Analysis of physico-chemical processes under maintenance of masonry enclosing structures

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Abstract. Technical condition of exterior brick walls of Ufa residential buildings built in 40-70s together with defects and damages detected is assessed herein, diagnostics of both physico-chemical and physico-mechanical values for serviceability of structures of 40s, 70s and 2000s is made. The expected protection mechanism is proposed to be used in every considered level of rehabilitation to maintain the residual service life and to increase serviceability of damaged residential building walls. The proposed levels of rehabilitation have been tested in cities of the Republic of Bashkortostan under the Program for total renovation of multi-apartment residential buildings.

1. Introduction
Silicate brick is one of the basic construction materials applied in current residential construction, with mass production thereof taken place in the USSR in 1940-70s due to fast industrialization and urgent solving of housing problems in the post-war years. Most residential houses in large cities of the Republic of Bashkortostan [1] (about 25-30%) are built of this material. The first factories in Ufa engaged in silicate brick production have been operating since the beginning of the 20 century. This material is obviously not widely studied in climatic conditions of the Republic, and is to be analyzed in application thereof in exterior walls of buildings. It should be mentioned that residential houses erected in 1940-70s fail to meet current heat engineering norms by heat-shielding performance of enclosing structures thereby predetermining obsolescence thereof.

2. Classification of buildings by level of damaging the enclosing wall structures
Physical state of exterior walls of residential houses in Ufa erected in 1940-70s was initially assessed visually and using special devices to examine exterior wall layers for defects and damages. Classification of buildings by level of damage of the enclosing wall structures [2] (Table 1) is proposed thereunder, and basic destructing factors affecting the silicate bricks inside exterior wall structures are found under the analysis made:

1) Alternating wetting and drying of exterior brick surface. There appears swelling-shrinkage differed by volume stipulated by sorption-desorption mechanism as well as capillary contraction stress thereby resulting in internal stress and local structural damage and destruction of the material. Moisture resistance of the material against this factor depends on amplitude and number of alternate wetting and drying cycles.
2) Alternating freezing and thawing of the surface layer. Phase transformations of liquid porous moisture take place inside the capillary-porous materials such as silicate brick under temperature below zero. Certain amount of moisture is transformed into ice with 9-fold volume increase. The solid phase therewith is affected by both ice pressure and hydrostatic pressure of still unfrozen water fastened by ice preventing exit thereof to reserve pores.

This mechanism is realized as numerous repeated exposure accompanied by local damage and strength reduction [3]. It is realized in surface layers of exterior masonry under periodic excessive moistening thereof with full destruction of the layers.

3) Carbonization of structure-forming phases. Chemical interaction between CO₂ in the air easily making through the porous structure of the silicate brick, and crystals and crystallites of hydrated calcium silicate (as a rule, low-basic ones of more than 20 years old) i.e. carriers of strength and water resistance of the material, results in carbonization of hydrosilicates phases with CaCO₃ formation accompanied by release of silicic acid and loss of crystal phase. Chemical interaction is increased under wetting and full drying.

**Table 1. Classification of damaging categories for residential silicate brick buildings erected in 1940-70s.**

| Features of wall construction damaging in accordance with damaging categories | Damaging categories for exterior walls of residential buildings made from silicate bricks in 1940-70s. | I | II |
|---|---|---|---|
| Availability of diagonal and vertical expansion-shrinkage cracks in window wall of the ground floor with crack growing by 5-6mm, fractures for up to 8 brick layers due to heavy load thereon; masonry damage in areas under the eaves, brick damage by 8-10mm and weathering of mortar from masonry of up to 50% and 20-30mm in depth. Indoor conditions are violated with temperature decreasing to 10-15°C in winter period. | Operating condition | Limited operating condition | Operating condition |
| Availability of diagonal expansion-shrinkage cracks in window wall of the ground floor up to 3-4mm, wetting areas in masonry under the eaves with surface scaling and brick damage by 3-4mm. Indoor conditions are satisfactory. | ~5-8 | ~20-25 |

Specific gravity of housing stock by category of buildings under review, % (for Ufa)

| Specific gravity of housing stock by category of buildings under review, % (for Ufa) | 15-20 | 30-40 |

Residual service life, years

Diagnostics of both physico-chemical and physico-mechanical values dealt with serviceability [4] of silicate brick in the wall is made with samples of 1940s, 1970s and 2000s.

