# Technical condition of brickwork of the Grado-Yakutsk Trinity Cathedral of the 18th-19th centuries

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**Abstract.** In the permafrost conditions of Yakutsk, the preserved old stone buildings made of locally produced ceramic bricks are of historical and scientific value. One of the first brick buildings in permafrost conditions is the Grado-Yakutsk Trinity Cathedral, which is now 315 years old since the start of construction. The article presents the results of the brickwork survey, the main being the strength characteristics determined under laboratory and field conditions. To ensure objectivity in determining the strength of bricks and brickwork, in addition to crushing the selected samples with a hydraulic press, the impact pulse method and the ultrasonic method were used. Significant heterogeneity of the brick structure and density was confirmed by ultrasonic examination of the selected samples and impact pulse examination of the wall structures directly at the site. The percussion-impulse determination of the strength of the masonry and the mechanical determination of the strength of the selected samples confirmed the grades of the compressive strength: XVIII century bricks - M50, XIX century bricks - M75. Thus, the satisfactory technical condition of the brickwork for the restoration and reconstruction of the building is confirmed. The physical properties of the samples show that the open porosity of the brick of the XVIII century is 1.4 per cent greater than that of the brick of the XIX century. It should be recognised that the difference in the pore structure of ceramic bricks of different years is most likely due to the composition of the raw material charge and the technology of their manufacture.

## 1 Introduction

The history of construction of stone buildings in Yakutsk starts from the early 18th century [1]. Like most large Siberian settlements, Yakutsk was initially built with wooden houses. Frequent fires and availability of available clay raw materials prompted the local administration to organise the production of burnt bricks and to start stone construction in permafrost conditions [2]. Good plasticity and cohesiveness, relatively low firing temperature of clay raw material ensure sufficiently high strength of bricks. That is why ancient masters widely used burnt brick in the construction of unique buildings of their time. The Provincial Chancellery - the first stone one-storey building made of burnt brick in

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Yakutsk was built in 1706-1707 and was used until the end of the 70s of the 20th century [3]. According to Professor N.P. Kradin [4] in the Provincial Chancellery the masonry of the 90 cm thick wall was made of flat bricks with dimensions 29×16×7 cm, and semicircular window platbands were made of shaped bricks. Later, during the XVIII-XIX centuries, church buildings in Yakutsk were mainly built of burnt brick [5]. The first of them was the Trinity Cathedral, the unique architectural appearance of which was formed over two centuries from 1708 to 1858, but "repair work" was carried out in 1901. [6] Since the 90s of the last century, a large amount of repair and restoration work has been carried out and a number of church buildings - unique architectural monuments, which include the Church of the Nativity of the Blessed Virgin Mary (1752-1773 years of construction), Grado-Preobrazhenskaya Church (1838-1845) and St Nicholas Cathedral (1847-1851). The craftsmen of those distant times were highly skilled and laid not only walls and vaults, but also the smallest details of patterns, using many locally produced figurative bricks. The impressive service life (185-315 years) of exterior walls made of low quality (M50-M75) and non-freeze-resistant (not more than F25) burnt hand-formed bricks for church buildings in the permafrost conditions of Yakutsk is difficult to explain and predict. Especially according to historical data brick walls were originally laid "in brick style" [7] [7], in other words, they were not covered with plaster. However, there were legends about the strength of old stone buildings made of local burnt bricks, especially when it came to their demolition, and our contemporaries often had to resort to the services of explosion technicians [8]. From the practice of construction, it is known that in dismantled fragments of brickwork in old buildings, where bricks break more easily than the joints on the lime-sand mortar between them [9]. In the restoration of the few architectural monuments of Yakutsk, the greatest difficulty is represented by buildings of old construction, which, first of all, includes the Grado-Yakutsk Trinity Cathedral. One of the main activities aimed at determining the category of technical condition and serviceability of the object, identifying defects and developing measures for their elimination is the examination of brickwork walls.

