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# Prediction of radiation changes in concrete and mortars under the influence of gamma radiation

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**Abstract.** The present research was carried out due to the insufficient study of the effect of gamma radiation on concrete and mortar. The research took into account the availability of developed and experimentally tested methods for the analytical determination of radiation, thermal, and radiation-thermal changes in concrete and its components under neutron irradiation and heating, as well as radiation changes in the aggregates and hardened cement paste (HCP) under the influence of gamma radiation. The aim of the work was to establish the possibility of using these existing analytical methods to predict radiation changes in concrete and mortar under the influence of gamma radiation. In this case, the existing experimental results of the influence of gamma irradiation on 7 different concretes and 11 cement mortars were used. The studies performed have shown the possibility of using existing analytical methods to predict radiation changes in the dimensions of concrete under the influence of gamma radiation. The results of the studies of predicting radiation changes in the strength of concrete and mortars under the action of gamma radiation showed significant differences between the calculated and experimental changes when using the existing analytical methods applied under neutron irradiation and heating without their correction. It is assumed that this is due to differences in the processes of acceleration of hydration and carbonization of HCP under the action of gamma radiation under neutron irradiation-heating and under gamma irradiation. It is proposed to take into account these differences in the values of one of the parameters of the method for analytical determination of strength changes in early age HCP and to introduce an additional correction factor that takes into account the effect of aragonite and vaterite formation during carbonization of mature HCP under the action of gamma radiation. The values of this parameter and its dependence on the change in the volume of early age HCP under the action of gamma radiation are established. The values of the additional coefficient taking into account the effect of aragonite and vaterite formation for the considered mature concretes and its dependence on the absorbed dose and the estimated amount of carbonates are determined. It is shown that by using the adjusted parameter for early age concrete and an additional coefficient for mature concrete, the existing analytical methods can be used to predict radiation-induced changes in the strength of concrete and cement mortars under the influence of gamma radiation.

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## 1. *Introduction*

Concretes, as the main materials for radiation protection of nuclear facilities, are exposed to ionizing radiation. These radiations cause changes in structure and composition, size and volume, physical properties, cracking of concrete and its components, release of water, hydrogen, and oxygen [1–15]. Radiation changes, release of water and gases can be significant, therefore excluding the possibility of using or long-term use of materials. In this regard, the issues of radiation resistance, radiation changes in concrete, and release of water and gases from them are quite important. At present, this is especially important when extending the operation of nuclear power plants and research reactors. Of greatest importance are changes in size and volume (radiation deformations), as well as physical and mechanical properties, since radiation deformations (like thermal ones) cause additional stresses in structures, and a decrease in physical and mechanical properties reduces the load-bearing capacity of structures.

The most significant radiation changes in concrete and its components occur under the influence of neutrons. In this regard, radiation changes in these materials because of neutron exposure have been studied most experimentally and theoretically. It has been established that radiation changes in concrete and its components significantly depend not only on the magnitude of radiation loads and irradiation conditions but also on the type, mineral composition of aggregates, characteristics of cement, and technological composition of concrete. Due to the impossibility of studying radiation changes in the entire variety of concrete, methods have been developed and experimentally tested for analytical determination of radiation and thermal (from accompanying heating) changes in concrete and its components, including:

1. Methods for the analytical determination of radiation changes in mineral crystals, radiation and thermal changes in hardened cement paste (HCP) based on data on radiation and thermal loads, irradiation conditions, described in the works [12, 16].
2. Methods of analytical determination of radiation and thermal changes:
   – aggregates based on data on mineral changes [12, 17];
   – cement mortars based on data on changes in fine aggregate and HCP [12, 18, 19];
   – concrete according to change data coarse aggregate and mortar [12, 18, 19].

The existing methods of analytical determination use a number of simplifications. The main simplifications are based on the fact that microstructural stresses in concretes and cement mortars at the level of interaction of aggregates and HCP completely relax due to cracking, and microstructural stresses in aggregates at the level of interaction of mineral crystals due to crack formation are reset to a value corresponding to the tensile strength of crystals. In this regard, the mathematical expressions of these methods have a fairly simple form, convenient for analysis and use. However, despite the simplifications, the possibility of practical use of these methods has been proven on experimental data.

The effects of gamma radiation on concretes, mortars, and their components have been less studied. Although the volumes of concretes from nuclear power plants and other nuclear power facilities exposed to gamma radiation are more significant than the volumes exposed to neutrons, there are only a few data on specific concretes, cement mortars, and their components [1, 2, 20–38], indicating the presence of radiation changes after exposure to gamma radiation.

The application of methods of group 2, developed for the analytical determination (prediction) of radiation changes in concrete and cement mortars under neutron irradiation and heating, under the influence of gamma radiation was considered in the works [21, 22] but was not tested on experimental data. It is noted that radiation changes in concrete and cement mortars under the influence of gamma radiation can be determined using the above methods, since the cause of the changes is not important, since the method has been tested both under the influence of neutrons and under the influence of heating. However, this requires data on radiation changes in aggregates and HCP, obtained experimentally or based on a forecast using analytical or empirical methods similar to the methods of group 1.

The assessment and justification of the prediction of radiation changes in aggregates and HCP under the influence of gamma radiation at different absorbed doses and irradiation temperatures are carried out in the works [39, 40]. Expressions for the analytical determination of radiation changes in minerals, aggregates, and HCP based on data on radiation and thermal loads, irradiation conditions (Methods of group 1 but applicable to gamma radiation) are obtained.

Based on these results, it is theoretically possible to predict radiation changes in concrete under the influence of gamma radiation using existing analytical methods. However, to justify the sufficient reliability of such a prediction, a test based on experimental data is necessary, which has not been carried out.

The aim of this work is to establish the possibility of using existing methods of analytical determination of radiation and thermal changes in concrete and mortars to predict radiation changes in concrete and mortars under the influence of gamma radiation.

To achieve this goal, it was necessary to solve the following main tasks:

1. Conduct a search for existing literature data on radiation changes in concrete, cement mortars, and their components under the influence of gamma radiation. Select from these data the results that will allow testing the possibility of using existing methods of analytical determination of radiation

changes in concrete to predict radiation changes in concrete under the influence of gamma radiation.

2. Using the methods listed above, perform calculations of radiation changes under the influence of gamma radiation for concretes and cement mortars, the experimental data, which were selected for research.
3. Based on a comparison of calculated and existing experimental data in the literature, establish the possibility and conditions for using existing methods of analytical determination of radiation and thermal changes in concrete and mortars to predict radiation changes in concrete and mortars under the influence of gamma radiation. They should also be adjusted if necessary.

## *2. Methods*

The search for existing experimental data on radiation changes in concrete and its components under the influence of gamma radiation was carried out using various databases and lists of literary sources in the articles found. The selection from these data of research results that will allow testing the possibility of using existing methods for analytical determination of radiation and thermal changes in concrete under the influence of neutrons and heating to predict radiation changes in concrete under the influence of gamma radiation was carried out based on the following conditions:

- the works present the results of a study of radiation deformations (changes in size or volume) and/or radiation changes in the mechanical properties of concrete and mortars;
- there is information on the technological composition, characteristics of the components, curing conditions, and age of the materials before the research, which allows us to determine the necessary parameters of the methods being studied.

It would be most simple to investigate the possibility of using existing methods of analytical determination of radiation and thermal changes in concrete and mortars under the influence of gamma radiation based on experimental data on radiation changes in aggregates and HCP obtained under the same conditions. However, such reliable data on aggregates and HCP are absent. In this regard, radiation changes in aggregates and HCP were determined using the methods described in [39, 40].

After that, using the existing methods of analytical determination of radiation changes in concrete and its components, developed under the influence of neutron radiation and heating, the radiation changes in concrete and mortars, which were studied experimentally under the influence of gamma radiation, were calculated. Then, based on the comparison of the calculated and experimental values of radiation changes, a conclusion was made on the possibility of using analytical methods developed under the influence of neutron radiation and heating, under the influence of gamma radiation. The need to adjust the existing analytical methods under the influence of gamma radiation was established.

The possibility of analytical relative changes in linear dimensions was considered $\frac{\Delta\ell}{\ell}$ (in %), volume $\frac{\Delta V}{V}$ (in %) and the change in strength in the form of relative residual strength $\frac{R}{R_0}$ (fractions of a unit), as changes in size, volume and strength value relative to size, volume and strength without irradiation or without heating. Existing analytical expressions led to a more convenient form.

When conducting the calculation studies, it was taken into account that in the works used in checking the possibility of the considered analytical methods for predicting radiation changes in concrete and mortars under the influence of gamma radiation, changes in linear dimensions were investigated and presented. In this regard, based on the calculated changes in volume, calculated changes in dimensions were calculated, which were compared with the values of the change in dimensions obtained experimentally. In this case, changes in the dimensions of concrete and mortars were determined from the calculated changes in volume using the formula:

$$\frac{\Delta\ell}{\ell} = \frac{1}{3}\frac{\Delta V}{V}. \tag{1}$$

Changes in the sizes and volumes of HCP, concretes and mortars have negative values. However, for the convenience of presentation and processing of the observed dependencies on the graphs of the figures, they are presented as positive values of the decrease in sizes and volumes (the minus sign is taken into account by the word *decrease*).

In the case of irradiation at elevated temperatures, it was taken into account that thermal changes occur mainly in the initial period of irradiation, and radiation changes accumulate mainly in the final period of irradiation. In this regard, when analyzing the results and conducting research, it was considered that the total changes in the volume and strength of materials are summed up in accordance with the following expressions:

$$\left(\frac{\Delta V}{V}\right)_{GT}=\left(\frac{\Delta V}{V}\right)_{G}+\left(\frac{\Delta V}{V}\right)_{T}; \tag{2}$$

$$\left(\frac{R}{R_0}\right)_{GT}=\left(\frac{R}{R_0}\right)_{G}\cdot\left(\frac{R}{R_0}\right)_{T}, \tag{3}$$

where $G$, $T$, and $GT$ are indices denoting radiation, thermal, and radiation-thermal changes in the volume and strength of materials, respectively.

Calculations of radiation (under the influence of gamma radiation) and thermal changes of the cement mortar were carried out according to data on radiation and thermal changes of fine aggregate and HCP based on the methods described in the works [12, 17–19]. In this case, the analytical expressions were reduced to a more convenient form with a slight error.

According to existing analytical methods, when exposed to neutrons and heating, radiation (under the influence of gamma radiation) and thermal changes in volume $\frac{\Delta V_{CM}}{V_{CM}}$ the cement mortar as a separate material or as part of concrete was calculated using the formula:

$$\frac{\Delta V_{CM}}{V_{CM}}=\frac{\Delta V_{FA}}{V_{FA}}\left(C_{com}^{FA}\right)^{\frac{1}{3}}+\left[1-\left(C_{com}^{FA}\right)^{\frac{1}{3}}\right]\frac{\Delta V_{HCP}}{V_{HCP}}, \tag{4}$$

where $\frac{\Delta V_{CM}}{V_{CM}}$, $\frac{\Delta V_{FA}}{V_{FA}}$ and $\frac{\Delta V_{HCP}}{V_{HCP}}$ are radiation or thermal changes in the volume of cement mortar, fine aggregate and HCP, respectively, %; $C_{com}^{FA}$ is the degree of compaction of fine aggregate in a mortar, as a separate material or in a mortar as part of concrete, determined by the formulas:

$$C_{com}^{FA}=\frac{V_{FA}}{V_{FA}^{com}} \text{ – in mortar, as in a separate material;} \tag{5}$$

$$C_{com}^{FA}=\frac{V_{FA}}{V_{CA+FA}^{com}-V_{CA}} \text{ – in mortar in concrete,} \tag{6}$$

where $V_{FA}$ is relative volume content of fine aggregate in the cement mortar as a separate material or in concrete, fractions of a unit; $V_{CA}$ is relative volume content of coarse aggregate in concrete, fractions of a unit; $V_{FA}^{com}$ is the maximum relative volume content of fine aggregate in the case of its maximally compacted state (without layers of HCP between the particles) (in fractions of a unit), amounting to 0.52–0.74. According to [12], it can be taken $V_{FA}^{com}$ = 0.63; $V_{CA+FA}^{com}$ is the maximum relative volume content of a mixture of fine aggregate and coarse aggregate in the case of their maximally compacted state (without layers of HCP between particles) (in fractions of a unit), amounting to 0.77–0.93. According to [12], it can be taken $V_{CA+FA}^{com}$ = 0.86.