Measuring of alkaline pH in samples (Figure 1) demonstrated reduction thereof in water extract of the brick from 12.5 (sample of 2010) to 7.9 (sample of 1940s).
Variation of calcite content (CaCO$_3$) in the brick and sand-cement mortar is found by X-ray phase analysis together with increase of peak intensities in previous early samples thereby indicating current carbonization processes both in the brick, and mortar. According to X-ray phase analysis the compound composition of silicate brick of 1940s and 1970s by basic structure-forming phase is presented by low-basic hydrated calcium silicate (xonotlite (C$_6$S$_6$H), tobermorite (C$_5$S$_6$H$_{1.5}$), gyrolite (C$_2$S$_3$H$_{1.5}$)) with CaO/SiO$_2$ ratio less than 1, calcite and α-quartz. The compound composition of “young” (2010) brick is largely presented by average and highly basic hydroxilicates (hillebrandite (C$_2$SH$_{1.17}$), foshagite (2C$_2$S$_3$H$_3$), afwillite (C$_3$S$_2$H$_{1.3}$)) with base-to-silica ratio over 1, calcite and α-quartz. Qualitative increase of low-basic hydroxilicates and calcite in “mature” brick is characterized by two-stage process of recrystallization of highly basic hydrated calcium silicate affected by CO$_2$ into low-basic ones and calcite 1, 2. Recrystallization of basic structure-forming phases of silicate brick is presented in Table 2.

The analysis of measuring strength properties [5] with samples of 1970s has demonstrated strength variation with hardening thereof in near-surface layers of brick stretching course of facing layer. Strength hardening is due to near-surface layer structure compacting [6] by carbonization and colmatation of pore volume in this brick area. Therewith strength of the near-surface layer proved to be 10-15% higher than the original compressive breaking strength of brick by GOST 8462-85 (Figures 2, 3).

According to on-site inspection of masonry elements affected by alternate wetting-drying in summer season and freezing-thawing in transition periods (autumn-winter, winter-spring) the depth of fully destroyed layer [7] in buildings of 1970s amounted to 3-4mm, in buildings of 1940s – 8-10mm.

Brick condition in 10-15 years will be worsening till the critical one in buildings of 1940s having defects and damage corresponding to the 1 damaging category of exterior wall (Table 1), unless protective measures are taken. Depth of destroyed layer will grow strongly and considering increasing moisture absorption the amount of moisture accumulated in the material will negatively affect both strength and heat engineering features thereof.
| Carbonization reaction | Molecular weight, $m_x$, g | Density, $\gamma_x$, g/cm$^3$ | Molecular weight, $m_y$, g | Density, $\gamma_y$, g/cm$^3$ | Crystalline phase volumetric factor | All solid phase volumetric factor |
|------------------------|---------------------------|-------------------------------|---------------------------|-------------------------------|-----------------------------------|----------------------------------|
| 1 Ca(OH)$_2$ + CO$_2$ => CaCO$_3$ + H$_2$O | 74.09 | 2.23 | 100.09 | 2.71 | - | - | 1.11 | 1.11 |
| 2.1 (hillebrandite) => (xonotlite) | 1159.8 | 2.64 | 714.96 | 2.69 | 600.54 | 2.71 | - | - | 1.11 | 1.11 |
| 6Ca$_2$SH + 6CO$_2$ => => Ca$_8$S$_8$H + 6CaCO$_3$ + 6H | - | - | 1201.1 | 2.71 | 360.54 | 2.32 | 1.01 | 1.36 |
| 2 (xonotlite) 6Ca$_2$S + 6CaCO$_3$ + 6H + 6CO$_2$ => => 12CaCO$_3$ + 6SiO$_2$ + 7H | - | - | 1001.2 | 1.27 | 360.54 | 2.32 | 0.957 | 1.36 |
| 3.1 (foshagite) => (xonotlite) 2Ca$_5$S$_5$H + 4CO$_2$ => => Ca$_8$S$_8$H + 4CaCO$_3$ + 5H | 1029.28 | 2.67 | 714.96 | 2.69 | 400.36 | 2.71 | - | - | 1.073 | 1.073 |
| 3.2 (xonotlite) 6Ca$_2$S + 4CaCO$_3$ + 5H + 6CO$_2$ => => 10CaCO$_3$ + 6SiO$_2$ + 6H | - | - | 1000.1 | 2.71 | 360.54 | 2.32 | 0.957 | 1.36 |
| 4.1 (afwillite) => (xonotlite) 3Ca$_5$S$_5$H + 3CO$_2$ => => Ca$_8$S$_8$H + 3CaCO$_3$ + 8H | 1027.14 | 2.64 | 714.96 | 2.69 | 300.27 | 2.71 | - | - | 0.994 | 0.994 |
| 4.2 (xonotlite) Ca$_8$S$_8$H + 3CaCO$_3$ + 8H + 6CO$_2$ => => 9CaCO$_3$ + 6SiO$_2$ + 9H | - | - | 600.54 | 2.71 | 360.54 | 2.32 | 0.877 | 1.28 |
| 5 (xonotlite) 6Ca$_2$S + 6CO$_2$ => => 6CaCO$_3$ + 6SiO$_2$ + H | 714.96 | 2.69 | 600.54 | 2.71 | 364.8 | 2.32 | 0.834 | 1.425 |
| 6 (riversideite) Ca$_8$S$_8$H + 5CO$_2$ => => 5CaCO$_3$ + 6SiO$_2$ + H$_3$ | 694.98 | 2.6 | 500.45 | 2.71 | 364.8 | 2.32 | 0.691 | 1.279 |
| 7 (tobermorite) Ca$_8$S$_8$H$_5$ + 5CO$_2$ => => 5CaCO$_3$ + 6SiO$_2$ + 5.5H$_2$O | 739.8 | 2.43 | 500.45 | 2.71 | 364.8 | 2.32 | 0.606 | 1.123 |
| 8 (gyrolite) Ca$_8$S$_2$H$_5$ + 2CO$_2$ => => 2CaCO$_3$ + 3SiO$_2$ + H$_2$O | 328.4 | 2.4 | 200.18 | 2.71 | 180.27 | 2.32 | 0.54 | 1.108 |
The following rehabilitation levels are recommended to keep the residual service life and increase the reliability [8] of damaged exterior walls of residential buildings:

I - Radical. Repairing of large defects and damaged surface of the exterior wall, heat insulation by either non-pressed or extruded foam polystyrene by arranging fire prevention pockets and further making multilayer water-proof protection.

II - Moderate. Restoration of finish and water-proof properties of exterior wall, repairing of face defects and making heat insulation.

III - Simplified. Elimination of defects by coating, lining and applying deeply-penetrating waterproofing agent by spraying or brushing.

The expected life of reliable operation of exterior wall [9] after qualitative maintenance by the 1st level of rehabilitation is at least 60-70 years, for the 2nd level – at least 30 years (example of evaluating residual service life of exterior walls is given in Table 3.

Mechanism for protecting the exterior wall [10, 11] for all three levels of rehabilitation first of all provides protection against the weather greatly affecting [12, 13] destructive processes in the material.

However, the radical level of rehabilitation including thermal modernization of the enclosing walls

![Figure 2. Strength distribution of a single brick by sections (sample of 1970s)](image1)

![Figure 3. Measuring results of grade strength of front silicate brick](image2)
enables to transform the construction of exterior wall into comfortable operational mode through the whole year round at reducing the heating expenses to 40-50%.

Table 3. Example of evaluating residual service life of both exterior and interior walls of residential silicate brick buildings erected in 1940-70s in Ufa as of 2010

| No | Building (street, house No.) | Exterior wall material | YBlt | Damaging level of exterior walls | Rehabilitation level realized in the building | Normal service life of walls, years* | Predicted residual service life of walls before rehabilitation, years | Predicted residual service life of interior walls after rehabilitation, years |
|----|-----------------------------|------------------------|------|---------------------------------|---------------------------------------------|--------------------------------------|---------------------------------------------------------------------|---------------------------------------------------------------------|
| 1  | October Ave, 118 silicate brick | 1976 I III 125 ≈20-25 ~85 ≈55 |
| 2  | Constitution, 13 silicate brick | 1949 I II 125 ≈15 ~60 ≈35 |
| 3  | Dostoevsky, 102/1 silicate brick | 1964 I I+II 125 ≈40 ~75 ≈65 |
| 4  | Mira, 15 silicate brick | 1954 I II 125 ≈15 ~70 ≈45 |
| 5  | October Ave, 82 silicate brick | 1968 I II 125 ≈20 ~80 ≈45 |
| 6  | Koltsevaya, 34a silicate brick | 1935 I I 125 ≈10 ~50 ≈50 |
| 7  | Koltsevaya, 36a silicate brick | 1938 I I 125 ≈15 ~55 ≈55 |
| 8  | Arkhitekturnaya, 20 silicate brick | 1942 I II 125 ≈10 ~60 ≈25 |
| 9  | Kalinin, 42 silicate brick | 1955 I I 125 ≈15 ~65 ≈35 |
| 10 | Kustarnaya, 35/37 silicate brick | 1976 II III 125 ≈20 ~85 ≈35 |

The proposed rehabilitation levels have been tested in cities of the Republic of Bashkortostan under the Republican program for total building renovation of multi-apartment residential buildings.

3. Conclusion
According to theoretical and experimental analyses the following three levels to rehabilitate the damaged exterior walls are recommended by the authors, with implementation thereof safe structural behavior being increased. The expected exterior wall protection mechanism is proposed to be used in every level of rehabilitation. The proposed levels of rehabilitation have been tested in cities of the Republic of Bashkortostan under the Program for total renovation of multi-apartment residential buildings. Implementation of measures recommended to be made will further enable to greatly reduce buildings and structures heating costs.

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