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Radiation changes in hardened Portland cement paste under the influence of gamma radiation

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Keywords: Portland cement, hardened cement paste, gamma radiation, influence of heating, radiation changes, radiation damage, thermal changes, linear dimensions, strength, forecasting.

Abstract. The possibility of using materials in radiation protection shields when designing new and extending the service life of existing nuclear energy facilities requires knowledge or the ability to predict their radiation changes. The studies were carried out due to the lack of data sufficient to predict radiation changes in hardened Portland cement paste (HPCP) and concrete under the influence of gamma radiation when used as radiation shield materials for nuclear energy facilities. The research is based on published data on the effect of gamma radiation on concrete at irradiation temperatures of 20–30 °C and on HPCP at 70–375 °C. The author carried out computational and analytical studies to assess and establish the possibility of predicting radiation changes in HPCP under the influence of gamma radiation. The studies were conducted using the previously developed and tested method of analytical determination of radiation changes in concretes according to data on changes in their components. The formulas used in this method made it possible to determine (restore) the radiation changes of the HPCP from experimental data on radiation changes in concretes and aggregates. According to the available results of concrete irradiation, changes in linear dimensions and strength during compression of HPCP under the action of only gamma radiation were calculated (restored). The dependences of radiation changes in HPCP on the magnitude of the absorbed dose in the range from $3.8{\cdot}10^4$ to $4.7{\cdot}10^8$ Gy after irradiation at 20–30 °C were established. According to the available data on the irradiation of HPCP with gamma radiation at temperatures from 70 °C to 375 °C, the effect of the irradiation temperature on radiation changes in the HPCP was revealed. Mathematical expressions that approximate the established dependencies are selected. On the basis of the obtained mathematical expressions, radiation changes in the linear dimensions and strength of HPCP for compression, caused only by the action of gamma radiation, after irradiation to the values of absorbed doses from $3{\cdot}10^4$ Gy to $1{\cdot}10^{10}$ Gy were calculated. The calculations of radiation-thermal changes in the linear dimensions and strength of HPCP under the action of gamma radiation and heating after irradiation to the values of absorbed doses from $3{\cdot}10^4$ Gy to $1{\cdot}10^{10}$ Gy and the accompanying heating at temperatures from 20 °C to 500 °C were estimated.

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1. *Introduction*

Facilities with various nuclear installations provide sources of ionizing radiation that can cause radiation changes in concrete building structures and radiation protection. The most important are radiation deformations (changes in linear dimensions (or dimensions) and volume) and strength.

The most significant radiation changes in concretes are caused by neutron radiation, so the effect of neutrons on concretes and their components is the most studied and described in the most detail in the research works [1–12]. There are methods of analytical determination (calculation) of radiation and thermal changes in concretes and their components described in the research works [9, 13–15]:

- concretes according to data on radiation and thermal changes in their components (aggregates and hardened cement paste);
- aggregates according to data on radiation and thermal changes in crystals of their constituent minerals;
- minerals under the action of neutrons according to data on fluence and neutron spectrum, irradiation temperature;
- hardened Portland cement paste (HPCP) under the action of neutrons according to data on fluence and neutron spectrum, irradiation temperature.

The available methods of analytical determination are based on a number of simplifications considering that microstructural stresses due to cracking in concretes completely relax, and in aggregates are reset to the value of tensile strength, therefore they have a fairly simple, convenient for analysis and use type. However, despite the simplifications, the possibility of practical use of these methods is shown experimentally.

Work is also being carried out on numerical modeling of the processes of radiation changes, crack formation, creep and plasticity of concretes and their components, described, for example, in the research works [16–22]. Numerical methods more strictly take into account the processes occurring in concretes and their components, but are associated with the use of a large number of parameters, not all of which can be determined accurately enough. In this regard, these methods do not give more accurate results than the methods described in the research work [9, 13–15].

The effect of gamma radiation on concretes and their components is not studied well, though the volumes of concrete exposed to gamma radiation are more significant than the volumes exposed to neutrons. Only a few data are available on specific concretes and mortars [1, 2, 7, 10–12, 23–38] indicating the presence of radiation changes after exposure to gamma radiation. Moreover, some authors (for example, [35, 36] associate changes in concrete after exposure to gamma radiation by the effect of heating in the process of irradiation. Although there is evidence, for example, [1, 2, 25], indicating a change in the linear dimensions and properties of concretes after irradiation at temperatures of 20–30 °C.

Radiation changes in concretes under the influence of gamma radiation can be determined by the mentioned above method of analytical determination of radiation and thermal changes in concretes from data on radiation and thermal changes in their components (aggregates and hardened cement paste). The use of this method is permissible, since the cause of the changes does not matter, since the method has been tested both when exposed to neutrons and when exposed to heating. However, this requires data on radiation changes in aggregates and HPCP. To do this, it must be possible to predict radiation changes in aggregates and HPCP under the influence of gamma radiation.

Evaluation and substantiation of forecasting radiation changes in concrete aggregates under the influence of gamma radiation at different absorbed doses and irradiation temperatures were performed in the research work [39].

For HPCP, it is not possible to predict its radiation changes. There are limited data [27, 29, 31–36, 38] on the change in linear dimensions, structure, mass, strength after irradiation with small doses of gamma radiation (up to $5{\cdot}10^7$ Gy mainly at elevated temperatures (from 70 to 375 °C). Moreover, changes in HPCP after irradiation with gamma radiation, as well as concretes, are associated mainly with the effect of heating accompanying irradiation. However, taking into account the results of the study of concrete after irradiation at 20–30 °C, gamma radiation causes a decrease in the dimensions (shrinkage) of HPCP, as there is a decrease in the dimensions of concrete. In this regard, further research is needed.

In general, the available experimental data do not allow to predict radiation deformations and changes in strength under the influence of gamma radiation for concretes of any composition and at higher absorbed doses. In this regard, the purpose of this research work is to establish, on the basis of existing experimental data, radiation changes in HPCP under the influence of gamma radiation and to establish the possibility of predicting them in a wide range of absorbed doses and temperatures of irradiation. Achieving this goal will make it possible to analytically determine the radiation changes in concretes under the influence of gamma radiation.

To achieve this goal, the following tasks were solved:

- Development of methods of computational and analytical studies;

- Selection and analysis of available published data on radiation changes in concretes and their components under the influence of gamma radiation, which can be used to perform computational studies;
- Establishment on the basis of available experimental data obtained on the basis of computational and analytical studies of radiation changes in HPCP under the influence of gamma radiation and their dependencies on the absorbed dose, temperature and possible other factors. Selection of mathematical expressions that approximate established dependencies.

2. Methods

The introduction showed that the available publications provided limited data on radiative changes in the linear dimensions and strength of HPCP under the influence of gamma radiation and mainly at elevated temperatures. However, there are data on radiation changes in concrete after irradiation with gamma radiation at 20–30 °C in a relatively wide range of absorbed doses. In this regard, the values of radiation changes in HPCP under the influence of gamma radiation alone and their dependence on the absorbed dose were determined by calculation from the available experimental data on the effect of gamma radiation on concretes at 20–30 °C. To do this, the method of analytical determination of radiation changes in concretes was used according to data on changes in their components. The formulas used in this method make it possible to reconstruct the radiation changes of the HPCP from the data on radiation changes in concretes and aggregates.

When calculating radiation changes in linear dimensions (deformations), the following formulas of the method of analytical determination of radiation deformations of concretes based on data on radiation deformations of their components (HPCP, fine aggregate, coarse aggregate), described in the research works [9, 13, 15], were used, given with a slight error in a more convenient form:

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

$$\frac{\Delta V_{C}}{V_{C}}=\frac{\Delta V_{CA}}{V_{CA}}\left(C_{com}^{CA}\right)^{\frac{1}{3}}+\left[1-\left(C_{com}^{CA}\right)^{\frac{1}{3}}\right]\frac{\Delta V_{CM}}{V_{CM}}, \tag{2}$$

where $\frac{\Delta V_{CM}}{V_{CM}}$ and $\frac{\Delta V_{C}}{V_{C}}$ are relative changes in the volume of mortar and volume of concrete, respectively, %; $\frac{\Delta V_{FA}}{V_{FA}}$, $\frac{\Delta V_{CA}}{V_{CA}}$ and $\frac{\Delta V_{CP}}{V_{CP}}$ show the radiation changes in the volume of fine aggregate, coarse aggregate and HPCP in the composition of concrete, respectively, %; C_{com}^{FA} and C_{com}^{CA} show the degree of compression of fine aggregate in mortar of concrete and coarse aggregate in concrete, determined by the formulas:

$$C_{com}^{FA}=\frac{V_{FA}}{V_{CA+FA}^{com}-V_{CA}}, \tag{3}$$

$$C_{com}^{CA}=\frac{V_{CA}}{V_{CA}^{com}}, \tag{4}$$

where V_{FA} and V_{CA} show the relative volume content of fine aggregate and coarse aggregate in concrete, respectively (in relative units); V_{CA+FA}^{com} is the maximum relative volume content of the mixture of fine aggregate and coarse aggregate in the case of their maximum compacted state (without layers of HPCP between particles) (in relative units), which is 0.77–0.93. By [9] V_{CA+FA}^{com} = 0.86 can be taken; V_{CA}^{com} is the maximum relative volume content of coarse aggregate in the case of its maximum compacted state (without layers of mortar between particles) (in relative units), which is 0.52–0.74. According to [9], we can take V_{CA}^{com} = 0.63.