In the restoration of architectural monuments, the analysis of archival documentation and visual inspection do not provide comprehensive information about the current state of the object, structural strength and reliability. In order to obtain detailed results, it is necessary to use instrumental methods, which will allow to make informed decisions on carrying out certain works. The main objective of the study is to determine the technical condition of the brickwork walls by examining its construction and performance characteristics after a period of time.

## 2 Materials and methods

To determine the technical condition of brickwork walls, standard methods of determining the construction and performance characteristics of bricks and brick wall fragments were used. It is known that various modern diagnostic methods are used to objectively assess the condition of the brickwork of historic buildings and, as a consequence, of the building as a whole. Objectivity of assessment of brick strength of historic buildings by the impact pulse method using the device IPS-MG4.03 is substantiated in [10, 11]. As established in [12], the wave impact method is a more informative method for qualitative assessment of masonry strength. Alternative methods, such as sampling and testing of cores [13], Flat-Jack Testing system, which is widely used abroad [14, 15], but has not found application in Russia due to the costliness of the works, the method of determining the adhesion of masonry mortars in masonry [16, 17], are also of scientific and practical interest. As noted in the articles [10-17], the strength of bricks selected from old buildings - architectural monuments, in any case is characterised by a wide range of values, which affects the

reliability of determining the design resistance of the masonry as a whole. In our research, the classical method of hydraulic press testing, as well as non-destructive methods - the impact pulse method and ultrasonic method - were used to assess the strength of bricks.

During the survey of the building, the nominal dimensions of bricks from different years of construction were initially determined. At the same time, the period of construction of different parts of the temple was determined from archival data and samples of the XVIII and XIX centuries were selected.

The determination and statistical processing of the results of measurements of the linear dimensions of the XVIII century bricks are given in Table 1.

**Table 1.** Linear dimensions of 18th century ceramic bricks.

| Parameter | Sample number | Actual value, mm | Absolute error, mm | Relative error, % | Average value, mm | Nominal value, mm |
|---|---|---|---|---|---|---|
| Length | 1 | 298 | 0.67 | 0.31 | 298.67 ±0.89 | 300 |
| | 2 | 300 | 1.33 | | | |
| | 3 | 298 | 0.67 | | | |
| Width | 1 | 161 | 0 | 0.83 | 161 ±1.33 | 160 |
| | 2 | 163 | 2 | | | |
| | 3 | 159 | 2 | | | |
| Height | 1 | 79 | 0 | 0.85 | 79 ±0.67 | 80 |
| | 2 | 78 | 1 | | | |
| | 3 | 80 | 1 | | | |

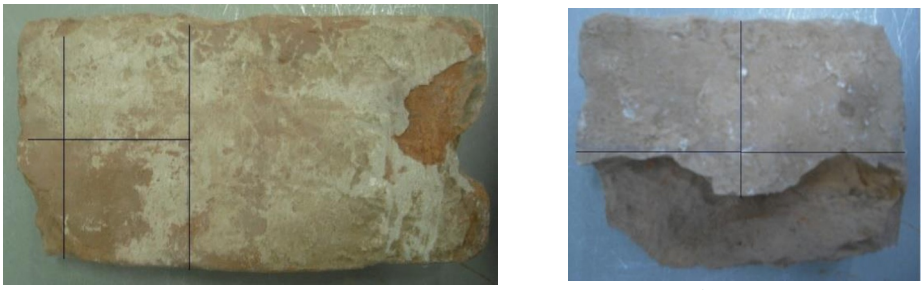
The linear dimensions of 19th century bricks were determined using the above methodology. All measurement results are summarised in Table 2 in comparison with modern standards.

**Table 2.** Comparative dimensions of ceramic bricks.

| No. | Sample name | Nominal dimensions, mm | | |
|---|---|---|---|---|
| | | length | width | thickness |
| 1 | Eighteenth-century brick | 300 | 160 | 80 |
| 2 | Nineteenth-century brick | 270 | 130 | 66 |
| 3 | Brick of XXI century (GOST 530-2007) | 250 | 120 | 65 |

## 3 Results

In order to determine the physical properties, bricks of different ages were sampled from the ground floor of the building from different wall constructions.



a) XVIII c. b) XIX c.

