doi: 10.18720/MCE.80.14

Analytical determination of thermal expansion of rocks and concrete aggregates

Аналитическое определение термического расширения горных пород и заполнителей бетонов

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Key words: thermal expansion and fracturing; analytical determination; rocks; concrete mineral aggregates

Ключевые слова: термическое расширение и растрескивание; аналитическое определение; горные породы; минеральные заполнители бетонов

Abstract. The article provides selection and approbation of the model and the model-based method for the analytical determination of thermal expansion and rock fracturing (decompression) and concrete mineral aggregates according to the data about thermal deformations of minerals based on information of the mineral composition, the average grain fineness of minerals and the elasticity modulus of rock. To accomplish the research, the author has used two models available in scientific publications: 1. Balashov and Zaraisky Model for calculating the thermal expansion and decompression of rock based on thermal deformations of minerals. The model does not take into account the structure and mechanical properties of rock. 2. The model of Denisov (one of the authors of this work) and Dubrovskiy was developed and evaluated earlier for the analytical determination of radiation expansion and rock fracturing when neutrons are irradiated by nuclear reactors on the basis of radiation deformation of minerals. The model takes into account the grain fineness and elasticity modulus of rock. The model is accepted for research on the basis of the analogy between the processes of thermal and radiation changes of rock at the level of interaction in mineral crystals. The approbation was done on the basis of both the information available in the scientific publications and experimental data obtained in this work which have shown thermal expansion of 22 in magmatic and sedimentary rock in the range from 20 to 700 °C. It has been determined that the model of Denisov and Dubrovskiy especially with correction introduction associated with the increase in the rock plasticity when heated is adequate and better than the Balashov and Zaraisky Model which describes the process of thermal expansion and rock fracturing. This model can be used for the analytical determination of thermal expansion and isotropic rock fracturing and concrete mineral aggregates at temperatures up to 700 °C (the most reliable – up to 500 °C) at normal pressure and humidity with the absence of included minerals that provide water and gases emission when heated.

Аннотация. Выполнен выбор и апробирование модели и основанного на ней метода аналитического определения термического расширения и растрескивания (разуплотнения) горных пород и минеральных заполнителей бетонов по данным о термических деформациях минералов на основании информации о минеральном составе, средней крупности зерен минералов и модуле упругости горных пород. Для исследований выбраны две имеющиеся в литературе модели: 1. Модель Балашова и Зарайского для расчета термического расширения и разуплотнения горных пород на основании термических деформаций минералов, не учитывающую структуру и механические свойства горных пород. 2. Модель Денисова (одного из авторов настоящей работы) и Дубровского, разработанная и апробированная ранее для аналитического определения радиационного расширения и растрескивания горных пород при облучении нейтронами ядерных реакторов на основании радиационных деформаций минералов, учитывающая крупность зерен и модуль упругости горной породы. Модель принята для исследования на основании аналогии между процессами термического и радиационного изменения горных пород на уровне взаимодействия кристаллов минералов. Апробирование выполнено на основании имеющихся в

Денисов А.В., Спринце А. Аналитическое определение термического расширения горных пород и заполнителей бетонов // Инженерно-строительный журнал. 2018. № 4(80). С. 151–170.

литературе и полученных в настоящей работе экспериментальных данных по термическому расширению 22 магматических и осадочных горных пород в интервале от 20 до 700 °С. Установлено, что модель Денисова и Дубровского особенно при введении поправки, связанной с увеличением пластичности горных пород при нагревании, адекватно и лучше, чем модель Балашова и Зарайского, описывает процесс термического расширении и растрескивания горных пород. Эта модель может быть использована для аналитического определения термического расширения и растрескивания изотропных горных пород и минеральных заполнителей бетонов при температурах до 700 °С (наиболее надежно до 500 °С) при нормальном давлении и влажности при отсутствии в их составе минералов, выделяющих при нагревании воду и газы.

1. Introduction

Thermal expansion of rock is very important for their thermal and physical properties Thermal expansion of rock is accompanied not only by the increase in the size and volume of rock massifs and processing of rock. Thermal expansion in rock generates thermomechanical stress at all levels, micro- and macro-cracking (decompression) occured until destruction, as well as a decrease in their physical properties [1–9]. In this regard:

- thermal destruction and rock drilling efficiency [4, 5, 10];

- rock metasomatism [6];

- possibility of using rock massifs to bury radioactive wastes [11–12];

- possibility of using rock massifs to store thermal energy [13, 14];

- thermal deformation and heat resistance of concretes when using crushed stone and sand made from rock as concrete aggregates [15–18].

It is known that thermal expansion and rock fracturing depend on the rock composition and structure and therefore can vary in a relatively wide range even in rock of the same type [1-9, 19-22]. In this regard, when selecting rock for use for various purposes, it is quite relevant to provide the analytical determination of thermal expansion and rock fracturing based on data on their mineral composition, structure and mechanical properties.

A model for describing the process of thermal expansion and rock decompression due to fracturing on the basis of thermal expansion and the content of the constituent mineral composition was developed in the works of Balashov and Zaraiskiy [21, 22]. Along with this one of the works [21] contains the notes about generally good coincidence between the calculated and experimental data, the results of a careful comparison were not shown, though. However, this model does not take into account the influence on the process of thermal expansion, fracturing and mechanical properties of rock.

Denisov A.V. (one of the authors of this work) previously, together with Dubrovskiy V. B. developed and tested a model for the analytical determination of radiation changes in the volume (deformation) of concrete rocks aggregates after irradiation by neutrons of nuclear reactors. This model described in works [23–26] takes into account not only the expansion and content of various minerals in rocks but also a feature of the rock structure such as grain fineness of minerals and also the elasticity modulus of rocks and minerals. Moreover, work [23] has demonstrated the analogies between the mechanisms of radiation and thermal damage of rock – aggregates of concretes at the level of interaction between crystals. The thermal expansion of rock of the work [2] was used in work [23] for preliminary verification of the proposed model. This verification has showed the principal possibility of using the developed model for the analytical determination of thermal changes in the volume of rock. However, the detailed verification of this model for heating process has not been done due to the lack of all necessary data.

The development results of such models have not been found in foreign sources.

The purpose of this work is to select and approbate the model and the model-based method for the analytical determination of thermal expansion and rock fracturing (decompression) according to the data on thermal deformations of minerals on the basis of information on their mineral composition, structure and mechanical properties.

The main objectives of the work were the following:

1. to choose a model or models for the analytical description of the process of thermal expansion and rock fracturing due to the thermal expansion of minerals;

2. to select experimental data available in scientific publications with a full set of information necessary for approbation of selected models;

3. to test scientific publications data on selected models and determine the necessity for additional experimental research;

4. to fulfill additional experimental research and approbate selected models for this data if required.

The article provides substantiation of the use of the evaluated model as the basis for the method of analytical determination of thermal expansion and rock fracturing (decompression) and concrete mineral aggregates for data on thermal deformations of minerals on the basis of information on the mineral composition, structure and mechanical properties of rock.

2. Methods

Both above mentioned models previously proposed for the analytical description of thermal expansion and rock fracturing were accepted for the research in this work.

In the model of Balashov and Zaraiskiy given in works [21, 22] thermal expansion of rock is considered as the sum of the average weighted relative thermal expansion of the minerals (crystal matrix) composing the rock and excessive relative rock expansion due to the formation of micro cavities (micro cracks) between the grains because of anisotropic and thermal expansion in the crystals composed in minerals; thermal expansion can be different in volume as well. In this case the volume of the excessive thermal expansion of rock is taken equal to the average value of all possible absolute values of deformation differences for three principal axes of the adjoining crystals of minerals with their random distribution and orientation. The contribution of each possible difference to their averaged value is taken proportionally to the volume content of minerals, the contiguity; the interaction between them was also being considered.

Thus, the relative linear thermal expansion of rock given in the model of works [21, 22] is determined by the formula:

$$\Delta\ell/\ell = (\Delta\ell/\ell)_{MIN} + (\Delta\ell/\ell)_{EKC} \quad (1)$$

where $\Delta\ell/\ell$ – relative linear thermal change of the rock size (linear thermal expansion of rock);

$(\Delta\ell/\ell)_{MIN}$ – average weighted relative thermal change in size of mineral composition of rock;

$(\Delta\ell/\ell)_{EKC}$ – excessive relative thermal change of rock size due to the formation of micro cavities (micro cracks) between the grains.