On the basis of formulas (1) and (2), taking into account that the relative change in volume $\frac{\Delta V}{V}$ and linear dimensions $\frac{\Delta \ell}{\ell}$ are related by the ratio $\frac{\Delta V}{V} \approx 3\frac{\Delta \ell}{\ell}$, according to the existing data of the research works [1, 2, 25] on radiation changes in the linear dimensions of Portland cement concretes under the influence of gamma radiation, changes in the dimensions of the mortar (on the 1st stage), and then the HPCP were calculated sequentially according to the formulas:

$$\frac{\Delta \ell_{CM}}{\ell_{CM}} = \frac{\frac{\Delta \ell_{C}}{\ell_{C}} - \frac{\Delta \ell_{CA}}{\ell_{CA}}\left(C_{com}^{CA}\right)^{\frac{1}{3}}}{\left[1-\left(C_{com}^{CA}\right)^{\frac{1}{3}}\right]}, \tag{5}$$

$$\frac{\Delta \ell_{CP}}{\ell_{CP}} = \frac{\frac{\Delta \ell_{CM}}{\ell_{CM}} - \frac{\Delta \ell_{FA}}{\ell_{FA}}\left(C_{com}^{FA}\right)^{\frac{1}{3}}}{\left[1-\left(C_{com}^{FA}\right)^{\frac{1}{3}}\right]}, \tag{6}$$

when calculating radiation changes in the strength of HPCP in the composition of concrete in the form of relative residual strength, the following formulas were used for the method of analytical determination of radiation changes in the strength of concretes and mortars according to data on radiation deformations and changes in the strength of their components (HPCP, fine aggregate, coarse aggregate), described in the research works [9, 15], given in a more convenient form:

$$\frac{R_C}{R_{C0}} = \frac{R_{CM}}{R_{CM0}}\left(\frac{R_{CA}}{R_{CA0}}\right)^{0.29}\left\{1+\left[A_C\left(\frac{\Delta V_C}{V_C}\right)_{cr}\right]^2\right\}^{-1}, \tag{7}$$

$$\frac{R_{CM}}{R_{CM0}} = \frac{R_{CP}}{R_{CP0}}\left(\frac{R_{FA}}{R_{FA0}}\right)^{0.29}\left\{1+\left[A_C\left(\frac{\Delta V_{CM}}{V_{CM}}\right)_{cr}\right]^2\right\}^{-1}, \tag{8}$$

where $\frac{R_C}{R_{C0}}$, $\frac{R_{CM}}{R_{CM0}}$, $\frac{R_{CA}}{R_{CA0}}$, $\frac{R_{CP}}{R_{CP0}}$, $\frac{R_{FA}}{R_{FA0}}$ is a relative after exposure to radiation residual strength of concrete, mortar, coarse aggregate, HPCP, fine aggregate, accordingly, unit fraction; A_C is parameter equal to:

A_C = 0.31 %$^{-1}$ – for compressive strength;

A_C = 0.53 %$^{-1}$ – for tensile strength;

$\left(\frac{\Delta V_C}{V_C}\right)_{cr}$ and $\left(\frac{\Delta V_{CM}}{V_{CM}}\right)_{cr}$ – radiation change in the volume of concrete and mortar due to the formation of microcracks, respectively, in %, determined by the formulas:

$$\left(\frac{\Delta V_C}{V_C}\right)_{cr} = \frac{\Delta V_C}{V_C} - \frac{\Delta V_{CA}}{V_{CA}}V_{CA} - \frac{\Delta V_{CM}}{V_{CM}}\left(1-V_{CA}\right), \tag{9}$$

$$\left(\frac{\Delta V_{CM}}{V_{CM}}\right)_{cr} = \frac{\Delta V_{CM}}{V_{CM}} - \frac{\Delta V_{FA}}{V_{FA}}\frac{V_{FA}}{1-V_{CA}} - \frac{\Delta V_{CP}}{V_{CP}}\left(1-\frac{V_{FA}}{1-V_{CA}}\right), \tag{10}$$

Based on existing experimental data in the work after determination by formulas (5) and (6) values $\frac{\Delta\ell_{CM}}{\ell_{CM}}$ and $\frac{\Delta\ell_{CP}}{\ell_{CP}}$ based on values $\frac{\Delta V_{CM}}{V_{CM}}=3\frac{\Delta\ell_{CM}}{\ell_{CM}}$ and $\frac{\Delta V_{CP}}{V_{CP}}=3\frac{\Delta\ell_{CP}}{\ell_{CP}}$ using the formulas (9) and (10) calculated the values $\left(\frac{\Delta V_C}{V_C}\right)_{cr}$ and $\left(\frac{\Delta V_{CM}}{V_{CM}}\right)_{cr}$. After that, on the basis of the expressions (7) and (8) $\frac{R_{CM}}{R_{CM0}}$ and $\frac{R_{CP}}{R_{CP0}}$ were calculated according to the formulas:

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

$$\frac{R_{CP}}{R_{CP0}}=\frac{R_{CM}}{R_{CM0}}\left(\frac{R_{FA}}{R_{FA0}}\right)^{-0.29}\left\{1+\left[A_C\left(\frac{\Delta V_{CM}}{V_{CM}}\right)_{cr}\right]^2\right\}, \tag{12}$$

The possibility of determining changes in the compressive strength of HPCP under the influence of gamma radiation was also considered from data on volume change. At the same time, the formula presented in the research works [9, 14] after irradiation in a nuclear reactor and heating was used:

$$\frac{R_{CP}}{R_{CP0}}=\left(A_{CP}+B_{CP}\frac{\Delta V_{CP}}{V_{CP}}\right)^{-1} \tag{13}$$

where A_{CP} and B_{CP} are parameters which values are [9, 14]: A_{CP} = 0.724; B_{CP} = – 0.0566 %$^{-1}$ for HPCP of "young" age (1 – 3 months of natural hardening); A_{CP} = 1.00; B_{CP} = –0.23 %$^{-1}$ – for HPCP of "mature" age (more than 8 months of natural hardening or after thermo-humid treatment of a lower age).

Although it should be borne in mind that the expression (13) does not take into account the possible increase in the strength of HPCP when exposed to gamma radiation due to a decrease in the porosity of HPCP due to carbonization, shown in the research works [26, 29, 32]. In this regard, when using formula (13), radiation changes may be somewhat overestimated. Therefore, the formula can allow us to evaluate the maximum possible effect of gamma radiation.

To establish, on the basis of computational and analytical studies, the magnitude of radiation changes in HPCP under the influence of gamma radiation and their dependence on the absorbed dose were used experimental data from the research work [1, 2, 25] on studies of the effect of gamma radiation on concretes. Radiation changes in aggregates (fine aggregate and coarse aggregate) were taken on the basis of the calculated data of the research work [39].

In the research work of McDowell [25], samples with a diameter of 105 mm, a height of 305 mm of concrete made of Portland cement "Sulfacrete", coarse aggregate with a linear dimensions of approximately 20 mm of limestone and quartz fine aggregate were examined. In the manufacture of samples, a water-cement ratio *of* W/C = 0.47 and the ratio of aggregate consumption (coarse aggregate CA + fine aggregate FA) to the consumption of Portland cement PC $(CA+FA)/PC$ = 4.5 were used. The plasticizer "Plastocrete" was injected in an amount of 0.005 by weight of cement. After aging for 24 hours in wet conditions, the samples were covered with POP (plaster of Paris), sealed in copper foil 0.127 mm thick and stored for a year until the tests. In this regard, samples of "mature" age were irradiated. Judging by the data of the granulometric composition of the aggregates based on the results of sieving, the proportion of coarse aggregate and fine aggregate consumption in the aggregate mixture was $CA/(CA+FA)$ = 0.61 and $FA/(CA+FA)$ = 0.39. The technological characteristics of the concrete mixture and concrete were determined on the basis of the above mentioned proportions of the components of the concrete mixture. At the same time, the density values of Portland cement, fine aggregate, coarse aggregate and concrete mixture took γ_{PC} =3100 Kg/m^3, $\gamma_{FA}=\gamma_{CA}$ = 2600 Kg/m^3, γ_{MC} = 2400 Kg/m^3, as the most likely values. Portland cement consumption PC, coarse aggregate *CA*, fine aggregate *FA* and water *W*, as well as the volumetric content of the aggregates were taken to be 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. Calculated by formulas [3] and [4] the degree of compression of aggregates with V_{CA+FA}^{com} = 0.86, V_{CA}^{com} = 0.63 was:

$$C_{com}^{S} = \frac{V_{FA}}{V_{CA+FA}^{com} - V_{CA}} = \frac{0.27}{0.86 - 0.42} = 0.614;$$

$$C_{com}^{CA} = \frac{V_{CA}}{V_{CA}^{com}} = \frac{0.42}{0.63} = 0.667.$$

Irradiation of samples was carried out at 30 °C on a gamma device with a Co^{60} emitting gamma quanta with energy E_γ = 1.17 and 1.33 MeV at a dose rate P_γ = 11.4·10^3 rad/h = 114 Gy/h for t = 10-314 days. The maximum absorbed dose of gamma radiation was D_G = $P_g t$ = 114·314·24 = = 8.6·10^{5}Gy. We studied the change in the linear dimensions of samples as a result of creep under load 10 H/mm^2 = 10 MPa and shrinkage. Creep and shrinkage deformations were measured during irradiation (when processes took place and under the action of gamma radiation and with natural hardening and drying in time) and without irradiation (when the processes took place only due to natural hardening and drying in time).

The advantage of the results of the research work [25] is the absence of significant heating during irradiation and the possibility of taking into account natural shrinkage. This made it possible to obtain in the present work the effect of the influence of gamma radiation according to the formula:

$$\left(\frac{\Delta\ell_C}{\ell_C}\right)_G = \left(\frac{\Delta\ell_C}{\ell_C}\right)_R - \left(\frac{\Delta\ell_C}{\ell_C}\right)_{WR}, \quad (14)$$

where $\left(\frac{\Delta\ell_C}{\ell_C}\right)_G$, $\left(\frac{\Delta\ell_C}{\ell_C}\right)_R$ and $\left(\frac{\Delta\ell_C}{\ell_C}\right)_{WR}$ is reduction of the dimensions (deformation of shrinkage) of concrete under the action of gamma radiation only, with- and without irradiation, respectively.

The disadvantage is the relatively low values of absorbed doses.

The results obtained in the work [25] showing the dependence of the shrinkage of the studied concrete on time with irradiation and without irradiation were used in this work and are given in Fig. 1. In this figure and beyond, a decrease in dimensions (shrinkage) was not seen as a change with a minus sign, but as a decrease without specifying a sign, given that the decrease implies a negative change. This was convenient for automatically constructing trend lines, like approximation lines, on charts.