In accordance with existing analytical methods, when exposed to neutrons and heating, radiation (under the influence of gamma radiation) and thermal changes in the strength of the cement mortar as a separate material or as part of concrete were calculated using the formula:

$$\frac{R_{CM}}{R_{CM0}} = \frac{R_{HCP}}{R_{HCP0}} \left( \frac{R_{FA}}{R_{FA0}} \right)^{0.29} \left\{ 1 + \left[ A_C \left( \frac{\Delta V_{CM}}{V_{CM}} \right)_{cr} \right]^2 \right\}^{-1}, \tag{7}$$

where $\frac{R_{CM}}{R_{CM0}}$, $\frac{R_{HCP}}{R_{HCP0}}$, and $\frac{R_{FA}}{R_{FA0}}$ are relative residual strength of cement mortar, HCP, and fine aggregate, respectively, after exposure to gamma radiation or heating, fractions of a unit; $A_C$ is a parameter equal to: $A_C$ = 0.31%$^{-1}$ is for compressive strength; $A_C$ = 0.53%$^{-1}$ is for tensile strength; $\left( \frac{\Delta V_{CM}}{V_{CM}} \right)_{cr}$ is relative radiation change in the volume of the cement mortar due to the formation of cracks, respectively, in %, determined by the formulas:

$$\left( \frac{\Delta V_{CM}}{V_{CM}} \right)_{cr} = \frac{\Delta V_{CM}}{V_{CM}} - \frac{\Delta V_{FA}}{V_{FA}} \frac{V_{FA}}{1 - V_{CA}} - \frac{\Delta V_{HCP}}{V_{HCP}} \left( 1 - \frac{V_{FA}}{1 - V_{CA}} \right). \tag{8}$$

Calculations of radiation and thermal changes in concrete were carried out using data on radiation and thermal changes in coarse aggregate and cement mortar based on the methods described in the works [12, 17–19].

According to existing analytical methods, when exposed to neutrons and heating, radiation (under the influence of gamma radiation) and thermal changes in volume $\frac{\Delta V_C}{V_C}$ concrete was calculated using the formula:

$$\frac{\Delta V_C}{V_C} = \frac{\Delta V_{CA}}{V_{CA}} \left( C_{com}^{CA} \right)^{\frac{1}{3}} + \left[ 1 - \left( C_{com}^{CA} \right)^{\frac{1}{3}} \right] \frac{\Delta V_{CM}}{V_{CM}}, \tag{9}$$

where $\frac{\Delta V_C}{V_C}$, $\frac{\Delta V_{CA}}{V_{CA}}$, and $\frac{\Delta V_{CM}}{V_{CM}}$ are relative change in the volume of concrete, coarse aggregate, and cement mortar in the composition and concrete, respectively, %; $C_{com}^{CA}$ is the degree of compaction of coarse aggregate in concrete, determined by the formula:

$$C_{com}^{CA} = \frac{V_{CA}}{V_{CA}^{com}}, \tag{10}$$

where $V_{CA}$ is relative volume content of coarse aggregate in concrete, fractions of a unit; $C_{com}^{CA}$ is the maximum relative volume content of coarse aggregate in the case of its maximally compacted state (without layers of cement mortar between the particles) (in fractions of a unit), amounting to 0.52–0.74. According to [9], it can be taken $C_{com}^{CA}$ = 0.63.

In accordance with existing analytical methods, when exposed to neutrons and heating, radiation (under the influence of gamma radiation) and thermal changes in the strength of concrete in the form of a relative strength value were calculated using the formula:

$$\frac{R_C}{R_{C0}} = \frac{R_{CM}}{R_{CM0}} \left( \frac{R_{CA}}{R_{CA0}} \right)^{0.29} \left\{ 1 + \left[ A_C \left( \frac{\Delta V_C}{V_C} \right)_{cr} \right]^2 \right\}^{-1}, \tag{11}$$

where $\frac{R_C}{R_{C0}}$, $\frac{R_{CM}}{R_{CM0}}$, $\frac{R_{CA}}{R_{CA0}}$ are relative residual strength of concrete, cement mortar, and coarse aggregate after exposure to gamma radiation or heating, fractions of a unit; $A_C$ is a parameter equal to: $A_C$ = 0.31%$^{-1}$ is for compressive strength; $A_C$ = 0.53%$^{-1}$ is for tensile strength; $\left(\frac{\Delta V_C}{V_C}\right)_{cr}$ is radiation change in the volume of concrete due to the formation of cracks, respectively, in %, determined by the formula:

$$\left(\frac{\Delta V_C}{V_C}\right)_{cr} = \frac{\Delta V_C}{V_C} - \frac{\Delta V_{CA}}{V_{CA}} V_{CA} - \frac{\Delta V_{CM}}{V_{CM}}\left(1 - V_{CA}\right). \tag{12}$$

In accordance with the results of the work [40], the radiation changes in the volume of HCP under the influence of gamma radiation were determined by the formula:

$$\frac{\Delta V_{HCP}}{V_{PCP}} = 3K_T a_G D_G^{b_G}, \tag{13}$$

where $D_G$ is absorbed dose rate of gamma radiation, Gy; $a_G$ = –0.000894 %, $b_G$ = 0.3497 at $D_G$ in Gy; $K_T$ is the coefficient of influence of temperature on radiation changes in HCP, calculated using the formula:

$$K_T = 7.77 \cdot 10^{-7} T^2 - 0.0023T + 1.045. \tag{14}$$

According to the work [40], change in HCP strength under gamma irradiation compression based on volume change data as a relative residual $\frac{R_{HCP}}{R_{HCP0}}$ determined by the formula:

$$\frac{R_{HCP}}{R_{HCP0}} = \left(A_{HCP} + B_{HCP}\frac{\Delta V_{HCP}}{V_{HCP}}\right)^{-1}, \tag{15}$$

where $A_{HCP}$ and $B_{HCP}$ are parameters whose values are [40]: $A_{HCP}$ = 0.724; $B_{HCP}$ = –0.0566%$^{-1}$ for HCP of “early” age (1–3 months of natural hardening); $A_{HCP}$ = 1.00; $B_{HCP}$ = –0.23%$^{-1}$ are for HCP of “mature” age (more than 8 months of natural hardening or after heat-moisture treatment of an early age HCP).

To test the possibility of using the methods developed under the influence of neutron radiation and heating to predict radiation changes in concrete under the influence of gamma radiation, the following experimental results of the works [1, 2, 21–30] presented below were used, with the following initial characteristics and experimental data.

1. Data No. 1, presented in work [21] on the results of gamma irradiation of samples with a diameter of 105 mm, a height of 305 mm of concrete made from Portland cement, limestone coarse aggregate up to 20 mm in size and quartz fine aggregate.

In the manufacture of the samples, a concrete mixture with a water-cement ratio of $W/C$ = 0.47 and a ratio of aggregate consumption (coarse aggregate $CA$ + fine aggregate $FA$) to Portland cement consumption $PC:(CA+FA)/PC$ = 4.5 was used. After 24 hours of exposure in humid conditions, the samples were covered with gypsum plaster, sealed in copper foil and stored for a year before testing at a “mature” age. Judging by the granulometric composition of the aggregates, the proportion of coarse aggregate and fine aggregate in the filler mixture was $CA/(CA+FA)$ = 0.61 and $FA/(CA+FA)$ = 0.39. The technological characteristics of the concrete mixture were calculated from the above proportions of the components of the concrete mixture, based on the density of Portland cement, fine aggregate, coarse aggregate and concrete mixture $\gamma_{PC}$ = 3100 kg/m$^3$, $\gamma_{CA}$ = $\gamma_{FA}$ = 2600 kg/m$^3$, $\gamma_M$ = 2400 kg/m$^3$, as the most probable values. The calculated values of consumption of Portland cement $PC$, coarse aggregate

$CA$, fine aggregate $FA$ and water $W$, as well as the volumetric content of aggregates, adopted in the calculations were taken equal to: $PC$ = 402 kg/m$^3$, $CA$ = 1105 kg/m$^3$, $FA$ = 705 kg/m$^3$, $W$ = 188 kg/m$^3$, $V_{CA}$ = 0.42, $V_{FA}$ = 0.27. The degrees of compaction of aggregates calculated using formulas (6) and (10) were: $C_{com}^{FA}$ = 0.614, $C_{com}^{CA}$ = 0.667.

The samples were irradiated at 30 °C with a gamma-ray installation with a Co$^{60}$ source at a dose rate of $P$ = 11.4×10$^3$ rad/h = 114 Gy/h for $t$ = 10–314 days. The maximum absorbed dose of gamma radiation was $D_G$ = $P \cdot t$ = 8.6×10$^5$ Gy. The change in the dimensions of the samples as a result of creep under a load of 10 MPa and shrinkage was studied. Creep and shrinkage deformations were measured under irradiation (when the processes occurred both under the action of gamma radiation and with natural hardening and drying over time) and without irradiation (when the processes occurred only due to natural hardening and drying over time).

The dependence of the measured changes in size with and without irradiation, as well as the changes in size due to gamma radiation calculated in accordance with formula (2), as the difference between the decrease in size with and without irradiation from the data of work [21] on the absorbed dose value are shown in Fig. 1.

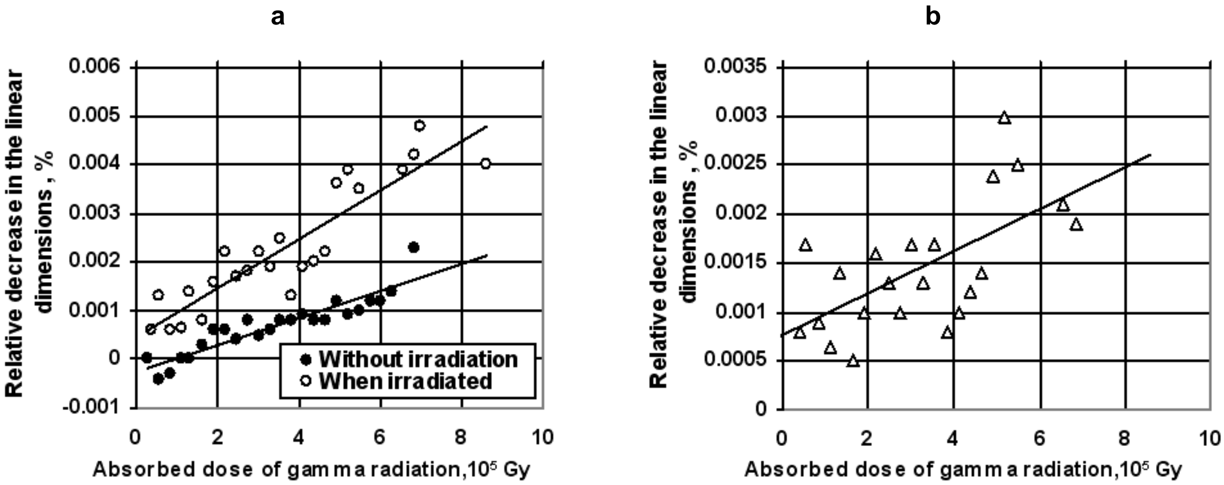


**Figure 1. Dependence of measured size changes with and without irradiation (a) and calculated size changes due to gamma radiation, as the difference between the decrease in size with and without irradiation (b) from the data of work [21] on the value of the absorbed dose of gamma radiation. Dots are individual results; lines are approximation lines.**

2. Data No. 2, presented in works [1, 2], in which the influence of gamma radiation of two types of concrete made from Portland cement with sandstone aggregates of density 2625 kg/m$^3$ and with limestone aggregate of density 2550 kg/m$^3$ was investigated. The ratio between the mass of Portland cement $PC$, coarse aggregate of approximately 10 mm size $CA$, fine aggregate $FA$, and water $W$ was:

$PC:CA:FA:W$ = 1:1.55:1.15:0.36 is for concrete No. 1 on crushed limestone and fine aggregate from sandstone (hereinafter concrete on sandstone and limestone);

$PC:CA:FA:W$ = 1:1.77:0.93:0.36 is for concrete No. 2 on limestone coarse aggregate and limestone fine aggregate (hereinafter referred to as concrete on limestone).

The density of concrete on sandstone was $\gamma_C$ = 2310 kg/m$^3$. The density of concrete on limestone was 2380 kg/m$^3$.

Based on the above proportions and density of aggregates at the most probable density of concrete mix $\gamma_{Cmix}$ = $\gamma_C$ + 100 kg/m$^3$ consumption of cement, aggregates, and water, as well as the volume content of aggregates in this study were taken equal to:

- $PC$ = 594 kg/m³, $CA$ = 921 kg/m³, $FA$ = 683 kg/m³, $W$ = 214 kg/m³, $V_{CA}$ = 0.361, $V_{FA}$ = = 0.260 is for concrete on limestone and sandstone;
- $PC$ = 611 kg/m³, $CA$ = 1081 kg/m³, $FA$ = 571 kg/m³, $W$ = 220 kg/m³, $V_{CA}$ = 0.424, $V_{FA}$ = 0.224 is for concrete on limestone.

The degrees of compaction of aggregates calculated using formulas (6) and (10) were taken as equal to:

- $C_{com}^{FA}$ = 0.511; $C_{com}^{CA}$ = 0.573 is for concrete on limestone and sandstone;
- $C_{com}^{FA}$ = 0.514; $C_{com}^{CA}$ = 0.673 is for concrete on limestone.

Irradiation of concrete samples with gamma radiation was carried out in a pool with radioactive substances at 20 °C with an absorbed dose rate of $5\times10^4$ Gy/h = $1.4\times10^1$ Gy/s. The maximum absorbed dose was $4.7\times10^8$ Gy. At the time of irradiation, the age of the samples was at least 3 months after their manufacture and storage under normal conditions, so in fact, the material studied was of a "young" age.