Value $(\Delta\ell/\ell)_{MIN}$ is determined by the formula:

$$(\Delta\ell/\ell)_{MIN} = \frac{1}{3}\sum_{k=1}^{n}\left[W_k(\Delta V/V)_k\right] \quad (2)$$

where W_k – the volume ratio of *k* mineral contained in rock with its total number n of unit fraction;

$(\Delta V/V)_k$ – relative thermal change of volume of *k* mineral contained in rocks, %;

3 – a coefficient connecting the change in volume with the change in the material sizes in case of isotropic deformation.

Value $(\Delta\ell/\ell)_{EKC}$ is determined by the formula:

$$(\Delta\ell/\ell)_{EKC} = \frac{1}{9}\sum_{k_1,k_2} W_{k_1}W_{k_2}\sum_{j_1,j_2}^{3}\left|(\Delta\ell/\ell)_{k_1}^{J_1} - (\Delta\ell/\ell)_{k_2}^{J_2}\right| \quad (3)$$

where k_1 = 1,……n and k_2 = 1,……n – numbers of minerals contained in rock with their total number n, the thermal changes in sizes are considered as a pair difference of thermal deformations. In this case $k_1 = k_2$ when considering the pair difference of deformations between changes in sizes along different axes for crystals of the same mineral;

f_1= 1, 2, 3 and f_2 = 1, 2, 3 – conditional counting numbers of the principal axes of the crystals; thermal change of sizes of the axes is considered in the pair difference;

$(\Delta\ell/\ell)_{k_1}^{J_1}$ and $(\Delta\ell/\ell)_{k_2}^{J_2}$ – relative thermal changes of sizes of crystals of k_1 mineral along f_1 axis and k_2 crystals of mineral along f_2 axis;

W_{k_1} and W_{k_2} – volume ratio of k_1 and k_2 minerals, the pair difference of deformations of which is considered;

$\left|(\Delta\ell/\ell)_{k_1}^{J_1} - (\Delta\ell/\ell)_{k_2}^{J_2}\right|$ – absolute value of the pair difference of the thermal deformations of k_1 and k_2 minerals by the conditional numbers of the main f_1 and f_2 axes.

$W_{k_1}W_{k_2}/9$ – contribution of each difference of deformations in the excessive thermal expansion of rock.

The thermal expansion in the form of a size change are increased threefold (coefficient of 3 is introduced) to determine the thermal expansion in the form of a volume change (volume thermal expansion).

The advantage of the model in works [21, 22] is its simplicity. However, the approach adopted in this model implies the assumption that the differences in the thermal deformations of crystals of minerals and the related microstructural intensions in this model are fully realized by void with complete relaxation of these intensions, regardless of their values and the strength of rock. The validity of this assumption in describing the process of thermal expansion requires careful verification.

More detailed approach was used when considering the interaction between crystals of minerals in the model of Denisov and Dubrovskiy described in works [23–26]. It was developed for the analytical determination of the radiation expansion of rock aggregates of concretes. This model was obtained on the basis of the following assumptions [23–26]:

1. It was taken into account that the radiation (or thermal) relative increase in the volume of rock aggregate of concretes as polycrystalline polymineral materials mainly consists of the values of the radiation (or thermal) relative change in the volume of crystal of mineral constituents of material and the value of volume change due to the formation of cracks.

2. It was assumed that the crystals composed in the material, which are the most expending during irradiation, are the main source of its radiation (or thermal) expansion and give the main contribution to the magnitude of the microstructural intentions (compression of the most expanding crystals and stretching of the rest ones) aroused in it. These stresses limit the development of radiation (or thermal) deformations of the most expanding crystals, but also cause fracturing of the material and therefore are relaxing. In this case the magnitude of the radiation change in the volume of the material can be determined by the magnitude of the change in the size of the crystals having the greatest free radiation (or thermal) deformations at least along one of the axes reduced to the value of their deformations under the action of the compressive microstructural stresses left after relaxation.

3. We considered crystals with the greatest radiation deformations at least along one of the axes as isotropically expanding, and their stress condition as volume compression. The difference of the considered stress condition and the real condition was taken into account by using their reduced content.

4. It was taken into consideration that the magnitude of microstructural intensions σ_{com} that compress the crystals of the most expanding minerals is related to the magnitude of the microstructural tensile stresses σ_{ctr}. In this case it was taken into account that the actual value σ_{ctr} in the material in the area between the cracks cannot exceed the tensile strength of the material in this area as because of cracking the stresses are relaxing until they reach this value. It was also assumed that while fracturing, when the distance between the cracks decreases to the grain size, the strength of the material in the area between the cracks in accordance with Weibull Strength theory increases until it reaches the tensile strength $R_{ctr.cr}$ of the individual crystals. In this case beginning with some deformation the microstructural intensions cease to grow and are maintained at a constant level determined by the condition $\sigma_{str} = R_{ctr.cr}$.

5. It was believed that the value $R_{ctr.cr}$ is determined by the Griffiths strength theory and the proportionality between the length of the critical crack and the grain size as well as between the surface energy and the elasticity modulus of crystals takes place.

6. The change in the mechanical properties of the crystals composed in minerals was neglected as they are much less than changes in rock.

Based on the realization of the initial assumptions for the analytical determination of the relative radiation (or thermal) change in the volume $\frac{\Delta V}{V}$ of aggregates (rock and ceramics) the expression [23–26] has been obtained:

$$\frac{\Delta V}{V} = \left(\frac{\Delta V}{V}\right)_1 = 3\left(\frac{\Delta \ell}{\ell}\right)_{M.M} - a_M \frac{E_0}{E_{M.M}\sqrt{d_{GR}}} * \frac{1 - V_{M.RED}}{V_{M.RED}} \text{ – at } \left(\frac{\Delta V}{V}\right)_1 \geq \left(\frac{\Delta V}{V}\right)_2 \qquad (4,a)$$

$$\frac{\Delta V}{V} = \left(\frac{\Delta V}{V}\right)_2 = \left(\frac{\Delta V}{V}\right)_{AD.M} + \frac{3\Delta\varepsilon_{AVE}}{1 + 2.2 a_M / (3\varepsilon_{AVE}\sqrt{d_{GR}})} \text{ - at } \left(\frac{\Delta V}{V}\right)_1 < \left(\frac{\Delta V}{V}\right)_2 \qquad (4,b)$$

where $\left(\frac{\Delta \ell}{\ell}\right)_{M.M}$ – maximum of the values of radiation (or thermal) relative changes in size in the most expanding direction of the crystals composed in minerals;

a_M = 3.4 10^{-2} % $cm^{0.5}$ – complex characteristic of the model;

E_0 – elasticity modulus of the material at zero porosity;

d_{GR} – the average size of the crystals composed in the minerals;

$E_{M.M}$ – elasticity modulus of crystals which have an extension $\left(\frac{\Delta \ell}{\ell}\right)_{M.M}$ along the axis where there extension exists $\left(\frac{\Delta \ell}{\ell}\right)_{M.M}$;

$\Delta\varepsilon_{AVE}$ – the average difference of the radiation (or thermal) changes in the crystal size along the various axes composing the material of the minerals;

$V_{M.RED}$ – the introduced relative volume content of crystals of minerals with a change in their sizes $\left(\frac{\Delta \ell}{\ell}\right)_{M.M}$, which takes into account the anisotropy of the radiation (or thermal) deformations and the presence of crystals which have size change $\left(\frac{\Delta \ell}{\ell}\right)_{M.i}$, (different from $\left(\frac{\Delta \ell}{\ell}\right)_{M.M}$ by no more than $a_M / \sqrt{d_{GR}}$);

$\left(\frac{\Delta V}{V}\right)_{AD.M}$ – an increase in the volume of material associated with a free radiation (or thermal) change in the volume of the crystals composed in minerals, and determined by the formula:

$$\left(\frac{\Delta V}{V}\right)_{AD.M} = \sum_{i=1}^{n}\left[\left(\frac{\Delta V}{V}\right)_i V_i\right] \qquad (5)$$

where $\left(\frac{\Delta V}{V}\right)_i$ and V_i – radiation (or thermal) change in the volume of expansion and volume content of the crystals composed in minerals.