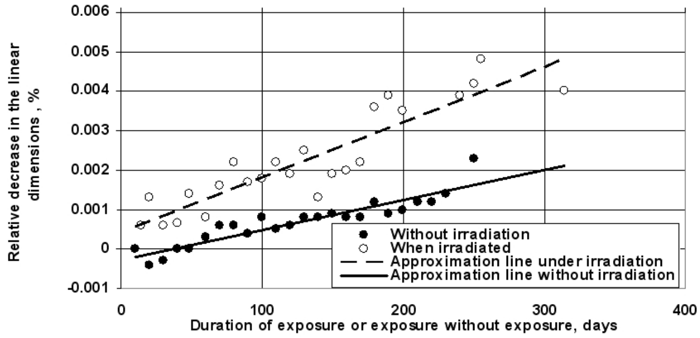

Figure 1. Dependence of the relative decrease in the linear dimensions of concrete (shrinkage) when irradiated with gamma radiation at an absorbed dose rate of 11^4 Gy/h at 30 °C and exposure without irradiation from the time of irradiation and exposure without irradiation according to [25].

In the research works [1, 2], samples in the form of disks with a diameter of 44.5 mm with a thickness of 12.7 mm of two types of concretes made on Portland cement with sandstone aggregates with a density of 2625 Kg/m^3 and with a limestone aggregate with a density of 2550 Kg/m^3 were examined. The ratio between the mass of Portland cement PC, coarse aggregate approximately up to 10 mm CA, fine aggregate FA and water W was the following:

$PC{:}CA{:}FA{:}W$ = 1:1.55:1.15:0.36 – for concrete from limestone coarse aggregate and sandstone fine aggregate (hereinafter concrete from sandstone and limestone);

$PC{:}CA{:}FA{:}W$ = 1:1.77:0.93:0.36 – for concrete from limestone coarse aggregate and limestone fine aggregate (hereinafter concrete from limestone).

The density of concrete from sandstone was γ_C = 2310 Kg/m^3. The density of concrete from limestone was 2380 Kg/m^3.

Based on the above-mentioned proportions and density of aggregates with the most likely density of the concrete mixture γ_{MC} = γ_C + 100 Kg/m^3, the consumption of cement, aggregates and water, as well as the volume content of aggregates, were taken to be equal:

– PC = 594 Kg/m^3, CA = 921 Kg/m^3, FA = 683 Kg/m^3, W = 214 Kg/m^3, V_{CA} = 0.361, V_{FA} = 0.260 in concrete from limestone and sandstone;
– PC = 611 Kg/m^3, CA = 1081 Kg/m^3, FA = 571 Kg/m^3, W = 220 Kg/m^3, V_{CA} = 0.424, V_{FA} = 0.224 in concrete from limestone;

Calculated from formulas (3) and (4), the degree of compaction of aggregates at V_{CA+FA}^{com} = 0.86, V_{CA}^{com} = 0.63 was:

– $C_{com}^{FA} = \dfrac{V_{FA}}{V_{CA+FA}^{com} - V_{CA}} = \dfrac{0.26}{0.86-0.351} = 0.511$; $C_{com}^{CR} = \dfrac{V_{CA}}{V_{CA}^{com}} = \dfrac{0.361}{0.63} = 0.573$ – in concrete from limestone and sandstone;
– $C_{com}^{FA} = \dfrac{V_{FA}}{V_{CA+FA}^{com} - V_{CA}} = \dfrac{0.224}{0.86-0.424} = 0.514$; $C_{com}^{CA} = \dfrac{V_{CA}}{V_{CA}^{com}} = \dfrac{0.424}{0.63} = 0.673$ – in concrete from limestone.

Irradiation of concrete samples with gamma radiation was carried out in a pool with radioactive substances (apparently, in the storage pool of spent fuel elements of a nuclear reactor) at 20 °C at an absorbed dose rate of $5{\cdot}10^4$ Gy/h = $1.4{\cdot}10^1$ Gy/s. The maximum absorbed dose was $4.7{\cdot}10^8$ Gy. By the time of irradiation, the age of the samples was at least 3 months after manufacturing and storing them under normal conditions, so the material of "young" age was actually studied.

The results obtained in the research works [1, 2] of the change in linear dimensions, mass and strength of concretes after irradiation with gamma radiation used in this work are given in Table 1.

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

Name of concrete by aggregates	Absorbed dose of gamma radiation, Gy	Relative linear dimension changes,% of the border average	Relative changes in mass, %	Relative residual strength, fractions of a unit
Concrete from limestone and sandstone	$2.27{\cdot}10^8$	-0.17 ….+0.076 -0.005±0.066	-0.77….-1.01 -0.903±0.072	-
	$4.7{\cdot}10^8$	-0.21 ….+0.04 -0.021±0.082	-1.74….-2.14 -1.91±0.14	0.91±0.23
Concrete from limestone	$2.27{\cdot}10^8$	-0.15 ….+0.04 -0.031±0.057	-0.95….-1.70 -1.15±0.24	1.0±0.09
	$4.7{\cdot}10^8$	-0.21 ….+0.04 -0.061±0.071	-1.42….-3.38 -2.36±0.67	0.93±0.05

*The average quadratic deviations calculated by the authors of this research work

The advantage of the results of the research work [1, 2] is the higher values of the absorbed doses of gamma radiation than in the research work [25]. The disadvantage of these results is the significant variation in the magnitudes of the shrinkage deformations of individual samples associated with the peculiarities of using samples in the form of disks, as well as the lack of measurement results without irradiation. However, the average changes in the linear dimensions of concrete samples in the research 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 concretes are caused by the release of water, accompanied by a decrease in mass, the deformation of shrinkage can also be estimated by the change in mass based on the relationship between mass reduction and shrinkage after irradiation in reactors and heating, shown in the research work [9].

In this regard, the assessment of the change in the linear dimensions of HPCP under the influence of gamma radiation was also carried out according to the data on the decrease in the mass of concrete.

By reducing the mass of concrete, based on the density of concrete and the consumption of aggregates, the relative decrease in the mass of HPCP was determined by the formula:

$$\frac{\Delta M_{CP}}{M_{CP}} = \frac{\Delta M_C}{M_C} \cdot \frac{\gamma_C}{\gamma_C - CA - FA} \tag{15}$$

where $\frac{\Delta M_C}{M_C}$ and $\frac{\Delta M_{CP}}{M_{CP}}$ are relative reduction in the mass of concrete and HPCP; γ_C is concrete density, Kg/m^3; CA and FA are consumption of coarse aggregate and fine aggregate, Kg/m^3; $\gamma_C - CA - FA$ is value equal to the content of HPCP in concrete, Kg/m^3.

Further, according to the magnitude of the decrease in the mass of HPCP according to the dependence shown in the research work [9], the change in volume was estimated, as well as decrease in the linear dimensions of the HPCP.

To do this, according to the ratio between the change in the volume and mass of the HPCP after irradiation in the reactors and heating, shown in the research work [9], the inverse relationship between the change in the mass and volume of the HPCP after these effects, presented in Fig. 2, was built and approximated.

According to the results of the approximation of the dependence of Fig. 2, the expression was used to determine the change in the linear dimensions of the HPCP by changing its mass:

$$\frac{\Delta \ell_{CP}}{\ell_{CP}} = \frac{1}{3} \cdot \frac{\Delta V_{CP}}{V_{CP}} = \frac{1}{3} \cdot 0.9304 \left(\frac{\Delta M_{CP}}{M_{CP}} \right)^{0.7282}. \tag{16}$$

According to the formulas (9) – (12), on the basis of data on radiation changes in the dimensions of concrete, HPCP and aggregates under the influence of gamma radiation, as well as data on changes in the strength of concrete and aggregates, the values of radiation changes in the strength of HPCP were calculated (restored).

The effect of irradiation temperature on radiation changes in HPCP under the influence of gamma radiation was determined on the basis of data from the research works [35, 36] on irradiation of HPCP at 70–375 °C.

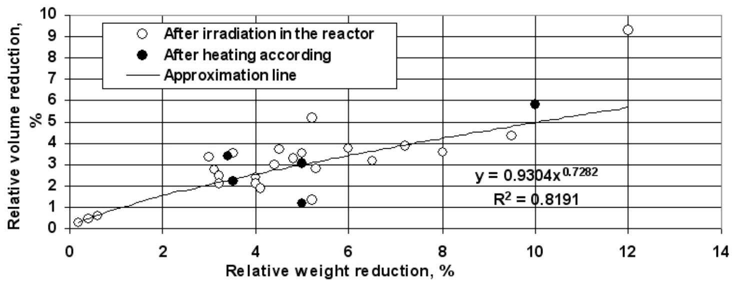

Figure 2. The relationship between the change in the mass and volume of the HPCP after irradiation in the reactor and after heating according to the data summarized in the research work [9].

3. Results and Discussion

The values obtained by formula (14) from the data of the research work [25] of the reduction in the linear dimensions of concrete only under the action of gamma radiation, as the difference between the change in dimensions during irradiation and without irradiation, are shown in Fig. 3 as a dependence on time and absorbed dose. It can be seen that with an increase in the irradiation time and the absorbed dose of gamma radiation, the magnitude of the decrease in the volume of concrete increases and reaches 0.002–0.003 % after irradiation for 10 – 250 days before the absorbed doses (0.38 – 6.8)·10^5 Gy.

a) b)

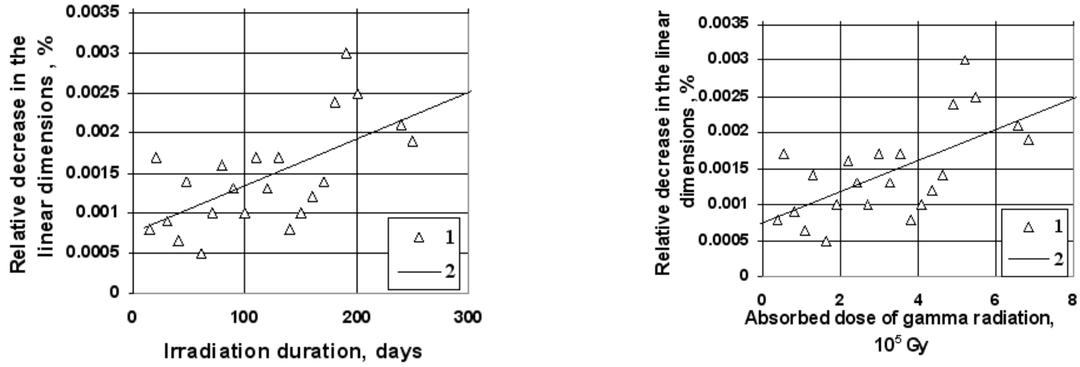

Figure 3. The dependence calculated from the data of the research work [25] on the irradiation time (a) and on the magnitude of the absorbed dose of gamma radiation (b) decrease in the linear dimensions of concrete under the action of gamma radiation, as the difference between the decrease in linear dimensions during irradiation and without irradiation.
1 – individual results; 2 – approximation line.

