Creep in expanded clay concrete at different levels of stress under compression and tension

Chorikul Raupov*, and *Ganisher* Malikov

Tashkent State Transport University, Tashkent, 100067, Uzbekistan

Abstract. The paper analyzes the results of experimental studies of the creep of light concrete and the influence of various factors on it.
A method for determining the boundary of linear creep of expanded clay concrete has been developed. Experimental studies have been carried out to determine the boundary of linear creep.
Experimental creep data and the kinetics of the change in the creep measure of expanded clay concrete over time under axial compression at different levels of long–term load (0.2 - 0.7)R_b are obtained. The limiting values of the relative creep deformation and shrinkage of expanded clay concrete are determined.
Empirical formulas for determining and describing the relative deformation of the nonlinear creep of expanded clay concrete, measures of the linear creep of expanded clay concrete under axial tension and compression (if there are no direct experimental data), and the nature of the change are proposed $\lambda(t;\tau_1) = C_{bt}(t;\tau_1)/C_b(t;\tau_1)$, depending on $(t;\tau_1)$ according to the linear law at each site, the nature of the influence of previous loading on the strength and modulus of elasticity of concrete, the limit values of the relative creep deformation and shrinkage of expanded clay concrete.

1 Introduction

The experience gained by research, design, and production organizations in the Republic of Uzbekistan and abroad shows that high-strength expanded clay concrete is a technological material with good physical and mechanical properties, which allow it to be effectively used in the manufacture of structural elements and in construction of a wide variety of crucial structures [1-4].

At present, the cost of expanded clay is at the level of the cost of local heavy aggregates and is significantly lower than the cost of imported ones. In areas where expensive imported crushed stone is used, the transition from heavy concrete to high-strength expanded clay concrete will significantly reduce the cost of 1 m^3 of concrete. The use of high-strength expanded clay concrete in areas with well-established expanded clay production can provide 10–20% savings [5-7].

The main characteristics of concrete taken into account in the calculations are the strength and modulus of elasticity of concrete at the time of load application and

*Corresponding author: raupovch@gmail.com

temperature-moisture effects, the measure of creep (creep characteristic) in concrete, shrinkage strain in concrete, etc. At present, the problem of creating and studying mechanical models of reinforced concrete which adequately reflect such characteristic properties of the material as creep and shrinkage is undoubtedly relevant [8].

In connection with the need to lighten the weight of structures, studies of the nature of the deformability of expanded clay concrete (in particular, creep) are of particular relevance. The creep value is the most important parameter taken into account when designing prestressed reinforced concrete structures. The creep of concrete has a strong influence on the force distribution in statically indeterminate systems, concrete and reinforced concrete dams, and long-span bridges [6-10].

Other well-known models for predicting the creep in designed structures include the European model 1990 Comite Euro-International du Beton (1990 CEB) [11] and the simplified BP (Bazant-Panula) model [12]. The 1990 CEB model is similar to the ACI Committee 209 model [13] and, in predicting the creep; it takes into account the factors of loading age, loading duration, cement type, ambient relative humidity, structure thickness and size. One of the basic differences between this model and the ACI Committee 209 model [13] is that it considers concrete strength as one of the variables in creep prediction. The second basic difference is that the influence of the ambient relative humidity and the size and thickness of the structure on the degree of creep is considered in addition to the influence of these variables on the total or ultimate creep. Failure to consider the influence of these factors on the degree of creep is a shortcoming of the ACI Committee 209 model [13].

The creep in concrete is of great practical importance for reinforced concrete structures since it leads to force redistribution in statically indeterminate structures, to a significant relaxation (damping drop in stress at a given constant strain) of temperature-shrinkage stresses.

The creep in concrete has a very important practical significance and is taken into account in the calculation and design of structures. A distinction is made between linear and non-linear creep in concrete. Under linear creep, the relationship between stresses and strains of creep can be considered linear. Such dependence is observed only at relatively low stresses - of the order of $\sigma < 0{,}5Rb$. . At higher stresses $\sigma \geq 0{,}5Rb$, non-linear creep strains develop in concrete; such strains grow faster than stresses [14].

With linear creep, the relationship between stresses and creep deformations can be considered linear. This dependence is observed only at relatively low voltages – about 0.5 Rb.

The modern theory of concrete creep is based on numerous experimental data and is, in essence, a phenomenological theory. The experimental foundations of this theory were laid by Davis, Dutron, Shenk, Glanville, and others. The theoretical foundations were developed in numerous studies of scientists in the Soviet and post-Soviet countries, starting from the second half of the 20th century. The most significant studies in the field of the theory of elasticity belong to N. Kh. Arutyunyan, S. V. Aleksandrovsky, V. M. Bondarenko, N. A. Budanov, A. A. Gvozdev, P. I. Vasiliev, I. I. Goldenblat, Ya. D. Livshits, G. N. Maslov, Yu. N. Rabotnov, A. R. Rzhanitsyn, I. E. Prokopovich, I. I. Ulitsky, S. V. Bondarenko, A. D. Beglov, R. S. Sanzharovsky, V. D. Kharlab and many other scientists [14 – 17]. The book by N. Kh. Arutyunyan and A. A. Zevin [18] presents methods for calculating solid bodies of various shapes and elements of reinforced rod systems using the example of a column, taking into account linear creep and aging of materials.

The currently available publications do not contain exhaustive answers to a number of questions related to the strength calculation of bending elements made of lightweight concrete, and the behavior of concrete under low-cycle and long-term loading; there is no data on creep and long-term strength of expanded clay concrete. Many important issues of design and calculation of expanded clay structures due to the difficulties of creating a complete theory of their strain and destruction are solved approximately, on an empirical or semi-empirical basis. The widespread use of artificial porous aggregates instead of natural heavy aggregates is a determining condition for increasing the efficiency of capital investments in the construction of transport and other critical structures.

2 Methods

The composition and main characteristics of concrete are given in Tables 1 and 2. Expanded clay gravel of two fractions 5–10 and 10–20 mm in a ratio of 40:60 was taken as a coarse aggregate produced in the Tashkent cement plant. As Portland cement, the cement of the Navoi cement plant was used, and the sand of the Tashkent quarry was used as quartz sand.

