XII DBMC
International Conference on Durability of Building Materials and Components
PORTO - PORTUGAL, April 12th-15th, 2011

Durability of Concrete and Brick Facades of Apartment Buildings Built Between 1960-90 in Estonia

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ABSTRACT

This paper analyzes durability issues related to brick and concrete facades of apartment buildings built between 1960-90 in Estonia. Frost resistance, compressive strength and problems of efflorescence, salt deterioration, carbonation, and corrosion were investigated among other topics in two large-scale research projects during 2008-2010. The apartment buildings studied were built with walls of prefabricated concrete elements and ceramic or calcium silicate bricks. The condition of 50-30 year old concrete or brick facades is of high concern in terms of residual frost resistance according to the common assessment standard. Nevertheless, this study shows that the current methodology used for the evaluation of the frost resistance of ceramic bricks needs to be improved for brick behaviour studies in real climatic conditions. Carbonation depth of a concrete facade varies from 0 to 70 mm (generally 10-40 mm) with faster carbonation of paint coated facades as compared to rubble bulk. Corrosion appeared mainly on the lower side of awning panels of both building types. It was also observed on concrete elements with thin (<10 mm) concrete covering layer and brick facades without zinc coating siding bonds. The condition of steel or brick bonds has to be carefully investigated before installing external insulation. Results of this research show that the situation is worrisome and that concrete and brick facades of apartment buildings built between 1960-90 need renovation.

KEYWORDS

Durability, Frost resistance, Carbonation, Corrosion.

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1 INTRODUCTION

According to statistics, more than 80 % of dwellings in Estonia have been built after World War II, mainly between 1961-1990. The majority of apartment buildings are composed of prefabricated concrete large-panels and bricks. First concrete panel buildings were erected at the beginning of the 1960s when the production technology was imported from France and the design was provided by a central designing institute in Moscow. Use of calcium silicate and ceramic bricks started even earlier. Concrete of facades is typically covered with rubble bulk or paint. Calcium silicate or ceramic hollow core facades are uncovered.

Estonian climate is strongly influenced by to the adjacent Baltic Sea and it is between maritime and continental. There are four seasons of near-equal length with average temperatures from 1961 to 1990 +16°C in July and -6°C in February, and with annual average of +5°C. The average precipitation range is from 535 to 727 mm and an annual number of rainy days is between 102 and 127. Average speed of wind is 4.3 m/s and time of the sunshine 1726 hours. Heating period lasts for about 7-8 months, at an average air temperature of about 0ºC.

Outdoor climate influences the durability of building`s facades in several ways. Outdoor temperature around 0ºC combined with driven rain influences the durability of building facades. When the water in the facade freezes, it expands and may decay the material of the facade. Corrosion of reinforcement is another factor that influences the durability of concrete facades due to surface cracking and subsequent spalling of the cover concrete due to the expansion of the corroding steel [Ahmad 2002]. The corrosion of fasteners influences the connection of the external layer of the external facade (both brick and concrete). Collapse of the fasteners is an important safety question. Carbonation of concrete or penetration of acidic gases into concrete are the main causes of the possibility of reinforcement corrosion. As concrete provides protection to reinforcing against corrosion due to its high alkalinity, during carbonation of concrete it is neutralized and the protection properties of steel are lost. Secondary ettringite mechanism formation has been suggested also as one of the critical mechanisms causing concrete deterioration. Damage of concrete results from ettringite swelling or crystal growth. Today the designed service life of older apartment buildings (50 years) is close to elapsing and to work out renovation solutions it is necessary to establish the current condition of the facade. The future of old apartment buildings is under discussion in Estonia, as well as internationally [Hagentoft 2010]. Even external walls need to be additionally insulated due to serious thermal bridges in them, high thermal transmittance of original external walls (0.7-1.0 $W/(m^2 \cdot K)$) and rising energy prices, the condition of original walls must be investigated to design fasteners for insulation and durability renovation measures.

In this study, the condition of concrete and brick facades of apartment buildings built between 1960-90 in Estonia was investigated using data from the primary source and laboratory measurements. As many factors affect the processes and the speed of deterioration, one of the most reliable ways to determine the current condition is to analyze different types of buildings. However, the extent of pilot research may appear insufficient to represent the whole building stock. Nevertheless, it may give useful information for future thoroughgoing research. The results presented in this paper are part of a larger national research project of the technical condition and service life of old multi-storey apartment buildings in Estonia [Kalamees *et al.* 2009] and [Kalamees *et al.* 2010].

