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Applicability of Non-Destructive Methods for Assessing the Strength of Masonry of Existing Structures

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Abstract

Introduction. The compressive strength of masonry is the most important mechanical characteristic assessed during inspections of buildings and is determined based on direct testing of bricks and mortar selected from the walls. However, current regulatory documents also recommend the use of non-destructive testing methods, particularly while examining cultural heritage buildings. However, non-destructive methods fail to take into account differences in the strength of bricks and mortar joints in the surface layers and their main volume, interaction of bricks and mortar, as well as anisotropy of the mechanical characteristics of masonry. The article presents the results of a study of the anisotropy of the compressive strength of ceramic bricks and an analysis of its influence on the results of assessing the strength of masonry using indirect methods.

Materials and Methods. The object of the research are two types of bricks: historical bricks from the walls of the barracks of the Brest Fortress built in 1933, as well as modern bricks produced in the Republic of Belarus. The strength of the brick was identified under a compressive load in the direction of the front, support and end surfaces on cubes with an edge size equal to the height of the brick.

Research Results. Graphs of the ratio between the obtained strength values of experimental cube samples under compression perpendicular to the front and end surfaces of the brick to the compressive strength perpendicular to its supporting surface are presented. Similar studies by other authors, including on ceramic cylinder samples, are analyzed. It was found that the compressive strength of the historical bricks perpendicular to its front and end surfaces was higher than their compressive strength perpendicular to the supporting surface. The opposite pattern was observed for modern bricks. However, due to the high variation of the results, it is not possible to establish a correlation between the compressive strength and the direction of the compressive force.

Discussion and Conclusion. The results of some studies that have shown that ceramic bricks are an anisotropic material are presented. A possibility of using non-destructive testing methods for brick strength has been evaluated, as well as that of designing a calibration ratio linking the compressive strength of a brick with the results of indirect testing of the front surface.

Keywords: masonry, brick, compressive strength, non-destructive testing methods, calibration ratio

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Оригинальное эмпирическое исследование

Применимость неразрушающих методов для оценки прочности каменной кладки существующих конструкций

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Аннотация
Введение. Прочность каменной кладки на сжатие является важнейшей механической характеристикой, оцениваемой при обследовании зданий, которая определяется на основании прямых испытаний отобранного из стен кирпича и раствора. Однако действующие нормативные документы также рекомендуют использовать неразрушающие методы контроля, особенно при обследовании объектов культурного наследия. Но неразрушающие методы не учитывают различия в прочности кирпича и растворных швов в поверхностных слоях и их основном объеме, взаимодействие кирпича и кладочного раствора, а также анизотропию механических характеристик кладки. В статье приведены результаты исследования анизотропии прочности на сжатие керамического кирпича и анализ ее влияния на результаты оценки прочности каменной кладки косвенными методами.
Материалы и методы. Объектом исследований является два типа кирпича: исторический кирпич из стен здания казармы Брестской крепости, построенного в 1933 г., и современный кирпич, произведенный в Республике Беларусь. Прочность кирпича определялась при действии сжимающей нагрузки в направлении лицевой, опорной и торцевой поверхностей на кубах с размером ребра, равным высоте кирпича.
Результаты исследования. Приведены графики отношения полученных значений прочности опытных образцов-кубов при сжатии перпендикулярно лицевой и торцевой поверхностям кирпича к прочности на сжатие перпендикулярно его опорной поверхности. Проведен анализ подобных исследований других авторов, в том числе на керамических образцах-цилиндрах. Установлено, что прочность исторического кирпича при сжатии перпендикулярно его лицевой и торцевой поверхностям оказалась выше прочности при сжатии перпендикулярно опорной поверхности. Для современного кирпича наблюдалась обратная закономерность. Однако из-за высокого разброса полученных результатов невозможно установить корреляционную зависимость прочности на сжатие от направления сжимающего усилия.
Обсуждение и заключение. Приведены результаты исследований, которые показали, что керамический кирпич является анизотропным материалом. Выполнена оценка возможности применения неразрушающих методов контроля прочности кирпича, а также возможность построения градуировочной зависимости, связывающей прочность на сжатие кирпича с результатами косвенного испытания лицевой поверхности.