Values $\Delta\varepsilon_{AVE}$ are determined by the formula:

$$\Delta\varepsilon_{AVE} = \sum_{i-1}\sum_{j=1}\left[\left|\left(\frac{\Delta\ell}{\ell}\right)_{ij} - \frac{1}{3}\left(\frac{\Delta V}{V}\right)_{AD.M}\right|\frac{V_i}{3}\right] \quad (6)$$

$$V_{M.RED}\ \frac{n_{m.m}V_{M.M}}{3} + \sum_{i=1}^{n}\left[\frac{n_{m.i}V_{M.i}}{3}\,\frac{\left(\frac{\Delta\ell}{\ell}\right)_{M.i}E_{M.i}}{\left(\frac{\Delta\ell}{\ell}\right)_{M.M}V_{M.M}}\right] \quad (7)$$

where $\left(\frac{\Delta\ell}{\ell}\right)_{ij}$ – an increase in the sizes of the crystals of the i-th mineral along the j-th axis (j = 1 ... 3 along the axes a, b and c) of the crystal;

$n_{m.m}$ and $n_{m.i}$ – number of axes in crystals (1, 2 and 3), along which the extension takes place $\left(\frac{\Delta\ell}{\ell}\right)_{M.M}$ and $\left(\frac{\Delta\ell}{\ell}\right)_{M.i}$ respectively;

$V_{M.M}$, $V_{M.i}$, $E_{M.M}$, $E_{M.i}$ – relative volume content and modulus of normal elasticity of the crystals of minerals with extension $\left(\frac{\Delta\ell}{\ell}\right)_{M.M}$ and $\left(\frac{\Delta\ell}{\ell}\right)_{M.i}$.

Radiation and thermal increase in volume of rock due to crack formation $\left(\frac{\Delta V}{V}\right)_{CR}$ is determined by the formula:

$$\left(\frac{\Delta V}{V}\right)_{CR.} = \frac{\Delta V}{V} - \left(\frac{\Delta V}{V}\right)_{AD.M} \quad (8)$$

Volume changes are increased threefold (a coefficient of 1/3 is introduced) to determine the radiation and thermal expansion in the form of a change in volume.

The model of Denisov and Dubrovskiy is stricter as it takes into account the influence of the grain size of minerals on the process of radiation and thermal expansion as one of the properties of the structure, as well as the elasticity modulus of rock and composing minerals, as properties characterizing the stiffness and correlating with durability. At the same time under the influence of heating the development of plastic deformations is much more likely than under exposure to radiation as the fragility of materials decreases with heating and increases with irradiation. In this regard the model based on the current research work approved for radiation expansion may require corrections for thermal expansion.

To test the possibility of using the models to describe the thermal expansion of rock, experimental data of works [21, 22] was used as test result of thermal expansion of 11 varieties of magmatic and sedimentary rocks. This data is the most complete information necessary for computational verification. The data on names, mineral composition, average size of mineral grains, the elasticity modulus, density and porosity and rock studied in works [21, 22] accepted in the calculations are given in Table 1. The samples in the form of discs with a diameter of 28 mm and a thickness of 5 mm were mainly used.

Table 1. Name, mineral composition, structure and properties of rock studied in works [21, 22]

No i/o	Rock	Minerals in rock composition and their content by volume	Average size of grains, mm	Elasticity modulus*, 10^4 MPa	Density, kg/m^3	Porosity, %
1	Biotitic granite	Quartz – 31%; Plagioclase No. 26 – 36%; Potassic feldspar – 26%, Biotite – 7%.	0.23	7.4	2650	0.33
2	Granite- aplite	Quartz – 26%; Plagioclase No. 7 – 47%; Potassic feldspar – 25%, Biotite – 2%.	0.27	3.3	2570	1.09
3	Granodiorite	Quartz – 24%; Plagioclase No. 25 – 46%; Potassic feldspar – 15%, Biotite – 10%, Hornblende – 5%.	0.80	3.5	2680	0.74
4	Diorite	Plagioclase No. 12 – 65%; Amphibole – 30%; Magnetite – 5%.	0.1	8.5	2810	2.21
5	Gabbro-dolerite	Plagioclase No. 23 – 55%; Pyroxene – 36%; Amphibole – 6%; Magnetite – 3%.	0.24	12.2	2990	0.86
6	Hornblendite	Amphibole – 77%; Biotite – 23%.	0.1	(10)**	3000	-
7	Andesit-dacitic porphyrite	Quartz – 20%; Plagioclase No. 12 – 30%; Potassic feldspar – 20%, Calcite – 15%, Hematite – 10%, Biotite – 7%.	0.04	5.8	2510	6.7
8	Diabase	Plagioclase №65 – 37%; Pyroxene – 32%; Magnetite – 12%; Glass – 15%.	0.04	(8)**	2870	-
9	Olivinic basalt	Plagioclase №60 – 40%; Pyroxene – 30%; Olivine – 10%; Magnetite – 5%.Glass – 15%.	0.08	2.4	2710	4.5
10	White marble	Calcite – 100%.	0.65	7.0	2700	0.42
11	Dark gray marble	Calcite – 95%; Carbon black – 5%.	0.05	5.5	2730	0.22
12	Magnetite ore	Magnetite – 80%; Chlorite – 20%	0.02	(27)**	4950	-

**Remarks:*

1. All values except elasticity modulus are taken from the data presented in the works [21, 22].

*2. The values of elasticity modulus marked with * were calculated according to the propagation velocities of ultrasound and density given in works [21, 22]. Approximate values accepted in the calculations are given in parentheses and marked ** as there is no data on the speed of propagation of ultrasound.*

The experimental data used to verify the selected models of the works [21, 22] on linear thermal expansion of the rock of Table 1 at different temperatures are shown in Figure 1. Figure 2 shows the relationship between the calculated average weighted thermal changes in the volume of minerals composed in rocks and the calculated thermal changes in the volume of rock according to the experimental data of the works [21, 22]. The difference between the second and the first values characterizes the excess thermal increase in rock volume due to the formation of micro cavities (micro cracks).

Due to the fact that the thermal expansion of basalt (No. 9) is substantially lower than the values of average expansion of the mineral constituents, the data on the thermal expansion of basalt for model verification have not been used. Thermal expansion of basalt as well as of other rock will be either approximately equal (within the error limits) or more (with significant micro cracking) of the average thermal expansion of minerals. And as this is not observed, it is possible that the mineral composition of the studied specific samples of basalt was significantly different from the average mineral rock composition.

In addition, control experimental measurements of thermal deformations of 11 varieties of rock were carried out in this work. At the same time, samples prepared for each rock from a single large monolith were used to exclude the influence of variations of the rock mineral composition during preparation and examination of specimens from various samples for measuring thermal deformations and petrographic studies. Samples in the form of cylinders in diameter 30 mm with a height of 50 to 70 mm were made by the diamond drilling method in the 1980s when performing studies of the radiation changes in rock presented in works [23–26] and stored up to fulfillment of studies in normal conditions. At the same time studies of the mineral composition, structure, and properties of these rocks were carried out and presented in works [23, 26].

The selection of data about the name, mineral composition, structure and properties of rock the thermal expansion of which was investigated is given in Table 2.

The thermal expansion of the samples (2–3 samples of each rock) was investigated in a quartz dilatometer at a heating velocity of 2 °C/min. The deformations were measured with an accuracy of 0.001 mm. The deviations of the values of the relative changes in the sizes of different specimens did not exceed the average values of each rock:

$$\Delta\left(\frac{\Delta\ell}{\ell}\right) = 0.01\% + 0.083\frac{\Delta\ell}{\ell} \tag{9}$$

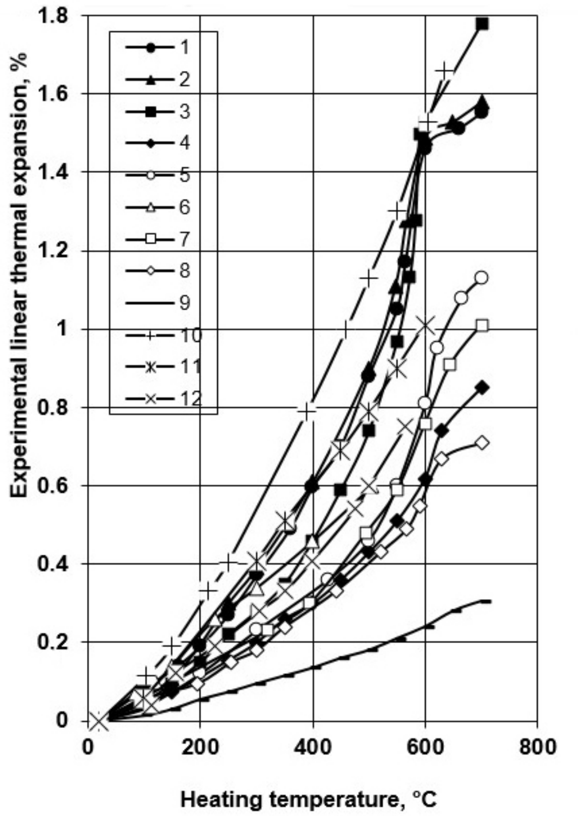

Figure 1. Experimental values of linear thermal expansion of different rocks from Table 1 depending on the heating temperature according to the works [21, 22]

