011). Therefore, the replacements should be recorded and accepted with caution.

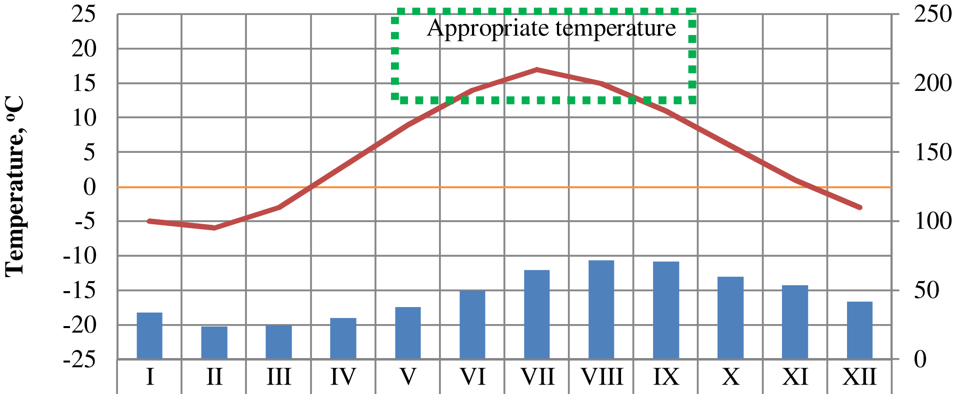
4.3 Actual on-site construction technology

In northern countries, one of the disruptive factors during the building process is the actual climate condition. Roughly 40%…50% of the year have a freezing risk in Estonia (Estonian_Environmental_Agency, 2014). Most of the technical instructions for the composite system materials recommend ETICS installations at temperatures +5°C...+25°C, relative humidity between 60%…80% and surface temperature ≥ +5°C. Therefore, approximately 50% of the year additional gas heaters are needed to meet the required climate conditions. Consequently air heaters (blowers) will avoid the freezing process of mortars, but increase notably the content of CO_2. As previously studied, the normal carbonation process in laboratory conditions decreases the porosity due to $CaCO_3$ crystal formations. Therefore, higher compressive strengths and durability in freeze/thaw processes are notable (Al-Zahrani et al., 2003). Regrettably, air heaters that are commonly used when applying mortars on facades in situ, produce additional CO_2, causing the shrinkage of materials. A study on this subject was also conducted (Metalss et al., 2012) and noted that shrinkage of carbonated mortars was approximately twice as high as the shrinkage of non-carbonated mortars. The increase of CO_2 from the heating process will rise the threat of cracking due to carbonation shrinkage. The rendering mortar will be applied on the previously cracked surface, while leading to a potentially weaker composite system and lower durability characteristics.

That is why the ETICS installation process should be avoided at temperatures below +5°C. It must be noted that additional gas heaters will partly ensure the required temperature, but at the same time they significantly increase the carbonisation process of adhesive mortars. The effect causes rapid shrinking process and micro-cracking due to the elevated CO_2 concentration. The appropriate time period for application is shown in Fig. 2.

4.4 Impact of installation team skills

In addition to climate factors, there are several human factors that should be considered during different construction phases. For the period of insulation installation the fixing parameters affect the durability of the exterior envelope. The main characteristics are the depth of anchors, the area covered by adhesive and the width of gaps between panels. The wide width of gaps can be directly associated with higher vapour transmission, which increases frost damage and mould growth risk (Sedlbauer and Krus, 2002). The missing anchors aggravate the movement of plates due to thermal expansion or shrinkage (Nilica and Harmuth, 2005*)*. The construction technology during application of mortar affects the thickness of layers which modifies the vapour transmission rate and decreases the quality of the exterior layer *(*Šadauskienė et al., 2009*)*.



	I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII
mm	34	24	25	30	38	50	65	72	71	60	54	42
oC	-5	-6	-3	3	9	14	17	15	11	6	1	-3

Fig.2. Climate diagram in Estonia (Tallinn).

One of the most common problems with the building technology in situ is the tendency for the retempering of mortars during the installation process to extend the application time. Adding periodically additional water to maintain the workability of the mortar mix leads to serious increases of the capillary porosity of the mortar and to the reduction of mechanical and physical characteristics. According to I. Odler and M. Rössler the main influence on strength properties of cement based mortars is the porosity *(*Odler and Rößler, 1985). Numerous studies have showed that a higher water-cement ratio increases porosity. X. Chen and S. Wu tested cement mortars with different water-cement ratios (0.4…0.6) and found that porosity can vary up to 50% with higher water-cement ratios (Chen and Wu, 2013). Retempering leads to a lower water-cement ratio which results in remarkably lower compressive strengths *(Rao, 2001)*. An experimental study revealed that cement mortar mix (1:3) with water-cement ratios between 0.4…0.8 can decrease compressive strength up to 50% with a higher water-cement ratio mix. In Fig. 3, the decreasing test results are presented on early (3 days hardening) adhesive strength after re-tempering of adhesive mortar (Sakret BAK) and extending workability during 8 hours (Haach et al., 2011). The water-cement ratio was changed via the retempering process from 0.30 to 0.60 as shown in Fig.3, where W/C is water cement ratio and R_{ad} is adhesive strength. As a result, adhesive strength of the mortar and insulation board (EPS100, dry) decreased by up to 65%. The presented tests were performed during this research study.