Ключевые слова: каменная кладка, кирпич, прочность на сжатие, неразрушающие методы контроля, градуировочная зависимость

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Introduction. The most important mechanical characteristic of masonry evaluated during inspection of stone buildings is its compressive strength. The compressive strength of masonry is commonly identified by means of calculating the test results of bricks and mortar taken from the walls of a building carried out in compliance with GOST 8462 "Wall Materials. Methods for Identifying Compressive and Flexural Strength Limits" and GOST 5802 "Building Mortars. Test Methods" [1–5]. This method is rather labor-intensive, thus while examining stone structures in order to identify the strength of bricks and mortar, lots of specialists tend to resort to non-destructive (indirect) methods that include sclerometric methods of elastic rebound, shock pulse, or the method of measuring the propagation velocity of an ultrasonic pulse. While making use of sclerometric methods, the compressive strength of bricks and mortar is identified using IPS MG-4 type sclerometers or Schmidt hammers where the calibration ratio "ceramic brick" is specified by the manufacturer. It is to be noted that in order to assess the strength characteristics of the brickwork of cultural heritage sites, GOST R 55567 "Procedure for Organizing and Conducting Engineering and Technical Research at Cultural Heritage Sites. Historical and Cultural Monuments. General Requirements" directly recommends prioritizing non-destructive testing using devices based on the elastic rebound method in compliance with GOST 24332 "Silicate Bricks and Stones. Ultrasonic Method for Identifying Compressive Strength" or other specialized and calibrated devices for identifying the strength characteristics of bricks and mortar. A correlation between the indicators of non-destructive testing devices and strength characteristics of masonry materials can be specified by means of comparing the average values of these characteristics obtained by non-destructive testing and laboratory tests of at least three samples for each type of masonry. Laboratory tests are conducted in compliance with the requirements of GOST 8462, GOST 5802.

It is known that non-destructive methods for assessing the compressive strength of masonry which has been in use for a long time have some drawbacks that are associated with uncertainties caused by the differences in the strength of bricks and mortar joints in the surface layers and their bulk, interaction of bricks and masonry mortar, as well as anisotropy of the mechanical characteristics of masonry [1, 3, 7, 9]. Overlooking these factors might cause significant errors in assessment of the compressive strength of masonry, and thereby underestimation or overestimation of the load-bearing capacity of stone structures. This article looks at the effect of anisotropy of the compressive strength of ceramic bricks on the strength of masonry identified by means of indirect methods.

Materials and Methods. The anisotropy of the compressive strength of ceramic solid bricks was investigated. Two types of bricks were tested: historical bricks taken from the walls of the Brest Fortress barracks built in 1933 as well as modern bricks produced in the Republic of Belarus. The historical brick had the following dimensions: length — 265 mm, width — 130 mm, height — 60 mm. Bricks produced in Poland in the second half of the 19th century correspond to these sizes [5]. The dimensions of the modern brick are as follows: length — 250 mm, width — 120 mm, height — 65 mm. Initially, the average values of the compressive and bending strength of the bricks were identified in compliance with GOST 8462 (Fig. 1).

a) *b)*

Fig. 1. Tests of the bricks: *a* — compression; *b* — bending

Based on the tests, it was found that the average value of the tensile strength of the historical bricks under compression is 16.9 MPa, in bending — 5.1 MPa, of the modern bricks — 17.3 MPa and 5.3 MPa, respectively.

In order to identify the strength of a ceramic brick under a compressive load in the direction of its front, support and end surfaces (Fig. 2), cubes with an edge size equal to the height of a brick were cut out of the bricks.