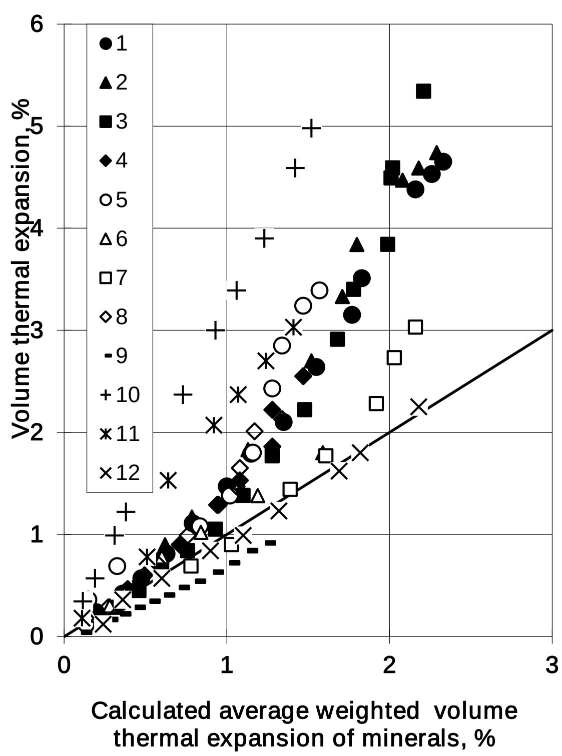

Figure 2. Relation between the calculated averages weighted volume thermal expansion of minerals composed in rock and the thermal volume thermal expansion of rocks from Table 1 calculated from the experimental data of the works [21, 22]

An inclined continuous straight line corresponds to the equality between them.

Table 2. Name, mineral composition, average size of grains and properties of rocks, thermal expansion of which was carried out in the present article based on the works [23, 26]

No. based on [23, 26]	Rock	Minerals in the rock composition and their content by volume	Average size of grains, cm	Elasticity modulus*, 10^4 MPa	Density, kg/m^3	Porosity, %
1	Granite coarse-grained	Quartz – 25%; Microcline – 50%; Oligoclase – 24%, Biotite – 1%.	0.5	1.9	2590	-
3	Granite medium-grained	Quartz – 30%; Microcline – 40%; Oligoclase – 25%, mining - 5%.	0.2	5.89	2620	-
4	Granite-porphyry fine-grained	Quartz – 40%; Microcline – 30%; Oligoclase – 15%, Muscovite -15%.	0.05	3.15	2570	-
5	Granodiorite medium-grained	Quartz – 20%; Microcline – 10%; Oligoclase – 40%, Hornblende - 15%; Biotite - 15%.	0.2	3.4	2680	-
7	Liparite aphanitic	Quartz – 35%; Microcline – 33%; Oligoclase – 32%	0.005	5.77	2640	-
14	Gabbro medium-grained	Labrador - 60%; Diopside – 40%.	0.2	10.7	2970	-
17	Diabase close-grained vesicular	Labrador - 60%; Diopside – 39%, Ore minerals -1%	0.03	3.22	2540	15
19	Diabase close-grained poikilitic	Labrador - 45%; Olivine - 30%; Homblende - 20%; Magnetite – 5%.	0.02	5.89	2760	-
20	Basalt close-grained	Labrador- 50%; Olivine - 30%; mining -10%, glass -10%.	0.01	5.94	2760	-
22	Peridotite medium-grained	Diopside - 15%; Olivine – 80, Ore minerals - 5%.	0.2	15.5	3300	-
29	Sandstone fine-grained	Quartz - 45%, fieldspar –45%, Ore minerals -10%.	0.03	1.98	2540	-

The experimental data used to verify the selected models of the works on the linear thermal expansion of the rock samples from Table 2 at different temperatures are shown in Figure 3. Figure 4 shows the relationship between the calculated average weighted thermal changes in the volume of minerals composed in rocks and the calculated thermal changes in the volume of rock according to the experimental data of the present work. The difference between the second and the first values characterizes the excess thermal increase in rock volume due to the formation of micro cavities (micro cracks).

Verification of the possibility to use the models for the analytical determination of the thermal expansion of rock was carried out by comparing the values calculated for these models and the experimental values of the thermal expansion of rock investigated in works [21, 22] and in this article. For clarity and compactness of such a comparison, the graphs of the relation between the calculated and experimental values of the thermal expansion of rock were constructed in the coordinates: calculated values of the linear thermal expansion $(\Delta\ell/\ell)_{CAL}$ along the horizontal axis X and experimental values of the linear thermal expansion $(\Delta\ell/\ell)_{EXP}$ along the vertical axis Y. Degree of deviation of values from a straight inclined line $(\Delta\ell/\ell)_{EXP} = (\Delta\ell/\ell)_{CAL}$ (match lines) clearly demonstrates the degree of coincidence of calculated and experimental data and makes it possible to easily calculate the necessary statistical characteristics. Data on the thermal deformation of minerals were taken by [1].

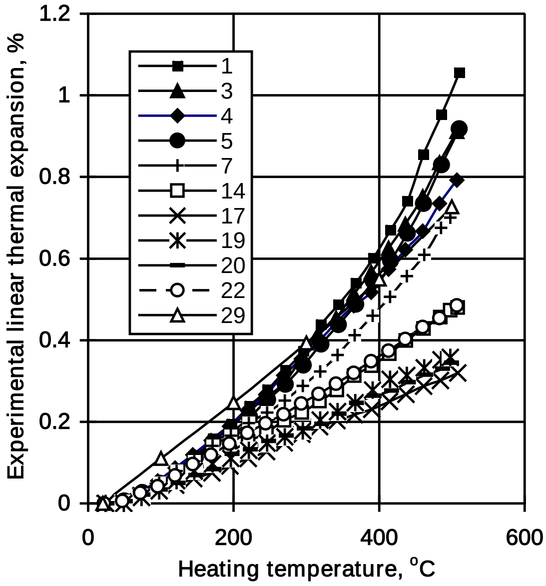

Figure 3. Experimental values of linear thermal expansion of different rocks from Table 2 depending on the heating temperature according to the present work

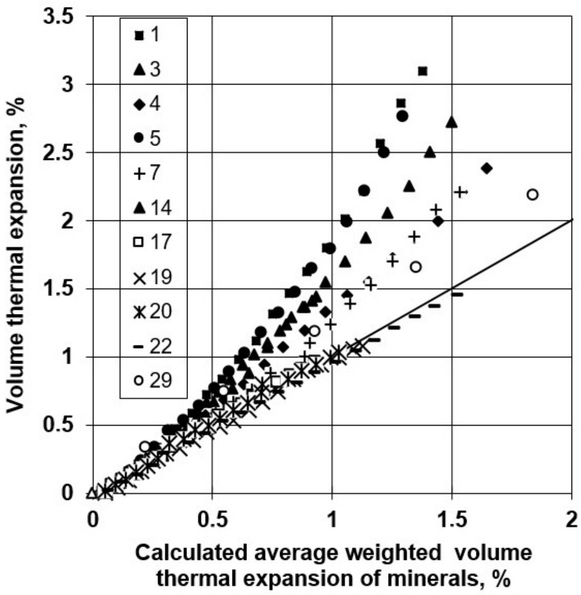

Figure 4. Relation between the calculated averages weighted volume thermal expansion of minerals composed in rock and the thermal volume thermal expansion of rocks from Table 2 calculated from the experimental data of the present work

3. Results and Discussion

The results of verification of the selected models based on the experimental data of works [21, 22] are shown in Figures 5 and 6 in the form of a relation between the values calculated for these models and the experimental data of the thermal change in rock size (linear thermal expansion).