The results of changes in the dimensions, mass and tensile strength of concrete after irradiation with gamma radiation obtained in works [1, 2] are presented in Table 1.

***Table 1. Results* of irradiation of concrete with gamma radiation in works [1, 2].***

| Name of concrete by aggregates | Absorbed dose of gamma radiation, Gy | Relative size changes, % borders average | Relative mass changes, % | Relative residual strength, fractions of a unit |
|---|---|---|---|---|
| Concrete No. 1 with limestone and sandstone | $2.27\cdot10^8$ | –0.17 …. +0.076<br>–0.005 ± 0.066 | –0.77 …. –1.01<br>–0.903 ± 0.072 | – |
| | $4.7\cdot10^8$ | –0.21 …. +0.04<br>–0.021 ± 0.082 | –1.74 …. –2.14<br>–1.91 ± 0.14 | 0.91 ± 0.23 |
| Concrete No. 2 with limestone | $2.27\cdot10^8$ | –0.15 …. +0.04<br>–0.031 ± 0.057 | –0.95 …. –1.70<br>–1.15 ± 0.24 | 1.0 ± 0.09 |
| | $4.7\cdot10^8$ | –0.21 …. +0.04<br>–0.061 ± 0.071 | –1.42 …. –3.38<br>–2.36 ± 0.67 | 0.93 ± 0.05 |

*The standard deviations calculated by the authors of this work are given.

The disadvantage of these results is the significant spread of the values of shrinkage deformations of individual samples, associated with the peculiarities of using disk-shaped samples, as well as the absence of measurement results without irradiation. However, the average changes in the dimensions of concrete samples in the works [1, 2] are approximately proportional to the changes in mass, which have smaller spreads and are more reliable. In addition, since shrinkage changes in the dimensions of concrete are caused by the release of water, accompanied by a decrease in mass, then shrinkage deformations can also be estimated from the change in mass. For this purpose, the relationships between the decrease in mass and shrinkage after irradiation were analyzed for these works [1, 2].

As a result, it was established that the change in the dimensions of concrete on average $\frac{\Delta\ell_C}{\ell_C}$ associated with weight loss $\frac{\Delta M_C}{M_C}$ ratio:

$$\frac{\Delta\ell_C}{\ell_C}=0.0229\frac{\Delta M_C}{M_C} \quad \text{is for concrete No. 1 with limestone and sandstone;} \tag{16}$$

$$\frac{\Delta\ell_C}{\ell_C}=0.0159\frac{\Delta M_C}{M_C} \quad \text{is for concrete No. 2 with limestone.} \tag{17}$$

The values of size changes recalculated based on the change in mass are presented in Table 2 and were also used in the analysis.

***Table 2. Values of change in dimensions of concrete works recalculated based on change in mass [1, 2].***

| Name of concrete by aggregates | Absorbed dose of gamma radiation, Gy | Relative mass changes, % | Calculated relative size changes, % |
|---|---|---|---|
| Concrete No. 1 with limestone and sandstone | $2.27 \cdot 10^8$ | –0.77 …. –1.01<br>–0.903 ± 0.072 | –0.023 ± 0.002 |
| | $4.7 \cdot 10^8$ | –1.74 …. –2.14<br>–1.91 ± 0.14 | –0.039 ± 0003 |
| Concrete No. 2 with limestone | $2.27 \cdot 10^8$ | –0.95 …. –1.70<br>–1.15 ± 0.24 | –0.020 ± 0.004 |
| | $4.7 \cdot 10^8$ | –1.42 …. –3.38<br>–2.36 ± 0.67 | –0.034 ± 0.010 |

3. Data No. 3 presented in the works [22, 23], in which three Portland cement mortars were investigated using cube-shaped samples measuring 2.54 cm × 2.54 cm × 2.54 cm.

Ordinary Portland cement I (with 11 % $3Ca0.Al_20_3$) and sulfate-resistant Portland cement V (with 3 % $3Ca0.Al_20_3$), standard Ottawa quartz sand, deionized water were used. When preparing one of the mortars, microsilica was added to the mixture (Silica fume) and superplasticizer “Melment”.

The compositions of the mixtures used to prepare the mortars are given in Table 3.

***Table 3. Compositions of mixtures in the preparation of cement mortars in works [22, 23].***

| Mortar code | View Cement | Consumption of components, g | | | | | |
|---|---|---|---|---|---|---|---|
| | | Cement | Sand | Water | Silica fume | Melment | Sum |
| I | I | 1180.64 | 3246.75 | 572.61 | – | – | 5000 |
| V | V | 1180.64 | 3246.75 | 572.61 | – | – | 5000 |
| V+PF/SF | V | 921.69 | 2981.93 | 433.73 | 162.65 | 32.53 | 4532.53 |

Based on the data in Table 3, the average density of concrete is 2155 kg/m$^3$ at the age of about 30 days, the density of sand particles is 2650 kg/m$^3$, the volumetric content of sand and the degree of compaction of sand calculated using formula (5) in this study were taken to be equal to:

– $V_{FA}$ = 0.573; $C_{com}^{FA}$ = 0.910 is for mortars I and V;

– $V_{FA}$ = 0.572; $C_{com}^{FA}$ = 0.908 is for the V+PF/SF mortar.

After hardening for 27–34 days, the samples were irradiated at 10 °C. At an absorbed dose rate of 31 Gy/h, the samples were irradiated for 182 and 365 days to absorbed doses of $1.4 \cdot 10^5$ Gy and $2.6 \cdot 10^5$ Gy. At an absorbed dose rate of 3.8 kGy/h, they were irradiated for 48.5, 110.5, and 225–245 days to absorbed doses of $4.4 \cdot 10^6$ Gy, $1.0 \cdot 10^7$ Gy, and $2.0 \cdot 10^7$ Gy. The control lot samples were kept for the same period at 20 °C and 10 °C. The changes in compressive strength after irradiation and aging without irradiation were studied. The results of the change in compressive strength of the studied mortars in the form of relative residual strength after various absorbed doses of gamma radiation are shown in Fig. 2.

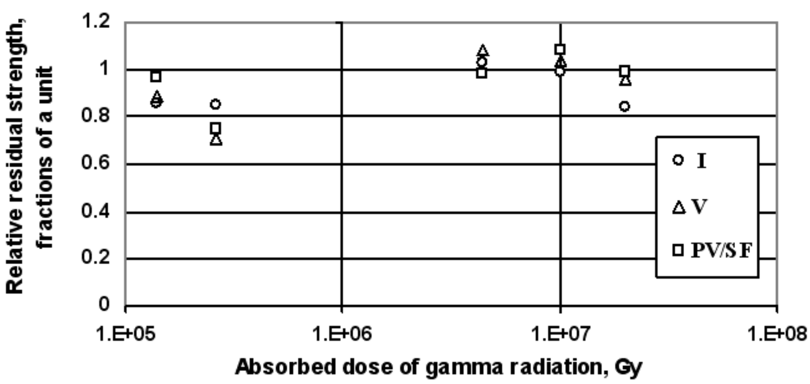


**Figure 2. Results of changes in compressive strength of I, V, PV/SV cement mortars in the form of relative residual strength after different absorbed doses of gamma radiation according to data from [22, 23].**

4. Data No. 4, presented in the work [24], in which the change in compressive strength after gamma irradiation of concrete samples in water was investigated, were adopted as described in other works [6–11, 13–15]. The following results were obtained for radiation changes in the form of relative residual strength after irradiation:

- 1.0 and 1.08 – after an absorbed dose of gamma radiation of $8 \cdot 10^7$ Gy;
- 1.04 and 1.7 – after an absorbed dose of gamma radiation of $1.0 \cdot 10^8$ Gy.
- 0.67 and 0.55 – after an absorbed dose of gamma radiation of $8 \cdot 10^8$ Gy;
- 0.42 and 0.75 – after an absorbed dose of gamma radiation of $1.8 \cdot 10^9$ Gy.

There is no data on age. However, judging by the changes, it was assumed that early age concrete was being studied. There is no data on the composition of concrete. In this regard, average typical values for concrete were adopted for the evaluation calculations $V_{FA}$ = 0.3, $V_{CA}$ = 0.4. The degrees of compaction of the aggregates calculated using formulas (6) and (10) were taken to be equal to $C_{com}^{FA}$ = 0.652, $C_{com}^{CA}$ = 0.634. Data on changes in samples without irradiation are not provided.

5. Data No. 5, presented in the work [25], were obtained from the results of irradiation of 40 × 40 × 160 mm samples of Portland cement concrete using several mineral aggregates.

The consumption of components per 1 m$^3$ of concrete mix during the production of samples was:

- 360 kg/m$^3$ – ordinary Portland cement;
- 180 kg/m$^3$ – water;
- 223 kg/m$^3$ – fine aggregate from a quarry with a density of 2500 kg/m$^3$;
- 550 kg/m$^3$ – fine aggregate from crushed gravel with a density of 2640 kg/m$^3$;
- 967 kg/m$^3$ – coarse aggregate with a density of 2660 kg/m$^3$;
- 0.25 % – air-entraining water-reducing additive.

Based on the consumption and density of the aggregates, their volume content was taken to be equal to: $V_{FA}$ = 0.297, $V_{CA}$ = 0.364. The degree of compaction of the aggregates was taken according to formulas (6) and (10) equal to: $C_{com}^{FA}$ = 0.599, $C_{com}^{CA}$ = 0.577.

The samples were kept in water at 20 °C for 4 weeks after production and then stored in air at 20 °C and 60 % RH until irradiation.

Different irradiated samples were kept for 1 and 2 months near the gamma radiation source and 2 months at some distance from the source, which allowed us to obtain different absorbed dose values. After irradiation, the samples were tested for bending with an examination of their stress-strain state. After the samples were broken into two halves, each of them was tested for compression. Samples without irradiation were also tested before the start of irradiation, after 1 and 2 months.

The relative residual compressive strength of concrete after irradiation and after holding without irradiation was:

- 1.22 after irradiation for 2 months to an absorbed dose of $4.6 \cdot 10^6$ Gy;
- 1.19 after irradiation for 1 month up to an absorbed dose of $7.2 \cdot 10^6$ Gy;
- 1.24 after irradiation for 2 months to an absorbed dose of $1.3 \cdot 10^7$ Gy;
- 1.22 after 1 month of exposure without irradiation;
- 1.11 after aging without irradiation for 2 months.

6. Data No. 6, presented in the works [26, 27] obtained from the results of irradiation of samples of 10 × 10 × 40 mm Portland cement mortar with siliceous fine aggregate with the inclusion of feldspars and micas. A superplasticizer based on polycarboxylate was introduced.

The consumption of components in the mortar mixture during the preparation of samples was:

- 2625 g – Portland cement CEM I 42.5R;
- 1000 g – water;
- 4200 g – fine aggregate with a grain size of 0–4 mm;
- 25 g – superplasticizer Glenium ACE 442;
- 7825 g – total.

Based on these data, with a density of quartz fine aggregate particles of 2650 kg/m$^3$ and a density of cement particles of 3100 kg/m$^3$, the volume content of fine aggregate and the degree of fine aggregate compaction calculated using formula (5) in this study were taken to be equal to $V_{FA}$ = 0.463; $C_{com}^{FA}$ = 0.734.

All samples were kept in water for 10 days and for another 62 days in a sealed state in polyethylene foil before the experiment. Samples were irradiated immediately after removing the insulation.

The samples were irradiated with a $^{60}Co$ source at a gamma radiation dose rate of 3.90 kGy/h to 4.71 kGy/h at a temperature of 16.2 °C and an average relative humidity of 50 %. After irradiation for 768 days (only during the daytime – 8.6 hours), the total absorbed dose was from 12.0 10$^3$ kGy to 15.0 10$^3$ kGy. Control samples were kept without irradiation under the same conditions but away from the gamma emitter. Samples compressed by a load of 10 MPa, 15 MPa and without a load were irradiated. Changes in dimensions during irradiation and holding without irradiation, as well as strength after completion of irradiation and holding after irradiation were studied.

The results of the studies of changes in the sizes of the samples were not analyzed, since due to significant scatter they do not allow us to isolate the influence of gamma radiation.

The changes in compressive strength used in this work in the form of the relative residual strength after irradiation to the strength of the control samples were:

- 0.71 – at an absorbed dose of 1.3·10$^7$ Gy;
- 0.69, 0.8, 0.9 – at an absorbed dose of 1.32·10$^7$ Gy;
- 0.81 – at an absorbed dose of 1.4·10$^7$ Gy;
- 0.81 – at an absorbed dose of 1.5·10$^7$ Gy.

7. Data No. 7, presented in the work [28], obtained from the results of irradiation of 40 × 40 × 160 mm samples of six cement mortars with fine-grained (0.08–0.16 mm) or fine (0.8–2.0 mm) iron fine aggregate with different ratios of cement and fine aggregate. The solutions with the ratio of cement consumption *C* to the amount of fine aggregate *FA* and with the density were studied: No. 1 with *C:FA* = 3:1 (0.08–0.16 mm) with a density of 2350 kg/m$^3$; No. 2 with *C:FA* = 2:1 (0.08–0.16 mm) with a density of 2520 kg/m$^3$; No. 3 with *C:FA* = 1:1 (0.08–0.16 mm) with a density of 2860 kg/m$^3$; No. 4 with *C:FA* = 1:2 (0.08–0.16 mm) with a density of 3640 kg/m$^3$; No. 5 with *C:FA* = 1:2 (0.8–2.0 mm) with a density of 3900 kg/m$^3$; No. 6 with *C:FA* = 1:3 (0.8–2.0 mm) with a density of 5130 kg/m$^3$. After production, the samples were stored under normal conditions for 28 days before irradiation.