Calculated from the values of Fig. 3 according to the formulas (3) – (6) the values of the reduction in the linear dimensions of the HPCP under the action of gamma radiation and their dependence on the absorbed dose are shown in Fig. 4a. At the same time, in accordance with the calculated data of the research work [39], it was assumed that the radiation changes in the aggregates of concrete at the doses considered are zero, since the volume change is less than 6·10^{-7}%, and the strength decreases by less than 1·10^{-5} %. It can be seen that the degree of reduction in linear dimensions in the studied range of absorbed doses from (0.38–1.6)·10^5 to (4.9–6.8)·10^5Gy is from 0.026–0.09 % to 0.1–0.16% and approximately linearly rises with an increase in the absorbed dose.

It was not possible to calculate the change in compressive strength using formulas (7) and (8) due to the lack of data on the change in the strength of concretes. In this regard, the change in the strength of HPCP was assessed according to the formula [13] with parameters for the material of "mature" age. The effect of reducing the porosity of HPCP due to carbonation, shown in the research works [26, 29, 32] in reserve was neglected. The calculated values of the relative residual strength of and their dependence on the absorbed dose are shown in Fig. 4b. It can be seen that in the studied range of absorbed doses (0.38–1.6)·105 to (4.9–6.8)·105 Gy, compressive strength decreases with an increase in the absorbed dose and the residual strength is from 0.94–0.98 to 0.9–0.935 from strength to irradiation.

a) b)

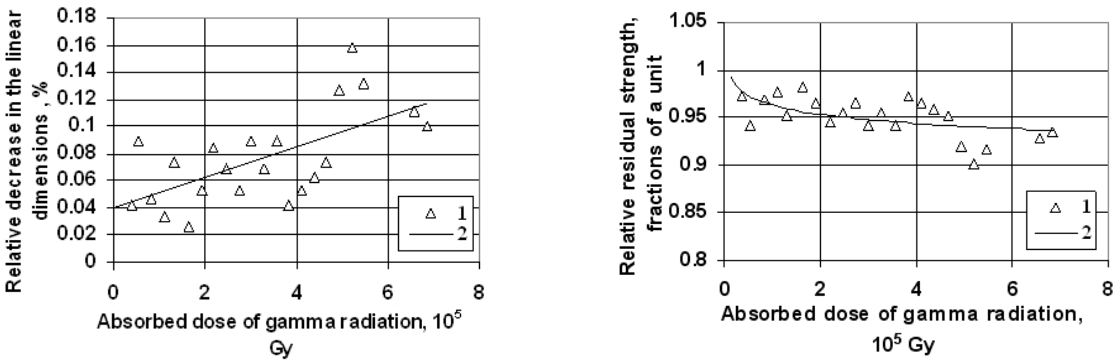

Figure 4. Calculated on the basis of the values shown in Fig. 3, the magnitudes of the linear dimensions reduction according to formulas (5, 6) (a) and the residual strength according to formula (13) (b) of HPCP under the action of gamma radiation as a function of the absorbed dose.
1 – individual results; 2 – approximation line.

When using these research works [1, 2], it is not possible to isolate the effect of irradiation alone, since there are no data on changes in concretes without irradiation. However, the absorbed doses of gamma radiation in the works [1, 2] are much higher than in the work [25]. In this regard, the contribution of natural changes in concrete in time is much lower and can be neglected.

The values of the reduction in the mass, linear dimensions and strength of HPCP under the action of gamma radiation calculated from these research works [1, 2] for concretes are shown in Table 2, as well as in Figure 5 as a dependence on the absorbed dose. At the same time, in accordance with the calculated data of the research work [39], it was assumed that the radiation changes in the aggregates of concrete at the considered doses are zero, since the volume change is less than $3 \cdot 10^{-4}$ %, and the strength decreases by less than $5 \cdot 10^{-3}$ %.

Table 2. Results of calculation of radiation changes* of HPCP according to the data of irradiation of concretes with gamma radiation at 30 °C in the research works [1, 2].

Name of concrete by aggregates	Absorbed dose of gamma radiation, Gy	Changes in the mass of HPCP, %	Relative changes in the dimensions of HPCP, %		Residual strength of HPCP, unit fraction	
			calculated from the change in the dimensions of concrete	calculated from the change in the mass of concrete	calculated from the change in the dimensions and strength of concrete	calculated from the change in the mass and strength of concrete
Concrete from limestone and sandstone	$2.27 \cdot 10^8$	-2.94±0.23	-0.15±1.94	-0.68±0.11	-	-
	$4.7 \cdot 10^8$	-6.28±0.46	-0.62±2.11	-1.18±0.15	1.01±0.29	1,00±0.24
Concrete from limestone	$2.27 \cdot 10^8$	-3.76±0.78	-1.26±2.31	-0.81±0.23	1.10±0.15	1.04±0.10
	$4.7 \cdot 10^8$	-7.7±2.2	-2.48±2.88	-1.37±0.45	1.28±0.14	1.04±0.07

*The average square deviations are given.

From Table 2 and Figure 5 it can be seen that under the influence of gamma radiation there is a decrease in the linear dimensions of the samples and mainly an increase in the strength of the HPCP. In the range of absorbed doses from $2.27 \cdot 10^8$ to $4.7 \cdot 10^8$ Gy, depending on the basis of calculations, there is a decrease in the linear dimensions of HPCP by 0.15–1.26 % to 0.62–2.48 %. At the same time, changes in HPCP obtained from data on changes in the linear dimensions of concretes have more significant standard deviations and variations of values than those obtained from changes in the mass of concrete, so they are less reliable statistically. However, changes in HPCP, obtained by changing the mass of concrete have a less reliable physical basis, since they are determined on the basis of the relationship of dimensional changes with changes in mass. At the same time, the average values obtained from the data on the two studied concretes, calculated from different data, are close to each other. This allows us to consider them sufficient to assess the radiation changes in HPCP under the conditions considered

The residual relative compressive strength increases from 1.04 – 1.1 to 1.0 – 1.28. The approximation line for the dependencies of changes on the absorbed dose has an approximately linear form, taking into account the fact that the change in linear dimensions and relative residual strength at the absorbed dose of zero are $\frac{\Delta V_{CP}}{V_{CP}} = 0$ and $\frac{R_{CP}}{R_{CP0}} = 1$.

a) b)

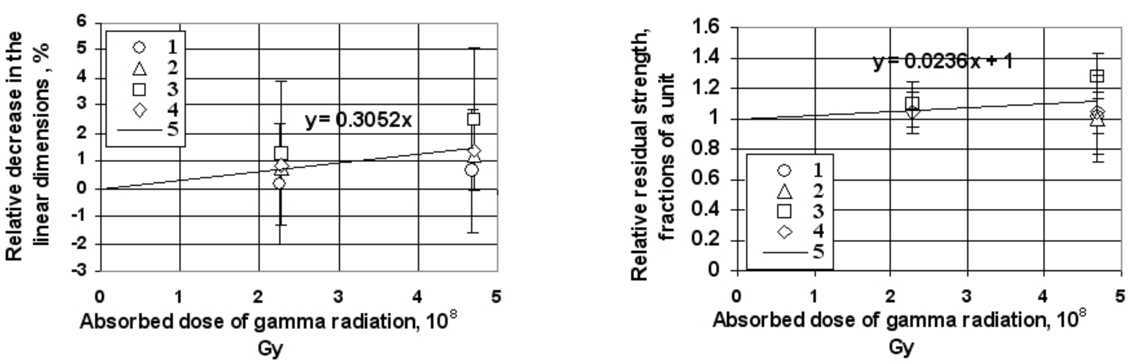

Figure 5. Calculated in Table 2 according to formulas (3) – (12) based on the data of the research works [1, 2] presented in Table 1, the magnitudes of the reduction in linear dimensions (a) and the compressive strength of HPCP under the action of gamma radiation as a dependence on the absorbed dose. 1 – reduce of the linear dimensions of concrete from limestone and sandstone; 2 – reduce of the mass of concrete from limestone and sandstone; 3 – reduce of the linear dimensions of concrete from limestone; 4 – reduce of the mass of concrete from limestone; 5 – approximation line.

Generalized for the values calculated from these research works [1, 2 and 25], the dependence of reducing the linear dimensions (shrinkage) of HPCP under the action of gamma radiation at 20–30 °C on the absorbed dose is shown in Fig. 6. It can be seen that the shrinkage of HPCP increases with an increase in the absorbed dose in the range from $3.8\cdot10^4$ to $4.7\cdot10^8$ Gy. Moreover, due to the absence of significant heating during irradiation, it can be considered that these changes occur only under the action of gamma radiation. Judging by the data [9], the effect of the composition, water-cement ratio, age of HPCP and the density of the flux of ionizing radiation on the shrinkage of HPCP under the action of ionizing radiation of the nuclear reactor is not observed. In this regard, the values of linear dimensions reduction calculated from the data of the research works [1, 2 and 25], where HPCP of different composition, W/C and age were used, irradiation was carried out at different rates of absorbed dose of gamma radiation can be considered as values of a single dependence on the absorbed dose. This dependence was approximated by the following expression:

$$\left(\frac{\Delta\ell_{CP}}{\ell_{CP}}\right)_G = a_G D_G^{b_G}, \tag{17}$$

where $\left(\frac{\Delta\ell_{CP}}{\ell_{CP}}\right)_G$ is a change in linear dimensions under the influence of gamma radiation, %; D_G is absorbed dose rate of gamma radiation; a_G = –0.000894, b_G = 0.3497 at D_G in Gy.