Table 1. Composition of expanded clay concrete (EC)

Actual consumption of materials per m^3 of concrete	Cement, kg	427
	sand, kg	629
	expanded clay, kg (l)	414 (727)
W/C (water/cement ratio)		0.49

Table 2. Characteristics of expanded clay concrete

Bulk density of dry expanded clay concrete, kg/m^3	1760
Cubic strength, R, MPa	33.0
Prism strength, R_b, MPa	28.4
Prism strength factor, R_b/R	0.86
Initial modulus of elasticity, E_b, Pa	15.4

Note: Specimens were tested at the age of 28 days. Prisms dimensions - 150x150x600 mm, cubes ribs - 150 mm. The cone slump of concrete mix - 1...2 cm.

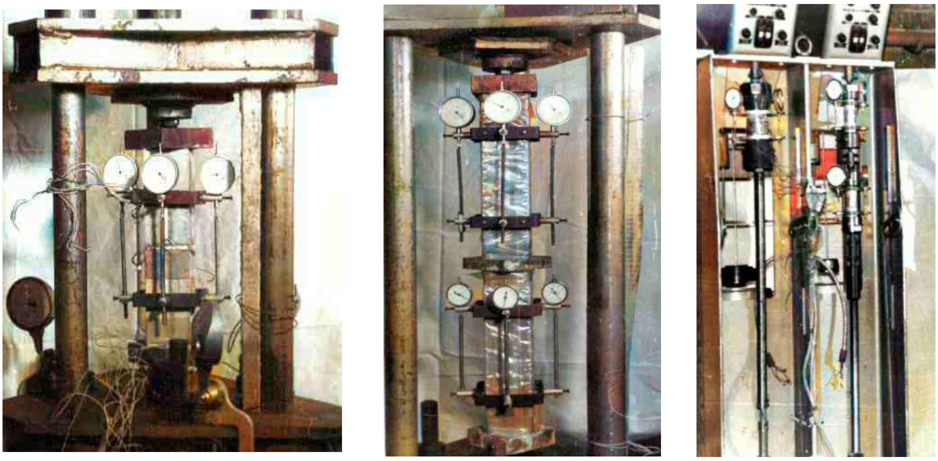
Specimens at different levels of compressive and tensile stresses were loaded in spring and lever installations with a maximum force of 210 kN and 30 kN, respectively.

When testing under compression, specimens - prisms - were installed with metal support plates 30 cm thick glued to the ends with ball joints, and under tension, specimens - cylinders - were mounted in the installation using collet grips and Hooke's hinges (Figure. 1). When loading at high load levels, one specimen was put in the installation (Figure. 1*a*); and when loading at low load levels, two samples were put (Figure. 1*b*).

When installing two prisms, metal plates 20 mm thick were laid between them, and when installing two cylinders, a Hooke hinge was laid. The load value was set according to the range of springs, pre-calibrated on the press, on which the short-term loading was conducted.

The range of spring during calibration was measured with PAO-6 deflection meters with a division value of 0.01 mm, installed on two opposite sides (generatrices) of springs.

To eliminate the error associated with non-additivity of shrinkage and creep, before loading, the specimens were waterproofed from the sides with a layer of paraffin 2-3 mm thick and two layers of polyethylene film, gluing the seams with insulating tape.



a) *b)* *c*

Fig. 1. Long-term testing of specimens under compression (a, b) and tension (c)

The method of a long-term study of expanded clay concrete under axial compression provides reaching (0.2–0.95) R_b stresses in prisms. The method of a long-term study of expanded clay concrete under axial tension provides reaching $0.3R_{bt}$ and $(0.8–0.95)R_{bt}$ stresses in cylinders.

In order to separate the elastic and inelastic components of the total strain, the specimens were loaded in steps of 0.10 of the breaking load with staying on the steps to a given level of compressive and tensile stresses until the increase in strain ceased. Under compression tests, the specimens were loaded with a hydraulic jack installed between the upper support plates of the spring installations, controlling the force with deflectometers mounted on three sides of the installation. After reaching the specified force, the corresponding parts (thrust nuts) were fixed and during the entire experiment, the readings of the deflectometers were constantly monitored. The decrease in the compressive force in time, due to the creep strain in specimens, was compensated by periodic additional loading to the initial level. In the tests, the stress drop in the specimens did not exceed 1 MPa, which is 0.05% of the specified level. The error in measuring the forces in the specimens was 0.01 MPa.

In the process of compression tests at low loading levels (for η = 0.2 - 0.7), dial gauges were used to measure the longitudinal strain of the specimens, with a division value of 0.01 mm or 0.001 mm; the gauges were installed stationary using metal frames on four faces of a prism with a base of 150 mm. At high loading levels (for η=0.7–1.0), longitudinal and transverse strains were measured with strain gauges with a base of 20 mm and 50 mm. Schemes of gluing strain gauges are shown in Figure. 2.

In the process of tensile tests at a low level of loading (for η = 0.3), to measure the longitudinal strain of the specimens, dial indicators with a division value of 0.001 mm were used, installed stationary with metal frames along two generatrices of the cylinder, and at a high level of loading (for η=0.70–0.95); strain gauges with a base of 20 mm and 50 mm were used. Schemes of gluing strain gauges are shown in Figures 4, *a, b*. At the level η = 0.70, the measurements were conducted in parallel using both methods. In order to develop the technique for long-term strain measurement and assess the reliability of the data obtained, methodological experiments were conducted, similar to the ones given in [14]; the strain was measured in parallel in expanded clay concrete and metal samples.

