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POLYPROPYLENE FIBER AS A FACTOR OF REDUCTION OF THE TOTAL SHRINKAGE STRAIN OF EXPANDED CLAY CONCRETE

V. A. Rzhevutskaya [1], Yu. G. Moskal'kova [2]

Belarusian-Russian University [1, 2]
Republic of Belarus, Mogilev

[1] *Senior Lecturer of the Dept. of Industrial and Civil Construction, tel.: +375(44)549-11-81, e-mail: valeriarzhevuckaya@gmail.com*
[2] *PhD in Engineering, Assoc. Prof. of the Dept. of Industrial and Civil Construction, tel.: +375(29)742-91-83, e-mail: julia43@tut.by*

Statement of the problem. The article presents the development features of the total shrinkage strain of expanded clay concrete, expanded clay fiber-reinforced concrete, expanded clay steel-reinforced concrete, and expanded clay fiber-steel-reinforced concrete. According to the analytical review, the shrinkage strain decrease as a result of the fibers adding was noted by the researchers without analyzing the reason for the phenomenon. Therefore the purpose of the study is to establish the reason for the decrease of the shrinkage strain of expanded clay concrete with the addition of polypropylene fibers.
Results. It has been confirmed that the polypropylene fiber addition reduces the total shrinkage strain of expanded clay concrete by 29—34 % on the 120th day with the volume content of fibers of 0.36 %. Empirical dependences of deformations compatibility for expanded clay fiber-reinforced concrete and expanded clay fiber-steel-reinforced concrete are set forth.
Conclusions. It has been experimentally established that fiber is a significant factor on the first days of the concrete mixture hardening, when the elastic modulus of the fiber is greater than or equal to the elastic modulus of the cement stone. Fibers act as a bond and affect the redistribution of shrinkage stresses within the composite, thus reducing the values of the total shrinkage strain.

Keywords: shrinkage, shrinkage strain, volumetric deformations, lightweight concrete, expanded clay concrete, fiber-reinforced concrete, polypropylene fiber.

Introduction. Concrete is a complex material, which is central to its elastic-plastic properties. Plastic deformations are particularly obvious during the initial period of concrete hardening and are the result of shrinkage. In normal sections of reinforced concrete elements, caused by shrinkage, tensile forces occur in the cement stone, and compressive forces in the reinforcement bars, i.e. by the time an external load is applied, the reinforced concrete element is already in a stress-strain caused by shrinkage development [9, 25, 29].

According to [4, 10, 18], the values of the ultimate relative shrinkage deformations of lightweight concrete on expanded clay gravel fluctuate within the range from 0.33 to 0.9 ‰, and in [15] the final values of expanded clay concrete shrinkage are within the range from 0.3 to 1 mm per 1 running meter. It should be noted that with the same components of the concrete mix, the values of shrinkage deformations can differ several times [1—3, 12—14, 30]. The wide range of the obtained values of shrinkage deformations directly depends on the physical and mechanical characteristics of the components of the concrete mix, i.e., is determined by the local raw material base. Thus, the study of this issue is relevant for each specific region.

Scholars from different countries [6, 11, 16, 21, 22, 28] have noted that the introduction of fiber into expanded clay concrete mixture improves the physical and mechanical properties of expanded clay concrete, including a decrease in shrinkage deformations. A review of experimental studies [5, 8, 17, 19, 20, 23, 24] dedicated to the shrinkage of lightweight fiber-reinforced concrete shows that the presence of fiber in the concrete mixture allows the values of relative shrinkage deformations to be reduced by 10—50 %. At the same time, scholars [5, 6, 8, 11, 16, 17, 19—24, 28] do not focus on the factor that affects the magnitude of total shrinkage deformations of fiber-reinforced concrete and helps to reduce their values in absolute value. We assumed that fiber fibers act as a bond during the first day of concrete mixture hardening and affect the redistribution of shrinkage stresses inside the composite. During the first few days, the value of the elastic modulus of expanded clay concrete is small and comparable to the elastic modulus of polypropylene fiber. In this regard, at the initial stage (the period of the most intensive development of shrinkage deformations), compressive stresses arise in fiber fibers by analogy with reinforcing bars. Since internal stresses in the composite system «expanded clay concrete — fiber» and «expanded clay concrete — fiber — longitudinal reinforcement» are balanced, then as a result of the work of polypropylene fibers, the value of tensile stresses in expanded clay concrete decreases, and therefore the value of shrinkage deformations also decreases. That is, during the period of the most intensive development of shrinkage (the first day following concreting), polypropylene fibers become an internal bond that prevents free deformations of expanded clay concrete. In order to confirm or refute this assumption, experimental studies of the development of shrinkage deformations in expanded clay concrete reinforced with rod, fiber and with combined reinforcement were carried out.