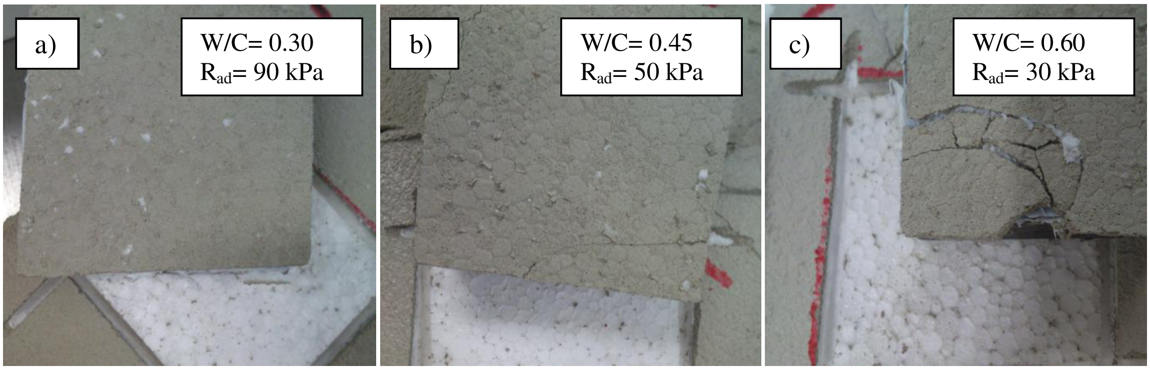


Fig.3. Early (3 days hardening) adhesive strength (R_{ad}) decreasing after re-tempering of mortar.

On the basis of the numerous research studies performed in the field of mortars and their characteristics, it is necessary to draw attention to mixes and requirements during in situ processes as the application technology and on-site conditions directly impact on the quality of ETICS facades.

5. Outline of on-site survey methodology

The choice of construction technology and specific actions are dependent on climate conditions. Therefore, the time of the survey is chosen to be during the period where the climate is shifting to a more hazardous period. In Estonia, the months of October and November provide diverse conditions (temperature and rainfall), and create a need to alter the construction technology. To gather information which may differ because of the construction phase, weather condition, craftsmen skills or any other variable, the selected construction sites will be visited 4 times during the 2 month period. The defects on construction sites can occur because of general construction management or because of specific factors. The general construction management patterns can be seen as the collected character of data is repeated at most of the times. The specific factors will be identified by analysing individual abnormalities. To get comparable collection of data, every detail is collected in 3 different areas with the same expected result.

5.1 Visual assessment and documentation of construction technology process

The visual assessment records the adaption of construction site to external factors and the use of construction technology. As described previously, there are numerous exterior influences which may affect the quality of the facade. On the construction site, the climate parameters are noted, the situation is recorded by camera and the fulfilment of additional quality demands is checked. It is expected that the climate conditions will change during the survey. For each work phase a list of actions and potential execution methods is compiled. As they lead to dissimilar problems, the execution of the processes is observed and documented. To get an overview of craftsmen's habits, three different surveys are conducted on the same construction site.

5.2 Usage of construction materials and collection of measurable quantities

The actual use of construction materials is documented during every visit in different area types. In the same area type, three different locations are observed to provide information about the repetition of the behaviour. The actual use is compared to design documents and the ETICS product manufacturer guidelines. The inspection gives an overview of the degree to which designers and construction workers follow the provided recommendations. The system manufacturers have provided information which will guarantee the sustainability of the facade. Afterwards, every replacement should be studied in detail to understand which properties are altered during this action. In addition, an evaluation by professionals in building physics must proceed.

To provide comparable results from the measurements, a detailed checklist, template and monitoring plan, which includes written and schematic guidelines, must be provided. The chosen time period opens an opportunity to collect data during and after the installation process. Various measurements are taken in different layers, locations and area types. To control which demands are met, the necessary quality requirements are noted from design documents and system providers' guidelines. In this form of collection the assessment is comparable even if different products are used. As there are various types of data, they must be collected by using calibrated measuring instruments and the mixture samples must be weighted directly after collection. As the survey covers various construction phases, it gives an overview of the whole ETICS construction process. Therefore, a detailed guideline must be provided, to collect data which may vary due to construction management, technology, climate conditions or craftsmen habits.

6. Conclusion

The construction process management with construction technology has a direct impact on building life-times and further costs. Therefore, the content of construction technology should be analysed in depth. Designs get more complicated as the goals of energy consumption rate increase rapidly. The insulation of existing dwellings improves energy consumption rates if a holistic approach is implemented. The ETICS is a complex collection of different construction materials which have to match each other perfectly. In the case of a failure in one layer, the result affects the exterior envelope of a building and leads to degradation. External factors, replaced construction material properties, construction technology and craftsmen skills have impacts on the quality of buildings. Better construction process management can improve the quality of construction technology. Therefore, on-site processes need to be defragmented and the evaluation of sub-processes needs to be conducted. As the presented area is being studied in depth, this gives an opportunity to supervise the details of construction sites more precisely and provide economic benefits to the owners of buildings.

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