Based on these data, the degree of hydration of cement at the age of 28 days is about 60 % with an average density of iron fine aggregate of 7850 kg/m$^3$ and the volume content of fine aggregate and the degree of compaction of fine aggregate calculated according to formula (5) in this study were taken to be equal to:

- $V_{FA}$ = 0.067; $C_{com}^{FA}$ = 0.106 – mortar No. 1;
- $V_{FA}$ = 0.097; $C_{com}^{FA}$ = 0.154 – mortar No. 2;
- $V_{FA}$ = 0.169; $C_{com}^{FA}$ = 0.268 – mortar No. 3;
- $V_{FA}$ = 0.294; $C_{com}^{FA}$ = 0.467 – mortar No. 4;
- $V_{FA}$ = 0.315; $C_{com}^{FA}$ = 0.500 – mortar No. 5;
- $V_{FA}$ = 0.472; $C_{com}^{FA}$ = 0.749 – mortar No. 6.

The samples were irradiated with a gamma radiation source with an energy of 1.25 MeV at a dose rate of 20 kGy/h at a temperature of no higher than 40 °C. To obtain an absorbed dose of 106 Gy and 107 Gy, the samples were irradiated for 4–5 days and about a month, respectively.

The changes in compressive strength used in this work in the form of the relative residual strength after irradiation to the strength of the control samples were:

- 1.0 and 1.02 – at absorbed doses of 10$^6$ Gy and 10$^7$ Gy for mortar No. 1;
- 1.0 and 1.0 – at absorbed doses of 10$^6$ Gy and 10$^7$ Gy for mortar No. 2;

- 1.01 and 1.01 – at absorbed doses of $10^6$ Gy and $10^7$ Gy for mortar No. 3;
- 1.02 and 1.02 – at absorbed doses of $10^6$ Gy and $10^7$ Gy for mortar No. 4;
- 1.0 and 1.0 – at absorbed doses of $10^6$ Gy and $10^7$ Gy for mortar No. 5;
- 1.05 and 1.06 – at absorbed doses of $10^6$ Gy and $10^7$ Gy for mortar No. 6.

8. Data No. 8, presented in the work [29], obtained from the results of irradiation of samples measuring 40 × 40 × 160 mm from Portland cement mortar.

The consumption of components per 1 m$^3$ of mixture during the production of samples was:

- 496 kg/m$^3$ – Portland cement;
- 248 kg/m$^3$ – water;
- 1487 kg/m$^3$ – quartz fine aggregate.

The density of the mortar mixture is 2231 kg/m$^3$.

Based on these data, with a density of quartz fine aggregate particles of 2650 kg/m$^3$, the volume content of fine aggregate and the degree of fine aggregate compaction calculated using formula (5) in this study were taken to be equal to $V_{FA}$ = 0.561; $C_{com}^{FA}$ = 0.890.

The samples were irradiated with a $^{60}$Co gamma radiation source at a dose rate of 0.5 to 4.5 kGy/h at a temperature of no more than 25–63 °C. The samples were irradiated for 21 days. After that, the samples were tested by non-destructive measurements and then placed under irradiation for another 27 days. After irradiation, the change in the dynamic modulus, flexural strength, and compressive strength relative to these characteristics of the samples without irradiation (before irradiation) were first investigated. After irradiation, some of the samples were exposed to water vapor at a temperature of 250 °C under a pressure of 1 MPa, and then cooled under the action of a boric acid mortar. Thus, an emergency situation at a nuclear power plant with the effect of a coolant on concrete was imitated. After that, the change in flexural strength and compressive strength relative to these characteristics of the irradiated samples was also investigated.

The changes in compressive strength used in this work in the form of the relative residual compressive strength after irradiation to the strength of the control samples were:

- 0.94 – after gamma radiation irradiation with an absorbed dose of (1.6–1.8)·$10^6$ Gy;
- 0.82 – after exposure to gamma radiation and exposure to water vapor at a temperature of 250 °C under a pressure of 1 MPa and a boric acid mortar.

9. Data No. 9, presented in the work [30], in which the change in compressive strength, elastic modulus, and mass of samples of two concretes (*Con-A* and *Con-B*) after irradiation with gamma radiation were investigated. Samples in the form of cylinders with a diameter of 50 mm and a height of 100 mm were used. Moreover, in addition to the irradiated concrete samples, samples were investigated after heating in the temperature mode of irradiated samples, as well as samples stored during the study period under normal conditions.

The concretes studied were based on quick-hardening Portland cement, *S* fine aggregate from sandstone with a density of 2610 kg/m$^3$, coarse aggregate (5–13 mm) in the form of crushed rock from modified tuff *GA* with a density of 2660 kg/m$^3$ or in the form of gravel from sandstone *GB* with a density of 2640 kg/m$^3$. The compositions of concrete mixtures in the manufacture of samples are given in Table 4.

***Table 4. Compositions of mixtures for the production of concrete in work [30].***

| Concrete cipher | Aggregates | | Consumption of components in kg/m$^3$ | | | |
|---|---|---|---|---|---|---|
| | Fine aggregate | Coarse aggregate | Cement *WITH* | Water $W$ | Fine aggregate $FA$ | Coarse aggregate $FA$ |
| *Con-A* | *S* | *GA* | 366 | 183 | 799 | 995 |
| *Con-B* | *S* | *GB* | 354 | 177 | 757 | 1057 |

Characteristics of *Con-A* concrete:

$V_{FA}$ = 0.306, $V_{CA}$ = 0.374; $C_{com}^{FA}$ = 0.634; $C_{com}^{CA}$ = 0.598.

Characteristics of *Con-B* concrete:

$V_{FA}$ = 0.290, $V_{CA}$ = 0.400; $C_{com}^{FA}$ = 0.628; $C_{com}^{CA}$ = 0.634.

The samples were irradiated with a $^{60}Co$ source at different dose rates due to different distances of the samples from the source for different irradiation times at maximum temperatures ranging from 35 °C to 50 °C.

The irradiation conditions and the obtained values of the absorbed dose of gamma radiation are given in Table 5.

***Table 5. Irradiation conditions and the obtained values of the absorbed dose of gamma radiation during irradiation of concrete in work [30].***

| Irradiation time, months | Absorbed dose, Gy at different dose rates and temperatures | | | |
|---|---|---|---|---|
| | 10 kGy/h, up to 50 °C | 5 kGy/h, up to 45 °C | 2.5 kGy/h, up to 40 °C | 1.25 kGy/h, up to 35 °C |
| 4 | $2.5 \cdot 10^7$ | – | – | – |
| 8 | $5 \cdot 10^7$ | $2.5 \cdot 10^7$ | – | – |
| 16 | $1 \cdot 10^8$ | $5 \cdot 10^7$ | $2.5 \cdot 10^7$ | – |
| 32 | $2 \cdot 10^8$ | $1 \cdot 10^8$ | $5 \cdot 10^7$ | $2.5 \cdot 10^7$ |

In addition to the irradiated samples, the change in properties after different holding times was investigated:

- samples stored in the mode of temperature and air humidity values of the irradiated samples;
- samples stored in the mode of air humidity values of the irradiated samples, but at normal temperatures.

The changes in compressive strength and elastic modulus did not differ significantly, therefore, in this work, only the change in strength was considered, as a more important value.

The change in concrete strength from the duration of irradiation, holding at irradiation temperatures and holding at the temperature of the irradiation room are shown in Fig. 3.

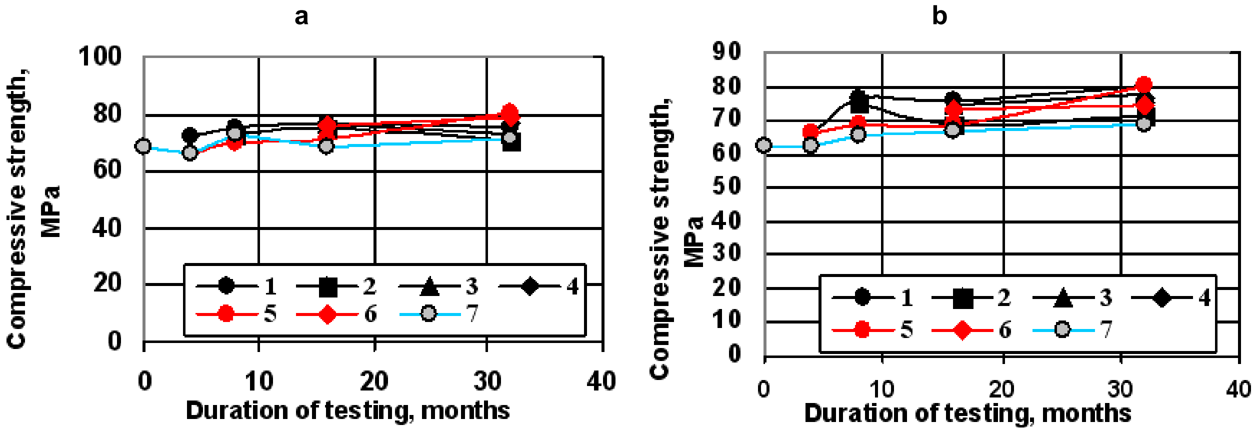


**Figure 3. Change in the strength of concrete *Con-A* (a) and *Con-B* (b) depending on the duration of irradiation, holding at irradiation temperatures and holding at the temperature of the irradiation room: 1 – irradiation at $P$ = 10 kGy/h; 2 – irradiation at $P$ = 5 kGy/h; 3 – irradiation at $P$ = 2.5 kGy/h; 4 – irradiation at $P$ = 1.25 kGy/h; 5 – without irradiation at $T$ up to 50 °C (as at 10 kGy/h); 6 – without irradiation at $T$ up to 35 °C (as at 1.25 kGy/h); 7 – without irradiation at room temperature.**

The values of relative residual compressive strength of concrete calculated from the data of work [30 ] from the effects of temperature and gamma radiation during irradiation (from $T_I$ + $D_G$), only the temperature accompanying the irradiation (from $T_I$), and from exposure to gamma radiation alone (from $D_G$) at different dose rates $P$ are given in Table 6.

***Table 6. Calculated from the data of work [30] values of relative residual strength of concrete under compression from the effects of temperature and gamma radiation during irradiation, only the temperature accompanying the irradiation, and from exposure to gamma radiation alone at different dose rates P and exposure times.***

| Irradiation time, months | Values of absorbed dose $D$ (Gy) and relative residual compressive strength $R/R_0$ from the effect of temperature and gamma radiation during irradiation (from $T_I$ + $D_G$), only temperature accompanying irradiation (from $T_I$), and from exposure to gamma radiation only (from $D_G$) at different dose rates $P$ and exposure times | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | $P$ = 10 kGy/h | | | | $P$ = 5 kGy/h | | | | $P$ = 2.5 kGy/h | | | | $P$ = 1.25 kGy/h | | | |
| | $D_G$, Gy | $R/R_0$, fractions of a unit | | | $D_G$, Gy | $R/R_0$, fractions of a unit | | | $D_G$, Gy | $R/R_0$, fractions of a unit | | | $D_G$, Gy | $R/R_0$, fractions of a unit | | |
| | | from $T_I + D_G$ | from $T_I$ | from $D_G$ | | from $T_I + D_G$ | from $T_I$ | from $D_G$ | | from $T_I + D_G$ | from $T_I$ | from $D_G$ | | from $T_I + D_G$ | from $T_I$ | from $D_G$ |
| *Con-A:* | | | | | | | | | | | | | | | | |
| 4 | $2.5 \cdot 10^7$ | 1.08 | 1.0 | 1.08 | – | – | – | – | – | – | – | – | – | – | – | – |
| 8 | $5 \cdot 10^7$ | 1.01 | 0.96 | 1.05 | $2.5 \cdot 10^7$ | 1.01 | 0.96 | 1.05 | – | – | – | – | – | – | – | – |
| 16 | $1 \cdot 10^8$ | 1.12 | 1.04 | 1.08 | $5 \cdot 10^7$ | 1.10 | 1.04 | 1.06 | $2.5 \cdot 10^7$ | 1.12 | 1.04 | 1.08 | - | - | - | - |
| 32 | $2 \cdot 10^8$ | 1.07 | 1.13 | 0.94 | $1 \cdot 10^8$ | 1.03 | 1.13 | 0.91 | $5 \cdot 10^7$ | 1.02 | 1.14 | 0.89 | $2.5 \cdot 10^7$ | 1.08 | 1.11 | 0.98 |
| *Con-B:* | | | | | | | | | | | | | | | | |
| 4 | $2.5 \cdot 10^7$ | 1.06 | 1.06 | 1.0 | – | – | – | – | – | – | – | – | – | – | – | – |
| 8 | $5 \cdot 10^7$ | 1.17 | 1.04 | 1.12 | $2.5 \cdot 10^7$ | 1.15 | 1.04 | 1.11 | – | – | – | – | – | – | – | – |
| 16 | $1 \cdot 10^8$ | 1.14 | 1.03 | 1.11 | $5 \cdot 10^7$ | 1.03 | 1.03 | 1.00 | $2.5 \cdot 10^7$ | 1.12 | 1.04 | 1.08 | – | – | – | – |
| 32 | $2 \cdot 10^8$ | 1.16 | 1.04 | 1.12 | $1 \cdot 10^8$ | 1.04 | 1.04 | 1.00 | $5 \cdot 10^7$ | 1.13 | 1.04 | 1.09 | $2.5 \cdot 10^7$ | 1.11 | 1.09 | 1.02 |

Note: The $R_0$ values are taken to be the strength of concrete after storing samples of a separate group under normal conditions during the time of irradiation and heating of samples of other groups.