Hence the object of this study was prism-shaped samples made of expanded clay concrete, expanded clay-reinforced concrete, expanded clay fiber concrete and expanded clay fiber reinforced concrete.

The subject of the study is the total deformations of free shrinkage of expanded clay concrete and constrained shrinkage of expanded clay fiber concrete, expanded clay-reinforced concrete and expanded clay fiber reinforced concrete.

The objective of the study is to establish the cause of the decrease in shrinkage deformations of expanded clay concrete while adding polypropylene fiber.

1. Theoretical prerequisites for the analytical determination of the strains of constrained shrinkage of dispersed and combined-reinforced expanded clay concrete. In accordance with the well-known equation of strain compatibility, the value of the strains of total free shrinkage of expanded clay concrete ε_{lcs} is as follows:

$$\varepsilon_{lcs} = \varepsilon_{lcs,s} + \varepsilon_{ss}, \tag{1}$$

where $\varepsilon_{lcs,s}$ are the relative shrinkage deformations of expanded clay concrete constrained by reinforcing bars; ε_{ss} are the relative deformations of reinforcement.

Based on the assumption that at an early age low-modulus polypropylene fibers act as a bond, the deformation compatibility equation for expanded clay fiber concrete can be presented in the following interpretation:

$$\varepsilon_{lcs} = \varepsilon_{lcs,f} + \varepsilon_{fs}, \tag{2}$$

where $\varepsilon_{lcs,f}$ are the relative shrinkage deformations of expanded clay concrete constrained by fiber; ε_{fs} are the relative deformations of fiber.

As it is assumed that, along with the rod reinforcement, the fiber fibers act as internal connections and experience compressive stresses, the following expression will be valid for expanded clay fiber reinforced concrete:

$$\varepsilon_{lcs} = \varepsilon_{lcs,f,s} + \varepsilon_{fs} + \varepsilon_{ss,f}, \tag{3}$$

where $\varepsilon_{lcs,f,s}$ are the relative shrinkage deformations of expanded clay concrete, constrained by fiber and reinforcing bars; ε_{fs} are the relative deformations of fiber; $\varepsilon_{ss,f}$ are the relative deformations of the reinforcement.

2. Design of a full factorial experiment of type 2^2. In conducting the experimental studies, a design of a full factorial experiment of type 22 (with two factors with variation at two levels) was implemented. The following factors were adopted as the variables:

– x_1 is the presence of dispersed reinforcement with polypropylene fiber with a volume content of 0.36 %, which in the proposed composition of expanded clay concrete mix is equivalent to 1.5 % by weight of the mass of cement (6.42 kg per 1 cubic meter);

– x_2 is the reinforcement with rod at a reinforcement percentage of 3.57 % over the cross-sectional area of the test sample.

The response function (y) was the value of the relative deformation of the total concrete shrinkage at 120 days. The planning matrix 22 is shown in Table 1.

Table 1

Second-order design (number of factors k = 2)

Experiment number	Sample labelling	Plan		Plan in the notes	
		x_1	x_2	x_1, %	x_2, %
1	KFZhB	+1	+1	0,36	3,57
2	KZhB	–1	+1	0	3,57
3	KFB	+1	–1	0,36	0
4	KB	–1	–1	0	0

Note: KFZhB — expanded clay fiber reinforced concrete, KZhB — expanded clay reinforced concrete, KFB — expanded clay fiber concrete, KB — expanded clay concrete.

3. Major materials for the preparation of expanded clay concrete and expanded clay fiber concrete mixes. The following materials were used to prepare the concrete mixture:

– expanded clay gravel produced by OJSC «Expanded Clay Gravel Plant of Novolukoml» according to STB 1217 (fraction 4—10 mm);

– Portland cement produced by OJSC «Belarusian Cement Plant» according to GOST 30515 and GOST 10178 (activity 42.5 MPa);

– river sand from the Pavlovskoye quarry in the Mogilev region (the Dnieper River floodplain) according to GOST 8736 (fineness modulus 2.13);

– water according to STB 1114.

For dispersed reinforcement, polypropylene fiber produced by Russeal LLC, made from granules of high-modulus thermoplastic polymer C3H6, was used. While selecting the length of the fiber fibers, the recommendations [6] were taken into account, according to which it is advisable to use a fiber length commensurate with the fraction of large filler (expanded clay). Therefore in this study, a 12 mm long round micro-reinforcing construction fiber was used as a reinforcing element.