**Fig. 1.** Brick fragments for prototype production.

The marking of brick sawing for the production of prototypes is shown in Fig. 1. Sawing was carried out with diamond discs on a cutting machine. The bricks were covered with a layer of lime-sand mortar approximately 2-4 mm thick, so their surface was carefully cleaned with a metal spatula.

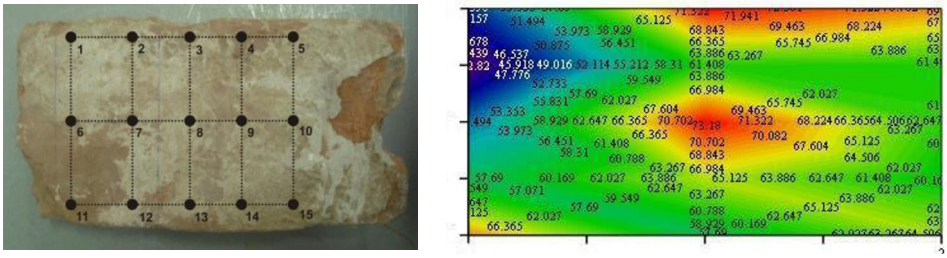
Density, porosity, hydrophysical and thermophysical properties, etc. were determined during the survey. Taking into account the number of samples obtained from the brick samples, it is possible to determine experimentally the values of the following physical characteristics of the material: average density, true density, porosity, closed porosity, sorption moisture, water absorption by volume, water absorption by mass, pore water saturation coefficient. The physical characteristics were determined according to the requirements of standard laboratory methods. The results of the calculation of the physical characteristics of ceramic bricks are given in Table 3.

**Table 3.** Physical characteristics of ceramic bricks.

| Name of indicator | Unit of measurement | Bricks of the Trinity Cathedral | |
|---|---|---|---|
| | | 18th century | 19th century |
| Average density | kg/m³ | 1650 | 1685 |
| True density | kg/m³ | 2681 | 2607 |
| Porosity | % | 37.1 | 36.7 |
| Closed porosity | % | 30.86 | 31.86 |
| Sorption moisture | % | 0.57 | 0.13 |
| Water absorption by volume | % | 6.24 | 4.84 |
| Water absorption by mass | % | 20.79 | 17.99 |
| Pore water saturation factor | - | 0.17 | 0.13 |

Prior to sawing, the seized samples were subjected to ultrasound examination. Figures 2a and 3a show the location marks of the piezometric transducers of the device. The ultrasonic pulse was passed through the given marks and the time of its passage was recorded in μs. The obtained data were linearly interpolated and plotted as a surface (Fig. 2b and 3b).

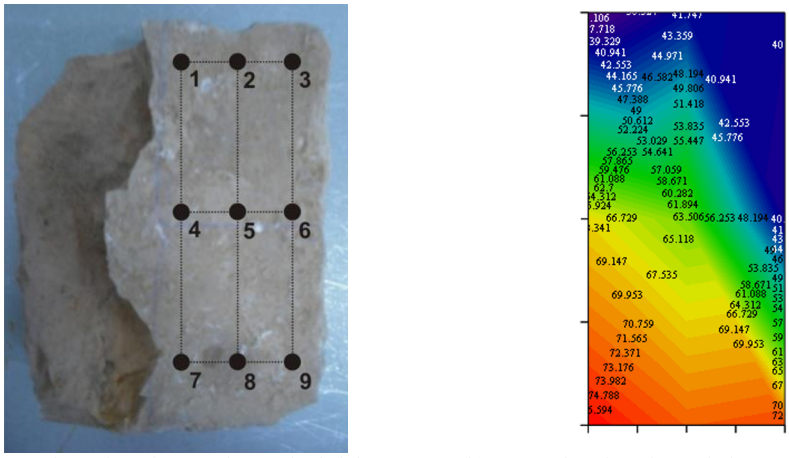
The blue colour shows the minimum values of the ultrasound transit time, and the red colour shows the high values, respectively. Transitions from blue to red colour illustrate transitions of ultrasound transit time variation.