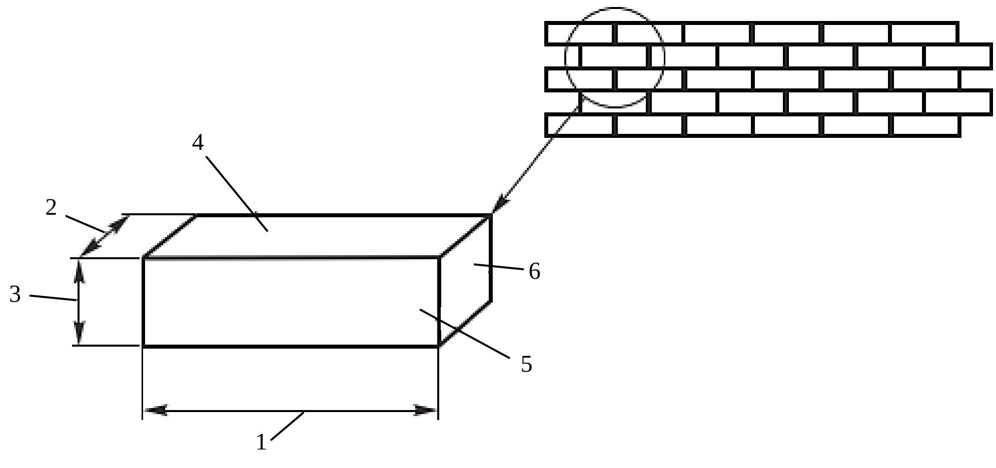


Fig. 2. Brick dimensions and surfaces: 1 — length; 2 — width; 3 — height; 4 — support surface; 5 — front surface; 6 — end/header surface

For each direction of the compressive load, 5-6 ceramic cube samples were made from different types of bricks. The surface of the cubes in contact with the press plates was leveled with a thin layer of gypsum mortar. The general view of ceramic cube samples prepared for the tests is shown in Fig. 3.

Fig. 3. Ceramic cube samples prepared for the tests

The ceramic cubes were loaded using a TP-1-500 testing machine. The cube samples were mounted with one of the selected faces on the lower base plate of the testing machine centrally relative to its longitudinal axis.

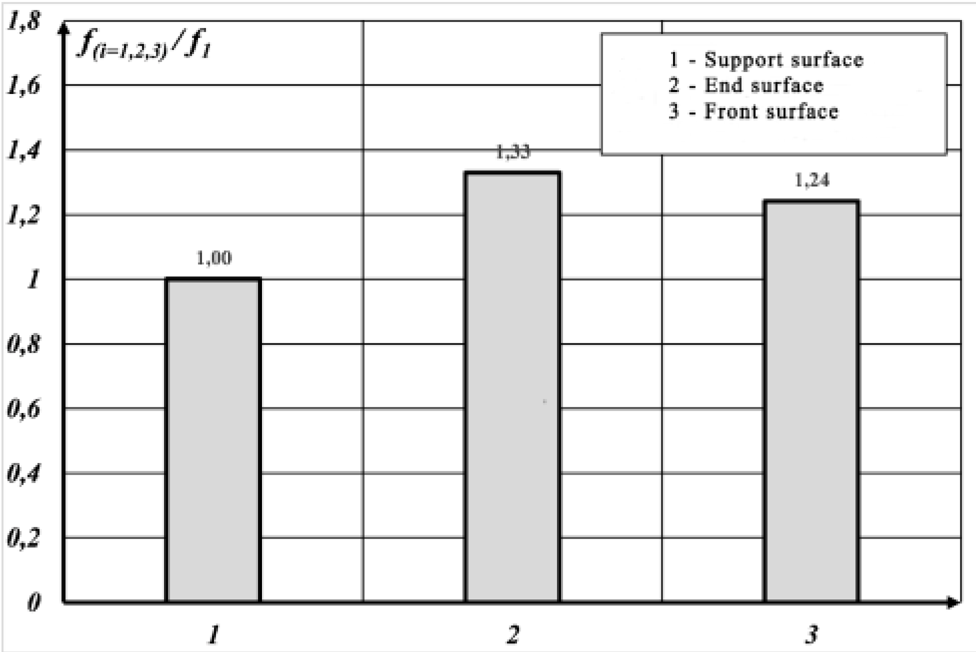
After the sample has been installed on the base plate, the upper plate of the machine was aligned with the upper support face of the sample so that their planes completely adjoined each other. The sample was loaded continuously at a rate that ensured its destruction within 30 seconds. The general appearance of the ceramic cube sample in the test facility and the nature of its destruction are shown in Fig. 4.

