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Size effect of cube specimen on strength of expanded clay fiber-reinforced concrete

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Keywords: lightweight concrete, expanded clay concrete, fiber reinforced concrete, fibers, polypropylene fibers, compressive strength, reference specimens, cube size, size effect

Abstract. The object of research is expanded clay concrete reinforced with polymer fiber made of polypropylene. Dispersed reinforcement with polymer fibers is one of the priority directions for modifying lightweight concrete, in particular, expanded clay concrete. The article presents the influence of the binary variability of the key factor (edge size of 100 and 150 mm of cube-shaped specimens) on the values of the compressive cube strength of expanded clay fiber-reinforced concrete. **Methods**. The article presents the experimental studies of the influence of the reinforcing polypropylene fibers content (1.5 % by cement weight) and edge size of cubes (100 mm or 150 mm) on the compressive cube strength of expanded clay fiber-reinforced concrete. **Results**. Even distribution of fiber throughout the volume provides the effect of crack stopping, regardless of the fiber and concrete type. However, this effect does not appear at small volumes of concrete (in cubes with dimensions of 100×100×100 mm). The empirical data allowed us to state that tests on 100 mm edge cube specimens may produce incorrect values of compressive cube strength. Therefore, it is recommended to test cubes with an edge of 150 mm or more. **Conclusions**. The results of testing cubes with an edge of 150 mm and 100 mm of lightweight fiber-reinforced concrete demonstrate fundamentally different effects, and testing cubes with an edge size of 100 mm does not guarantee obtaining correct results.

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1. Introduction

The object of the study is expanded clay concrete reinforced with polymer fiber made from polypropylene C_3H_6.

Expanded clay concrete is a promising building material for the manufacture of load-bearing structures since this type of concrete allows reducing thermal conductivity, material consumption, and significantly increasing fire resistance of these structures [1, 2]. Many studies of researchers are devoted to lightweight concrete (including expanded clay concrete) modified with polypropylene fiber (PPf). There is no consensus on the optimal percentage of dispersed reinforcement of lightweight concrete with polypropylene fiber; however, based on the results of studies of various researchers [3–5], it was established that the content of polymer fiber in concrete should not be more than 2 % by concrete volume. The synthetic fiber content in concrete should be in the range of 0.5–1.5 %, as stated in [4]. For instance, according to [5], the percentage value of fiber reinforcement of 2 % is the upper limit. If this reinforcement percentage is higher, it is problematic to achieve the concrete mixture homogeneity. If this value is exceeded, the strength of fiber-reinforced concrete is always lower than the strength of unreinforced concrete, and it can lead to an attenuation of the structure due to oversaturation with polymer fiber [6] and cause of defects [7, 8].

The results are often contradictory despite numerous studies. According to an analysis of the PPf effect on the strength characteristics of lightweight concrete, the obtained results can be conditionally divided into four groups:

1. strength does not change;
2. strength changes unevenly;
3. strength decreases;
4. strength increases.

The results of the analytical review are shown in Table 1.

Table 1. Analytical review devoted to the effect of dispersed reinforcement with polymer fiber on the strength of lightweight concrete.