a) Piezo transducer location marks on the brick.

b) Interpolated surface of ultrasound propagation time variation by marks (μs)

**Fig. 2.** Results of ultrasonic measurements for 18th century bricks.




a) Piezo transducer location marks on the brick

b) Interpolated surface of ultrasound propagation time variation by marks (μs)

**Fig. 3.** Results of ultrasonic measurements for 19th century brick.

The patterns obtained show the relative heterogeneity of material density throughout the entire volume of both 18th century and 19th century samples. Therefore, the strength characteristics of ceramic bricks were determined by two methods: non-destructive and destructive.

There are quite a large number of non-destructive methods of controlling the strength of building materials, but in this study used the method of impact pulse device IPS-MG4-03. The strength measurements were made directly on the surface of the wall structure in places where there was no plaster coating (Fig. 4). The brick surface was cleaned with a dry cloth before measurement.

a) XVIII c. b) XIX c.

**Fig. 4.** Brick masonry fragments for non-destructive strength testing.

To ensure the correctness and reliability of the results of brick strength measurements using the impact pulse method, wall surfaces not in contact with the external environment were tested. The wall surfaces were cleaned from plaster and other finishing materials.

For objective interpretation of the obtained data and for visualisation of the results of statistical processing of measurements the so-called control charts are constructed, the charts of which represent the value of the confidence interval. The STATISTICA

application software was used for construction of control charts. The following types of control charts for the variability of the compressive strength of ceramic bricks were constructed:

1. *X-bar map.* Sample mean values are plotted on this control chart to show the deviation from the mean value.

2. *R-map.* It is used to show the degree of variability of a continuous variable. In a control chart of this type, the values of sample spreads are plotted.

In controlled samples of volume n, the mean value of compressive strength is measured. In each sample, the average value of the trait is calculated $\overline{x}_{comp}$ and its scope :

$$R_i = x_{max}^{comp} - x_{min}^{comp}$$

At *X-bar* lower and upper control limits on the map (LCL/UCL) for the mean at fixed confidence α are calculated using the formulas :

$$LCL = \bar{\bar{x}} - A\overline{R} \quad UCL = \bar{\bar{x}} + A\overline{R}$$

where $\bar{\bar{x}}_{comp} = \frac{1}{n}\sum_{i=1}^{n}\overline{x}_{comp}$ – arithmetic mean for the current sample;

$\overline{R}_{comp} = \frac{1}{n}\sum_{i=1}^{n}R_i$ – arithmetic mean of the spread in the current sample;

*A* – coefficient, the values of which depend on the chosen significance level and are given in special tables.

The sample number and compressive strength values of the bricks are given in Table 4.

**Table 4.** Sample numbers and compressive strength values of ceramic bricks.

| Brick of the 18th century. | | Brick of the 19th century. | |
|---|---|---|---|
| Sample number | Compressive strength, MPa | Sample number | Compressive strength, MPa |
| 1 | 22.4 | 1 | 36.5 |
| | 13.3 | | 14.5 |
| 2 | 15.4 | 2 | 27.6 |
| | 20.7 | | 31.3 |
| 3 | 16.9 | 3 | 23 |
| | 10.5 | | 21.7 |
| 4 | 7.2 | 4 | 18.1 |
| | 20.2 | | 29 |
| 5 | 6.5 | 5 | 15 |
| | 26 | | 25.5 |
| 6 | 10.6 | 6 | 14.7 |
| | 13.9 | | 27 |
| 7 | 5.4 | 7 | 28.6 |
| | | | 39.4 |
| | 19.6 | 8 | 17.5 |
| | | | 17 |

Based on the test results, X-bar and R maps of compressive strength of ceramic bricks of XVIII and XIX centuries were constructed (Fig. 5 and 6).