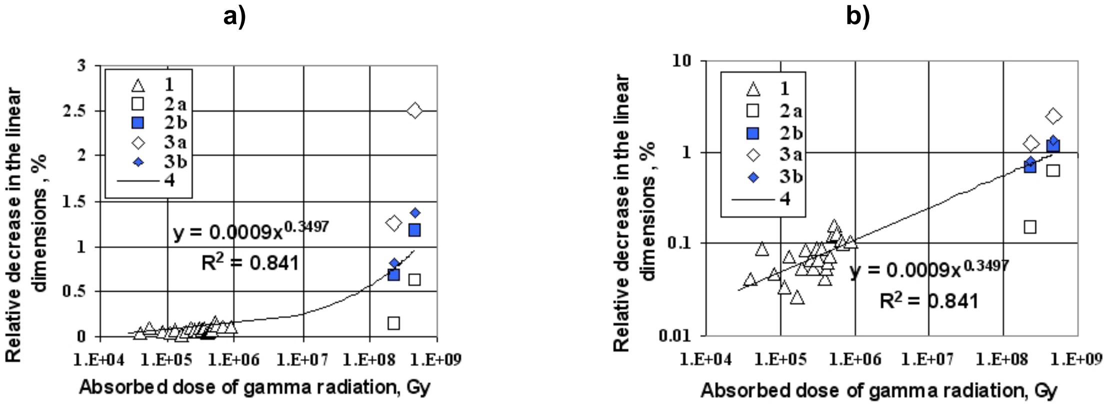

Figure 6. Generalized for the values calculated from these research works [1, 2, 25], the dependence of the reduction in linear dimensions (shrinkage) of HPCP under the action of gamma radiation at 20–30 °C on the absorbed dose in the semilogarithmic (a) logarithmic scale (b).
1 – from the data [25]; 2a – from the data [1, 2] on reducing the linear dimensions of concrete from limestone and sandstone; 2b – from the data [1, 2] on reducing the mass of concrete from limestone and sandstone; 3a – from the data [1, 2] on reducing the linear dimensions of concrete from limestone; 3b – from the data [1, 2] on reducing the mass of concrete from limestone; 4 – approximation line.

However, according to the results of irradiation with gamma radiation to absorbed doses of $1\cdot10^7$–$5\cdot10^7$ Gy at temperatures from 70 to 375 °C in the research works [35, 36] it was noted that changes in HPCP under these conditions are mainly caused by the influence of heating accompanying irradiation. However, this conclusion was made on the basis of a comparison of the decrease in mass, and not the linear dimensions of HPCP after irradiation and heating without irradiation at irradiation temperatures and at sufficiently large spreads in results. In addition, the decrease in the mass of the studied HPCP after heating established in the research works [35, 36] exceeds all the data known to the authors at the same temperatures for unknown reasons. In addition, the relationship between the shrinkage of HPCP and the decrease in mass after irradiation differs significantly from the dependence shown in Fig. 2. This calls into question that the relationship between the established change in mass and linear dimensions is the same under irradiation and heating, and also calls into question the reliability of this inference based on changes in mass.

The addition of these research works [35, 36] after irradiation at temperatures from 70 to 375 °C to the dependence of Fig. 6 is shown in Fig. 7. It can be seen that the data of high-temperature irradiation, despite significant variations, mainly differ from the values of the approximation line obtained at 20–30 °C. It is most likely that this difference is due to the presence of additional changes under the influence of heating, since it is most likely that, as with neutron irradiation [9, 14], dimensional changes after irradiation can be represented as a sum of radiation and thermal changes and described by the formula:

$$\left(\frac{\Delta\ell_{CP}}{\ell_{CP}}\right)_{GT}=\left(\frac{\Delta\ell_{CP}}{\ell_{CP}}\right)_{G}+\left(\frac{\Delta\ell_{CP}}{\ell_{CP}}\right)_{T}, \tag{18}$$

where $\left(\frac{\Delta\ell_{CP}}{\ell_{CP}}\right)_{GT}$ is the total change in the dimensions of the HPCP after irradiation under the influence of gamma radiation and temperature; $\left(\frac{\Delta\ell_{CP}}{\ell_{CP}}\right)_{G}$, $\left(\frac{\Delta\ell_{CP}}{\ell_{CP}}\right)_{T}$ is changing the dimensions of HPCP after irradiation from exposure to gamma radiation only and from exposure to temperature only, respectively.

Since there are no data on changes in the linear dimensions of HPCP under the influence of heating in the research works [35, 36], it is not possible to determine purely radiation changes in the dimensions of HPCP under the influence of gamma radiation from these works. However, it is possible to use the data available in the research works [9, 40, 41] on the reduction in the dimensions of various HPCP of "mature" age after heating for a time commensurate with the time of irradiation, and compare them with the results of shrinkage after irradiation with gamma radiation at the same temperatures.

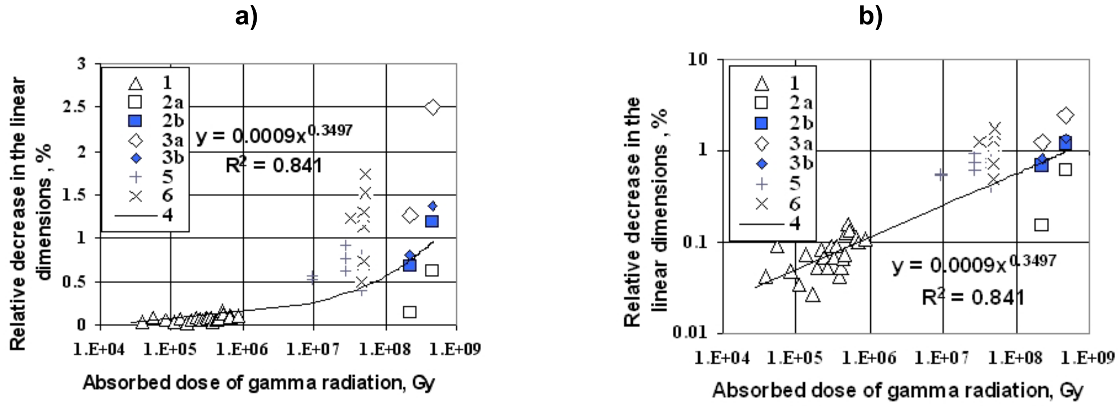

Figure 7. Generalized for the values calculated from the data of the research works [1, 2, 25], the dependence of reducing the linear dimensions (shrinkage) of HPCP under the action of gamma radiation at 20–30 °C on the absorbed dose with the addition of the research works [35, 36] after irradiation at temperatures from 70 to 375 °C at a semilogarithmic (a) logarithmic scale (b).
1 – from data [25]; Explanations of 1, 2a, 2b, 3a, 3b and 4 are given in Fig. 6; 5 – data of research works [35, 36], obtained at 70–120 °C; 6 – data of research works [35, 36], obtained at 260–375 °C.

A comparison of changes in the linear dimensions of HPCP after irradiation with gamma radiation at temperatures from 70 to 375 °C according to the data of the research works [35, 36] with changes in linear dimensions after heating without irradiation of various HPCP of "mature" age after heating for a time commensurate with the time of irradiation, according to the data of the research works [9, 40, 41] is shown in Fig. 8.

It can be seen that the changes in the linear dimensions of the HPCP studied in the research works [35, 36] mainly exceed the changes in the linear dimensions of various HPCP according to the data of the research works [9, 40, 41] after heating at the same temperatures during a commensurate heating time, although there are data spreads. This indicates that radiation changes under the influence of gamma radiation at temperatures higher than 30 °C occur as well. However, it can be seen that the differences between the data shown in the figure, and hence the contribution of radiation changes with increasing temperature decrease to about zero at a temperature of more than 550 °C.

This can be explained as follows. It is known that free and physically bound water is removed from the HPCP when heated in the range from 50 °C to 105 °C. Chemically bound water is removed in the range from 105 °C to 600 °C. After 600 °C, almost all water from HPCP is released. It is characteristic that after heating, the shrinkage of the HPCP according to [41] and the release of water according to the data [42] occurs most intensively in the initial heating period, and the contribution of gamma radiation is manifested mainly towards the end of irradiation, when the maximum absorbed dose to which the changes are tied is reached. In this case, the higher the irradiation temperature, the less water remains in the HPCP, which can be released under the influence of gamma radiation. In this regard, the rate of development of shrinkage of HPCP under the action of gamma radiation and shrinkage at a fixed absorbed dose decreases with an increase in the irradiation temperature.

To take into account the effect of temperature on radiation changes in the linear dimensions of HPCP under the influence of gamma radiation, it is possible to introduce a temperature influence coefficient K_T. For this, according to the data of the research works [35, 36], first, on the basis of Fig. 8, the radiation changes in the linear dimensions of the HPCP were determined as the difference between the change in dimensions after irradiation and the change in dimensions after heating at irradiation temperatures. Then the dependence of radiation changes from the temperature of irradiation was studied. Although the results of the research work [35, 36] were obtained at absorbed doses from $1 \cdot 10^7$ to $5 \cdot 10^7$ Gy, the effect of the absorbed dose in this range is not great, so the differences in the absorbed doses at different temperatures can be neglected. After that, we studied the coefficient K_T of the influence of temperature on the radiation change in the linear dimensions of the HPCP at absorbed doses of $1 \cdot 10^7$–$5 \cdot 10^7$ Gy as the ratio of radiative changes in dimensions after irradiation at temperature T to radiation changes at 20 °C obtained on the basis of extrapolation using the approximation line (–0.48 %).