a) *b)*

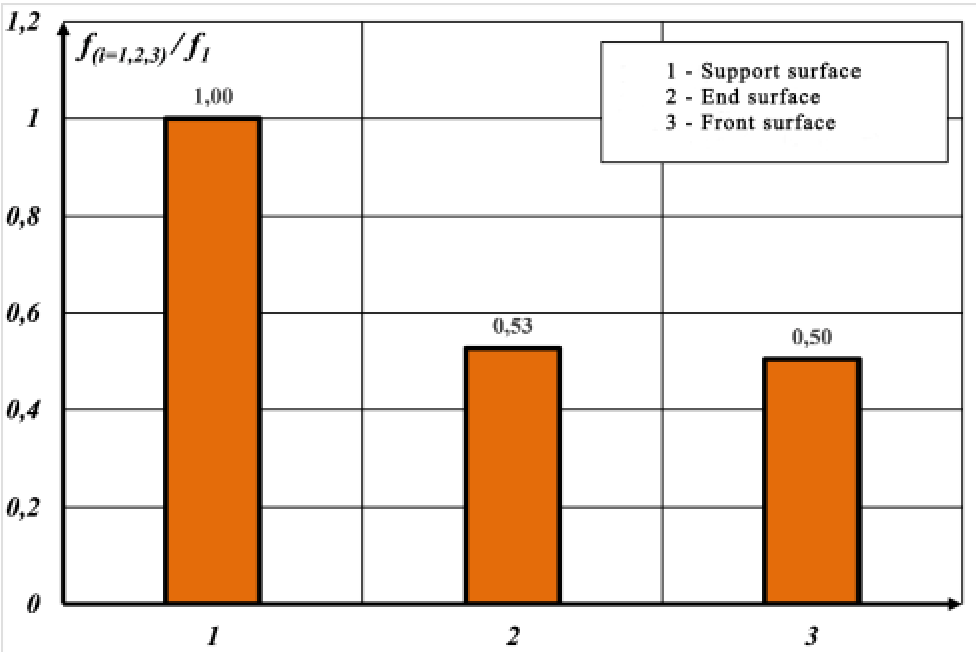
Fig 4. Testing of ceramic cubes: *a* — the general appearance of the sample; *b* — the nature of destruction

The maximum force attained during the tests was assumed to be a destructive load. The compressive strength of the sample was identified as the quotient of the destructive load divided by the working area of its cross-section. Based on the test results of the cube samples, the average strength values of the samples were identified under compressive forces in the direction of the front, support and end surfaces of the brick.

Research Results. Fig. 5, 6 show the graphs of the ratio of the resulting strength values of the experimental cube samples when compressed perpendicular to the front (f_3) and end (f_2) surfaces of the brick to the compressive strength perpendicular to its supporting surface (f_1).



a)



b)

Fig. 5. Results of identifying the strength of ceramic cube samples: *a* — historical brick; *b* — modern brick

According to Fig. 5, the strength of ceramic cube samples sawn from historical bricks when compressed perpendicular to its front and end surfaces turned out to be 24% and 33% higher, respectively, than that obtained by applying a compressive force perpendicular to the supporting surface.

The reverse pattern was observed for the modern bricks. The strength of ceramic cubes subjected to compressive loads perpendicular to the front and end surfaces of the brick was 50% and 47% lower than the compressive strength perpendicular to the support surface, respectively.

While testing the ceramic cube samples, the coefficient of variation in compressive strength was 25–40% for the historical bricks and 10–15% for the modern bricks.

The results of the studies of the anisotropy of compressive strength of the modern bricks are in a fairly good agreement with the test results of the ceramic cylinder samples provided in [7]. Cylinder samples with a diameter of 56 mm were selected from solid ceramic bricks of the grades M150 (Novgorod), M200 (Vitebsk) and M250 (St. Petersburg) perpendicular to its front and support surfaces. It was found that the ratio of the compressive strength of cylindrical samples taken orthogonally to the front and support surfaces of the brick was approximately 0.6.

The test results of the cylindrical samples taken from the historical bricks were characterized by a significant range of values (the coefficient of variation of 30–45%) [8]. It was not possible to establish a ratio for them between the compressive strength orthogonally to the front and support surfaces of the brick. This is accounted for by the high heterogeneity of the material within a single brick, as well as the use of different types of bricks in the masonry.