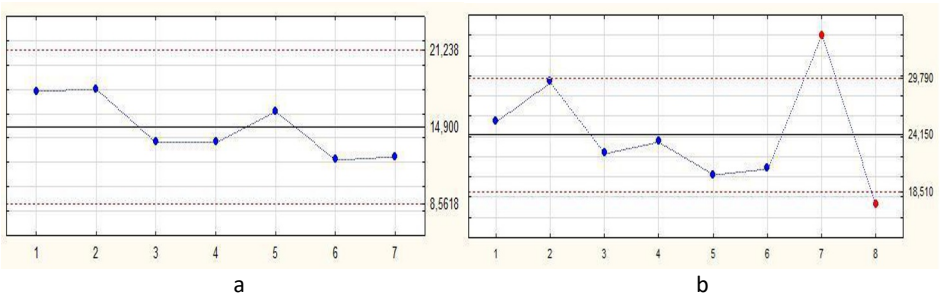



**Fig. 5.** X-bar map of variability of compressive strength of ceramic bricks XVIII c (a) and XIX c (b).

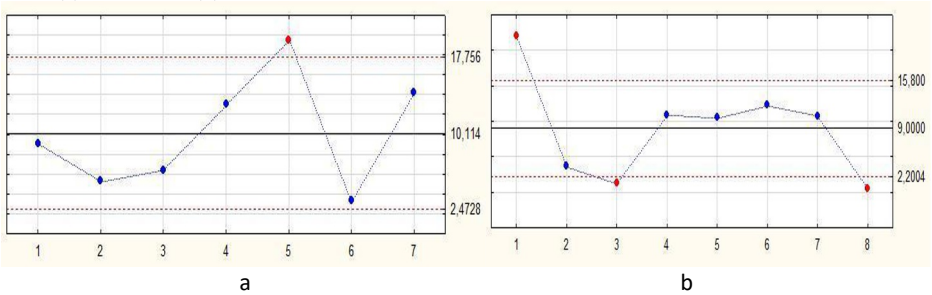



**Fig. 6.** R map of variability in the spread of ceramic bricks of the 18th century (a) and 19th century (b).

For clarity of comparison of brick strength, a ranked series of each individual measurement in ascending order is constructed (Fig. 7).

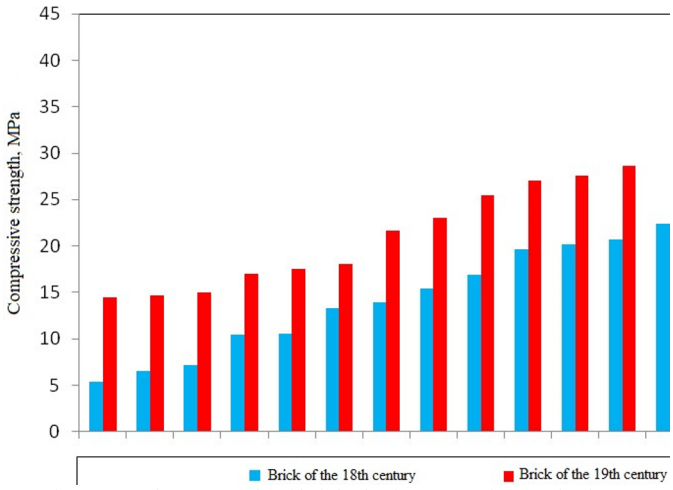



**Fig. 7.** Comparison of compressive strength of bricks by impact pulse method.

As expected, despite the considerable variation in the measurement results, the arithmetic mean compressive strength of 19th century bricks is 1.5 times greater than that of 18th century bricks. Most likely, this can be explained by the service life of the bricks.