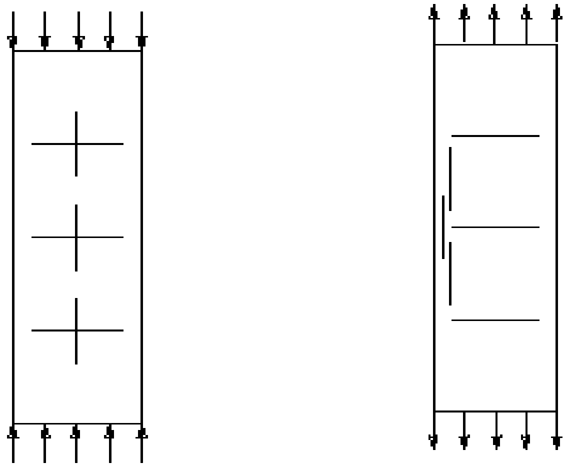


Fig. 2. Scheme of gluing strain gauges on prisms (a) and cylinders (b)

To reduce the effect of shrinkage phenomena that occur during adhesive curing, the strain gauges were glued to the samples three months before the test and waterproofed with special mastic to exclude the effect of ambient humidity fluctuations on the readings.

All samples were under the same conditions of long-term loading (T=20±2^{o} C, W=70–80%). During the entire period of testing, the stability of the measuring scheme was regularly checked by turning on the control half-bridge gauge AID-4. During the experiment, it was determined that minor fluctuations in temperature and humidity (by 1–3°C or 3–5%) do not lead to a change in the strain values.

In the process of developing the method of long-term strain measurement, the main factors that violate the stable operation of the measuring circuit, including strain gauges, the age of the strain gauge gluing, and the second strain gauge, were established. The methodical approaches noted above ensured sufficiently stable operation of the measuring scheme for 400 days (the "zero" deviation of the measuring scheme during this time did not exceed $\pm 2{,}0 \times 10^{-5}$). An analysis of the results of the experiments conducted allows us to consider insignificant the difference in measurements (by indicators and strain gauges) of strains in concrete under a long-term load. The results of measurements of strains in concrete under a long-term load are comparable.

Thus, the results obtained allow us to conclude that the creep strain in concrete can be measured quite reliably with paper strain gauges, provided observing the requirements for waterproofing strain gauges, the required duration (more than a month) for the polymerization of the adhesive and stabilization of the zero position of strain gauges.

To consider strains associated with minor changes in ambient temperature and humidity, unloaded isolated twin samples were used. Simultaneously with the strain measurements of the samples placed under a long-term constant load, the strains of unloaded twin samples were measured to determine the shrinkage strain.

Before the samples were loaded with a long-term loading, the twin samples were tested in a similar way on a press under a short-term loading until failure. The cubes were tested on the same dates.

Load testing of samples under low levels of loading (0.20 - 0.70) R_b and $0{,}3R_{bt}$ lasted for 210 days, and then they were unloaded and the strain effects were measured for 56 days. With the expiration of 56 days after unloading, the main and reference samples were brought to failure under a short-term action of compressive load. The modulus of elasticity and compressive strength were determined to estimate the value of function $m(t,\tau_1) = R'/R \cong E'/E$ (where R', R, E', E – are the strength and elastic modulus of the main and reference samples, respectively), which takes into account the effect of the previous loading of the material on the short-term strength and elastic modulus.

Creep strains under compression and tension were calculated taking into account the strains that occur during staying under short-term stepwise loading of samples to a given stress level.

In these studies, the verification of the homogeneity of concrete and the selection of groups of twin samples were given the most serious attention. Nevertheless, despite the careful selection of groups of twin samples, the scatter of experimental data in time to failure turned out to be quite significant. In this regard, it was necessary to abandon the assessment of test results "by groups" and switch to individual samples. The "actual" level of stresses in concrete was refined on the basis of a joint analysis of strain curves "η–σ_x" obtained when the samples were long-term loaded and available "reference" curves "η–σ_x" obtained during a short-term test.

The kinetics of changes in the measure of creep in expanded clay concrete in time under axial compression and tension are shown in Figures 3 and 4, and shrinkage strains are shown in Figure 5. The growth of curves of the creep measure of the specimens have the greatest rise at the initial time after the load application (30 days), then there is a slight decrease in the growth of the creep measure with a tendency to stabilization. It can be assumed that the intensive development of the creep measure in the first days after the load application is due to significant structural strains in concrete.

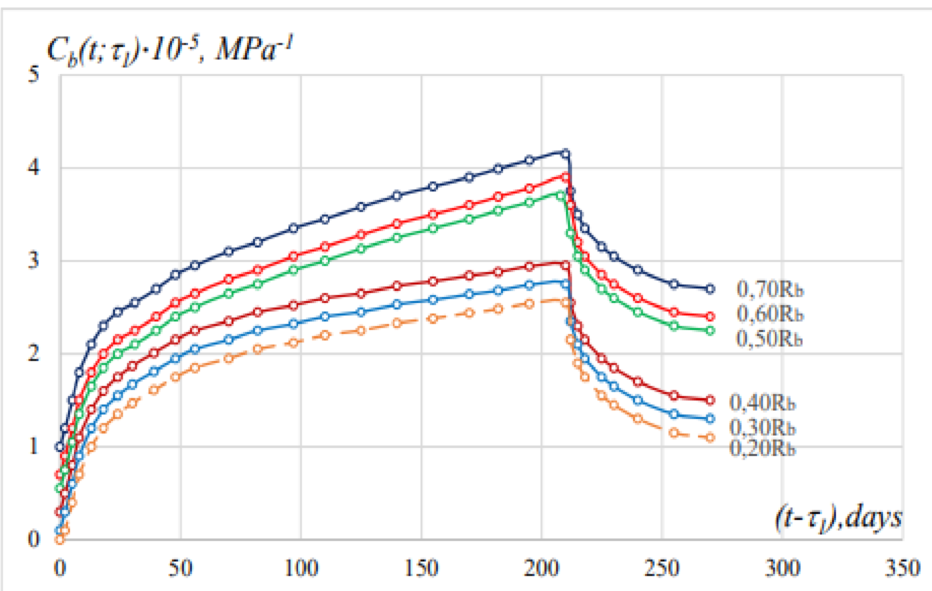


Fig. 3. Kinetics of change in the measure of creep in expanded clay concrete in time under axial compression at different levels of long-term loading