[9] presents the results of studies of the anisotropy of compressive strength of historical ceramic bricks of the Austrian standard with a length of 290 mm, width of 150 mm and height of 65 mm, with a normalized compressive strength of 19.28 MPa and modern German NF standard bricks (length — 250 mm, width — 120 mm, height — 65 mm) with a normalized compressive strength of 28 MPa. The anisotropy of the compressive strength of the brick was identified based on tests of cores with a diameter of 45 mm selected at different angles to the supporting surface of the brick (Fig. 6*a*).

Studies have shown that for modern bricks when the compressive force is directed at an angle to the support plane of 0 ° < φ ≤ 60 °, the compressive strength is close to that perpendicular to the support plane, φ = 0° (Fig. 6*c*). The minimum values of compressive strength occurred at φ = 90 ° (f_0/f_{90} = 1.3).

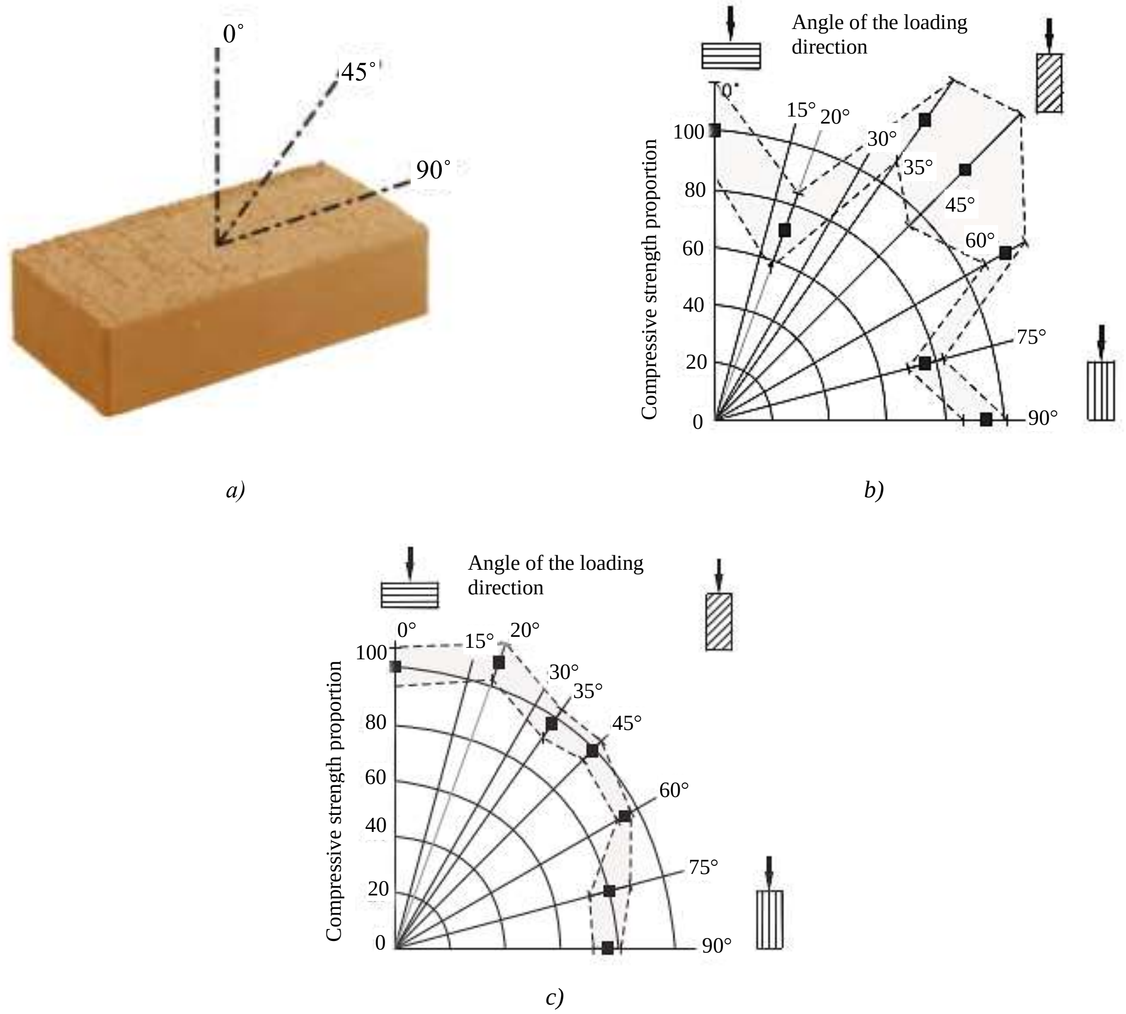


Fig. 6. Results of identifying the compressive strength of the cylinder samples: *a* — sampling directions; *b* — historical brick; *c* — modern brick [6]