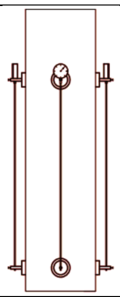
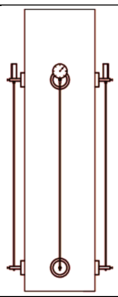
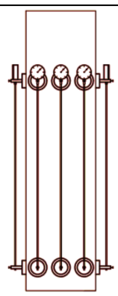
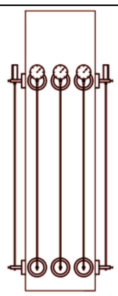
According to the previous studies [26, 27], for expanded clay fiber concrete, the percentage of fiber reinforcement of 0.36 % by volume of concrete is the most effective of those considered (the polypropylene fiber content of 0.12, 0.24 and 0.36 % by volume was considered). Thus the following options for the percentage of polypropylene fiber were adopted in this study: ρ_{PPf} = 0 %; ρ_{PPf} = 0.36 % by volume of expanded clay concrete. When manufacturing test samples reinforced with rod reinforcement, the following reinforcing bars were used: 16 mm in diameter, class S500 (longitudinal reinforcement, percentage of longitudinal rod reinforcement ρ_s = 3.57 %); 6 mm in diameter, class S240 (transverse reinforcement).

4. Methodology for measuring the total shrinkage deformations of expanded clay concrete, expanded clay-reinforced concrete, expanded clay fiber concrete and expanded clay fiber

reinforced concrete. Through the course of the development of shrinkage deformations, they were recorded on samples in the form of prisms with dimensions of 150 × 150 × 600 mm in accordance with the requirements of GOST 24544. Three series of twin samples were successively tested (three twin samples in each series). Table 2 presents the characteristics of the test samples. Shrinkage deformations of expanded clay concrete on the open face of the test prisms started being measured no more than 3 hours following concreting. Therefore the base of the steel benchmarks was immersed in the concrete mix to a depth of at least the maximum size of the filler. The deformations of the reinforcement resulting from the shrinkage of concrete were measured on the open face of the prisms immediately following concreting (the method for measuring the deformations of constrained shrinkage of reinforced expanded clay concrete is described in detail in [7]). The shrinkage deformations of expanded clay concrete and the deformations of the reinforcement on the remaining faces of the prisms were recorded immediately following stripping the samples a day following concreting. The duration of taking readings was 120 days in accordance with GOST 24544.

Table 2

Major characteristics of prototypes and controlled parameters

Description of experimental prism samples	Labelling			
	KB	KFB	KZhB	KFZhB
Characteristics of the concrete mix	$Ц : П : К$ = = 1 : 1,84 : 0,79, $В/Ц$ = 0,52	$Ц : П : К$ = = 1 : 1,84 : 0,79, $В/Ц$ = 0,52	$Ц : П : К$ = = 1 : 1,84 : 0,79, $В/Ц$ = 0,52	$Ц : П : К$ = = 1 : 1,84 : 0,79, $В/Ц$ = 0,52
Characteristic value of cylindrical strength f_{lck}, MPa	13,79	13,79	13,79	13,79
Longitudinal reinforcement	–	–	Four 16mm diameter rods made of grade reinforcement S500 (ρ_s = 3,57 %)	Four 16mm diameter rods made of grade reinforcement S500 (ρ_s = 3,57 %)
Dispersed reinforcement (polypropylene fiber with fiber length 12 mm)	–	ρ_{PPf} = 0,36 % in the volume (6,42 kg/cubic meter)	–	ρ_{PPf} = 0,36 % in the volume (6,42 kg/cubic meter)
Installation of indicators of the clock type (division value 1 μm), measurement base 400 mm	On the concrete	On the concrete (between the fiber fibers)	On the concrete (between the reinforcing bars)	On the concrete (between the reinforcing bars and fibres)
	–	–	On the reinforcement	On the reinforcement
General view of the prototype in the form of a prism after stripping with installed clock-type indicators				
Types of relative shrinkage deformations recorded during the experiment	Relative deformations of free shrinkage of expanded clay concrete ε_{lcs}	Relative shrinkage deformations of expanded clay concrete, constrained by reinforcement:		
		with fiber $\varepsilon_{lcs,f}$	with reinforcement rods $\varepsilon_{lcs,s}$	reinforcing bars and fiber fibers $\varepsilon_{lcs,f,s}$
	–	–	Relative deformations of reinforcement ε_{ss}	Relative deformations of reinforcement $\varepsilon_{ss,f}$

Note: Ц — cement, П — sand, К — ceramsite gravel, В/Ц — water cement ratio.

5. Results of the experimental studies of the development of deformations of free and constrained shrinkage of expanded clay concrete. As a result of the conducted studies, experimental data were obtained on the development of complete shrinkage deformations of expanded clay concrete, expanded clay fiber concrete, expanded clay reinforced concrete and expanded clay fiber reinforced concrete over 120 days. The experimental data are shown in Table 3. Based on the experimental data (Table 3), it can be concluded that while adding polypropylene fiber to the expanded clay concrete mix, a decrease in shrinkage deformations was recorded over 120 days, which confirms our assumption: at an early age, low-modulus polypropylene fibers act as a bond. Throughout the strength gain period, the modulus of elasticity of polypropylene fibers is higher than the modulus of elasticity of cement stone, resulting in a redistribution of stresses in the «cement stone — fiber» system contributing to a considerable reduction in the deformations caused by hardening.