Verifying the model of Balashov and Zaraiskiy [21, 22] we can seen (Figure 5) that the averaged line between the calculated and experimental values (regression line) of the thermal expansion of rock formations is diverted from the line $(\Delta\ell/\ell)_{EXP} = (\Delta\ell/\ell)_{CAL}$ up to 0.1 % and approximated by the expression:

$$(\Delta\ell/\ell)_{EXP} = (\Delta\ell/\ell)_{CAL}^{REF} = 0.9055(\Delta\ell/\ell)_{CAL}^{1.1659} \tag{10}$$

where $(\Delta\ell/\ell)_{CAL}^{REF}$ - revised estimated change of sizes, %.

In addition, there are quite large deviations in the values of the experimental data from the calculated values of the thermal expansion of rocks. These deviations are up to $\Delta = \pm 0.6$ % from the match line and up to $\Delta = \pm 0.5$ % from the regression line. The reliability magnitude of the approximation is R^2 = 0.9324. The average square deviation of the experimental values from the regression line described by expression (10) and the variance estimate are S_{res} = ±0.19 % and S_{res}^2 = 0.036 %^{2}.

Verification the model of Denisov and Dubrovskiy has shown (Figure 6) that the regression line between the calculated and experimental values of the thermal expansion of rock deviates from the line $(\Delta\ell/\ell)_{EXP} = (\Delta\ell/\ell)_{CAL}$ up to 0.2 % and is approximated by the expression:

$$(\Delta\ell/\ell)_{EXP} = (\Delta\ell/\ell)_{CAL}^{REF} = 0.8992(\Delta\ell/\ell)_{CAL}^{1.0015} \tag{11}$$

In addition, there are quite large deviations in the values of the experimental data from the calculated values of the thermal expansion of rocks. These deviations are up to $\Delta = \pm 0.6$ % from the match line and up to Δ = ±0.5 % from the regression line. The reliability magnitude of the approximation is R^2 = 0.9341, the average square deviation of the experimental values from the regression line and the variance estimate are S_{res} = ±0.16 % and S_{res}^2 = 0.026 %^{2} respectively.

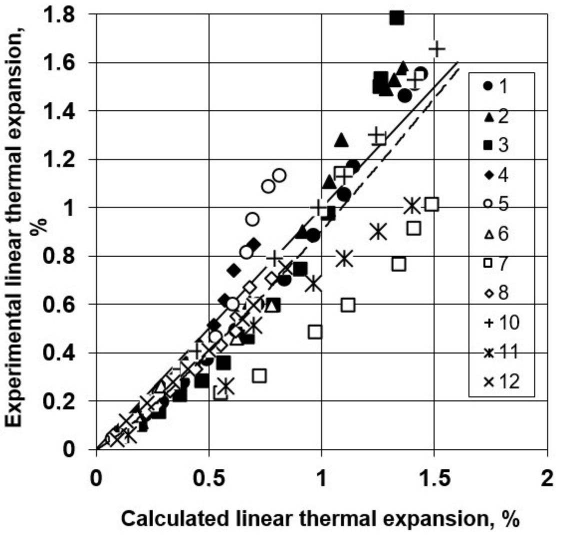

Figure 5. Relation between calculated linear thermal expansions for the model of Balashov and Zaraiskiy [21, 22] and experimental linear thermal expansion of rock dimensions from Table 1 obtained in works [21, 22]

An inclined continuous straight line corresponds to the equality between them. The dotted line shows the regression line. The equation and the value of approximation reliability of the regression line are also given.

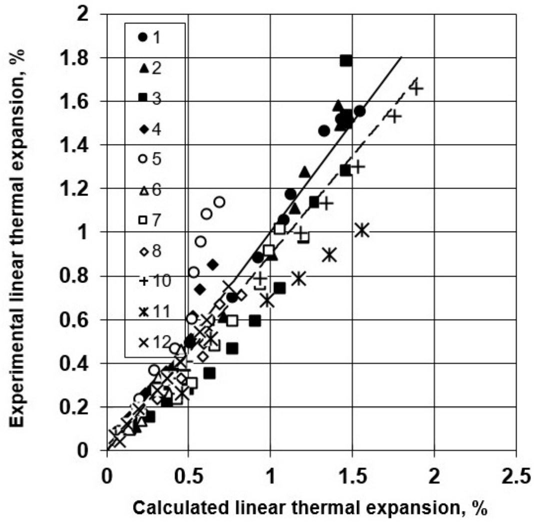

Figure 6. Relation between calculated linear thermal expansions for the model of Denisov and Dubrovskiy [23–26] and experimental linear thermal expansion of rock dimensions from Table 1 obtained in works [21, 22]

An inclined continuous straight line corresponds to the equality between them. The dotted line shows the regression line. The equation and the value of approximation reliability of the regression line are also given.

Thus, when using the experimental data of the works [21, 22] for verification of selected models there are relatively large deviations of the experimental data from the calculated values, which substantially exceed the error of 2 % indicated in these works.

In case of such deviations, it is not possible to establish the most adequate model to describe the process of thermal expansion of rock. Although using the model based on the current research work shows slightly smaller deviations in the values of experimental data from the calculated values of the thermal expansion of rock, which indicates a certain advantage of this model.

The following circumstances can be the causes of significant ranges of differences between the experimental and calculated values of thermal expansion of rocks.

1. Models do not adequately describe the process of thermal expansion.

2. There is influence of additional factors which increase the dispersion of the experimental data.

However, it is unlikely that both very different models are almost not adequate equally. It is possible that large deviations between the calculated and experimental thermal expansion values for the results of works [21, 22] are associated with some differences in the real mineral composition of the investigated rock samples from the average composition of the rock due to variations in the composition of different samples.

The verification results of the selected models based on the experimental data obtained in this article under the conditions of minimizing the possible differences in the indicated and actual characteristics of the mineral composition and the structure of the sample materials are shown in Figures 7–10. The figures show the relation between the models calculated for these models and experimental data of thermal changes in rock size data obtained in this article

During the verification of the model of Balashov and Zaraiskiy [21, 22] we can see (Figure 7) that although the regression line between the calculated and experimental values of the thermal expansion of rock deviates from the line $(\Delta\ell/\ell)_{EXP} = (\Delta\ell/\ell)_{CAL}$ up to 0.2 %, deviations of the values of the experimental data from the calculated values of the thermal expansion of rock is approximately twofold lower than when using data of the works [21, 22].

Deviations of the experimental data for the model of the works [21, 22] are up to $\Delta = \pm 0.35$ % from the match line and up to $\Delta = \pm 0.25$ % from the regression line. The average square deviation of the experimental values from the regression line and the variance estimate while using the experimental data amounts to S_{res} = ±0.088 % and S_{res}^2 = 0.0077 %². The reliability magnitude of the approximation is R^2 = 0.9217.

The regression line between the calculated and experimental values of the thermal expansion of rocks is approximated by the expression which describes the correction to be applied to the calculation results by the model as follows:

$$(\Delta\ell/\ell)_{EXP} = (\Delta\ell/\ell)_{CAL}^{REF} = 0.1964(\Delta\ell/\ell)_{CAL}^2 + 0.6802(\Delta\ell/\ell)_{CAL} \quad (12)$$

After recalculating of the calculated values of thermal expansion using formula (12), the relation between the calculated and experimental thermal deformations is shown in Figure 8 and more clearly illustrates the degree of deviation of the experimental data from the calculated ones.

Verification the model of Denisov and Dubrovskiy [23–26] on the experimental results of this work is shown in Figure 9. Figure 9 shows that although the regression line between the calculated and experimental values of the thermal expansion of rock also deviates from the line $(\Delta\ell/\ell)_{EXP} = (\Delta\ell/\ell)_{CAL}$ (in this case up to 0.16 %), the deviation of the values of the experimental data from the calculated values of the thermal expansion of rock is lower than when using data of the works [21, 22].

Moreover when using experimental data of this work to verify this model, the deviation of experimental values from the calculated values of thermal expansion of rock is less than in the model of the works [21, 22] during verification with the same data and is up to $\Delta = \pm 0.25$ % from the match line and up to $\Delta = \pm 0.15$ % from the approximation line. The average square deviation of the experimental values from the regression line using the data of this work is also less and amounts to S_{res} = ±0.033 % on S_{res}^2 = 0.0011 %². The reliability magnitude of the approximation is R^2 = 0.9786.