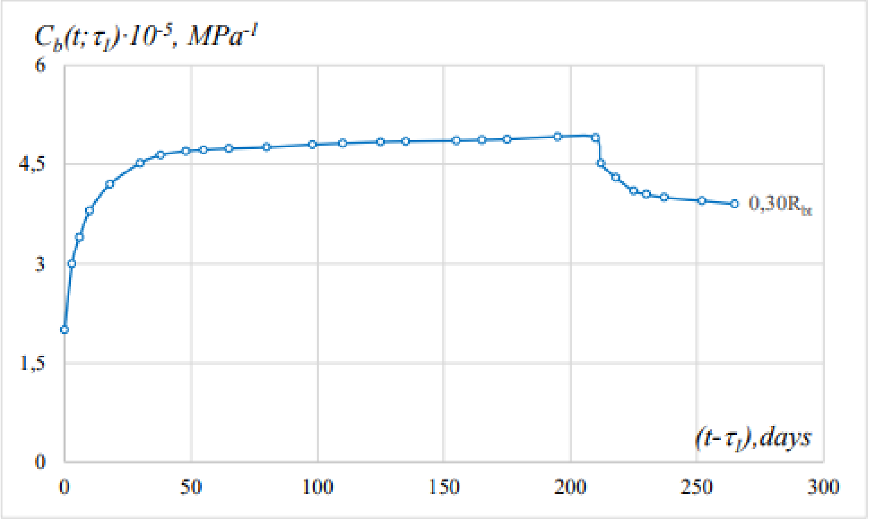


Fig. 4. Kinetics of change in the measure of creep in expanded clay concrete in time under axial tension

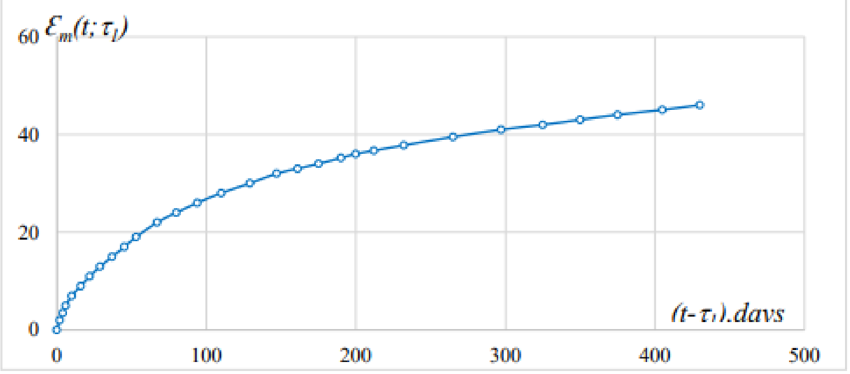


Fig. 5. Kinetics of change in the shrinkage strain of expanded clay concrete in time

Up to stresses $0.4R_b$, the creep strain in expanded clay concrete under compression develops practically in a conditional linear region. At $0.5R_b$, creep strains develop clearly not according to a linear law, it can be assumed that in the case of $\sigma_1/R_b > 0.4$ microcracks begin to form in the samples.

When analyzing the pattern of change in creep strains, a simpler method was used to reveal the nonlinearity of their development. Figure 6 shows the graphs of dependences of the ultimate creep strain $\varepsilon_{x,p}$ (∞,τ_1) (determined according to state standards All-Union State Standard) 24544–97) on the value of relative stresses under long-term compression σ/R_b. As follows from this graph, in expanded clay concrete up to stresses $0,4R_b$, creep strains develop almost in a linear region. The results obtained are in good agreement with the data given in [19-22].

Figures 3-5 show the calculated curves plotted using one of the equations (1) of the theory of an elastic-creeping body, obtained on the basis of a modification of the of N.Kh.Arutyunyan theory of an elastic-creeping body with the core [18]. The results obtained indicate good convergence of the calculated curves with the experimental data (the discrepancy is no more than 10%).

In [23], the following dependence was proposed to determine the relative strain of the nonlinear creep in expanded clay concrete:

$$\varepsilon_{x,p}(t;\tau_1) = (\sigma_{bl} + \alpha\sigma_{bl}^3)C_b(t;\tau_1) \quad (1)$$

where σ_{bl} is the working stress, MPa; α is a numerical coefficient determined from tests; $C_b(t;\tau_1)$ is a measure of linear creep in expanded clay concrete, which can be determined by the dependence proposed in [23].

For the numerical solution of equation (1), it is necessary to determine the values of the short-term strength limit under axial compression and tension and the creep measures $C_b(t;\tau_1)$, $C_{bt}(t;\tau_1)$, its change in time, and the values of the modulus of elasticity and functions $m(t;\tau_1)$.

The values of the measure of linear creep in the mortar part of expanded clay concrete under axial tension (if there are no direct experimental data) are determined by formula (3):

$$C_{bt}^*(t;\tau_1) = \lambda(t;\tau_1)C_b(t;\tau_1); \quad (2)$$

Where

$$C_b(t;\tau_1) = \frac{70R_b^2(\tau_1-2)+13000R_b-140000}{(177R_b-1700)R_b\tau_1^{3/2}}10^{-5} + \frac{0.2R_b+15\tau_1-0.2R_b+100}{R_b}\left[1-e^{-y(t-\tau_1)}\right]10^{-5}; \quad (3)$$

$$\gamma_1 = 0.015 + 18/R_b; \quad (4)$$

the second factor in formula (4) is taken into account at $\tau_1 > 16$ days.

$$\lambda(t;\tau_1) = a + \frac{b(t;\tau_1)}{t_1}. \quad (5)$$

for expanded clay concrete of dense structure (on quartz sand)[18]:

$a = 2.15$; $b = 0.63$ at $0 < (t-\tau_1) \le 2$ days.
$a = 3.40$; $b = -0.077$ at $2 < (t-\tau_1) \le 15$ days.
$a = 2.25$; $b = -0.03$ at $15 < (t-\tau_1) \le 100$ days.
$a = 2.00$; $b = 0$ at $(t-\tau_1) > 100$ days.

for expanded clay concrete of porous structure (on expanded clay sand):

$a = 2.0$; $b = 1.0$ at $0 < (t-\tau_1) \le 2$ days.
$a = 4.06$; $b = 0.03$ at $2 < (t-\tau_1) \le 100$ days.
$a = 1.0$; $b = 0$ at $(t-\tau_1) > 100$ days.