Table 3

Average values of the relative deformations caused by shrinkage for the experimental prism samples

Brief description of the experimental samples		Symbols for relative deformations	Average values of relative deformations at a given time t, × 10^5							
Labelling	Series		7 days	10 days	14 days	28 days	42 days	62 days	91 days	120 days
KB	1	$\varepsilon_{lc, cs}$	0,895	3,158	5,976	13,630	19,737	24,332	27,474	28,105
	2		0,782	3,100	5,762	13,661	17,763	23,947	26,842	28,500
	3		0,903	3,272	6,189	13,741	18,221	23,655	28,475	29,450
	Average in series 1—3		**0,860**	**3,177**	**5,976**	**13,677**	**18,574**	**23,978**	**27,597**	**28,685**
KFB	1	$\varepsilon_{lcs, f}$	–0,188	1,534	3,500	9,272	13,084	17,048	19,355	20,022
	2		–0,148	1,441	3,373	9,284	12,869	17,501	19,473	19,899
	3		–0,095	1,639	3,486	9,143	12,379	16,224	18,435	19,350
	Average in series 1—3		**–0,144**	**1,538**	**3,453**	**9,233**	**12,777**	**16,924**	**19,088**	**19,757**
KZhB	1	$\varepsilon_{lcs, s}$	0,378	0,952	2,525	5,695	7,557	10,076	12,846	13,854
	2		0,360	0,930	2,540	5,728	8,369	10,512	13,111	14,326
	3		0,384	0,937	2,551	6,388	8,649	11,193	13,414	14,610
	Average in series 1—3		**0,374**	**0,940**	**2,539**	**5,937**	**8,192**	**10,593**	**13,124**	**14,263**
	1	ε_{ss}	0,480	2,293	3,542	7,811	11,032	12,780	15,027	15,934
	2		0,461	2,052	3,539	7,403	10,372	12,727	15,332	15,984
	3		0,479	2,270	3,531	7,240	10,430	12,522	15,017	15,897
	Average in series 1—3		**0,473**	**2,205**	**3,537**	**7,485**	**10,611**	**12,676**	**15,126**	**15,938**
KFZhB	1	$\varepsilon_{lcs, f, s}$	–0,186	0,708	2,322	5,355	6,950	8,289	10,106	11,603
	2		–0,198	0,879	2,308	5,395	7,394	8,798	10,715	12,194
	3		–0,330	0,814	2,281	5,252	6,996	9,289	10,532	10,801
	Average in series 1—3		**–0,238**	**0,800**	**2,304**	**5,334**	**7,113**	**8,792**	**10,451**	**11,533**
	1	$\varepsilon_{ss, f}$	0,096	0,756	1,522	3,834	5,869	7,141	8,923	10,061
	2		0,064	0,666	1,566	3,778	6,110	7,501	9,399	10,015
	3		0,197	0,796	1,384	4,348	6,097	7,705	9,556	10,108
	Average in series 1—3		**0,119**	**0,739**	**1,491**	**3,987**	**6,025**	**7,449**	**9,292**	**10,061**

Accordingly, due to the reduction of deformations in the early period, a decrease in the total shrinkage deformations is observed in the following days: on the 120th day, a decrease in the value of relative deformations of the total shrinkage of expanded clay fiber concrete was recorded by approximately 30 % compared to expanded clay concrete without dispersed reinforcement (by 28.76 % for series 1, by 30.18 % for series 2, and by 34.30 % for series 3). The values of relative deformations of the total shrinkage of the test samples on the 120th day are shown in Table 4 (based on the data in Table 3).

Table 4

Values of relative deformations of the total concrete shrinkage

Experiment number	Sample labelling	Conventional designation of relative deformations	Values of parallel measurements of response functions y, × 10^5 per 120 days			Average $\bar{y}$, ×10^5	Dispersion S_j^2 ×10^{10}
			Series № 1	Series № 2	Series № 3		
1	KFZhB	$\varepsilon_{lcs, f, s}$	11,60	12,19	10,80	11,53	0,489
2	KZhB	$\varepsilon_{lcs, s}$	13,85	14,33	14,61	14,26	0,146
3	KFB	$\varepsilon_{lcs, f}$	20,02	19,90	19,35	19,76	0,128
4	KB	$\varepsilon_{lc, cs}$	28,10	28,50	29,45	28,68	0,478
					Σ	74,24	1,241

The calculated value of Cochran's criterion is

$$G = \frac{S^2_{j,\max}}{\sum_{j=1}^{N} S_j^2} = \frac{0,489\cdot 10^{-10}}{1,241\cdot 10^{-10}} = 0,394.$$

Critical value of Cochran's criterion is $G_{crit} = G_{0,05;3;3} = 0,798$ (at the significance level $\alpha = 0,05$; number of freedom degrees $f = 3$).