The analysis of the test results showed that the strength of ceramic bricks varies within a very wide range. For example, for the XVIII c brick the strength varies from 5.4 to 22.4 MPa, which determines the difference between the maximum and minimum strength value

by a factor of 4, and for the XIX brick by a factor of 2.7. On this basis, the XIX brick has a lower variability than the XIX c brick.

The greatest influence on the variability of measurement results is the condition of the wall surface. The visual assessment of the wall condition is generally unsatisfactory (Figure 4), with a rough surface, lime efflorescence and irregularities, which is likely to have led to the high variability of the test results. Nevertheless, in some areas of the wall surface, there are bricks that crumbled when rubbed with a metal trowel. Therefore, in order to objectively assess the brick strength, all measurement results are taken into account. This wide range of values is the result of the complex influence of the following factors:

1. Presence of brick pores. It is known that ceramic bricks are materials with a fairly branched system of pores with different diameters, which affect the level of plastic deformation of the brick surface under the influence of the device;
2. The striker of the appliance hitting loose areas of the brick. Considering the fact that bricks were made by hand in those days, there is a high probability that there are insufficiently compacted areas;
3. Difference in the roughness of the brick surface;
4. Uneven surface, which increases the possibility that the supports will not rest correctly;
5. The presence of shells and chips causes incorrect results.

In the destructive method of determining the compressive strength of ceramic brick samples of the XVIII and XIX centuries we used a hydraulic press in parallel with an ultrasonic device. In this case, the samples obtained by sawing were tested in compression until complete destruction with a parallel determination of the ultrasound velocity through the sample.

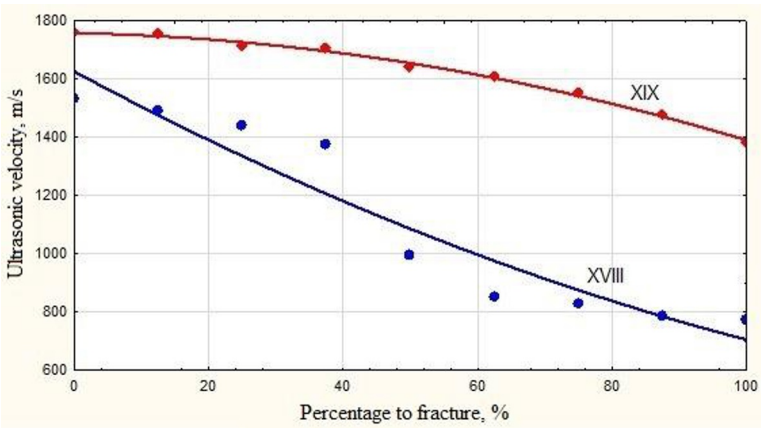



**Fig. 8.** Variation of ultrasound propagation velocity in the process of brick fracture.

By mechanical destructive method it was determined that ceramic bricks of the XVIII century have a compressive strength of 6.5 MPa, and XIX - 7.1 MPa. The ultrasound velocity depending on the degree of destruction of the samples is shown in Fig. 8, where clear regression lines can be seen, which confirm the fact that the ultrasound velocity decreases in the structure with defects.

## 4 Conclusion

The results of ceramic bricks testing on a hydraulic press showed that they have grades of compressive strength: XVIII-century brick - M50, XIX-century brick - M75. When

determining the physical properties of the ceramic samples, it was found that the open porosity of the bricks of the XVIII century is 1.4 per cent greater than that of the bricks of the XIX century, which affected the reduction of all other indicators and the strength of the bricks, among others. Significant heterogeneity in the structure of the 18th century bricks was confirmed by ultrasonic examination of the selected samples and impact and pulse examination of the structures directly on site. Most likely, the difference in the pore structure of ceramic bricks of different centuries is due to the composition of the raw materials and the technology of their manufacture.

In general, the condition of the brick samples extracted directly from the wall construction is good. The brick grades obtained comply with the GOST requirements, on the basis of which the authorisation for the restoration and reconstruction of the building should be confirmed.

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