The regression line between the calculated and experimental values of the thermal expansion of rocks is approximated by the expression which describes the correction to be applied to the calculation results by the model as follows:

$$(\Delta\ell/\ell)_{EXP} = (\Delta\ell/\ell)_{CAL}^{REF} = 0.2036(\Delta\ell/\ell)_{CAL}^2 + 0.6331(\Delta\ell/\ell)_{CAL} \quad (13)$$

After recalculating of the calculated values of thermal expansion using formula (13), the relation between the calculated and experimental thermal deformations is shown in Figure 10 and more clearly illustrates the degree of deviation of the experimental data from the calculated ones.

At the same time, Figure 10 demonstrates some asymmetry in dispersion of the experimental data due to an abnormally high deviation of diabase No. 19 and basalt No. 20.

The research has shown that in formula (4a) only the correction factor C = 0.5% can be introduced instead of using a general correction to the calculation results of formula (13).

In this case, formula (4,a) takes the form:

$$\frac{\Delta V}{V} = \left(\frac{\Delta V}{V}\right)_1 = 3\left(\frac{\Delta\ell}{\ell}\right)_{M.M} - a_M \frac{E_0}{E_{M.M}\sqrt{d_{GR}}} * \frac{1 - V_{M.RED}}{V_{M.RED}} - C \text{ – at } \left(\frac{\Delta V}{V}\right)_1 \geq \left(\frac{\Delta V}{V}\right)_2 \quad (4,a^{I})$$

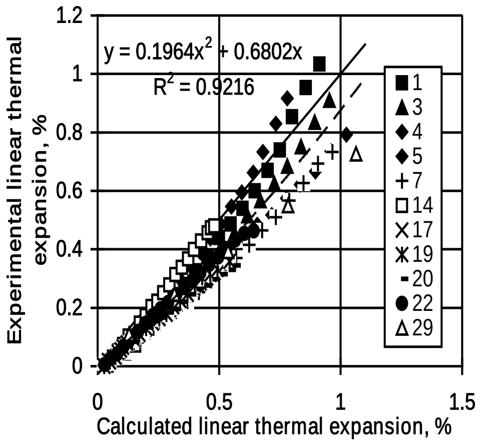

Figure 7. Relation between calculated linear thermal expansions for the model of Balashov and Zaraiskiy [21, 22] and experimental linear thermal expansion of rock dimensions from Table 2 obtained this article

See remarks to Figures 5 and 6 for explanation to the lines.

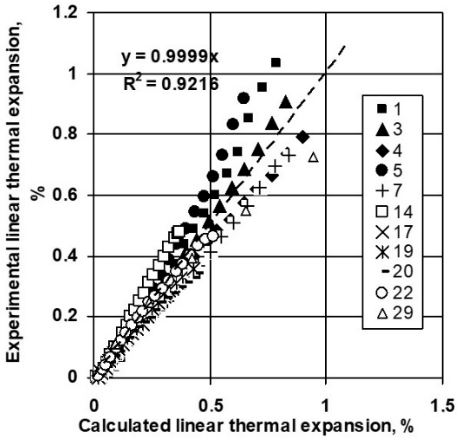

Figure 8. Relation between calculated linear thermal expansions for the model of Balashov and Zaraiskiy [21, 22] with expression correction. (12) and experimental linear thermal expansion of rock dimensions from Table 2 obtained this article

See remarks to Figures 5 and 6 for explanation to the lines.

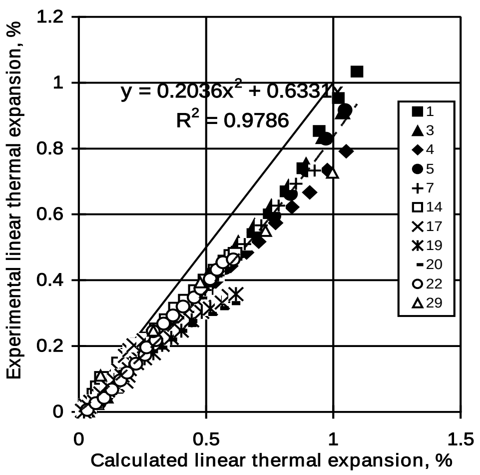

Figure 9. Relation between calculated linear thermal expansions for the model of Denisov and Dubrovskiy [23–26] and experimental linear thermal expansion of rock dimensions from Table 2 obtained in this article

See notes to Figures 5 and 6 for an explanation to the lines.

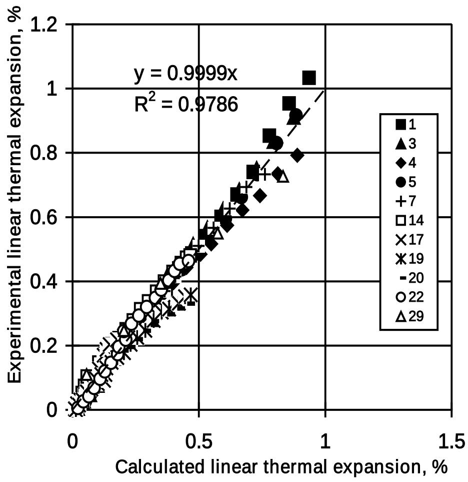

Figure 10. Relation between calculated linear thermal expansions for the model of Denisov and Dubrovskiy [23–26] with the expression correction (13) and experimental linear thermal expansion of rock dimensions from Table 2 obtained in this article

See notes to Figures 5 and 6 for an explanation to the lines.

Taking into account C = -0.5 % (Figure 11) the dispersion of the experimental data becomes more symmetrical, the abnormal deviation of diabase No. 19 and basalt No. 20 disappears, the errors do not change significantly. The maximum and standard square deviation of the experimental values from the regression line $(\Delta\ell/\ell)_{EXP} = (\Delta\ell/\ell)_{CAL}$ as well as the variance estimate are up to $\Delta = \pm 0.13$ %, S_{res} = ±0.038 % and S_{res}^2 = 0.0014 %^{2} respectively. The reliability magnitude of the approximation is R^2 = 0.9745.

Thus, while using the model of Denisov and Dubrovskiy [23–26], there are less deviations between the calculated and experimental values of the thermal expansion of rock than while using the model of Balashov and Zaraiskiy [21, 22] which is clearly shown in Table 3.

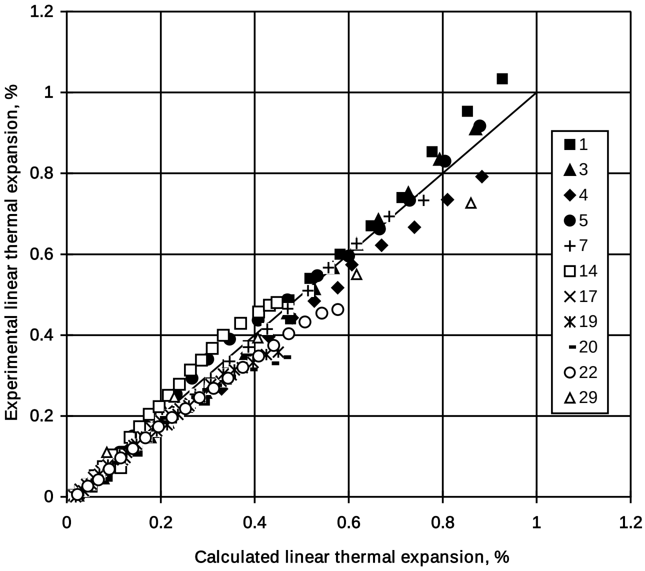

Figure 11. Relation between calculated linear thermal expansions for the model of Denisov and Dubrovskiy [23–26] at C = 0.5 % and experimental linear thermal expansion of rock dimensions from Table 2 obtained in this article.

An inclined continuous straight line corresponds to the equality between them and the regression line.

Table 3. Summarized data about verification results of studied models on the basis of various experimental data

Model	Verification based on works [21, 22]				Verification based on the current research work			
	Deviations of experimental data from regression line	R^2	S_{res}, %	S_{res}^2, %2	Deviations of experimental data from regression line	R^2	S_{res}, %	S_{res}^2, %2
Model of Balashov and Zaraiskiy [21, 22]	up to 0.5 % (Figure 5)	0.9324	0.19	0.036	up to 0.25 % (Figure 8)	0.9217	0.088	0.0077
Model of Denisov and Dubrovskiy [23–26]	up to 0.5 % (Figure 6)	0.9341	0.16	0.026	up to 0.15 % (Figure10)	0.9786	0.033	0.0011
					up to 0.13 % (Figure11)	0.9745	0.038	0.0014

The deviation of the experimental data from the calculated data based on this model is commensurate with the dispersion of the experimental data when measuring the thermal change in the sizes of individual samples of rock which indicates the adequacy of the model to the experimental data without detailed statistical analysis based on the Fisher criterion.