Condition $G \le G_{crit}$ is met and the experiments are thus reproducible.

The estimate of the homogeneity of variance is

$$S_y^2 = \frac{1}{N}\cdot\sum_{j=1}^{N} S_j^2 = \frac{1}{4}\cdot 1,241\cdot 10^{-10} = 0,310\cdot 10^{-10},$$

at the selection size $N = 4$.

The estimate of the dispersion of the average value is

$$S_{\bar{y}}^2 = \frac{S_y^2}{K} = \frac{0,310\cdot 10^{-10}}{3} = 0,103\cdot 10^{-10},$$

at the number of simultaneous experiments $K = 3$.

In order to establish the significance of the regression coefficients, the error in their estimation was calculated:

$$S_b = \sqrt{\frac{S_{\bar{y}}^2}{N}} = \sqrt{\frac{0,103\cdot 10^{-10}}{4}} = 0,161\cdot 10^{-5}.$$

At the number of the freedom degrees $f = N\cdot(K-1) = 4\cdot(3-1) = 8$. The value of the Student's criterion is $t = 1,860$. Then $S_b \cdot t = 0,161\cdot 10^{-5}\cdot 1,860 = 0,299\cdot 10^{-5}$.

The calculation of the coefficients of the regression equation is shown in Table 5 (based on the data in Table 1). The values of the regression coefficients are shown in Table 6.

Table 5

Calculation of the coefficients of the regression equation

Experiment number	Sample labelling	x_1, ×10^5	x_2, ×10^5	$x_1 \cdot x_2$, ×10^5	Average $\bar{y}$, ×10^5
1	KFZhB	11,53	11,53	11,53	11,53
2	KZhB	–14,26	14,26	–14,26	14,26
3	KFB	19,76	–19,76	–19,76	19,76
4	KB	–28,68	–28,68	28,68	28,68
	Σ	–11,66	–22,65	6,20	74,24

Table 6

Value of the regression coefficients

b_0, ×10^5	b_1, ×10^5	b_2, ×10^5	b_{12}, ×10^5
18,6	–2,9	–5,7	1,6

As the values of the regression coefficients are not less than $S_b \cdot t = 0{,}299 \cdot 10^{-5}$, we state that all regression coefficients are significant.

The regression equation in coded variables is:

$$y = 18{,}6 \cdot 10^{-5} - 2{,}9 \cdot 10^{-5} \cdot x_1 - 5{,}7 \cdot 10^{-5} \cdot x_2 + 1{,}6 \cdot 10^{-5} \cdot x_1 \cdot x_2.$$

The adequacy of the equation was checked using the Fisher criterion as follows:

$$S^2_{ад} = \frac{1}{N-B} \cdot \sum_{j=1}^{N} \left(y_j^{опытн} - y_j^{теор} \right)^2 = \frac{1}{4-3} \cdot 0{,}024 \cdot 10^{-10} = 0{,}008 \cdot 10^{-10},$$

where B is the number of significant regression coefficients of the equation (B = 3); $y_j^{опытн}$ is the experimental value of the response function; $y_j^{теор}$ is the theoretical value of the response function.

The calculation of the empirical and estimated values of the response function is shown in Table 7.

Table 7

Testing the adequecy of the regression equation

Experiment number	Sample labelling	Obtained results		Difference, $\left(y_j^{опытн} - y_j^{теор} \right)$, ×10^5	Square of difference, $\left(y_j^{опытн} - y_j^{теор} \right)^2$, ×10^{10}
		Experimental, $y_j^{опытн}$, ×10^5	Estimated, $y_j^{теор}$, ×10^5		
1	KFZhB	11,53	11,60	–0,067	0,005
2	KZhB	14,26	14,20	0,063	0,004
3	KFB	19,76	19,80	–0,043	0,002
4	KB	28,68	28,80	–0,115	0,013
				Σ	0,024

According to the results, the regression equation in coded variables adequately describes the experimental data, a the calculated value of the Fisher criterion does not exceed its critical value:

$$F = \frac{S^2_{ад}}{S^2_{\bar{y}}} = \frac{0{,}008 \cdot 10^{-10}}{0{,}103 \cdot 10^{-10}} = 0{,}076 < F_{0{,}05;3;8} = 4{,}066.$$

The factor that has the strongest influence on the response function is x_2, which is the percentage of reinforcement with rod reinforcement (it has the coefficient that is the largest in absolute value); the second most influential factor on the response is the factor x_1 is the percentage of dispersed reinforcement with polypropylene fiber; pair interaction also has a significant effect $x_1 \cdot x_2$, i.e., ratio of rod and dispersed types of reinforcement.