The values of function $m(t;\tau_1)$, taking into account the effect of a long-term loading on the change in the surface energy of the material in the crack zone for expanded clay concrete, are calculated by formula (6)

$$m(t;\tau_1) = a_1 + b_1 lg(t-\tau_1), \quad (6)$$

where $a_1 = 1.091$; $b_1 = 0.035$ at $\tau_1 \le 28$ days.

$a_1 = 1.033$; $b_1 = 0.029$ at $\tau_1 > 28$ days.

The limiting values of the relative creep and shrinkage strain in expanded clay concrete were determined by the method of constructing regression curves of the form

$$(t-\tau_1)\,/\varepsilon_{x,p}(t;\tau_1) = [A + B(t-\tau_1)]10^{-5} \tag{7}$$

(according to State All-Union Standard 24544–97), which make it possible to linearize the curves describing creep and shrinkage strains in time.

The numerical values of coefficients A and B of equation (7) taken to describe the curves of changes in the shrinkage and creep strain under compression are given in table 3.

Table 3. Results of statistical processing of tests (value of coefficients A and B)

σ_1/R_b	A	B
0.2	1.329	0.053
0.3	0.745	0.032
0.4	0.463	0.023
0.5	0.667	0.014
0.6	0.513	0.011
0.7	0.295	0.009
Shrinkage	1.976	0.017

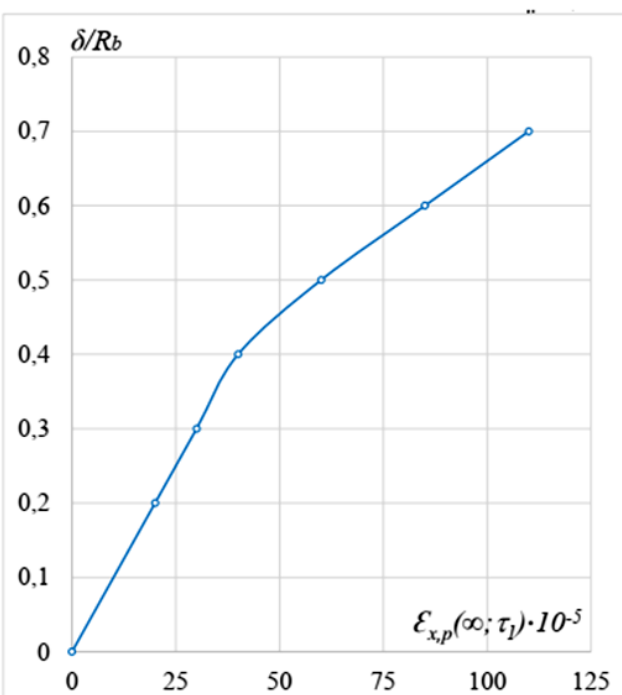


Fig. 6. Change in ultimate creep strains depending on the level of long-term loading

Table 4 shows the values of the total longitudinal and transverse strain in concrete (including the total strains during the loading time), creep strains (considering the strains during the staying time), and the differential coefficient of transverse strain by the moment of destruction of the samples. As seen from the data obtained, the limiting value of creep strains depends on the stress intensity and increases with the level of long-term stresses. It can be seen that the creep strain was 75-90% of the ultimate creep strain.

Table 4. Results of the study of creep strain under axial compression and tension

Series	$\sigma_l/R_b\,(R_{bt})$	Strain			
		Elastic	Creep	Limit	
		by the time of application of long-term load	for 210 days	Creep strain	Measure of creep
Under compression					
	0.2	38	18	19	2.76
	0.3	57	28	31	3.01
CC	0.4	76	40	44	3.21
	0.5	95	64	74	4.31
	0.6	114	79	96	4.42
	0.7	133	97	109	4.62
Under tension					
CC	0.3	2.8	3.1	–	–

As seen from the data obtained, the short-term tensile strength of expanded clay concrete, which underwent long-term tension, tended to 10% increase compared to an unloaded sample and the elastic modulus increased up to 8%.

The results of determining the values of functions $m(t;\tau_1)$ (Table 5) show that at stresses (0.2-0.4)R_b, the increase in strength and modulus of elasticity under compression was 6-15% and 1-5%, respectively, which is confirmed by the findings in [19 – 22]. The hardening zone is shifted towards lower stresses (0.2-0.4) R_b.

Table 5. Effect of the previous loading on the strength and modulus of elasticity of concrete (Above the line - data on strength, below the line – data on the modulus of elasticity)

The value of function m($t;\tau_1$) at the intensity of previous stresses						
Compression						Tension
$0.2R_b$	$0.3R_b$	$0.4R_b$	$0.5R_b$	$0.6R_b$	$0.7R_b$	$0.3R_{bt}$
1.13/1.03	1.09/1.05	1.06/0.97	0.90/0.78	0.90/0.78	0.88/0.76	1.10/1.08

The increase in the strength of compressed and strained concrete can be explained by the removal of internal stresses, and redistribution of stresses between structural elements, which in turn levels the stress field due to the ongoing physical and chemical processes of cement stone hardening, and by certain compaction of the concrete structure. Large stresses ($\sigma/R_b \geq 0.5$) mainly cause a decrease in strength and elastic modulus to 10-12% and 22-24%, respectively. (Larger values correspond to higher stresses). The decrease in strength and elasticity modulus of specimens subjected to long-term compression can be explained by the fact that in the case of $\sigma/R_b \geq 0.5$, microcracks begin to appear in the specimens.

By analyzing the relationship between ultimate creep strains and the relative level of long-term stresses (Figure. 6), we can rightly conclude that the creep in expanded clay concrete at a loading level not exceeding $\sigma/R_b = 0.5$ can be considered conditionally linear, and the highest level of long-term stresses at which the short-term strength and modulus of elasticity of the main samples that have undergone long-term compression do not differ from those for the reference twin-samples $m(t;\tau_1)$=1.

Due to the fact that the data on the study of creep in concrete with porous aggregates under axial tension are very limited, we compared the measures of creep in expanded clay concrete under axial compression and tension to specify the pattern of change in their relationship in time. It can be seen that the value of the ratio of the indicated values of the creep measure changes according to a curvilinear law depending on the observation period (Figure 7).