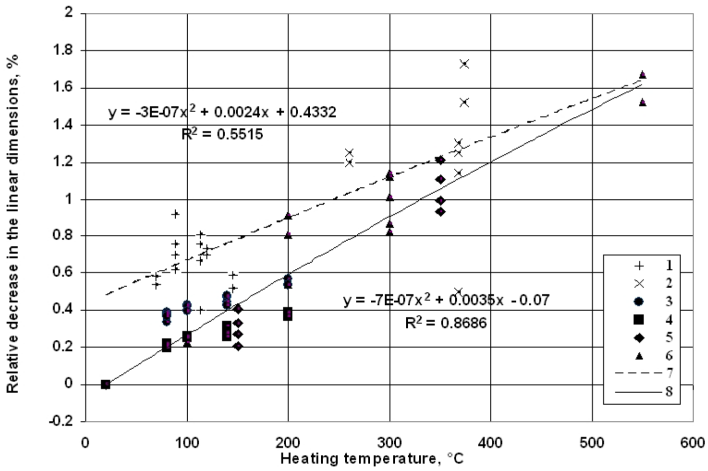

Figure 8. Comparison of changes in the linear dimensions of HPCP after irradiation with gamma radiation at temperatures from 70 to 375 °C according to the data of the research works [35, 36] with changes in dimensions after heating of various HPCP of "mature" age after heating for a time commensurate with the time of irradiation, according to the data of the research works [9, 40, 41].
1 – after irradiation of HPCP with W/C = 0.4 at the age of 1.5 years for 37.2 days at 70–120 °C according to the data of the works [35, 36]; 2 – after irradiation of HPCP with W/C = 0.4 at the age of 1.5 years for 6.3 days at 260–375 °C according to the data of the work [35, 36]; 3 – after heating HPCP with W/C = 0.26–0.35 at the age of 1 year for 30 days according to the work data [41]; 4 – after heating HPCP with W/C = 0.26–0.35 at the age of 1 year for 1 day according to the data of the work [41]; 5 – after heating HPCP with W/C = 0.26–0.35 at the age of 9 months for 5 hours according to work data [40]; 6 – after heating HPCP with W/C = 0.28–0.5 at the age of 30 months for 90–200 days according to the work data [9]; 7 – approximation line for the dependence of dimensions reduction after irradiation on temperature; 8 –approximation line for the dependence of reducing the dimensions after heating on the temperature.

The dependences of radiation changes in the linear dimensions of HPCP only under the influence of gamma radiation, calculated from the research works [35, 36] and the K_T coefficient on the irradiation temperature T, as well as the results of their approximation are shown in Fig. 9.

It can be seen that the changes in the linear dimensions of the cement stone only under the influence of gamma radiation and the values of the Kt coefficient at absorbed doses of $1 \cdot 10^7$–$5 \cdot 10^7$ Gy decrease with increasing heating temperature and can be described by the expressions:

$$\left(\frac{\Delta\ell_{CP}}{\ell_{CP}}\right)_G = -3.74 \cdot 10^{-7} T^2 + 0.0011T - 0.5032 \quad (19)$$

$$K_T = 7.77 \cdot 10^{-7} T^2 - 0.0023T + 1.0454. \quad (20)$$

It is characteristic that at T = 20 °C according to the formula (19) we get

$$\left(\frac{\Delta\ell_{CP}}{\ell_{CP}}\right)_G = -0.48\%$$

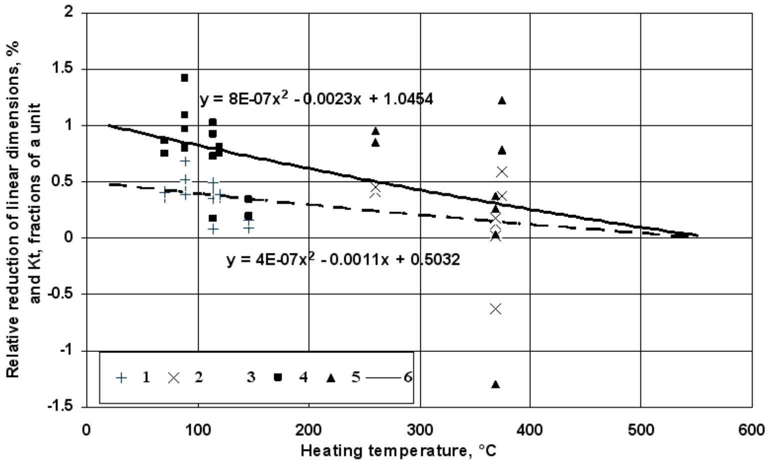

Figure 9. Dependencies of radiation changes in the linear dimensions of HPCP only under the influence of gamma radiation, calculated from research works [35, 36] and the coefficient K_T on the irradiation temperature, as well as the results of their approximation:
1 – reduction in linear dimensions only under the influence of gamma radiation after irradiation of HPCP for 37.2 days at 70–120 °C; 2 – reduction in linear dimensions only under the influence of gamma radiation after irradiation of HPCP for 6.3 days at 260–375 °C; 3 –approximation line for the dependence of linear dimensions reduction only under the influence of gamma radiation after irradiation of at 70–375 °C on temperature; 4 – values of the K_T coefficient after irradiation of HPCP at 70 – 120 °C;5 – values of the K_T coefficient after irradiation of HPCP at 260–375 °C; 6 –approximation line for the dependence of the K_T coefficient on the irradiation temperature.

According to the formula (17) at absorbed doses from $1{\cdot}10^7$ to $5{\cdot}10^7$ Gy we get $\left(\frac{\Delta\ell_{CP}}{\ell_{CP}}\right)_G$ = -0.25 – -0.44 %. This is commensurate with the value $\left(\frac{\Delta\ell}{\ell}\right)_P$ = 0.48 %, obtained from the formula (19), therefore confirms the sufficient correctness of the formula (19) for the determination of radiation changes in the HPCP and at absorbed doses from $1{\cdot}10^7$ to $5{\cdot}10^7$ Gy. This allows us to recommend the obtained approximating dependence (17), taking into account the expression (20) for the calculated determination (assessment) of radiation changes in the linear dimensions of the HPCP only under the influence of gamma radiation in the following form:

$$\left(\frac{\Delta\ell_{CP}}{\ell_{CP}}\right)_G = K_T a_G D_G^{b_G}. \qquad (21)$$

A comparison of the relationship between changes in compressive strength of HPCP with a decrease in volume calculated from the data of research work [1, 2] after gamma radiation and after irradiation in nuclear reactors and heating of HPCP of "young" age according to [9] is given in Fig. 10. It can be seen that these relationships are commensurate. In this regard, it can be concluded that the main thing for changes in the strength of HPCP, regardless of the type of impact that causes the release of water, is a decrease in its linear dimensions.

This gives grounds to recommend the use of the expression (13) for the analytical determination of radiation changes in the strength of HPCP under the influence of gamma radiation of both young and "mature" age. Although due to the fact that the reduction of porosity due to carbonation is not taken into account, the expression (13) will give an estimate of the maximum possible effect of gamma radiation.

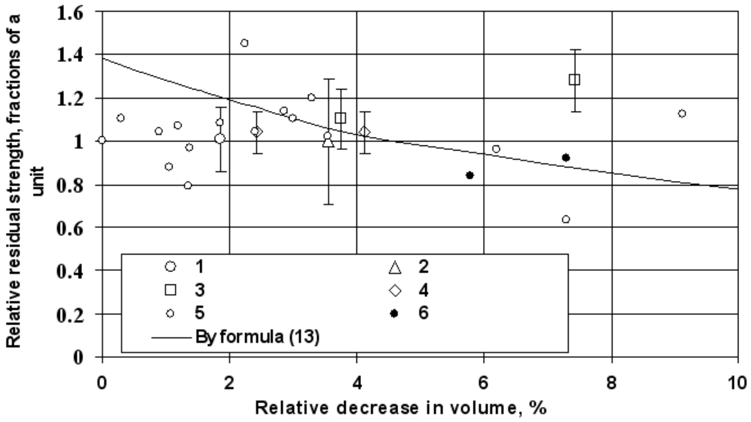

Figure. 10. Comparison of the relationship between changes in the compressive strength of HPCP with a decrease in volume under the influence of gamma radiation, calculated from the data of the research work [1, 2], with the relationship between these changes in HPCP of young "age" after irradiation in nuclear reactors and heating according to the data [9].
1 – reduce of the linear dimensions and strength of concrete from limestone and sandstone from the data [1, 2]; 2 – reduce of the mass and strength of concrete from limestone and sandstone from the data [1,2]; 3 – reduce of the linear dimensions and strength of concrete from limestone from the data [1, 2];
4 – reduce of the mass and strength of concrete from limestone from the data [1, 2];
5 – according to the data of the research work [9] after irradiation in nuclear reactors;
6 – according to the data of the research works [9] after prolonged heating without irradiation.

The results of calculations according to the formulas (21) and (13) of radiation changes in the linear dimensions and compressive strength of HPCP, caused only by the action of gamma radiation, after irradiation to the values of absorbed doses from $3{\cdot}10^4$ Gy to $1{\cdot}10^{10}$ Gy are shown in Fig. 11. It can be seen that the radiation decrease in linear dimensions increases, and the residual strength decreases with an increase in the absorbed dose and vice versa, the radiation decrease in linear dimensions decreases, and residual strength grows with rise of temperature associated with irradiation. With an absorbed dose of gamma radiation of 10^{10} Gy, the linear dimensions reduction will be 2.8 % after irradiation at 20–30 °C and 0.25 % after irradiation at 500 °C. With an absorbed dose of gamma radiation of 10^{10}Gy, the residual compressive strength will be 0.83 after irradiation of HPCP of "young" age and 0.34 after irradiation of HPCP of "mature" age at 20–30 °C; 1.3 after irradiation of "young" age material and 0.85 after irradiation of "mature" age material at 500 °C according to formulas (21) and (13), with (18) taking into account.

The results of estimated calculations of total changes under the influence of gamma radiation and concomitant heating of changes in the linear dimensions and strength (radiation-thermal changes) of HPCP after prolonged (more than 90 days) irradiation to absorbed doses from $3{\cdot}10^4$ Gy to $1{\cdot}10^{10}$ Gy at temperatures from 20 to 500 °C are shown in Fig. 12. At the same time, radiation changes in dimensions were determined by the formula (21). Thermal changes in the dimensions of the HPCP after prolonged heating were calculated on the basis of the data of the research work [9] according to the formula:

$$\left(\frac{\Delta\ell_{CP}}{\ell_{CP}}\right)_T=\frac{1}{3}\left(\frac{\Delta V_{CP}}{V_{CP}}\right)_T=\frac{1}{3}a_T T^{b_T}, \tag{22}$$

where T is temperature during irradiation (in °C); a_T = –0.091 %, b_T = 0.73 – for HPCP of "young" age by [9]; a_T = –0.0146 %, b_T = 0.93 – for HPCP of "mature" age according to the results of the approximation of the average shrinkage values presented in the research work [9].

Radiation-thermal changes in the strength of HPCP were calculated according to the formula (13) on the basis of radiation-thermal volume changes calculated from radiation-thermal changes in linear dimensions.