Based on this, the following conclusions can be made: the experiments are reproducible, the obtained regression equation adequately describes the experimental data, all coefficients of the regression equation are significant.

Thus, the previously made assumption is confirmed that the fibers act as a bond in the early age of expanded clay fiber concrete and reduce shrinkage deformations similar to rod reinforcement.

6. Verification of the suggested method for analytically determining the deformations of constrained shrinkage of a dispersed and combined-reinforced expanded clay concrete element based on experimental data. Let us experimentally verify the assumption that the polypropylene fiber acts as a bond, as a result of which it helps to reduce the total shrinkage deformations of expanded clay concrete. The experimental values of the relative deformations occurring in the polypropylene fibers are determined based on the data in Table 3. It was found that the shrinkage deformations of expanded clay reinforced concrete, recorded on concrete, were greater than the values of shrinkage deformations of expanded clay fiber reinforced concrete, measured on concrete: $\varepsilon_{lcs,\,s} > \varepsilon_{lcs,\,f,\,s}$.

Similarly for the deformations fixed on the reinforcement: $\varepsilon_{ss} > \varepsilon_{ss,\,f}$.

The observed change in the magnitude of deformations can be accounted for only by the influence of fiber fibers on the stress-strain state of the element, since other influencing factors were excluded.

The results of verification using the experimental data are shown in Table 8.

Based on the results shown in Table 8, it is obvious that the values of the relative deformations of the fiber $\varepsilon_{fs}^{КФБ}$ turned out to be roughly equal to $\varepsilon_{fs}^{КФЖБ}$, and the deviation of no more than 11 %, which allows us to consider the equality to be fair $\varepsilon_{fs}^{КФБ} = \varepsilon_{fs}^{КФЖБ}$.

Table 8

Experimental values of the relative deformations of polypropylene fiber due to shrinkage

Age, days	Relative deformations in fiber, × 10^5 calculated based on the experimental data using the above formula				Deviation $\frac{\varepsilon_{fs}^{КФБ} - \varepsilon_{fs}^{КФЖБ}}{\varepsilon_{fs}^{КФЖБ}} \cdot 100$ %
	For KFB	For KFZhB			
	$\varepsilon_{fs} = \varepsilon_{lcs} - \varepsilon_{lcs,f}$	$\Delta\varepsilon_{lcs,f,s} = \varepsilon_{lcs,s} - \varepsilon_{lcs,f,s}$	$\Delta\varepsilon_{ss,f} = \varepsilon_{ss} - \varepsilon_{ss,f}$	$\varepsilon_{fs} = \Delta\varepsilon_{lcs,f,s} + \Delta\varepsilon_{ss,f}$	
7	**1,004**	0,612	0,354	**0,967**	3,86 %
10	**1,639**	0,139	1,465	**1,605**	2,11 %
14	**2,523**	0,235	2,046	**2,281**	10,57 %
28	**4,445**	0,603	3,498	**4,101**	8,37 %
42	**5,796**	1,078	4,586	**5,664**	2,33 %
62	**7,054**	1,801	5,227	**7,029**	0,36 %
91	**8,509**	2,673	5,833	**8,506**	0,03 %
120	**8,928**	2,731	5,877	**8,608**	3,72 %

Note: $\Delta\varepsilon_{lcs,\,f,\,s}$ are the relative deformations of the fiber, obtained as the difference between the relative deformations of the shrinkage of expanded clay concrete, constrained by fiber fibers and reinforcing bars, and the relative deformations of the reinforcement; $\Delta\varepsilon_{ss,\,f}$ are the relative deformations of the fiber, obtained as the difference between the relative deformations of the shrinkage of expanded clay concrete, constrained by the reinforcing bars, and the relative deformations of the reinforcement.

Deformations of the fibers in the sample with dispersed reinforcement $\varepsilon_{fs}^{КФБ}$ are comparable in absolute value to the deformations of fiber fibers in the samples with combined reinforcement $\varepsilon_{fs}^{КФЖБ}$, i.e., regardless of the type of reinforcement, with the same content of fibers, approximately equal compression deformations caused by shrinkage of the cement stone arise in them, and therefore, compressive stresses of similar magnitude. Hence it has been empirically proven that polypropylene fiber works as a bond helping to reduce shrinkage deformations of expanded clay concrete at an early age, when the modulus of elasticity of the fiber is greater than or equal to the modulus of elasticity of the cement stone.