2 METHODS

2.1 Buildings studied

The buildings studied were typical apartment buildings with 5, 9 or 16 floors, built mainly between 1961-90. As apartment buildings composed with prefabricated concrete large-panels and bricks were most widely used for structural solutions during this period, these building types were investigated. Prefabricated concrete large-panel external walls are composed of two layers of reinforced concrete

(75…130 mm thick loadbearing inner layer and 50…60 mm thick external core) and insulation material between them (50…125 mm thick of fibrolite (chip-cement plate), mineral wool, expanded polystyrene, or phenolic foam). Concrete of the facade is typically covered with rubble bulk or paint.

Brick walls have a similar principal solution: 250…630 mm thick loadbearing inner layer (typically calcium silicate brick), 60…120 mm thick mineral wool and 120 mm external core layer (calcium silicate or ceramic brick). In this study plastered brick walls were not investigated.

2.2 Field study

Overall technical conditions of facades were investigated to predict their durability as part of a large-scale research project. Field study comprised large-scale visual inspection (based on experience) of the facades, opening representative envelopes locally, and taking specimens of facades for future laboratory tests. Specimens of facades were taken by drilling Ø 110 mm holes to the concrete facade or removing bricks from the brick facade. Specimens for laboratory tests were taken only from visually undamaged areas.

2.3 Laboratory tests

2.3.1 Frost resistance

Concrete samples drilled from seven buildings were tested according to the Estonian standard for frost resistance of concrete [EVS 814]. A test piece of 50 mm thickness was sawn out from the cylinder and the parallel surface with the facade was tested. Mass loss from the surface (kg/m^2) was measured after 7, 14, 28, 42 and 56 freeze-thaw cycles. Careful visual survey and rapping of the facade were done and a representative spot was chosen before action.

Calcium silicate and ceramic brick samples were taken from the facades of twelve building (6 calcium silicate and 6 ceramic) and to find out residual frost resistance, three different methods were used:

- To compare the concrete and the brick facade both calcium silicate and ceramic bricks were tested according to the standard for the frost resistance of concrete [EVS 814].
- In addition, calcium silicate bricks from two buildings were tested according to [EVS-EN 772-18]. Test specimens were sawn out and put into water step by step during 24 hours at the temperature +20 ± 5 °C. After taking out from water, specimens were frozen and later thawed in water. Damages were estimated visually after 50 freeze-thaw cycles and damaged pieces were tested for compressive strength.
- Ceramic bricks were also tested after [GOST 7025] because no modern standardized methods are available to evaluate the frost resistance of ceramic bricks. Test specimens with ~50 mm thickness were sawn out and the previous surface of the facade was tested in the refrigerating device with air circulation at the temperature -18 ± 2 °C for 4 to 16 hours. Thawing in regular water lasted from 6 to 18 hours. Visual inspection and weighting of mass was conducted after 25, 50, 75 and 100 freezing-thawing cycles. The result is considered to be satisfactory if no visual damages or changes of mass appear.

To assess the test results the lowest environmental class for the impact of freezing/melting XF1 was used, i.e. moderately saturated with water and without anti-icing agent (example: vertical concrete surfaces unprotected from rain and cold). Target values of frost resistance class KK1 were used, which allows 0.5 kg/m^2 seceded amount of material after 56 freeze-thaw cycles.

2.3.2 Compressive strength

To study the compressive strength, samples were taken from the walls of seven buildings according to [EVS-EN 12504-1] and were tested according to two methods:

- Destructive method where pieces were sawn into cubes and cylinders, then pressed according to EVS-EN 12390.
- Non-destructive test with the Schmidt hammer was carried out according to EVS-EN 12504-2.

Bricks were taken from facades of twelve buildings (6 calcium silicate and 6 ceramic), cut into half and compressed according to EVS-EN 772-1. Since compressive strength of a wall depends on the properties of bricks and mortar, also status of mortar was estimated during the extraction process of bricks.

2.3.3 Corrosion of steel
Corrosion of reinforcement of concrete large-panels and brick walls was studied via visual survey. Also, elements of balconies and awning panels connected to brick walls were inspected. In some places, constructions were locally exposed, depending on the purpose. In addition, a few chosen samples of concrete were investigated with a light microscope.

2.3.4 Carbonation of concrete
Two methods were used to detect carbonation depth of the concrete of the facade:

- First, phenolphthalein was used to visualize the depth of carbonation of 112 test pieces. Measurements were taken both from the inside and outside of the test piece and rubble bulk layer was excluded from the readout.
- Secondly, X-Ray diffractometry (XRD) was used to analyze the content of $Ca(OH)_2$ and $CaCO_3$ in the powder made of the sample.