This confirms the conclusions obtained in earlier studies with the mixes on lithoid pumice and expanded clay sands [23]. At the initial observation time $(t;\tau_1) \leq 2$ days, the measure of creep in expanded clay concrete under tension significantly exceeds the measure of creep under compression; then their ratios begin to decrease and at $(t;\tau_1) > 100$ days, it practically stabilizes (Figure 7).

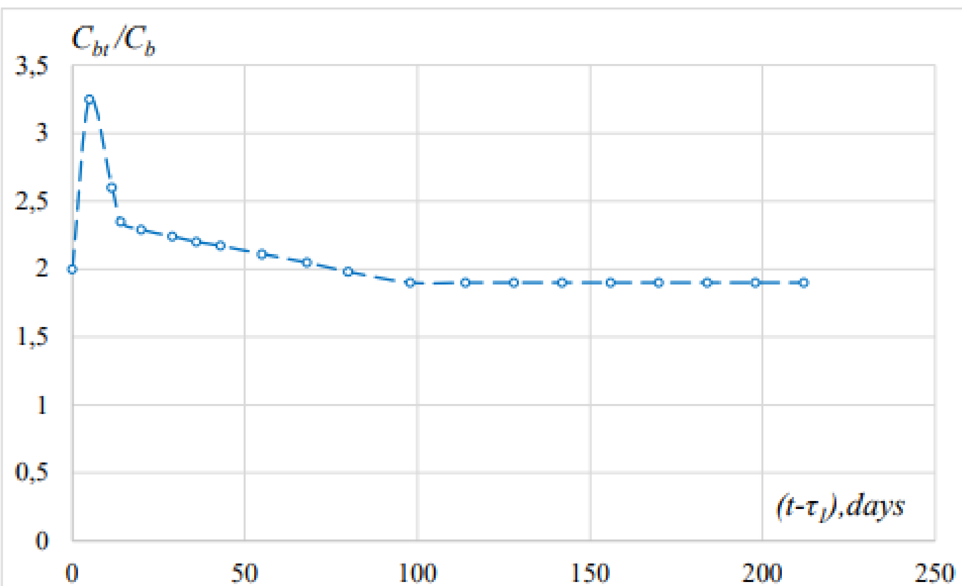


Fig. 7. Comparison of the measure of creep in expanded clay concrete under axial tension and compression

For calculation, the curve can be divided into four sections and take changes $\lambda(t;\tau_1) = C_{bt}(t;\tau_1)/C_b(t;\tau_1)$, (8) depending on $(t;\tau_1)$ according to a linear law in each section:

$$\lambda(t;\tau_1) = \frac{a+b(t-\tau_1)}{t_1}, \quad (9)$$

where $a = 2.15$; $b = 0.63$ for $0 < (t-\tau_1) \leq 2$ days;
$a = 3.40$; $b = -0.077$ for $2 < (t-\tau_1) \leq 15$ days;

$a = 2.25$; $b = -0.03$ for $15 < (t-\tau_1) \le 100$ days;
$a = 1.95$; $b = 0$ for $(t-\tau_1) > 100$ days.

The values obtained in the experiments for measures of creep in expanded clay concrete under tension and compression and their ratios $C_{bt}(t;\tau_1)/C_b(t;\tau_1)$ at the age $(t-\tau_1)>100$ days are given in Table 2, which shows that the measure of creep in expanded clay concrete under tension is approximately 2 times greater than under compression.

Ivanov-Dyatlov I.G. et al. [8] showed that the measure of creep in expanded clay concrete under compression varies within (2-7) 10^{-5} МПa^{-1} and is 1.4 ... 1.6 times greater than that of equal-strength heavy concrete.

G.A.Buzhevich [8] believes that the creep in expanded clay concrete in all cases is greater than that of traditional concrete. They found that the creep strain in expanded clay concrete is 1.5 times greater than that of equal-strength heavy concrete. Approximately the same data for expanded clay concrete were obtained by other researchers [18, 19]. The measure of creep C_b in lightweight concrete (with a degree of stress compression of samples not exceeding $0.5R_b$) ranges from 2 to $7\text{x}10^{-5}$ MPa^{-1} and increases to $20\text{x}10^{-5}$ MPa^{-1} as the class of concrete decreases

R.K.Zhitkevich, in his study in [24], analyzing experimental data and summarizing the results of other researchers, reports that the creep strain in structural expanded clay concrete is 1.3 ... 3.0 times greater than that of equal-strength heavy concrete (with equal absolute values of stresses).

For samples destroyed during staying under load, the strain development graphs are given up to the last report recorded, however, not all of them are the maximum values since some samples were destroyed at night.

As seen from Figures. 8-12, in all samples that collapsed under long-term loading, the development of strains in concrete can be characterized by three stages:

1) fast growth immediately after loading;
2) slow long-term growth of strains after a short period of loading;
3) the accelerated growth of strains before the exhaustion of the bearing capacity.

The acceleration in the growth of creep strains at the third stage ends with the complete destruction of the specimens. The last stage of the sample operation is characterized by a particularly significant increase in the transverse strains in concrete under compression due to the progressive development of micro- and macrocracks.

Certain patterns can be seen in the graphs of increase in the longitudinal creep strain under tension. As seen from Figures. 8-12 creep strains vary depending on the stress level.

For predicting the behavior of the reference samples under long-term loading, data on their deformability are essential. One of these indices is the differential coefficient of transverse strain.

Based on the data obtained on the transverse and longitudinal strains in the samples, the relative change in volume and the differential coefficient of transverse strain (for each sample) were determined, according to the pattern of change in time, which can imply the destructive changes occurring in concrete.