This allows us to recommend the model provided of Denisov and Dubrovskiy with the correction factor C=0.5% for the analytical determination of the thermal expansion of the most part of rocks and concrete mineral aggregates according to the data on thermal deformations of minerals based on information on the mineral composition, the average grain size of the minerals and the elasticity modulus of the rock. The model is applicable in case of heating up to 700 °C under normal pressure and humidity for isotropic rocks with no minerals in them that can decompose at these temperatures with water and gases emission.

The maximum deviations between the calculated and experimental thermal changes in the size based on this model with heating up to 510 ˚C with minimal dispersion of mineral composition, structure and properties amounts are:

$$\Delta\left(\frac{\Delta\ell}{\ell}\right)=\begin{cases}0.02\%+0.2\frac{\Delta\ell}{\ell}-at\ \ \frac{\Delta\ell}{\ell}\le 0.55\%\\ 0.13\%-at\ \ \frac{\Delta\ell}{\ell}\ge 0.55\%\end{cases} \quad (14)$$

In the range of 50-700 °C the maximum deviations between the calculated and experimental thermal changes in size are from 0.05 % to 0.5 % when the size is changed from 0 to 1.5–1.7 % respectively.

As this model is used for the analytical determination of the radiation expansion of rock the results of the work confirmed the analogy between the mechanisms of radiation and thermal changes in rock at the level of interaction of the crystals of minerals. However, the necessity to introduce the correction confirms some differences in the mechanisms of thermal and radiation damage of rock associated with the growth of the contribution of plastic deformations to the relaxation of microstructural intensions with increasing temperature.

The correction can be made according to the data of the works [21, 22] in case of high values of pressure and humidity of the environment (in the hydrothermal conditions of the Earth's crust, for example).

The possibility of using the model for anisotropic (stratified, for example) rock, as well as in case of presence of minerals in the rock composition which decompose when heating with water and gases emission, requires additional studies. The thermal expansion of anisotropic rock due to the distribution of minerals in space can vary in different directions. Even if the deformation of the minerals is taken into account, an increase in the expansion of rock can occur due to additional crack opening under the influence of the pressure of gases and water vapor (if water and gases are released).

The possibility of using the model at temperatures over 500 °C and especially more than 700 °C also requires additional studies. The experimental data did not allow reliable verification of the model at temperatures from 500 °C to 700 °C. Although it is possible to use the model for these temperatures taking into account that the inaccuracy can be up to 0.5 %. At the same time as the temperature rises the plasticity of the rock increases, therefore, it may be necessary to use additional corrections at temperatures over 500 °C for more reliable calculations. In addition, some minerals (carbonates, serpentines, chlorites) can partially or completely decompose with water and gases emission at these temperatures which may be the source of the additional expansion mentioned above. In the range of 700–1000 °C, according to the experimental data of the work [27] and the estimated calculations based on formulas (4) experimental thermal changes in the rock size may exceed the calculated values by up to 1 %.

The thermal change in the volume of rock due to the formation of cracks $\left(\frac{\Delta V}{V}\right)_{CR}$ is determined by formula (8) and does not require special verification. The difference in the values of the thermal expansion of different rocks is determined by differences in the degree of their cracking and by differences in the average expansion of the mineral constituents. In this regard, the shown possibility of using the model for the analytical determination of the thermal expansion of rocks shows the possibility of using this model for calculating volume changes due to the formation of cracks.

According to the data of the works [21, 22] and the present work, the residual deformations of rock are observed after heating at temperatures over 200—300 ˚C.

When the temperature is lowered, the formed cracks during heating will be closed. But due to some displacement of the crystals relative to each other only its partial closing occurs which explains the appearance of residual deformations after heating. The values of these deformations increase with increasing heating temperature, the values of thermal expansion, and hence the values of expansion due to the crack formation.

In this regard, it is interesting to consider the dependence of the values of the thermal residual deformations of rock from the values of deformations due to the crack formation. It is obvious that the thermal residual deformations of rock will depend not only on the magnitude of the volume change due to the crack formation but also due to the number of heating cycles, the environmental conditions (humidity, especially). The residual deformations will increase while the number of heating and humidity cycles increases as the degree of crystal displacement rises with the number of cycles and the wedging effect of water increases with increasing humidity. The data of the works [4, 21, 22] have confirmed this.

In this regard, the base deformations will be the thermal residual deformations of rock after the initial heating $\left(\frac{\Delta V}{V}\right)_{RES}$ The influence of the number of cycles and humidity can be estimated from the data of the works [4, 21, 22].

The graphic dependencies $\left(\frac{\Delta V}{V}\right)_{RES}$ from $\left(\frac{\Delta V}{V}\right)_{CR.}$ are shown in Figures 12 and 13 and demonstrate the presence of the dependence of residual deformations of rock after heating from the deformations of rock when heated due to the formation of cracks. As in the case of thermal expansion, fairly large dispersion is observed according to the data of the works [21, 22]. These dispersions are much lower for the data shown in the present article.

The dependencies shown in Figures 12, 13 and their approximation equations at x = $\left(\frac{\Delta V}{V}\right)_{RES}$ and y = $\left(\frac{\Delta V}{V}\right)_{CR}$ can be used for the analytical determination of residual thermal deformations of rock after the first heating and cooling in normal conditions.

Due to residual deformations during rock reheating, as shown in Figures 14 and 15, based on the results of the present work, the change in their sizes relative to the sizes before the first heating, mainly exceeds the size changes during the first heating. However, the temperature is higher so the difference is less. Therefore, at a temperature equal to the maximum temperature of the first heating, the change in size during the second heating is slightly larger than the change in sizes during the first heating. The change in size during cooling after the second heating (including residual deformations) is slightly different from the changes in sizes during the cooling after the first heating.

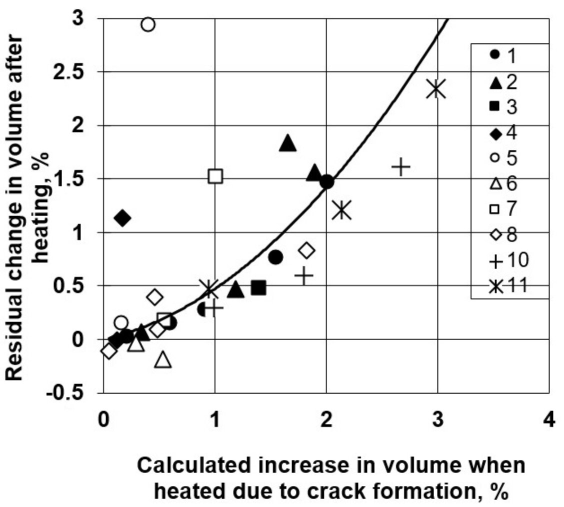

Figure 12. Relation between the calculated increase in volume due to the crack formation of rock from Table 1 when heated and the experimental residual increase in volume after heating to 300–700 °C according to the data of the works [21, 22]

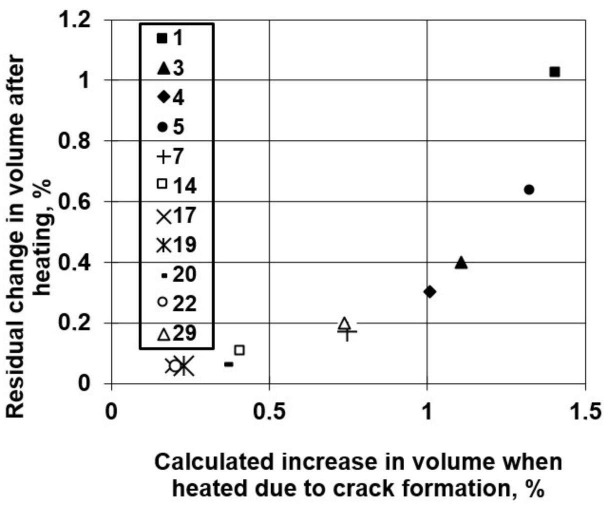

Figure 13. Relation between the calculated volume increase due to the crack formation of rock from Table 2 when heated and the experimental residual volume increase after heating to 490-510 °C according to the data of the current research work