It was not possible to use data on radiation changes in HCP, since the change in flexural strength was investigated, and not in compression, as in concrete.

Data on radiation changes in aggregates showed that there is no significant influence of gamma radiation at the studied doses with the observed scatter of results, since the change in size and strength are commensurate. Moreover, this is consistent with the results of work [39].

# 3. Results and Discussion

## 3.1. Radiation-induced Changes in Size

The results of comparison of radiation changes in the linear dimensions of concrete under the influence of gamma radiation, calculated using methods of analytical determination of radiation changes in concrete, developed under neutron irradiation and heating, and obtained experimentally are shown in Figs. 4 and 5.

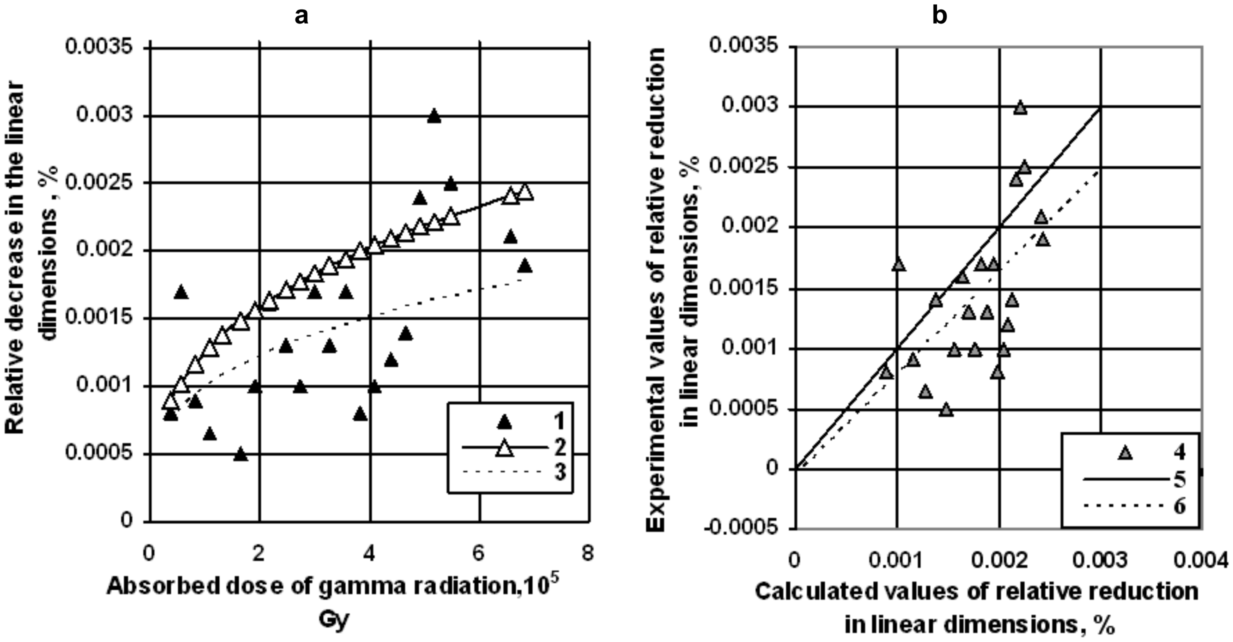


**Figure 4. Comparison of calculated and experimental values of radiation changes in the dimensions of concrete for the data of work [21] in the form of a dependence on the value of the absorbed dose (a) and in the form of a ratio between calculated and experimental values (b):**
1 – experimental data; 2 – calculated data; 3 – approximation line for experimental data;
4 – experimental data corresponding to calculated data;
5 – line corresponding to the equality of calculated and experimental data;
6 – the line of the actual relationship between the experimental and calculated results and its parameters.

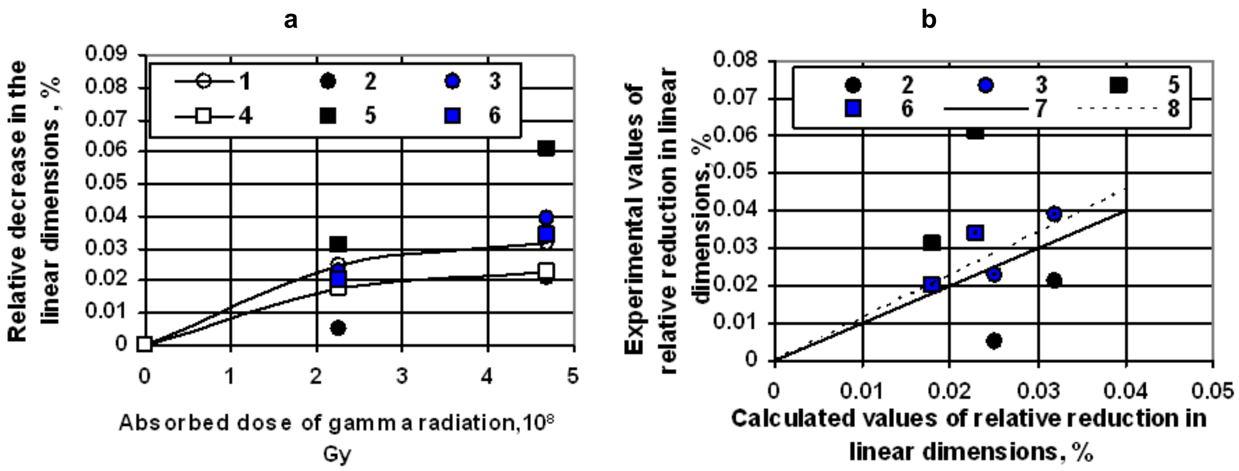


**Figure 5. Comparison of calculated and experimental values of radiation changes in the dimensions of concrete for the data of works [1, 2] in the form of a dependence on the value of the absorbed dose (a) and in the form of a ratio between calculated and experimental values (b):**
1 – concrete on limestone and sandstone – calculation;
2 – concrete on limestone and sandstone – an experiment on changing dimensions;
3 – concrete on limestone and sandstone – mass reduction experiment;
4 – concrete on limestone – calculation;
5 – concrete on limestone – an experiment on changing dimensions;
6 – limestone concrete – mass change experiment;
7 – limestone of equality of experimental and calculated values;
8 – line of actual relationship between experimental and calculated values.

Fig. 4 shows a comparison of the calculated and experimental values of radiation changes in the dimensions of concrete obtained in the work [21] after irradiation to absorbed doses of $0.38{\cdot}10^5$ to $7{\cdot}10^5$ Gy. Fig. 5 shows a comparison of the calculated and experimental values of radiation changes in the dimensions of concrete obtained in the works [1, 2] after irradiation to absorbed doses of gamma radiation from $2.27{\cdot}10^5$ to $4.7{\cdot}10^5$ Gy.

In Figs. 4a and 5a, the comparison is given in the form of dependences on the absorbed dose value. In Figs. 4b and 5b, the comparison is given in the form of a ratio between the calculated and experimental values.

At absorbed doses less than $7{\cdot}10^5$ Gy (Fig. 4), when the relative decrease in size $\Delta\ell/\ell$ does not exceed 0.003 %, calculated values on average up to $\Delta^{e/c}_{\Delta\ell/\ell}$ = 0.0005 % exceed the experimental data. However, there is a relatively large scatter of experimental data relative to the average values and relative to the calculated values. In this case, the standard deviation of the experimental data from the calculated ones is $S^{e/c}_{\Delta\ell/\ell}$ = ±0.00063 %. This value is close in magnitude to the scatter of experimental results $\Delta^{e}_{\Delta\ell/\ell}$ = ±(0.0005–0.001) % and standard deviations $S^{e}_{\Delta\ell/\ell}$ = (0.00028–0.00042) % at close doses.

When grouping data, the average value of the *F*-criterion is $F_e = \left(S^{e/c}_{\Delta\ell/\ell} / S^{e}_{\Delta\ell/\ell}\right)^2$ = 3.24. The tabular value of the *F*-criterion at a significance level of $\alpha$ = 0.95 is $F_{0.95}$ = 5.83. Since $F_e < F_{0.95}$, we can assume that these deviations are statistically insignificant.

Since $a < b$, we can assume that these deviations are statistically insignificant.

At absorbed doses $(2.27–4.7){\cdot}10^8$ Gy (Fig. 5), when the relative reduction in size reaches 0.06 %, the calculated and experimental values along the mean lines differ insignificantly. Although there is also a relatively large scatter of experimental data relative to the calculated values. In this case, the standard deviation of the experimental data from the calculated ones is $S^{e/c}_{\Delta\ell/\ell}$ = ±0.018 %. This value is close to the magnitude of the scatter of experimental results. $\Delta^{e}_{\Delta\ell/\ell}$ = ±(0.01–0.03) % and standard deviations $S^{e}_{\Delta\ell/\ell}$ = (0.012–0.015) % at the same doses.

When grouping data, the average value of the *F*-criterion is $F_e = \left(S^{e/c}_{\Delta\ell/\ell} / S^{e}_{\Delta\ell/\ell}\right)^2$ = 1.78. The tabular value of the *F*-criterion at a significance level of $\alpha$ = 0.95 is $F_{0.95}$ = 4.88. Since $F_e < F_{0.95}$, we can assume that these deviations are statistically insignificant.

Thus, it follows from the figures that there is a satisfactory convergence of the calculated and experimental values of the change in dimensions, taking into account the variability of the experimental data. In this regard, the results obtained showed the possibility of using existing analytical methods to predict radiation changes in the dimensions of concrete when exposed to gamma radiation. The maximum prediction error is $\Delta^{c}_{\Delta\ell/\ell}$ = ±0.001 % at absorbed doses less than 7·10$^5$ Gy and $\Delta^{c}_{\Delta\ell/\ell}$ = ±0.04 % at absorbed doses (2.27–4.7)·10$^8$ Gy.

Although in the range of absorbed doses from 7·10$^5$ Gy up to 2.27·10$^8$ Gy experimental data are not available, existing methods for analytical determination of radiation deformations of concrete, developed under the influence of neutron radiation, can be used for analytical assessment of radiation deformations of concrete under the influence of gamma radiation. In this range of absorbed doses, no additional effects are expected.

### *3.2. Radiation Changes in the Strength of Early Age Concretes and Mortars*

The results of comparison of radiation changes in the strength of early age concrete and cement mortars under the influence of gamma radiation calculated using methods of analytical determination of radiation changes in concrete and mortars under neutron irradiation, and obtained experimentally, are shown in Fig. 6.

In Fig. 6a, the comparison is given in the form of dependences of the calculated and experimental relative residual strength on the value of the absorbed dose. In Fig. 6b, the comparison is given in the form of a ratio between the calculated and experimental values of the relative residual strength.

It is evident from Fig. 6 that the calculated radiation changes in the strength of early age concrete and mortars are generally less than the experimental changes, since the calculated relative residual strength is higher than the experimental one. Moreover, the differences reach up to 0.6 (60 %). Deviations are minimal at an absorbed gamma radiation dose of about (1–4)·10$^5$ Gy and increase with increasing absorbed dose.

Since the main contribution to the radiation change in the strength of concrete and mortars under the influence of gamma radiation in accordance with the analytical method under consideration is made by the change in HCP, then the formula (15) requires correction. The use of this formula in this form (as with neutron irradiation and heating) was proposed earlier in the work [40]. In this case, it was assumed that the processes of acceleration of hydration and carbonization of early age HCP under the influence of gamma radiation with the same value of volume change are the same as under the influence of irradiation and heating. However, this is apparently not the case. It is most likely that for early age concrete, these differences in the degree of change in strength are associated, first of all, with differences in the processes of acceleration of hydration under irradiation. The effect of additional hydration is mainly taken into account by the parameter $A_{HCP}$ formulas (15). In connection with this, in further studies for all experimental data the values of the parameter were calculated $A_{HCP}$, which should be the case when the calculated and experimental changes in strength are equal, and then the dependence of this parameter on the calculated decrease in the volume of HCP was investigated.

It would be more correct to consider the dependence of the parameter $A_{HCP}$ from the dose rate and the irradiation time. However, there is little data for this. In addition, with an increase in the dose rate and the duration of irradiation, the absorbed dose increases and, therefore, the degree of reduction in the volume of HCP, and more significant doses are usually obtained at higher values of dose density and irradiation time. In this regard, the values of the volume reduction are more complex and representative parameters.