3 RESULTS

3.1 Frost resistance

Both visual inspection of buildings (Figure 1) and laboratory tests (Figure 2) indicated to problems with the residual frost resistance of concrete and brick facades. Only half of the specimens fulfilled the criteria for the frost resistance of concrete in the XF1 environmental class: loss of mass ≤ 0.5 kg/m^2. Frost resistance of older buildings were in the worst condition. To compare concrete and brick according to the same conditions, brick specimens were tested according to the standard for the frost resistance of concrete [EVS 814] (Figure 2 right). It was found that brick showed much worse performance than concrete, independent of the building age. Nevertheless, frost resistance tests of two buildings based on calcium silicate brick [EVS-EN 772-18] showed no loss of compressive strength after freeze-thaw cycles. Frost resistance tests of ceramic bricks (three buildings) according to the old GOST 7025 test method did not show large mass loss in most of the specimens. Furthermore, the mass of some test specimens grew due to filling cracks of brick with water.

In addition to differences in test procedures, also the place where the test specimens were taken influences the results. South and southwest facades were found to be in the worst conditions in terms of frost resistance. In the building with brick facade the residual frost resistance was satisfactory up to three storeys. Bricks from higher storeys, below windows, around the balcony and loggia, and around the downpipe were in a worse condition.

Figure 1. Frost damages of concrete (left), ceramic (centre) and calcium silicate brick (right) facades.

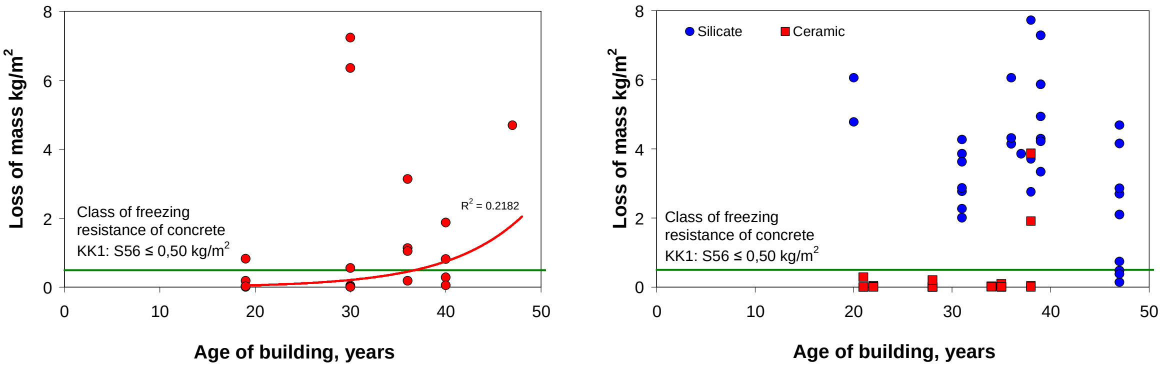

Figure 2. Mass loss of concrete (left) and brick (right). Green line refers to maximum allowed mass loss for a concrete facade 0.5 kg/m^2.

3.2 Compressive strength

As a result of the comparison of compressive strength of all concrete and brick test specimens (Figure 3) for the reference designed value 15 N/mm^2, it is possible to conclude that the compressive strength of concrete or brick is not the limiting factor for loadbearing capacity or stability that were set to it at the time of erection. In all the specimens, compressive strength exceeded the value, $f_{c,cube}$>15 N/mm^2 that characterizes the compressive strength of the concrete mark 150 (corresponds to 15 N/mm^2). Strength of mortar between bricks was variable: in some cases mortar was removed quite simply by handtools and striking drill had to be used in other cases.