Conclusions

1. It has been experimentally confirmed that at an early age, low-modulus polypropylene fibers act as a bond. Throughout the period of expanded clay concrete strength gain, the elastic modulus of polypropylene fiber is higher than that of cement stone, resulting in a redistribution of stresses in the «cement stone — fiber» system, which contributes to a considerable reduction in the deformations caused by hardening processes.

2. The equations for the compatibility of the deformations for expanded clay fiber concrete (expanded clay concrete reinforced with polypropylene fiber) and expanded clay fiber reinforced concrete (expanded clay concrete with combined reinforcement — rod reinforcement and fibers) are set forth followed by verification using the experimental data.

3. It has been empirically found that with a percentage of dispersed reinforcement of 0.36 % by volume, the presence of polypropylene fiber in expanded clay concrete mix allows one to reduce the deformations of the total shrinkage by approximately 30 % at 120 days under natural hardening conditions compared to expanded clay concrete without dispersed reinforcement.

4. It seems promising to investigate the kinetics of changes in the elastic modulus of expanded clay fiber concrete over time, particularly at an early age (3—7 days). Based on the value of the elastic modulus of expanded clay fiber concrete, it seems feasible to develop an algorithm for determining the total shrinkage deformations at any time $t < 120$ days.

References

1. Ahverdov I. N. (1981) “*Osnovy fiziki betona”* [Fundamentals of concrete physics], M., Strojizdat, 464 p.

2. Dovzhik V. G., Dorf V. A., Petrov V. P. (1976) “*Tehnologija vysokoprochnogo betona”* [Technology of high-strength concrete], M., Strojizdat, 136 p.

3. Karimov I. Sh. (2010) “Mehanizm usadochnyh deformacij betona i faktory, vlijajushhie na nih (obzor). Part 1”, *Tehnologii betonov*, no. 5—6, pp. 22—24.

4. Kravchenko S. A., Posternak A. A. (2017) “Issledovanie svojstv konstrukcionno-teploizoljacionnyh legkih betonov na poristyh zapolniteljah”, *Aktual'nye nauchnye issledovanija v sovremennom mire*, no. 12 (32), pp. 129—135.

5. Kurjatnikov Ju. Ju., Kochetkov R. S. (2019) “Razrabotka matematicheskih modelej fiziko-mehanicheskih svojstv modificirovannogo keramzitobetona”, *Innovacii i modelirovanie v stroitel'nom materialovedenii* [Innovations and modeling in building materials science]*:* materialy IV Mezhdunar. nauch.-tehn. konf., Tver', 19—20 fevralja 2019 g., pp. 64—69.

6. Belousov I. V. [et al.] (2017) “Primenenie fibrobetona v zhelezobetonnyh konstrukcijah”, *Inzhenernyj vestnik Dona*, no. 4, pp. 1—16.

7. Semenjuk S. D., Moskal'kova Ju. G., Rzhevuckaja V. A. (2020) “Osobennosti opredelenija stesnennoj usadki keramzitozhelezobetona”, *Vestnik Polockogo gos. un-ta. Serija F. Stroitel'stvo. Prikladnye nauki*, no. 8, pp. 58—65.

8. Suvorov I. O. (2015) “Dispersnoe poliarmirovanie kak sposob snizhenija usadki fibropenobetona: dis. … kand. tehn. nauk: 05.23.05”, SPb, 137 p.

9. Lazovskij D. N. [et al.] (2021) “Uchet polzuchesti i usadki betona po SP 5.03.01-2020 pri raschete zhelezobetonnyh konstrukcij na osnove deformacionnoj raschetnoj modeli”, *Vestnik Brestskogo gosudarstvennogo tehnicheskogo universiteta*, no. 2 (125), pp. 7—12, https://doi.org/10.36773/1818-1212-2021-125-2-7-12.

10. Shtern V. O. (1990) “Konstruktivnye svojstva keramzitozolobetona i osobennosti raboty izgibaemyh jelementov iz nego: avtoref. dis. … kand. tehn. nauk: 05.23.01”, Cheljabinsk, 17 p.

11. Altalabani D., Bzeni D. K. H., Linsel St. (2020) “Mechanical properties and load deflection relationship of polypropylene fiber reinforced self-compacting lightweight concrete”, *Construction and Building Materials*, vol. 252, p. 119084, https://doi.org/10.1016/j.conbuildmat.2020.119084.

12. Bazant Z. P. (2001) “Prediction of concrete creep and shrinkage: past, present and future”, *Nuclear Engineering and Design*, vol. 203, iss. 1, pp. 27—38, https://doi.org/10.1016/S0029-5493(00)00299-5.

13. Bogas J. A., Nogueira R., Almeida N. G. (2014) “Influence of mineral additions and different compositional parameters on the shrinkage of structural expanded clay lightweight concrete”, *Materials & Design*, vol. 56, iss. 4, pp. 1039—1048, https://doi.org/10.1016/j.matdes.2013.12.013.