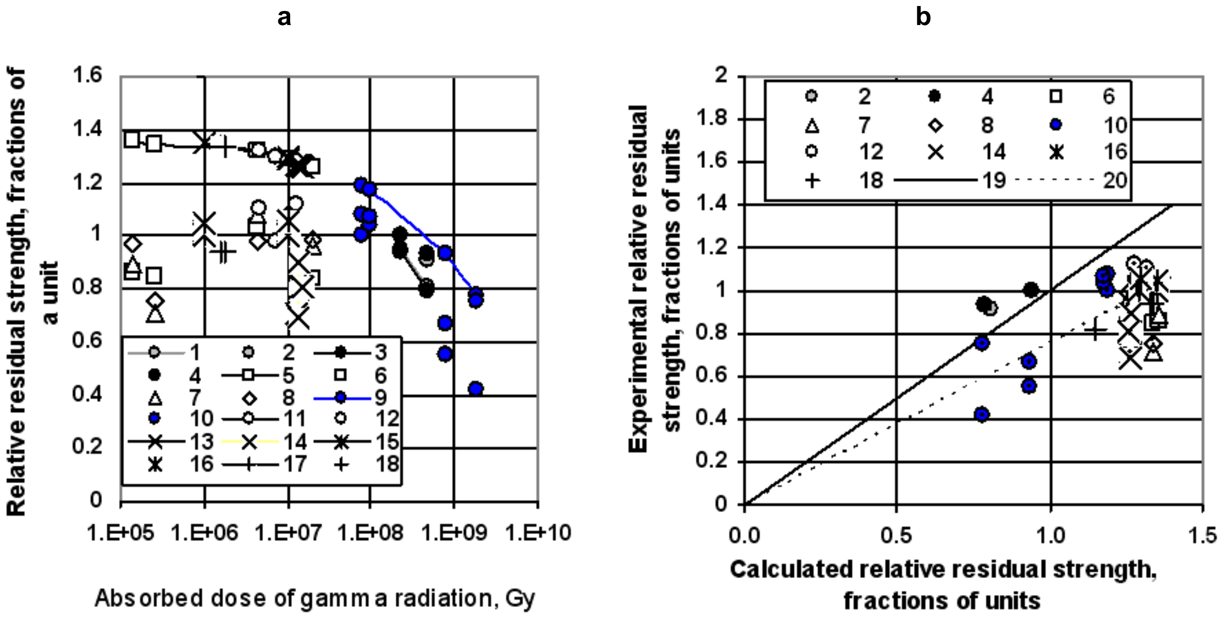


**Figure 6. Comparison of calculated and experimental values of radiation changes in the strength of concrete and mortars as a function of the absorbed dose (a) and as a ratio between calculated and experimental values (b):**
1 – concrete No. 1 from [1, 2] – calculation; 2 – concrete No. 1 [1, 2] – experiment;
3 – concrete No. 2 from [1, 2] – calculation; 4 – concrete No. 2 from [1, 2] – experiment;
5 – mortar I from [22, 23] – calculation; 6 – mortar I from [22, 23] – experiment;
7 – mortar V from [22, 23] – experiment; 8 – mortar V+PF/SF from [22, 23] – experiment;
9 – concrete from [24] – calculation; 10 – concrete from [24] – experiment;
11 – concrete from [25] – calculation; 12 – concrete from [25] – experiment;
13 – mortar from [26, 27] – calculation; 14 – mortar from [26, 27] – experiment;
15 – mortars from [28] – calculation; 16 – mortar from [28] – experiment;
17 – mortar from [29] – calculation; 18 – mortar from [29] – experiment;
19 – line of equality of experimental and calculated values;
20 – approximation line of the actual relationship between experimental and calculated values.

Dependence of calculated values $A_{HCP}$ with the equality of the calculated and experimental results of the change in the strength of concrete and mortar under the influence of gamma radiation from the decrease in the volume of HCP is shown in Fig. 7. It is evident that the values $A_{HCP}$ with the increase in the magnitude of the decrease in volume, HCP first decreases and then increases. Moreover, the value of the approximation line $A_{HCP}$ always exceeds the value $A_{HCP}$ = 0.724 for neutron irradiation and heating.

It has been established that dependence $A_{HCP}$ from changes in HCP volume $\frac{\Delta V_{HCP}}{V_{HCP}}$ is approximated by the expression:

$$A_{HCP} = 0.0705\left(\frac{\Delta V_{HCP}}{V_{HCP}}\right)^2 - 0.3364\frac{\Delta V_{HCP}}{V_{HCP}} + 1.2625, \quad (18)$$

where $\frac{\Delta V_{HCP}}{V_{HCP}}$ – relative change in the volume of HCP with the sign "–" due to a decrease in volume.

In this case, the spread of individual values relative to the approximation line is up to =±0.4 with standard deviation $S_A$ = 0.193. However, given that the coefficient of variation $v_R = S/R$ strength is usually 0.1–0.15, then when calculating $\frac{R}{R_0}$ standard deviation of the calculation $\frac{R}{R_0}$ makes up $S^c_{R/R_0} = \left(2v_R^2\right)^{1/2}$ = 1.4 $v_R$ = 0.14–0.21, and the standard deviation of the calculation $A_{HCP}$ makes up

$S_A^c = \left(4v_R^2\right)^{1/2}$ = 2 $v_R$ = 0.2–0.3. It follows that the values $S_A^c$ and $S_A$ are close in magnitude. It follows that the values $S_{R/R_0}^{e/c} < S_{R/R_0}^{e}$, therefore $F_e < F_{0.95}$. In this regard, and without determining the actual values of the $F$ -criteria, it can be considered that the above deviations are statistically insignificant.

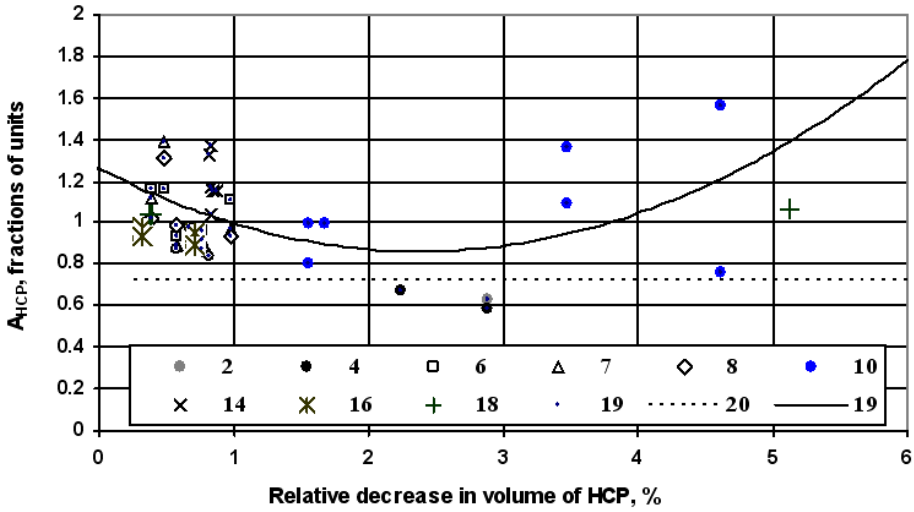


**Figure 7. Dependence of calculated values $A_{HCP}$ withequality of the calculated and experimental results of changes in the strength of concrete and mortars under the influence of gamma radiation from a decrease in the volume of HCP:**
2 – concrete No. 1 from [1, 2]; 4 – concrete No. 2 from [1, 2]; 6 – mortar I from [22, 23]; 7 – mortar V from [22, 23]; 8 – V+PF/SF mortar from [22, 23]; 10 – Sommers concrete from [24]; 12 – concrete from [25]; 14 – mortar from [26, 27]; 16 – mortar from [28 ]; 18 – mortar from [29]; 19 – approximation line 20 – under neutron irradiation and heating.

Thus, in formula (15) for early age HCP, instead of the value $A_{HCP}$ = 0.724, as is used for neutron irradiation and heating, when gamma radiation is applied to early age concrete, the values calculated using formula (18) must be used.

At the same time, formula (15) is not correct when the change in the volume of HCP is equal to zero. When exposed to gamma radiation, since in the absence of deformations of HCP $A_{HCP} > 1$, the residual strength will be lower than the original $\left(\frac{R_{HCP}}{R_{HCP0}} < 1\right)$, which does not correspond to the initial conditions. Under neutron irradiation and heating, such a formula was proposed in a simplified manner based on the fact that accelerated hydration processes occur much earlier than the manifestation of significant HCP deformations.

When exposed to gamma radiation, to fulfill the condition $\frac{R_{HCP}}{R_{HCP0}} = 1$ at $\frac{\Delta V_{HCP}}{V_{HCP}} = 0$ in formula (18) you can add the expression $-0.2625e^{-13.93}$, ensuring the fulfillment of this condition and present formula (18) in the form:

$$A_{HCP} = 0.0705\left(\frac{\Delta V_{HCP}}{V_{HCP}}\right)^2 + 0.3364\frac{\Delta V_{HCP}}{V_{HCP}} + 1.2625 - 0.2625e^{-13.93\frac{\Delta V_{HCP}}{V_{HCP}}}. \quad (18)$$

Results of comparison of radiation changes in the strength of early age concrete and mortars under the influence of gamma radiation calculated using methods of analytical determination of radiation changes in concrete and mortars under neutron irradiation heating with corrected values $A_{HCP}$, and obtained experimentally, are shown in Fig. 8.

In Fig. 8a, the comparison is given in the form of dependences of the calculated and experimental relative residual strength on the value of the absorbed dose. In Fig. 8b, the comparison is given in the form of a ratio between the calculated and experimental values of the relative residual strength.

From Fig. 8, it is evident that the calculated radiation changes in the strength of early age concrete and mortars with the adjusted values $A_{HCP}$ and the experimental changes differ less significantly than with $A_{HCP}$ = 0.724, and along the average lines they differ by no more than 0.1 (10 %). In this case, the maximum deviations and the standard deviation of the experimental results from the calculated data are $\Delta_{R/R_0}^{e/c}$ = 0.3 and $S_{R/R_0}^{e/c}$ = 0.14. Value $S_{R/R_0}^{e/c}$ close to the values of standard deviations shown above when determining $R/R_0$ $S_{R/R_0}^{e}$ = 0.14–0.21. It follows that the values $S_{R/R_0}^{e/c} < S_{R/R_0}^{e}$, therefore $F_e < F_{0.95}$. In this regard, and without determining the actual values of the $F$ -criteria, it can be considered that the above deviations are statistically insignificant.

In this regard, the results obtained using the adjusted parameters $A_{HCP}$ demonstrated the possibility of using existing analytical methods to predict radiation-induced changes in the strength of early age concrete and mortars under the influence of gamma radiation. The maximum prediction error is $\Delta_{R/R_0}^{f}$ = ±0.28 (28 %).

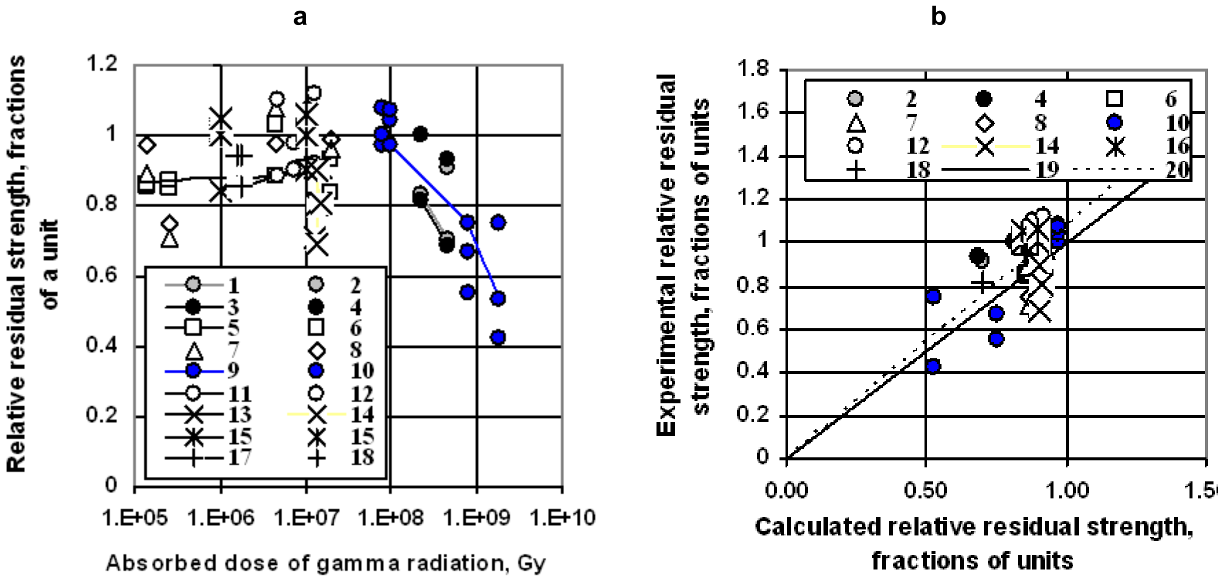


**Figure 8. Comparison of calculated and experimental values of radiation changes in the strength of concrete and mortars as a function of the absorbed dose (a) and as a ratio between calculated and experimental values (b) with corrected values $A_{HCP}$.**
**The symbols are shown in Fig. 6.**

### *3.3. Radiation Changes in the Strength of Mature Concrete*

The results of comparison of experimental (according to the data of the work [30]) and calculated radiation-thermal and radiation changes in the strength of mature concrete under the influence of gamma radiation, calculated using analytical determination methods under neutron irradiation and heating, are shown in Fig. 9.