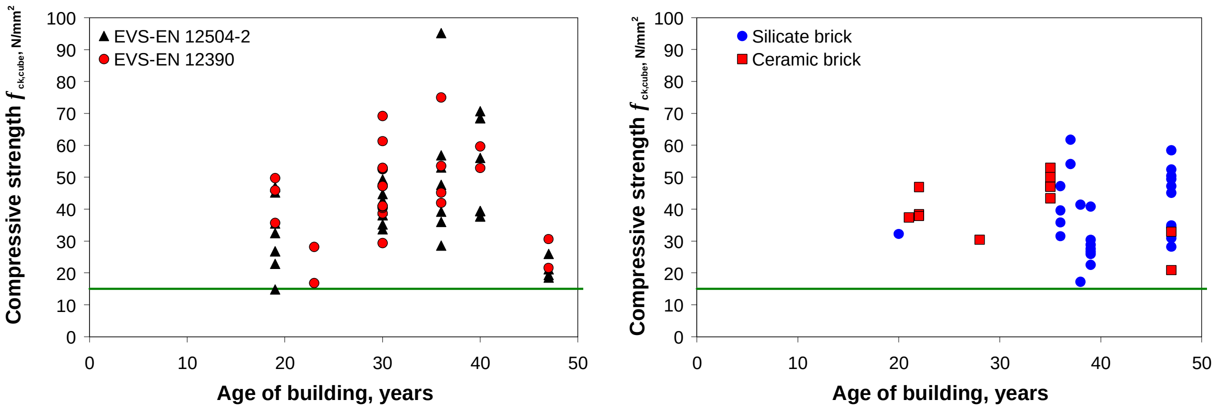

Figure 3. Compressive strength of concrete (left), calcium silicate and bricks ceramic bricks (right).

3.3 Corrosion of steel

Corrosion of concrete large-panels and brick walls was studied via visual survey and with a light microscope (Figure 4). Corrosion of reinforcements of external wall layers of panel concrete in apartment buildings was generally minor. Reinforcement was corroded only when it was very close (≈<2 cm) to the external surface (Figure 4 left). Serious corrosion of reinforcement existed at awning panels and balconies and also in places of concrete wall panels. These structural elements have more severe water loads, therefore small frost resistance has made cracks into concrete and corrosion may develop more easily.

3.4 Carbonation of concrete facades

Carbonation depth of concrete facades was between 0-70 mm, typically 10-40 mm, see Figure 5. left. Comparison of paint finish and rubble bulk finish showed that facades with paint layer had significantly larger carbonation. The speed of carbonation can be calculated also with the square root function [Pentti *et al*. 1998]:

$$x = k \cdot \sqrt{t} \ ,$$

where x is carbonation depth, mm; k is carbonation constant (normally 1.5…3.5 mm/$\sqrt{\text{year}}$; t is the age of concrete in years. The distribution of the carbonation constant is presented in Figure 5. right.

Based on the comparison of XRD measurement and phenolphthalein measurement results, it can be concluded that the result of phenolphthalein measurements is not adequate.. It means that though with phenolphthalein no possible carbonation was detected, there existed $CaCO_3$ crystals in concrete.

Figure 4. Corrosion of reinforcement via visual survey (left) and microscope: non-corroded (2nd from left), partly corroded (2nd from right) and fully corroded (right) reinforcement.

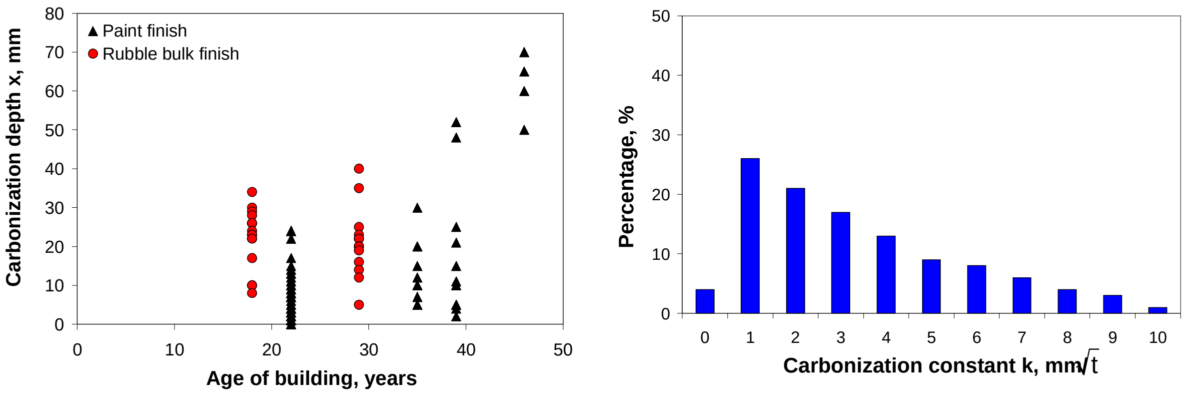

Figure 5. Carbonation depth of concrete of the apartment buildings composed with concrete large panels (left). Carbonation constant to calculate the theoretical carbonation depth (right).

4 DISCUSSION

The main target of the study was to find the condition and durability of concrete and brick facades of apartment buildings built between 1960-90 in Estonia and to collect information for further research.