Fig. 12 shows that after irradiation of HPCP with gamma radiation at high temperatures the decrease in linear dimensions increases and the residual strength decreases with a rise in the absorbed dose to $2{\cdot}10^9$ Gy and the irradiation temperature. On the contrary, the radiation-thermal reduction in linear dimensions decreases and the residual strength increases with a rise in the absorbed dose above $2{\cdot}10^9$ Gy and with an increase in the temperature accompanying irradiation. With an absorbed dose of gamma radiation of 10^{10} Gy, the reduction in the linear dimensions of HPCP will be 2.8 % after irradiation at 20–30 °C and 0.25 % after irradiation at 500 °C. With an absorbed dose of gamma radiation of 10^{10} Gy, the residual compressive strength will be 0.83 after irradiation at the age of 1–3 months and 0.34 after irradiation at the age of more than 8 months at 20–30 °C with; 1.3 after irradiation in HPCP of "young" age and 0.85 when irradiating HPCP of "mature" age at 500 °C. To obtain a more accurate result for a particular HPCP, it is necessary to use real thermal changes in the HPCP when performing estimates.

a) b)

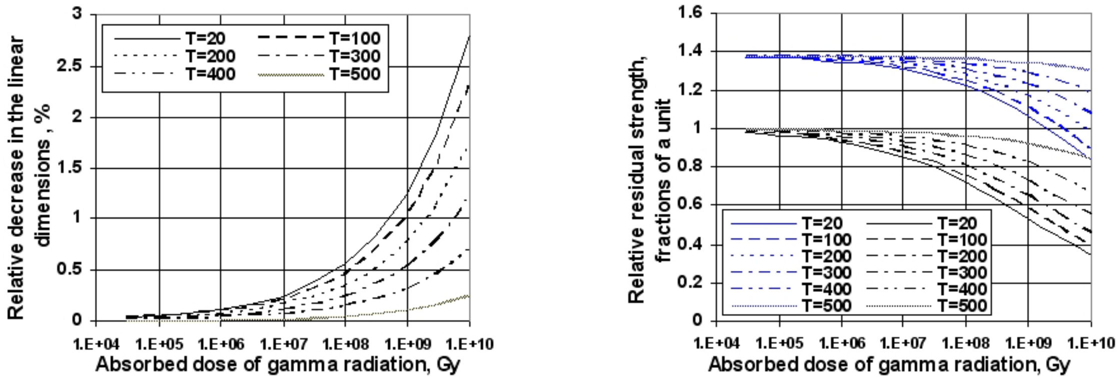

Figure. 11. Results of calculations according to formulas (21) and (13) of radiation changes in the linear dimensions and compressive strength of HPCP caused only by the action of gamma radiation, after irradiation to the values of absorbed doses from 3·10^4 Gy to 1·10^{10}Gy at different irradiation temperatures T in °C.
Blue lines are given for HPCP of "young" age. Black lines are given for HPCP of "mature" age.

a) b)

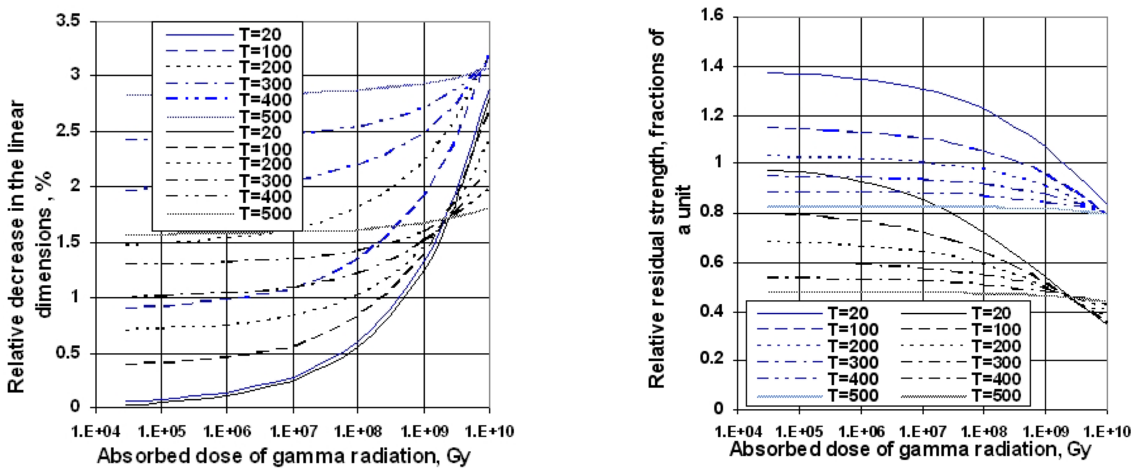

Figure 12. The results of the estimated calculations of the total changes under the influence of gamma radiation and the concomitant heating of changes (radiation-thermal changes) in the dimensions (a) and strength (b) of the HPCP after prolonged (more than 90 days) irradiation to the values of the absorbed doses from 3·10^4 Gy to 1·10^{10} Gy at different irradiation temperatures T in °C. Blue lines are given for HPCP of "young" age. Black lines are given for HPCP of "mature" age.

The results obtained can be used to predict changes in the linear dimensions, volume and strength of HPCP and concrete under the influence of gamma radiation. At the same time, the effect of the mineral composition and water-cement ratio of W/C, the intensity of radiation on the radiation changes in the HPCP should not be significant, since, judging by [9] it is not noticeable during irradiation in nuclear reactors. The effect of age on radiation changes in linear dimensions with prolonged exposure should not be significant, since radiation changes are most pronounced by the end of irradiation, when the age of the materials will always be sufficiently mature.

4. Conclusions

1. The research is based on the published data on the effect of gamma radiation on concretes at irradiation temperatures of 20–30 °C and on hardened Portland cement paste (HPCP) at 70–375 °C. The author carried out calculation and analytical studies to assess and establish the possibility of predicting radiation changes in HPCP under the influence of gamma radiation. The studies were conducted using the previously developed and tested method of analytical determination of radiation changes in concretes

according to data on changes in their components. The formulas used in this method made it possible to determine (restore) the radiation changes of HPCP from data on radiation changes in concretes and aggregates. When conducting computational and analytical studies, the author additionally used the existing relationship between the reduction in the mass of HPCP and its shrinkage, as well as known data on thermal changes in HPCP after its heating at different temperatures and holding time.

2. As a result of the studies carried out on the available results of irradiation of concretes, changes in linear dimensions and strength during compression of HPCP only under the action of gamma radiation are calculated (restored). The dependencies of radiation changes in HPCP on the magnitude of the absorbed dose in the range from $3.8 \cdot 10^4$ to $4.7 \cdot 10^8$ Gy after irradiation at 20–30 °C are provided. According to the available data on the irradiation of HPCP with gamma radiation at temperatures from 70 to 375 °C, the effect on radiation changes in the HPCP of the irradiation temperature is revealed. It is shown that radiation changes in HPCP increase with increasing absorbed dose and, conversely, radiation changes decrease with increasing temperature accompanying irradiation.

3. Based on the obtained approximating mathematical expressions, the paper provides the calculations of radiation changes in the dimensions and compressive strength of HPCP, caused only by the action of gamma radiation, after irradiation to absorbed doses from $3 \cdot 10^4$Gy to $1 \cdot 10^{10}$ Gy. Using the results of these calculations and the available data on thermal changes in HPCP, the authors supplies the estimates of radiation-thermal changes in the linear dimensions and strength of HPCP under the action of gamma radiation and heating. These calculations were made after irradiation up to absorbed doses from $3 \cdot 10^4$ Gy to $1 \cdot 10^{10}$ Gy and concomitant heating at temperatures from 20 to 500 °C.

4. The obtained results can be used to predict radiation changes in the linear dimensions, volume and strength of HPCP under the influence of gamma radiation. Based on these changes in HPCP, using existing analytical methods makes it possible to predict radiation changes in concrete.