For the historical bricks, under a compressive force at the angles of 35° ≤ φ ≤ 60°, the compressive strength turned out to be 20–25% higher than that at an angle φ = 0° (Fig. 6*b*). The minimum compressive strength was obtained at the angles φ = 20° and 75°. When a compressive force was directed perpendicular to the end surface of the brick, φ = 90°, the compressive strength was 23% lower than that at an angle φ = 0°.

Based on the test results, it was concluded that due to the high variation of the results for historical bricks, it is not possible to identify a ratio between the compressive strength and the direction of a compressive force.

Studies [6] have shown that while testing bricks in masonry, the amount of elastic rebound is affected not only by the direction of impact, but also by the quality of brick sealing in masonry, which is largely due to the type and condition of the mortar joints. This is accounted for by the influence of these factors on the degree of absorption of the impact energy of the test hammer on the brick surface.

Discussion and Conclusion. The results of this study as well as [7–9] have shown that ceramic bricks are an anisotropic material. The degree of anisotropy of the strength characteristics of a brick is due to a host of factors, with the technology of its manufacture and the raw materials used as the primary ones. At the same time, for historical bricks it is difficult to identify any patterns of compressive strength from the direction of a compressive force due to the high values of the coefficients of variation of the test results. It is not possible to design a calibration ratio connecting the compressive strength of such a brick in the direction of the support surface with the results of indirect testing of the front surface of the brick by means of the elastic rebound method or measuring the propagation velocity of an ultrasonic pulse.

While examining stone structures, tests to identify the elastic rebound of a hammer enable measurements of the surface hardness of the front surface of the brick, but not to evaluate its quality over the entire section and, which is more, to obtain compressive strength values in the direction of a compressive force acting in the section of a stone structure.

The velocity of propagation of an ultrasonic pulse in masonry is impacted a broad range of major factors: heterogeneity of the structure of bricks and mortar joints, thickness of the joints and quality of their execution, humidity of masonry, as well as degree of degradation of bricks and mortar [10].

The results of non-destructive testing methods are challenging for interpretation as the material in the surface areas of bricks and mortar might be different from their deeper layers. As an example, Fig. 7 shows a section of a ceramic modern brick where the different color of its outer and inner layers is clearly distinct, which indicates the difference in their strength characteristics. This is of particular relevance for historical bricks whose degree of firing and cross-sectional strength can vary considerably.

Fig. 7. Ceramic bricks in the section: different color of the outer and inner layers

It is recommended that indirect methods for assessing the compressive strength of bricks of existing structures are used in order to assess the uniformity of masonry as well as to identify the locations of brick and mortar selection. These methods can also be employed in order to control the strength of factory-made bricks where it is possible to design particular calibration ratios for each set of parameters (a type of raw material, molding method, temperature and duration of firing, a type of brick, etc.) [7]. At the same time, as noted in [6], use of sclerometric methods for assessing the strength of ceramic products is possible only if the volume of their voids is not over 10%. While testing masonry products with a large volume of voids, there is significant absorption of impact energy making it not possible to assess the strength of products in a reliable manner.

It is to be noted that the results of assessing the strength of the masonry obtained based on the tests of individual bricks and hardened mortar taken from its body have a low degree of reliability, as they fail to take into account the interaction of the brick and mortar in the masonry. The only methods that allow reliable data to be obtained on the compressive strength of masonry of existing structures are its structural tests or laboratory tests of masonry samples selected from a structure under study[1,2] [2, 3, 5, 9–14].

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Claimed contributorship:

VN Derkach: scientific supervision, formation of the basic concept, aims of the study, preparation of the manuscript, formation of the conclusions.

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PI Matyas: analysis of the research results, formation of the references.

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И.Е. Демчук: анализ результатов исследований, подготовка текста.

П.И. Матяс: анализ результатов исследований, формирование списка литературы.

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