It is evident from Fig. 9 that the experimental radiation-thermal and radiation changes in the strength of mature concrete are lower than the calculated changes, since the values of the experimental relative residual strength are higher than the calculated values. The differences are from 0.17 to 0.58 (17–58 %). Moreover, the experimental data are closer to the calculated ones for early age concrete.

The differences between the calculated and experimental values of the strength of mature concrete after exposure to gamma radiation can be taken into account by the coefficient $K_{e/c}$, determined by the formula:

$$K_{e/c} = \left(\frac{R_C}{R_{C0}}\right)_{\exp} \Bigg/ \left(\frac{R_C}{R_{C0}}\right)_{com}, \qquad (19)$$

where $\left(\frac{R_C}{R_{C0}}\right)_{\exp}$ and $\left(\frac{R_C}{R_{C0}}\right)_{com}$ are experimental and calculated values of the relative residual strength of concrete after exposure to gamma radiation.

Dependence of coefficients $K_{e/c}$ from the absorbed dose of gamma radiation for radiation-thermal and radiation changes in mature concrete, calculated for the data [30] is presented in Fig. 10.

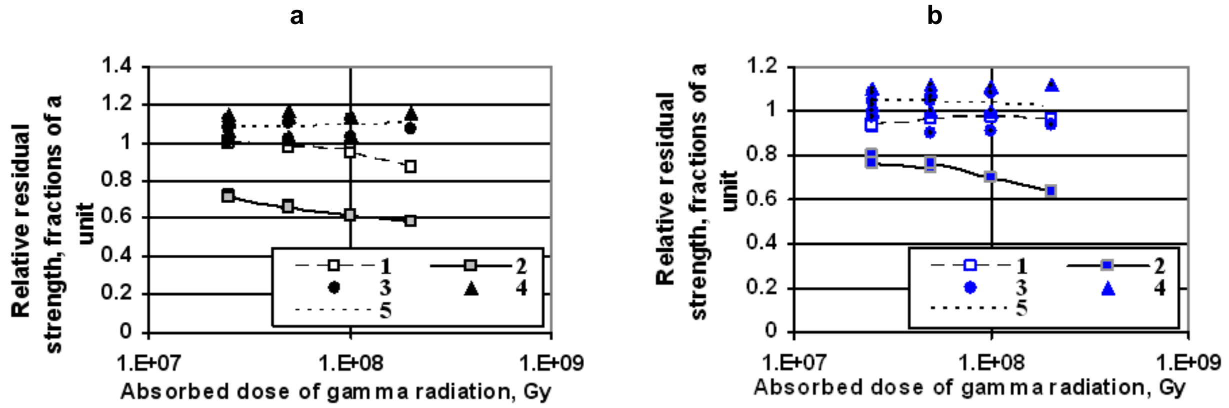


**Figure 9. Comparison of calculated and experimental radiation-thermal (a) and radiation (b) changes in the compressive strength of mature concrete studied after gamma irradiation in [30]:**
1 – calculation results for early age concrete (for comparison);
2 – calculation results for mature concrete; 3 – experimental data on concrete A;
4 – experimental data on concrete B; 5 – approximation line for experimental data.
Radiation-thermal changes are highlighted in black. Radiation changes are highlighted in blue.

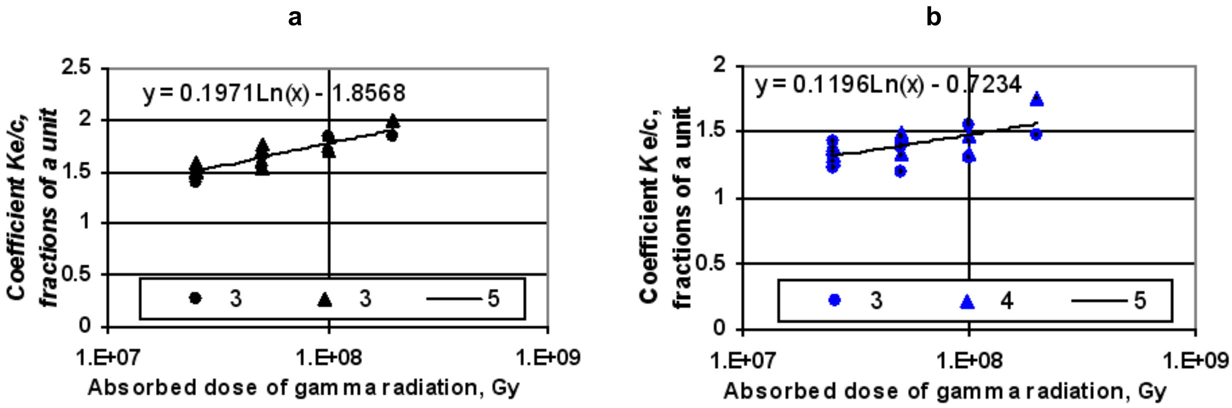


**Figure 10. Dependence of the coefficient $K_{e/c}$ from the dose of gamma radiation for radiation-thermal (a) and radiation (b) changes in mature concrete, calculated for the data [30]:**
3 – based on experimental data for concrete A; 4 – based on experimental data for concrete B;
5 – approximation line.
Radiation-thermal changes are highlighted in black. Radiation changes are highlighted in blue.

For radiation-thermal changes, the dependence of the coefficients $K_{e/c}$ from the absorbed dose of gamma radiation is approximated with the standard deviation $S_{K_{e/c}}$ = 0.078 by the expression:

$$K_{e/c} = 0.1934\ln\left(D_G\right) - 1.7834 \pm 0.16. \qquad (20)$$

For radiation changes, the dependence of the coefficients $K_{e/c}$ from the absorbed dose of gamma radiation is approximated with the standard deviation $S_{K_{e/c}}$ =0.097 by the expression:

$$K_{e/c} = 0.1196\ln\left(D_G\right) - 0.7234 \pm 0.20. \quad (21)$$

Considering that the coefficient of variation $v_R = S/R$ compressive strength in work [30] based on the various results presented there is 0.05–0.1, then when calculating $K_{e/c}$ standard deviation of the calculation $K_{e/c}$ is not less than $S^c_{K_{e/c}} = \left(2v_R^2\right)^{1/2}$ = 1.4 $v_R$ = 0.07–0.14 – for radiation-thermal changes and $S^c_{K_{e/c}} = \left(2v_R^2\right)^{1/2}$ = 1.4 $v_R$ = 0.1–0.2 – for radiation-thermal changes.

It follows that the values $S_{K_{e/c}}$ and $S^c_{K_{e/c}}$ are close in magnitude. It follows that the values $S^{e/c}_{R/R_0} < S^e_{R/R_0}$, therefore $F_e < F_{0.95}$. In this regard, and without determining the actual values of the $F$-criteria, it can be considered that the above deviations are statistically insignificant.

Higher values of residual strength of mature concrete according to experimental data than according to calculations and $K_{e/c} > 1$ cannot be explained by more intensive additional hydration of HCP, since the age of concrete was 11 months and quick-hardening cement was used. The reason for the differences between the considered calculation results and experimental data can be explained by a more significant effect of carbonation during irradiation of mature concrete with gamma radiation than with neutrons and during heating. The increase in the strength of concrete under the action of gamma radiation of the considered concretes was explained in the work [30] by an increase in the degree of carbonation due to the formation of, first of all, vaterite and aragonite, and not calcite.

To verify this statement, the carbonate content in the concretes studied was assessed. The results of determining the carbonate content in mature HCP samples stored before irradiation at a relative humidity of 100 % and 50 %, after irradiation with gamma radiation to an absorbed dose of $5 \cdot 10^7$ Gy and heating in the irradiation temperature mode, presented in the work [41], were used as a basis. The vaterite and aragonite content according to these data in HCP samples stored before irradiation at a relative air humidity of W = 100 % (SDS 100) and 50 % (SDS 100) and the interpolation results at W = 60 % are given in Table 7. The results at W = 60 % were taken as the values of the carbonate content in HCP concretes at an absorbed dose of $5 \cdot 10^7$ Gy and after heating. The carbonate content in HCP concretes at other absorbed doses was taken proportionally to the DTG peak values for concrete *Con-A* in the temperature range of about 600° from work [30]. In this case, the peak value at an absorbed dose of $5 \cdot 10^7$ Gy for 1.

The results of the assessment of the content of vaterite and aragonite in HCP concretes studied in the work [30] are presented in Table 8.

***Table 7. Content of vaterite and aragonite after gamma irradiation up to an absorbed dose of $5 \cdot 10^7$ Gy and heating up to 35 °C According to the data of work [41], the HCP samples stored before irradiation at relative air humidity $W$ = 100 % and 50 % and the interpolation results at $W$ = 60 %.***

| Carbonate | Vaterite and aragonite content (g/g) after gamma irradiation to an absorbed dose of $5 \cdot 10^7$ Gy and heating | | | | | |
|---|---|---|---|---|---|---|
| | for samples hardened at $W$ = 100% (SDS 100) | | for samples hardened at $W$ = 50% (SDS 100) | | interpolation for samples hardened at $W$ = 60% | |
| | after irradiation | after heating | after irradiation | after heating | after irradiation | after heating |
| Aragonite | 0.2258 | 0.0952 | 0.1321 | 0.0557 | 0.151 | 0.064 |
| Vaterite | 0.2364 | 0.0874 | 0.0891 | 0.0515 | 0.119 | 0.059 |

***Table 8. Results of the assessment of the content of vaterite and aragonite in HCP concretes studied in the work [30].***

| **Relative value of DTG peak Δ and the carbonate in question** | **Results of the assessment of the content of vaterite and aragonite (g/g) in HCP concretes studied in the work [30] after irradiation with different absorbed doses of gamma radiation** | | | |
|---|---|---|---|---|
| | **at $D_G$ = 2.5·10^7 Gy** | **at $D_G$ = 5·10^7 Gy** | **at $D_G$ = 1·10^8 Gy** | **at $D_G$ = 2·10^8 Gy** |
| From the effects of radiation and associated heating: | | | | |
| Peak value Δ DTG in the temperature range of about 600°With respect to the peak value at $D_G$ = 5·10^7 Gy | 0.72 | 1.0 | 0.91 | 1.18 |
| Aragonite | 0.108 | 0.151 | 0.137 | 0.178 |
| Vaterite | 0.085 | 0.119 | 0.107 | 0.139 |
| Aragonite + vaterite | 0.193 | 0.270 | 0.244 | 0.317 |
| From the effects of radiation (minus the effect of accompanying heating): | | | | |
| Aragonite | 0.044 | 0.087 | 0.073 | 0.114 |
| Vaterite | 0.026 | 0.060 | 0.048 | 0.080 |
| Aragonite + vaterite | 0.070 | 0.147 | 0.121 | 0.194 |

Dependence of coefficients $K_{e/c}$ for radiation-thermal and radiation changes in the strength of mature concrete [30] from the calculated content of vaterite and aragonite + vaterite in the HCP of concrete are shown in Fig. 11. It is evident that between the content of the considered carbonates and the coefficient $K_{e/c}$ a positive correlation is observed, therefore the increase in the strength of mature concrete can be explained by the increase in the content of aragonite + vaterite in HCP concrete under the influence of gamma irradiation. In this regard, the obtained values of the coefficients and the dependencies approximating them, shown in Fig. 10 and in formulas (20) and (21) can be used as a multiplier in formula (15):

$$\frac{R_{HCP}}{R_{HCP0}} = K_{e/c}\left(A_{HCP} + B_{HCP}\frac{\Delta V_{HCP}}{V_{HCP}}\right)^{-1}. \quad (15^I)$$

a b

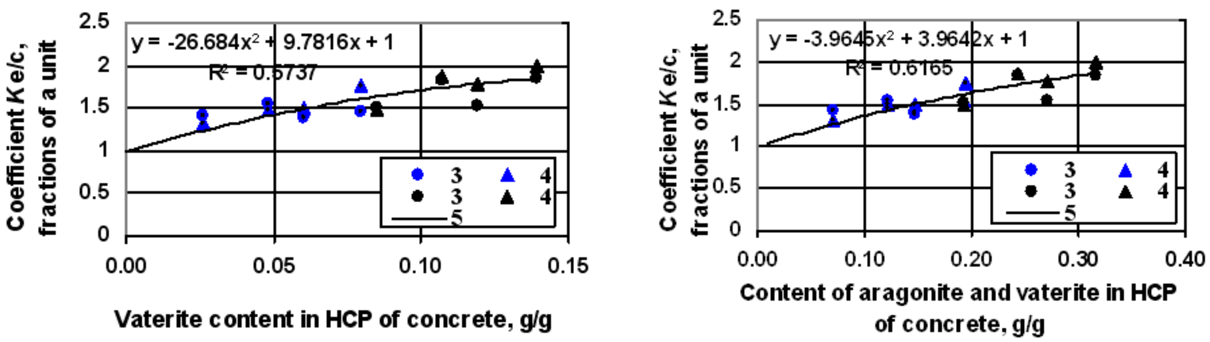


**Figure 11. Dependence of coefficients $K_{e/c}$ for radiation-thermal and radiation changes in the strength of mature concrete [30] from the calculated content of vaterite (a) and aragonite + vaterite (b) in the HCP concrete. Explanations of the symbols are given in Fig. 10.**

Results of comparison of experimental (according to the data of the work [30]) and calculated radiation-thermal and radiation changes in the strength of mature concrete under the influence of gamma radiation, calculated using existing analytical methods for neutron irradiation and heating, taking into account the obtained values $K_{e/c}$, are shown in Figs. 12 and 13.