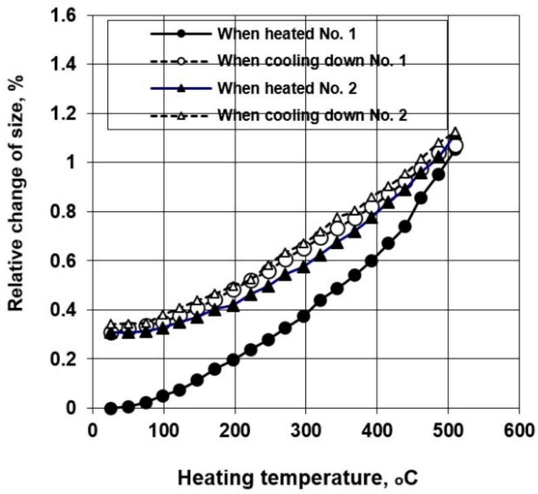

Figure 14. Experimental values of the thermal increase in the size of granite No. 1 according to the Table 2 in case of the first and second heating and cooling

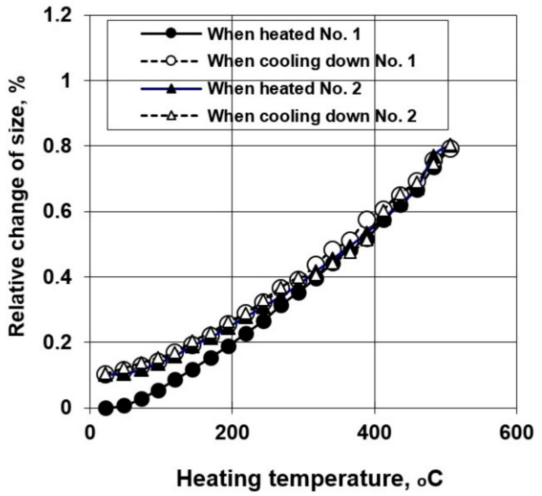

Figure 15. Experimental values of the thermal increase in the size of granite-porphyry No. 4 according to the Table 2 in case of the first and second heating and cooling

In this regard, the thermal expansion, with respect to the sizes before the first heating, is larger and, with respect to the sizes after the first heating, is less than during the first heating when rocks are reheated and can approximately be described by the following expressions:

$$\left(\frac{\Delta\ell}{\ell}\right)_{T2} = \left(\frac{\Delta\ell}{\ell}\right)_{T1} \frac{\left(\frac{\Delta\ell}{\ell}\right)_{TMAX1} - \left(\frac{\Delta\ell}{\ell}\right)_{T1RES}}{\left(\frac{\Delta\ell}{\ell}\right)_{TMAX1}} (1+k_n) + \left(\frac{\Delta\ell}{\ell}\right)_{T1RES} \quad (15)$$

$$\left(\frac{\Delta\ell}{\ell}\right)_{T2RES} = (1+k_n)\left(\frac{\Delta\ell}{\ell}\right)_{T1RES} \quad (16)$$

- in relation to the sizes before the first heating;

$$\left(\frac{\Delta\ell}{\ell}\right)_{T2} = \left(\frac{\Delta\ell}{\ell}\right)_{T1} \frac{\left(\frac{\Delta\ell}{\ell}\right)_{TMAX1} - \left(\frac{\Delta\ell}{\ell}\right)_{T1RES}}{\left(\frac{\Delta\ell}{\ell}\right)_{TMAX1}} (1+k_n) \quad (17)$$

$$\left(\frac{\Delta\ell}{\ell}\right)_{T2RES} = k_n\left(\frac{\Delta\ell}{\ell}\right)_{T1RES} \quad (18)$$

- in relation to the sizes after the first heating (before the second heating),

where $\left(\frac{\Delta\ell}{\ell}\right)_{T1}$ – the relative change in sizes upon the first heating up to temperature T;

$\left(\frac{\Delta\ell}{\ell}\right)_{T2}$ – the relative change in sizes during the second heating up to temperature T in relation to the sizes before the first heating in formula (15) and to the sizes after the first heating in formula (17);

$\left(\frac{\Delta\ell}{\ell}\right)_{TMAX1}$ and $\left(\frac{\Delta\ell}{\ell}\right)_{T1RES}$ – relative change in sizes at the maximum temperature during the first heating and the residual sizes after the first heating, respectively;

$\left(\frac{\Delta\ell}{\ell}\right)_{T2RES}$ – residual changes in sizes after the second heating with respect to the sizes before the first heating in formula (15) and the sizes after the first heating in formula (17);

k_n – coefficient equal to $k_n \approx 0.1$ for the second heating according to the data of the present research work.

In this regard, the model will overestimate thermal deformations of rocks if the rock formation was subjected to high temperature heating before calculating of the thermal expansion and this will not be taken into account by formulas (17) and (18) (if nothing is known about this, for example). Moreover, the temperature of the preceding heating can be restored by the discrepancy between the calculated and experimental thermal deformations of rocks. Prior to the calculations heating of rock and mineral aggregates of concrete in the form of natural gravel and sand must be taken into account if there were no processes of metasomatism and metamorphism after heating. The cracks formed during heating will be filled with new minerals and closed under pressure during metasomatism and metamorphism of the rock formation. The previously fulfilled heating of concrete aggregates made by crushing of rock after their manufacture must be accounted by formulas (15) and (18).

4. Conclusions

1. The article provides selection and approbation of the model and the model-based method for the analytical determination of thermal expansion and rock fracturing (decompression) and concrete mineral aggregates according to the data about thermal deformations of minerals based on information of the mineral composition, the average grain fineness of minerals and the elasticity modulus of rock.

2. To accomplish the research, the author has used two models available in scientific publications:

- Balashov and Zaraiskiy Model for calculating the thermal expansion and decompression of rock based on thermal deformations of minerals. The model does not take into account the structure and mechanical properties of rock.

- The model of Denisov (one of the authors of this work) and Dubrovskiy was developed and evaluated earlier for the analytical determination of radiation expansion and rock fracturing when neutrons are irradiated by nuclear reactors on the basis of radiation deformation of minerals. The model takes into account the grain fineness and elasticity modulus of rock. The model is accepted for research on the basis of the analogy between the processes of thermal and radiation changes of rock at the level of interaction in mineral crystals.

3. To test chosen models, experimental data was selected. It contained all the necessary information on thermal expansion of 11 varieties of magmatic and sedimentary rocks in the range 20 to 700 ˚C. In addition, experimental research of the thermal expansion of 11 varieties of magmatic and sedimentary rocks in the range from 20 to 510 ˚C was carried out to verify the models under the conditions of the minimal influence of the rock dispersion and rock composition by means of a quartz dilatometer. At the same time, there were prepared samples for each rock. Each was taken from a single large monolith to exclude the influence of variations of the rock mineral composition during preparation and examination of various samples taken for measuring thermal deformations and petrographic studies.

4. The model of Denisov and Dubrovskiy describes the process of thermal expansion and rock fracturing. It is more adequate and better than Balashov and Zaraiskiy Model especially when introducing the correction associated with an increase in plasticity of rocks when heated.

This allows us to recommend the model provided of the author of the current research work for the analytical determination of the thermal expansion of the most part of rocks and concrete mineral aggregates according to the data on thermal deformations of minerals based on information on the mineral composition, the average grain size of the minerals and the elasticity modulus of the rock. The model is applicable in case of heating up to 700 °C (is more reliable for 500 °C heating) under normal pressure and humidity for isotropic rocks with no minerals in them that can decompose at these temperatures with water and gases emission.

5. The possibility of using the model for anisotropic rock, in the presence of minerals in the rock composition which decompose when heating with water and gases emission, requires additional studies. The correction can be made according to the scientific literature data in case of high values of pressure and humidity of the environment (in the hydrothermal conditions of the Earth's crust, for ex-ample).

6. There current research established approximate dependence of the residual rock deformations after the first heating from the increase in volume when heated due to the cracks formation. The article also shows the relationship between thermal changes in rock size during the first and second heating and cooling stages.

7. Prior to the calculations heating of rock and mineral aggregates of concrete in the form of natural gravel and sand must be taken into account if there were no processes of metasomatism and metamorphism after heating. The previously fulfilled heating of concrete aggregates made by crushing of rock after their manufacture should be also taken into account.

8. The results of the work can be used to solve the problems of thermal destruction efficiency and rock drilling, rock metasomatism, possibility of using rock massifs to bury radioactive wastes, store thermal energy, predict thermal deformations and heat resistance of concretes with mineral aggregates.

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