14. Bremner T. W. (2008) “Lightweight concrete”, *Developments in the Formulation and Reinforcement of Concrete*, pp. 307—323.

15. Clarke J. L. (2005) “*Structural lightweight aggregate concrete”*, Glasgow, UK, Blackie Academic & Professional, an Imprint of Chapman & Hall, 2005, 161 p.

16. Li J. J. [et al.] (2017) “Comparison of flexural property between high performance polypropylene fiber reinforced lightweight aggregate concrete and steel fiber reinforced lightweight aggregate concrete”, *Construction and Building Materials*, vol. 322, pp. 729—736, https://doi.org/10.1016/j.conbuildmat.2017.09.149.

17. Costa H., Júlio E., Lourenço J. (2012) “New approach for shrinkage prediction of high-strength lightweight aggregate concrete”, *Constructions and Buildings materials*, vol. 35, pp. 84—91, https://doi.org/10.1016/j.conbuildmat.2012.02.052.

18. Maghfouri M. (2017) “Drying shrinkage properties of expanded polystyrene (EPS) lightweight aggregate concrete: A review”, *Case Studies in Construction Materials*, vol. 16, p. e00919, https://doi.org/10.1016/j.cscm.2022.e00919.

19. Zhao H. [et al.] (2022) “Effect of clay content on shrinkage of cementitious materials”, *Construction and Building Materials*, vol. 157, p. 125959, https://doi.org/10.1016/j.conbuildmat.2021.125959.

20. Zhao S. [et al.] (2016) “Experimental study on autogenous and drying shrinkage of steel fiber reinforced lightweight-aggregate concrete”, *Advances in Materials Science and Engineering*, vol. 2016, p. 9, https://doi.org/10.1155/2016/2589383.

21. Fallah S., Nematzadeh M. (2017) “Mechanical properties and durability of high-strength concrete containing macro-polymeric and polypropylene fibers with nano-silica and silica fume”, *Construction and Building Materials*, vol. 132, pp. 170—187, https://doi.org/10.1016/j.conbuildmat.2016.11.100.

22. Fantilli A. P., Chiaia B., Gorino A. (2016) “Ecological and mechanical assessment of lightweight fiber-reinforced concrete made with rubber or expanded clay aggregates”, *Construction and Building Materials*, vol. 127, pp. 692—701, https://doi.org/10.1016/j.conbuildmat.2016.10.020.

23. Gong J., Zeng W., Zhang W. (2018) “Influence of shrinkage-reducing agent and polypropylene fiber on shrinkage of ceramsite concrete”, *Construction and Building Materials,* vol. 159, pp. 155—163, https://doi.org/10.1016/j.conbuildmat.2017.10.064.

24. Hussein Z. M., Khalil W. I., Ahmed H. K. (2020) “Shrinkage and impact strength of fibre-reinforced artificial lightweight aggregate concrete”, *Materials Science and Engineering*, vol. 671, iss. 1, P. 1—11.

25. Lobacheva N., Griniov V. (2019) “Comparative analysis of calculations of strip foundation, taking into account the influence of adjoined building with different soil models”, *XXII International Scientific Conference on Advanced in Civil Engineering Construction the Formation of Living Environment*, vol. 97, p. 9, https://doi.org/10.1051/e3sconf/20199704006.

26. Maskalkova Y. G., Rzhevutskaya V. A. (2020) “The effective reinforcement ratio of expanded clay concrete by polypropylene fiber”, *Construction of Unique Buildings and Structures*, vol. 93, iss. 8, p. 11, https://doi.org/10.18720/CUBS.93.3.

27. Maskalkova Y. G., Rzhevutskaya V. A. (2022) “Compressive cylinder strength and deformability of expanded clay fiber-reinforced concrete with polypropylene fiber”, *International Journal for Computational Civil and Structural Engineering*, vol. 18, iss. 2, pp. 31—42, https://doi.org/10.22337/2587-9618-2022-18-2-31-42.

28. Zhang B. (2022) “Shrinkage mechanisms and shrinkage-mitigating strategies of alkali-activated slag composites: A critical review”, *Constructions and Buildings Materials*, vol. 318, p. 125993, https://doi.org/10.1016/j.conbuildmat.2021.125993.

29. Zhang J., Wang J., Ding X. (2018) “Calculation of shrinkage stress in concrete structures with impact of internal curing”, *Engineering Fracture Mechanics*, vol. 192, pp. 54—76, https://doi.org/10.1016/j.engfracmech.2018.02.002.

30. Zhang X., Liu Z., Wang F. (2019) “Autogenous shrinkage behavior of ultra-high performance concrete”, *Constructions and Buildings Materials,* vol. 226, pp. 459—468, https://doi.org/10.1016/j.conbuildmat.2019.07.177.