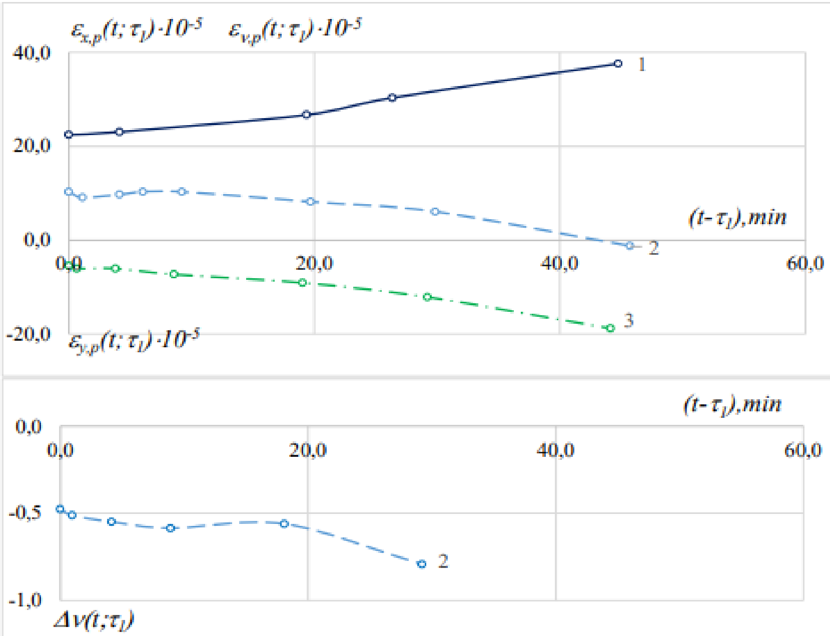


Fig. 8. Kinetics of changes in the strain characteristics of expanded clay concrete destroyed under long-term loading ($t\!-\!\tau_1 < 60$) min. (Numbers near curves correspond to specimen numbers)

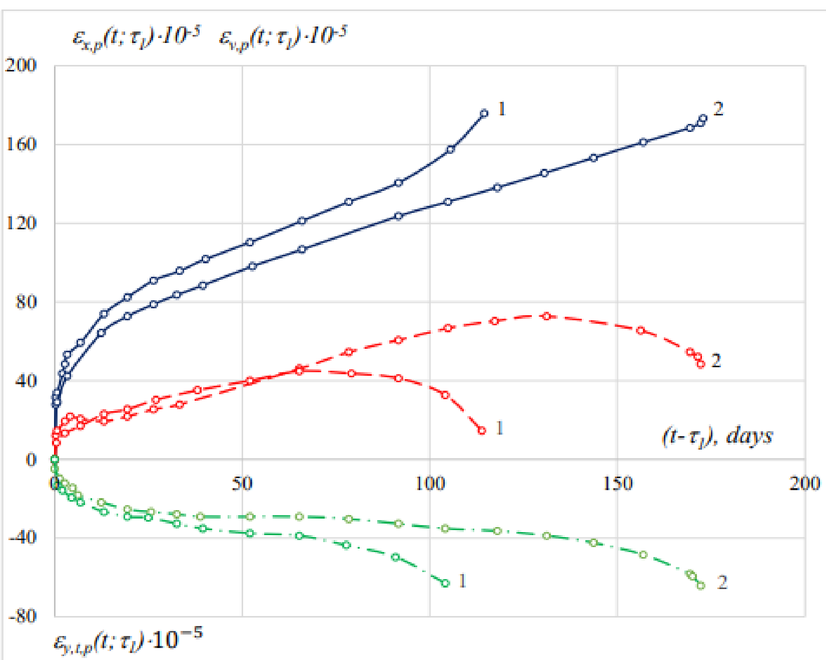


Fig. 9. Kinetics of changes in the strain characteristics of expanded clay concrete specimens destroyed under long-term loading (100 days < $t\!-\!\tau_1$ < 200 days). (Numbers near curves correspond to specimen numbers)

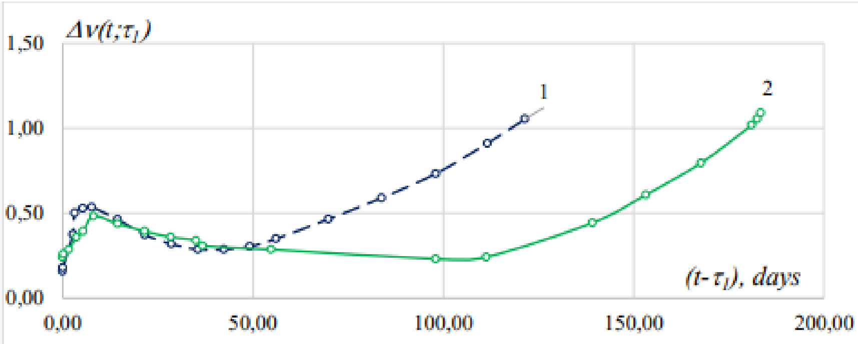


Fig. 10. Kinetics of changes in the coefficient of transverse strain in expanded clay concrete samples under long-term constant loading (100 days < t–τ_1 < 200 days). (Numbers near curves correspond to specimen numbers)