References

1. Kelly, B., Brocklehurst, J., Mottershead, D., McNearney, S. The Effects of Reactor Radiation on Concrete. Proceedings of the Second Information Meeting on Pre Stress Concrete and Reactor Pressure Vessels and their Thermal Isolation. EUR-4531, 1969. Pp. 237–265.
2. Gray, B.S. The Effect of Reactor Radiation on Cements and Concrete. Proceedings of an information exchange meeting on results of concrete irradiation programmes. EUR 4751 f-e Brussels (Belgium), April 19, 1971. Commission of the European Communities, Luxembourg, 1972. Pp. 17–39.
3. Elleuch, L., Dubois, F., Rappeneau, J. Effects of Neutron Radiation on Special Concretes and Their Components. Special Publication of The American Concrete Institute SP-34, 1972. Pp. 1071–1108.
4. Hilsdorf, H. K., Kropp, J., Koch, H.J. The effects of nuclear radiation on the mechanical properties of concrete. Proceedings of the Douglas McHenry International Symposium on Concrete and Concrete Structures. ACI SP 55-10. American Concrete Institute. Mexico City. Mexico, 1978. Pp. 223–251.
5. Kaplan, M.F. Concrete Radiation Shielding. Concrete Design and Construction Series. Harlow: Longman Scientific, 1989. 457 p.
6. Fillmore, D. L. Literature Review of the Effects of Radiation and Temperature on the Aging of Concrete. Technical Report INEL/EXT-04-02319. Idaho National Engineering and Environmental Laboratory. Bechtel BWXT Idaho, LLC. Prepared for the Central Research Institute of Electric Power Institute. September 2004.
7. Kontani, O., Ichikawa, Y., Ishizawa, A., Takizawa, M., & Sato, O. Irradiation effects on concrete structures. Int. Symp. On the Ageing Manag. of Nucl. P. P., 2010. Pp. 173–182. DOI: 10.1002/9781118536254.ch27
8. Maruyama, I., Kontani, O., Ishizawa, A., Takizawa, M., & Sato, O. Development of system for evaluating concrete strength deterioration due to radiation and resultant heat. Salt Lake City: Proceedings of 3rd International Conference on NPP Life Management for Long Term Operations. 2012.
9. Denisov, A.V., Dubrovskiy, V.B., Solovyev, V.N. Radiatsionnaya stoykost mineralnykh i polimernykh stroitelnykh materialov [Radiating stability of mineral and polymer building materials]. M.: Izdatelskiy dom MEI, 2012. 284 p. (rus)
10. William, K., Xi, Y., Naus, D. A review of the effects of radiation on microstructure and properties of concretes used in nuclear power plants. Tech. Rep. NUREG/CR-7171 ORNL/TM-2013/263, US Nuclear Regulatory Commission, Oak RidgeNational Laboratory, 2013.
11. Field, K.G., Remec, I., Le Pape, Y. Radiation effects in concrete for nuclear power plants – Part I: Quantification of radiation exposure and radiation effects. Nuclear Engineering and Design. 2015. 282. Pp. 126–143.
12. Rosseel, T.M., Maruyama, I., Le Pape, Y., Kontani, O., Giorla, A.B., Remec, I., Wall, J. J., Sircar, M., Andrade, C., Ordonez, M. Review of the Current State of Knowledge on the Effects of Radiation on Concrete. Journal of Advanced Concrete Technology. 2016. 14. Pp. 368–383. DOI: 10.3151/jact.14.368
13. Muzalevskiy, L. P. Prognozirovaniye stepeni izmeneniya prochnosti i radiatsionnykh deformatsiy betona [Forecasting of degree of change of durability and radiating deformations of concrete]. Trudy Tretyey Vsesoyuznoy nauchnoy konferentsii po zashchite ot ioniziruyushchikh iz¬lucheniy yaderno-tekhnicheskikh ustanovok. Vol. V. Tbilisi: Iz-vo TGU.1985. Pp. 116–125. (rus)
14. Denisov, A.V., Dubrovskiy, V.B., Yershov, V.Yu. et. al. Radiatsionno-temperaturnyye izmeneniya svoystv portlandtsementnogo kamnya betona i zavisimosti dlya ikh prognozirovaniya [Radiation -thermal changes of properties of hardened cement paste and functions for their predictions]. Voprosy atomnoy nauki i tekhniki. 1989. 2. Pp. 20–35. (rus)
15. Denisov, A. V., Dubrovskiy, V. B., Muzalevskiy, L. P. Prognozirovaniye radiatsionnykh izmeneniy neorganicheskikh stroitelnykh materialov [Prediction of radiation changes in inorganic building materials]. Voprosy atomnoy nauki i tekhniki. Ser. Proyektirovaniye i stroitelstvo.1990. 3. Pp. 98–102. (rus)

16. Le Pape, Y., Field, K.G., Remec, I. Radiation effects in concrete for nuclear power plants, Part II: Perspective from micromechanical modeling. Nuclear Engineering and Design. 2015. 282. Pp. 144–157.
17. Giorla, A., Vaitova, M., Le Pape, Y., Stemberk, P. Meso-scale modeling of irradiated concrete in test reactor. Nuclear Engineering and Design. 2015. 295. Pp. 59–73.
18. Pomaro, B. A Review on Radiation Damage in Concrete for Nuclear Facilities. Experiments to Modeling. Modelling and Simulation in Engineering. 2016. Pp. 1–10. Article ID 4165746. DOI: 10.1155/2016/4165746 (date of application: 11.01.2023).
19. Giorla, A.B., Le Pape, Y., Dunant, C. F. Computing Creep-Damage Interactions in Irradiated Concrete. Journal of Nanomechanics and Micromechanics. 2017. 7(2). 04017001. DOI: 10.1061/(ASCE)NM.2153-5477.0000118
20. Le Pape, Y., Alsaid, M.H.F., Giorla, A.B. Rock-forming minerals radiation induced volumetric expansion – revisiting the literature data. Journal of Advanced Concrete Technology. 2018. 16. Pp. 191–209. DOI: 10.3151/jact.16.191
21. Sasano, H., Maruyama, I., Sawada, S., Ohkubo, T., Murakami, K., Suzuki, K. Meso-Scale Modelling of the Mechanical Properties of Concrete Affected by Radiation-Induced Aggregate Expansion // Journal of Advanced Concrete Technology. 2020. 18(10). Pp. 648–677. DOI: 10.3151/jact.18.648
22. Khmurovska, Y., Štemberk, P. Catalogue of Radiation-Induced Damage of Rock Aggregates Identified by RBSM Analysis.Journal of Advanced Concrete Technology. 2021. 19. Pp. 668–686.
23. Alexander, S. Effects of Irradiation on Concrete Final Results. Technical Report HL.63/6438," Atomic Energy Research Establishment, Harwell 1963. In Hilsdorf 1978.
24. Sommers, J.F. Gamma radiation damage of structural concrete immersed in water. Health Physics. 1969. 16. Pp. 503–508.
25. McDowall, D.C. The Effect of Gamma Irradiation on the Creep Properties of Concrete. Proceedings of an information exchange meeting on results of concrete irradiation programmes. EUR 4751 f-e Brussels (Belgium), April 19, 1971. Commission of the European Communities, Luxembourg, 1972. Pp. 55–69.
26. Vodák, F., Trtík, K., Sopko, V., Kapičková, O., Demo, P. Effect of γ-Irradiation on Strength of Concrete for Nuclear Safety Structures. Cement and Concrete Research. 2005. 35. Pp. 1447–1451.
27. Lowinska-Kluge, A., Piszora, P. Effect of gamma irradiation on cement composites observed with XRD and SEM methods in the range of radiation dose 0-1409 MGy. Acta Physica Polonica-Series A General Physic, 2008. 114. p. 399–411.
28. Kitsutaka, Y., Matsuzawa, K. The effect of gamma radiation on the fracture properties of concrete. Proceedings of FraMCoS-7, May 23-28, 2010. Fracture Mechanics of Concrete and Concrete Structures – Recent Advances in Fracture Mechanics of Concrete. Korea Concrete Institute, Seoul, ISBN 978-89-5708-180-8. Pp. 61–64.
29. Vodák, F., Vydra, V., Trtík, K., Kapičková, O. Effect of γ-irradiation on Properties of Harderned Cement Paste. Materials and Structures. 2011. 44. Pp. 101–107.
30. Kontani, O., Ichikawa, Y., Ishizawa, A. Irradiation Effects on Concrete Durability of Nuclear Power Plants. Proceedings of ICAPP 2011. France, 2011. Paper 11361.
31. Kontani, O., Sawada, S., Maruyama, I., Takizawa, M., Sato, O. Evaluation of irradiation effects on concrete structure: gamma-ray irradiation tests on cement paste. Proceedings ASME 2013 Power Conference, Boston, USA 29 July-1 August 2013. New York, USA: American Society of Mechanical Engineers, 2013-98099.
32. Maruyama, I., Kontani. O., Takizawa, M., Sawada, S., Ishikawa, S., Yasukouchi, J., Sato, O., Etoh, J., Igari, T. Development of the soundness assessment procedure for concrete members affected by neutron and gamma-irradiation. Journal of Advanced Concrete Technology. 2017. 15. Pp. 440–523. DOI: 10315/jact.15.440
33. Ishikawa, S., Maruyama, I., Takizawa, M., Etoh, J., Kontani, O., Sawada S. Hydrogen Production and the Stability of Hardened Cement Paste under Gamma Irradiation. Journal of Advanced Concrete Technology. December 2019. 17. Pp. 673–685. DOI: 10.3151/jact.17.673
34. Varlakov, A.P., Kapustin, V.V., Varlakova, G.A., Zherebtsov, A.A., Petrov, V.G., Shirshin, E.A., Kalmykov, S.N. The effect of radiation doses typical for high-level waste on the properties of the cement matrix. Radioactive Waste. 2018. 1(2). Pp. 89–96 (rus).
35. Reches, Y.A multi-scale review of the effects of gamma radiation on concrete. Results in Materials. DOI: 10.1016/j.rinma.2019.100039 (date of application: 11.01.2023)
36. Sanchez, F., Kosson, D., Oskay, C. Development of a Nano-Modified Concrete for Next Generation of Storage Systems, US Department of Energy Nuclear Energy University Programs. Vanderbilt University, 2018. Nashville, TN2018. Project No. 13-4840.
37. Khmurovska, Y., Štemberk, P., Sikorin, S., Žák, J., Khaladkevich, Y., Pavalanski, E., & Fatseyeu, V. (2019b). Cement mortar creep under exposure to gamma-ray irradiation. Journal of Nuclear Research and Development, 18, 24–28.
38. Khmurovska, Y, Štemberk, P, Sikorin, S., Němeček, J., Jóźwiak Niedźwiedzka, D., Doleželová, M., Kaladkevich, Y., Pavalanski, E., Fatseyeu, V. Effects of Gamma-Ray Irradiation on Hardened Cement Mortar. International Journal of Concrete Structures and Materials. 2021. 15(3). Pp. 303–316. DOI: 10.1186/s40069-020-00452-7
39. Denisov, A.V. Radiation changes of concrete aggregates under the influence of gamma radiation. Magazine of Civil Engineering. 2020. 4(96). P. 94–109. DOI: 10.18720/MCE.96.8
40. Falikman, V.R., Vaselova, V.I., Yershov, V.Yu., Muzalevskiy, L.P. Povedeniye tsementnogo kamnya s khimicheskimi dobavkami v usloviyakh kratkovremennogo vozdeystviya vysokikh temperatur [Behavior of a cement stone with chemical additives in the conditions of short-term influence of high temperatures]. Voprosy atomnoy nauki m tekhniki. Ser. Proyektirovaniye i stroitelstvo. 1987, vyp. 1. P. 3–15.
41. Yershov, V. Yu., Dubrovskiy, V. B., Muzalevskiy, L.P. Kolesnikov, N. A. Povedeniye tsementnogo kamnya s khimicheskimi dobavkami v usloviyakh dlitelnogo vozdeystviya vysokikh temperatur [Behaviour of a cement stone with chemical additives in the conditions of long influence of high temperatures]. Voprosy atomnoy nauki m tekhniki. Ser. Proyektirovaniye i stroitelstvo. 1988. 2. Pp. 120–129. (rus)
42. Nekrasov, K.D., Zhukov, V. V., Gulyayev, V. F. Tyazhelyy beton v usloviyakh povyshennykh temperatur [Heavy concrete at elevated temperatures]. M.: Stroyizdat, 1972. 128 p. (rus)

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