According to the tests of the frost resistance of concrete and brick facades, the condition of the facades is serious. The results of the evaluations also depend on the criteria and methods of evaluation. In this study different methods were used to evaluate the frost resistance of bricks. Results of the laboratory tests showed the result opposite to that observed in the field survey. According to the tests, ceramic tiles perform much better than concrete or calcium silicate bricks. Visual inspection of buildings can provide the opposite result: facades with old ceramic bricks are in the worst condition in Estonia. There can be many reasons for this difference:

- The horizontal surface of ceramic bricks has much higher capillarity properties as compared to vertical surfaces. In standard test conditions there are no suction possibilities from horizontal surface, but these exist in real facades. Therefore, if ceramic bricks are tested according to the concrete frost resistance standard, test conditions should be modified to be closer to the real condition of bricks in the facade.

- The bricks tested were visually undamaged and it may be assumed that visually undamaged bricks have also better residual frost resistance. Thus, in future studies both visually damaged and undamaged bricks should be tested.
- The capillarity speed and suction properties of brick and concrete are different. Therefore the amount of water sucked during the wetting period in the frost resistance test is different. Larger amounts of water influence the result of the loss of mass. If bricks are tested according to the concrete frost resistance standard, the period of wetting should be shorter for testing the bricks.

Our research has proved that problems exist in choosing the proper method for testing the frost resistance of ceramic bricks in Estonia. In a comparative research, they [Mačiulaitis *et al.* 2004] conclude that the frost resistance of ceramics and concrete depends mostly on density, reserve of porous volume and effective porosity - the higher the density, the reserve of porous volume and the smaller the effective porosity of the porous material, the higher is the exploitation of the frost resistance of ceramic and concrete products. At the same time in common engineering practice it is also necessary to develop quick methods for the estimation of residual frost resistance and the compressive strength of the facade, because thorough tests are not always possible due to high time consumption and expenses.

Since none of the apartment buildings composed with large concrete panels were found to fulfil the criterion for the frost resistance and the tested specimens were visually undamaged, a question was raised if the limit value for the loss of the mass (0.5 kg/m^2) is relevant for testing the facades. Further studies and the comparison of different methods are needed when producing new test standards.

Comparison of compressive strength of all concrete and brick test specimens fulfilled the reference designed value 15 N/mm^2. The compressive strength of mortar influences also the compressive strength of the brick wall. The condition of mortar was evaluated only visually. The compressive strength of mortar should be studied more thoroughly in the future.

There is also a question about measuring accurary of carbonation depth. Theoretically, there is a partly carbonated zone [Thiery *et al.* 2007] which is not detected by phenolphthalein. Light microscope detected elements of $CaCO_3$ were also found in the area not detected by phenolphthalein.

5 CONCLUSION

Overall condition of concrete facades is satisfactory, except the low frost resistance and corrosion of reinforcement when the reinforcement was situated close to the facade. Carbonation depth has reached reinforcement in some cases, but corrosion of reinforcement of the outer core is still minor.

Condition of brick facades is variable. Main problems are related to the low frost resistance of ceramic bricks and bonding of the facade, which tend to be broken in some cases (that occurs more often where inner and outer layers are composed of different types of bricks – silicate and ceramic).

Nevertheless, though the test methods and interpretation of results are somewhat problematic, based on this preliminary study it may be concluded that low frost resistance is the critical property of the facades of apartment buildings built between 1960-90 in Estonia. Depending on the extent of the damage, two basic options for renovation should be considered:

- Facades which have not yet been significantly damaged should be covered. It is economically reasonable to apply additional insulation, as because of high thermal transmittance (U_{walls} ~0.7-1.0 W/m^{2}K) and rising energy prices it is presently expedient.
- Facades with more severe damages should be renovated first. Loose particles can be removed by blasting sand or water and gaps could be filled up. Several technologies for concrete covering have been worked out - with mineral or organic protective layers and impregnation. Secondly, additional insulation could be installed.

Covering the concrete facade is effective in terms of corrosion – temperature in a previous facade is higher and RH lower, which means a slower corrosion process. Furthermore, carbonation process could slow in covered concrete. For both concrete and brick walls, lower temperature gradient means smaller temperature based deformations. Constant temperature over 0°C avoids freeze-thaw cycles.

ACKNOWLEDGMENTS

The financial support of the Credit and Export Guarantee Fund KredEx and Tallinn University of Technology are gratefully acknowledged.

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