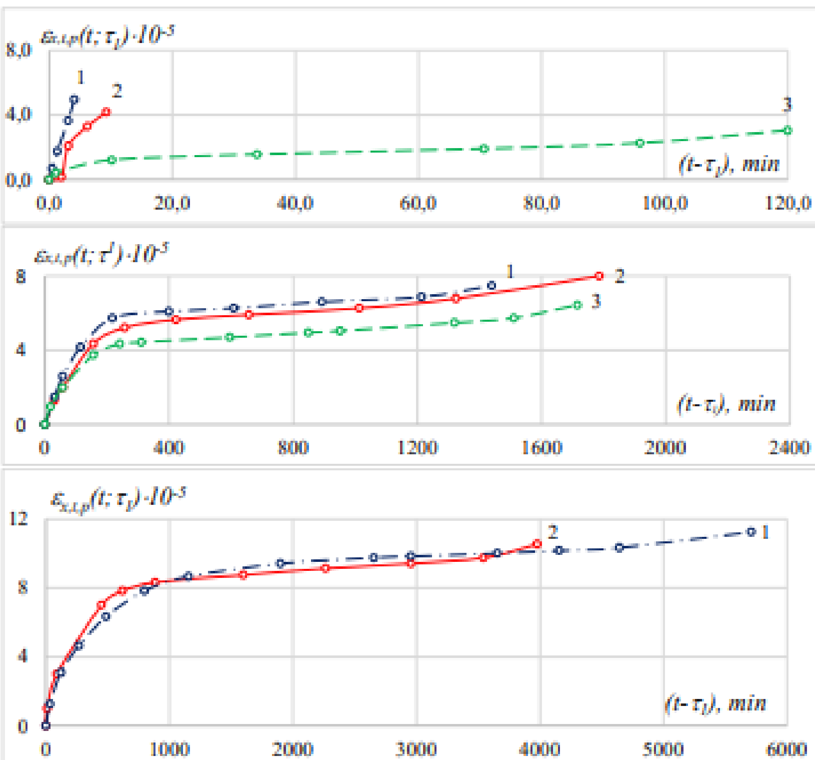


Fig. 11. Kinetics of changes in the longitudinal strain in expanded clay concrete specimens destroyed under a long-term constant loading (t–τ_1 < 120 min). (Numbers near curves correspond to specimen numbers)

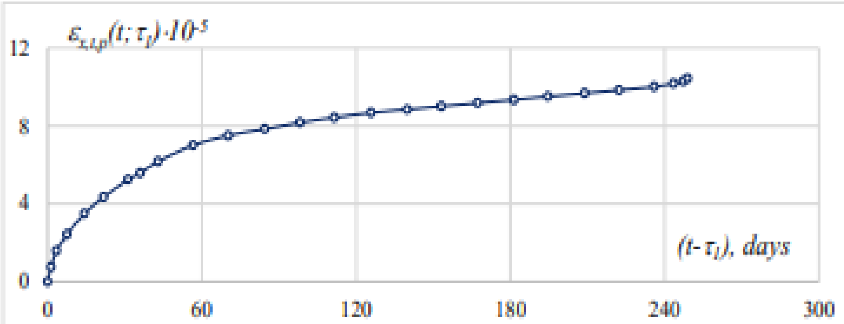


Fig. 12. Kinetics of changes in the longitudinal strain in expanded clay concrete specimens destroyed under long-term constant loading ($t–\tau_1 < 300$ days). (Numbers near curves correspond to specimen numbers)

Figure 10 shows graphs of the change in time of coefficient $\Delta\nu_t$ for expanded clay concrete samples, destroyed within a few hours after applying a constant load. Figure 11 shows the pattern of change in this coefficient over 450 days.

For all specimens collapsed under long-term loading by stress $\sigma_{bl} = (0.85\text{-}0.95)R_b$, there was an intense increase in the transverse strain coefficient over time. So, if by the time of applying a long-term load to the samples, the coefficient of transverse strain $\Delta\nu_t$ was less than 0.5, then just before the destruction, its value was greater than 0.5. All destroyed samples are characterized by a high value of coefficient $\Delta\nu_t$ – more than 0.5. A significant increase in this coefficient over time is observed as a result of a large development of transverse strains (associated with destructive changes) and indicates a self-accelerating process of destruction.

In samples that did not destroy under long-term loading, a completely different picture was observed (Figure 12).

In samples loaded to a stress level of $0.8R_b$, a particularly rapid increase in coefficient $\Delta\nu_t$ was noted on the first day after the load was applied. Over time, the rate of increase in coefficient $\Delta\nu$ began to decrease. A similar pattern can be traced to the relative change in volume of these samples.

Figures 8-11 show that after applying high long-term stresses $(0.85–0.95)R_b$ to the samples, an intensive relative increase in volume $\varepsilon_{v,p}(t;\tau_1)$ was observed due to the progressive formation and development of micro- and macro cracks at a time close to destruction.

In this regard, we can assume that the progressive increase in the transverse strain coefficient $\Delta\nu_t$ in time and the simultaneous significant relative increase in volume $\varepsilon_{v,p}(t;\tau_1)$ are the features, the presence of which makes it possible to predict the destruction of a sample under long-term loading.

Based on the analysis of the patterns of change in $\Delta\nu_t$ and $\varepsilon_{v,p}(t;\ \tau_1)$ of undestroyed samples under long-term stress, it can be assumed that the samples will not fail, as evidenced by the stabilization of these parameters over time.

3 Conclusions

1. An empirical formula appropriate for practical application was obtained to define and describe:

- he relative strain of non-linear creep of expanded clay concrete (1);

- the measures of linear creep in expanded clay concrete under axial tension and compression (if there are no direct experimental data) (2, 3);
- the pattern of change in $\lambda(t;\tau_1) = C_{bt}(t;\tau_1)/C_b(t;\tau_1)$, (8) depending on $(t;\tau_1)$ according to a linear law in each section (9);
- the pattern of effect of the previous loading on the strength and modulus of elasticity of concrete (6);
- limiting values of relative strain under creep and shrinkage in expanded clay concrete (7).

2. It was experimentally proved that the creep in expanded clay concrete under compression at a loading level of $\eta < 0.5$ is within the conditional linear dependence.

3. It was determined that the highest level of long-term stress, at which the short-term strength and elasticity modulus of expanded clay concrete are equal to the strength and elasticity modulus of reference samples, corresponds to the limit of conditional linear creep in expanded clay concrete. It was shown that the previous action of a long-term compressive load of low intensity ($\eta < \cong 0.5$) increases the strength and elasticity modulus of expanded clay concrete by 6–15% and 1-5%, respectively, and high intensity ($\eta \geq \cong 0.5$) reduces the strength and elasticity modulus to 10-12% and 22–24%, respectively. The previous action of a long-term tensile load of low intensity ($\eta = 0.3$) increases the strength and modulus of elasticity of concrete under axial tension up to 8–10%.

4. It was determined that the creep strains in expanded clay concrete at an equal relative level of stresses ($\eta = 0.3$) under axial tension exceed the creep strain under compression by about 3.5...4.0 times. It was also revealed that the value of the ratio of the measure of creep under tension to the measure of creep under compression increases intensively at the initial time after loading ($t-\tau_1$) ≤ 2 days), then begins to decrease, (2 days < ($t-\tau_1$) ≤ 100 days), and, with the passage of time, at long-term periods of observation it stabilizes, ($t-\tau_1$) > 100 days.

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