In Fig. 12, the comparison is given in the form of dependences of the calculated and experimental relative residual strength on the value of the absorbed dose. In Fig. 13, the comparison is given in the form of the ratio between the calculated and experimental values of the relative residual strength.

From Figs. 12 and 13, it is evident that the calculated radiation changes in the strength of mature concrete, taking into account the coefficients $K_{e/c}$ and the experimental radiation-thermal and radiation changes coincide on average. In this case, the maximum deviations and the standard deviation of the experimental results from the calculated data are $\Delta^{e/c}_{R/R_0}$ = ±0.1 and $S^{e/c}_{R/R_0}$ =±0.05 for radiation-thermal changes and $\Delta^{e/c}_{R/R_0}$ = ±0.15 and $S^{e/c}_{R/R_0}$ = ±0.07 – for radiation changes.

Considering that the coefficient of variation $v_R = S/R$ compressive strength in work [30], as shown above, is 0.05–0.1, then the standard deviations in determining $R/R_0$ make up $S^{c}_{R/R_0} = \left(2v_R^2\right)^{1/2}$ = 1.4 $v_R$ = 0.07–0.14. It follows from this that the values $S^{e/c}_{R/R_0}$ and $S^{c}_{R/R_0}$ are close in magnitude. It follows that the values $S^{e/c}_{R/R_0} < S^{e}_{R/R_0}$, therefore $F_e < F_{0.95}$. In this regard, and without determining the actual values of the $F$-criteria, it can be considered that the above deviations are statistically insignificant.

In this regard, the results obtained using the coefficient $K_{e/c}$ demonstrated the possibility of using existing analytical methods to predict radiation-induced changes in the strength of mature concrete under the influence of gamma radiation, taking into account carbonation. The maximum prediction error for the concretes under consideration with the carbonation occurring in them is $\Delta^{f}_{R/R_0}$ = ±0.14 (14 %).

At the same time, it should be taken into account that the carbonation of concrete has not been sufficiently studied. In this regard, with a reserve, radiation, and radiation-thermal changes in mature concrete under the influence of gamma radiation are still preferably determined at $K_{e/c}$ = 1 (excluding carbonation).

Further studies should be devoted to a more rigorous justification of the method for accounting for the growth of the strength of HCP and concrete under gamma irradiation due to carbonization. For this purpose, it is necessary to study in more detail the processes of carbonization of concrete under gamma irradiation, check and, if necessary, clarify the dependences of strength and coefficients $K_{e/c}$ from carbonation parameters.

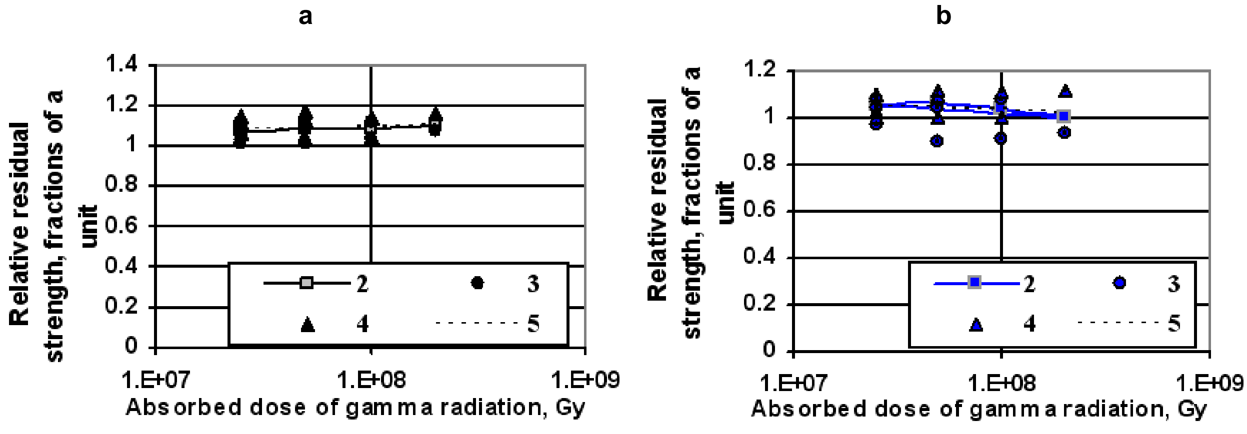


**Figure 12. Comparison of calculated and experimental radiation-thermal (a) and radiation (b) changes in the compressive strength of mature concrete studied after gamma irradiation in [30]:**
**2 – calculation results for mature concrete; 3 – experimental data on *Con-A* concrete; 4 – experimental data on *Con-B* concrete; 5 – approximation line for experimental data. Explanations of the symbols are given in Fig. 10.**

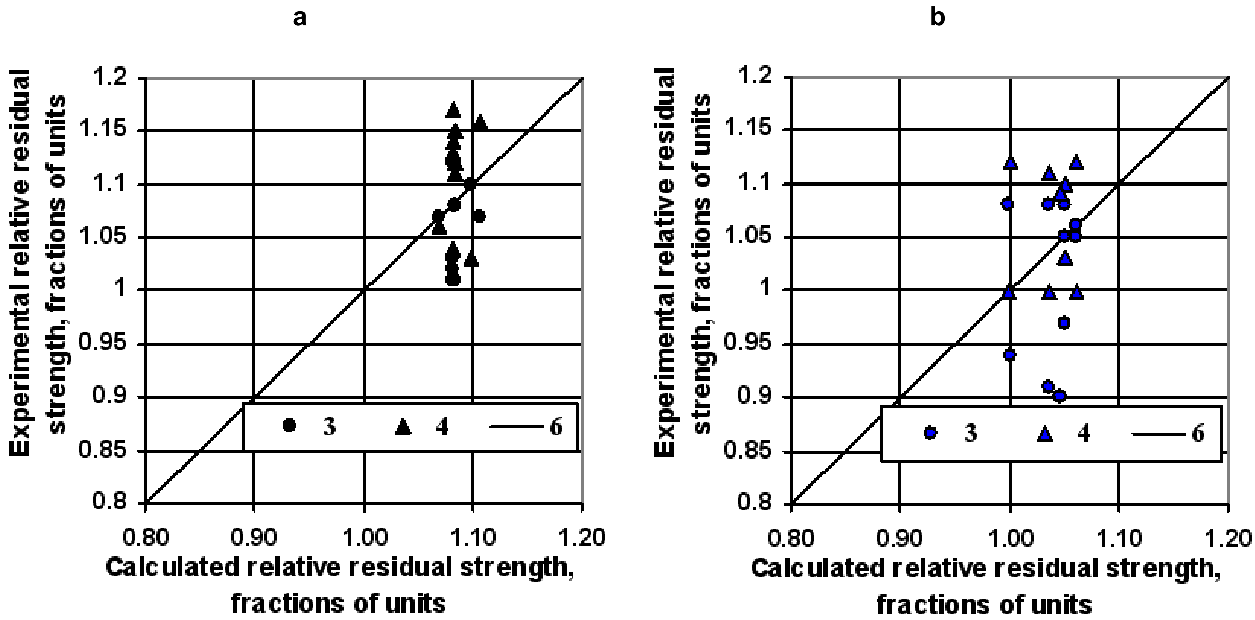


**Figure 13. Comparison of calculated and experimental values of radiation-thermal (a) and radiation (b) changes in the strength of mature concrete studied after gamma irradiation in [30] in the form of a ratio between calculated and experimental values using the obtainedvalues $K_{e/c}$: 6 – line of equality of experimental and calculated values. Other explanations for the symbols are given in Fig. 10.**

## 4. Conclusion

1. The studies carried out in this work were carried out due to insufficient knowledge in effects of gamma radiation on concrete compared to the study of the effects of neutron radiation. Although the volumes of concrete at nuclear power plants and other nuclear power facilities exposed to gamma radiation are more significant than the volumes exposed to neutrons.
2. When conducting the research, we took into account the availability of developed and experimentally tested methods for analytical determination of radiation, thermal and radiation-thermal changes in concrete and its components under neutron irradiation and heating, as well as radiation changes in aggregates and HCP under the influence of gamma radiation. In this regard, the aim of this work was to establish the possibility of using these existing analytical methods to predict radiation changes in concrete and mortar under the influence of gamma radiation. In this case, we used the experimental results of the influence of gamma irradiation on 7 different concretes and 11 cement mortars available in the literature.
3. Research carried out in the work demonstrated the possibility of using existing analytical methods to predict radiation-induced changes in the dimensions of concrete when exposed to gamma radiation. The maximum prediction error is $\Delta^{c}_{\Delta\ell/\ell}$ = ±0.00 1% at absorbed doses less than $7 \cdot 10^5$ Gy and $\Delta^{c}_{\Delta\ell/\ell}$ = ±0.04 % at absorbed doses $(2.27–4.7) \cdot 10^8$ Gy.
4. The results of the studies of predicting radiation changes in the strength of early age concrete and cement mortars under the influence of gamma radiation showed significant differences between the calculated and experimental changes when using existing analytical methods applied under neutron irradiation and heating without their correction. This required revising the previously accepted position that the processes of accelerating hydration and carbonization of early age HCP under the influence of gamma radiation with the same value of volume change are the same as under the influence of irradiation and heating. Apparently, in these processes (especially acceleration of hydration) under neutron irradiation-heating and under gamma irradiation there are differences, which it is proposed to take into account in the parameter $A_{HCP}$ for HCP.

5. Based on calculations from experimental data parameter values $A_{HCP}$ and comparing their values with the HCP deformations, the dependence of the parameter was established $A_{HCP}$ from the calculated decrease in the volume of HCP of early age concretes and mortars. A mathematical expression has been established that adequately approximates this dependence.

6. Results of computational studies using adjusted parameters $A_{HCP}$ demonstrated the possibility of using existing analytical methods to predict radiation-induced changes in the strength of early age concrete and mortars under the influence of gamma radiation. The maximum prediction error is $\Delta^{f}_{R/R_0}$ = ±0.28 (28 %)

7. The results of the studies of predicting radiation changes in the strength of mature concrete under the influence of gamma radiation, as of early age showed significant differences between the calculated and experimental changes when using existing analytical methods applied during neutron irradiation and heating without their correction. At the same time, the differences between the calculated and experimental values of residual relative strength are from 0.17 to 0.58 (17–58 %). It is proposed to take into account the differences between the calculated and experimental values of the strength of mature concrete after exposure to gamma radiation by the coefficient $K_{e/c} \geq 1,$ the values of which increase with increasing absorbed dose.

8. The authors who experimentally studied these concretes explained the increase in the strength of the considered concretes under the influence of gamma radiation by an increase in the degree of carbonization due to the formation of, first of all, vaterite and aragonite, and not calcite. In this regard, higher values of residual strength of mature concretes according to experimental data than according to calculations and $K_{e/c} > 1$ can be explained by a more significant influence of carbonation during irradiation of mature concrete with gamma radiation than with neutrons and during heating. The results of the assessment of the content of aragonite and vaterite in the HCP of concretes of the considered concretes and the established correlation between $K_{e/c}$ and the content of these carbonates confirm the validity of this statement.

9. Results of calculation studies using the coefficient $K_{e/c}$ demonstrated the possibility of using existing analytical methods to predict radiation-induced changes in the strength of mature concrete under the influence of gamma radiation, taking into account carbonation. The maximum prediction error for the concretes under consideration with the carbonation occurring in them is $\Delta^{f}_{R/R_0}$ = ±0.14 (14 %). At the same time, it should be taken into account that the carbonation of concrete has not been sufficiently studied. In this regard, with a reserve, radiation, and radiation-thermal changes in mature concrete under the influence of gamma radiation are still preferable to determine at $K_{e/c}$ = 1 (excluding carbonation).

10. Further research should be devoted to a more rigorous justification of the method for accounting for the growth of the strength of HCP and concrete under gamma irradiation due to carbonization. For this purpose, it is necessary to study in more detail the processes of carbonization of concrete under gamma irradiation, check, and, if necessary, clarify the dependences of strength and coefficients $K_{e/c}$ from carbonation parameters.

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