Strength change	Authors	Year of publication	The main features of the study	Research results
1. Strength does not change	Kroviakov, S.O., Mishutin, A.V., Pishev, O.V., Kryzhanovskij, V.O. [9]	2018	Modified expanded clay concrete with the addition of polypropylene fiber in an amount of 0–1.2 kg/m^3 was investigated.	The compressive strength of specimens practically did not change; an increase of flexural tensile strength was noted.
	Kastornykh, L.I., Detochenko, I.A., Arinina, E.S. [10]	2017	Self-compacting lightweight concrete (5–10 mm grain size of expanded clay aggregate, 12 mm PPf length) was investigated.	The compressive strength of self-compacting expanded clay fiber-reinforced concrete practically did not change.
	Fantilli, A.P., Chiaia, B., Gorino, A. [11]	2016	Expanded clay concrete (3–8 mm grain size of coarse aggregate) with the addition of PP-fiber in amounts of 0 %, 1.4 %, and 2.0 % (by cement weight) was investigated.	The strength changes were insignificant (strength values of 21.51 MPa, 23.36 MPa, and 22.91 MPa with a fiber contents of 0 %, 1.4 %, and 2.0 %, respectively).
	Bogutskii, V.L. [7]	2013	Modified shipbuilding expanded clay concrete was investigated with the addition of polypropylene fiber in an amount of 0–1.2 kg/m^3.	The insignificant effect of polymer fiber on the compressive strength was noted.
2. Strength changes unevenly	Karamloo, M., Afzali-Naniz, O., Doostmohamad, A. [12]	2020	Self-compacting lightweight concrete with polyolefin macro fibers in an amount of 0.1 %–0.5 % by concrete volume (0.48 %–2.43 % by cement weight) was studied.	The fiber content of 0.1 % by concrete volume had a positive effect on the strength; in other cases, the strength decreased.
	Altalabani, D., Bzeni, D.K.H., Linsel, S. [13]	2020	Self-compacting lightweight concrete (2–10 mm grain size of coarse aggregate) with micropolypropylene fiber 12 mm length and a dose of 0.91 kg/m^3 was investigated.	The uneven change of the strength characteristics of self-compacting lightweight concrete was noted.
	Qiu, J., Xing, M., Zhang, C., Guan, X. [14]	2020	Coal gangue ceramsite concrete with the addition of polypropylene fiber in the amount of 0.07–0.13 % by concrete volume (0.17–0.34 % by cement weight) was investigated.	The fiber content of 0.07 % by concrete volume had a positive effect on the compressive strength of concrete; in other cases, the strength decreased with the increase of the reinforcement percentage.
	Ghasemzadeh Mousavinejad, S.H., Shemshad Sara, Y.G. [15]	2019	Scoria lightweight aggregate concrete with polypropylene fiber addition in the amount of 0.2 % by concrete volume (0.1 % by cement weight) was investigated. Cement content of 500 kg/m^3 and 425 kg/m^3 were considered.	The uneven change of strength with different cement content was noted according to the results.

Strength change	Authors	Year of publication	The main features of the study	Research results
3. Strength decreases	Yahaghi, J., Muda, Z.C., Beddu, S.B. [16]	2016	Oil palm shells concrete reinforced with polypropylene fiber in an amount of 0.1–0.3 % by concrete volume (0.38–1.15 % by cement weight) was studied.	The decrease of concrete strength with the increase of the fiber amount was noted in all cases.
4. Strength increases	Loh, L.T., Yew, M.K., Yew, M.C., Beh, J.H., Lee, F.W., Lim, S.K., Kwong, K.Z. [17]	2021	Lightweight concrete modified with polypropylene, basalt, and a mixture of these types of fiber in the amounts of 0.1 %, 0.3 %, and 0.1 + 0.3 % by concrete volume, respectively, was investigated.	The strength increase of lightweight fiber-reinforced concrete was found in all cases.
	Divyah, N., Thenmozhi, R., Neelamegam, M., Prakash, R. [18]	2021	Lightweight concrete modified with basalt fiber 18 mm length was studied.	Dispersed reinforcement made it possible to increase the compressive strength of lightweight concrete.
	Kuryatnikov, Iu.Iu., Kochetkov, R.S. [6]	2019	Lightweight concrete modified with basalt fiber 1 cm length was studied.	Dispersed reinforcement made it possible to increase the compressive strength of lightweight concrete from 45.7 to 62.6 MPa (by more than 30 %).
	Li, J.J., Niu, J.J., Wan, C.J., Liu, X., Jin, Z. [19]	2017	High performance lightweight aggregate concrete reinforced by polypropylene fiber in an amount of 0.53–1.37 % by concrete volume (0.26–0.67 % by cement weight) was investigated.	The increase of the strength of high performance lightweight aggregate fiber-reinforced concrete was established in all cases.
	Li, J.J., Niu, J.G., Wan, C.J., Jin, B., Yin, Y.L. [20]	2016	High performance lightweight aggregate concrete with the addition of polypropylene fiber in the amount of 0.53–1.37 % by volume of concrete was studied.	The strength increase of high performance lightweight aggregate concrete was established in all cases, except for reinforcement ratio of 1.37 % by concrete volume.
	Corinaldesi, V., Moriconi, G. [21]	2015	Self-compacting lightweight aggregate concrete with micro polypropylene fiber (dose of 5 kg/m^3) was investigated.	The strength increase of self-compacting fiber-reinforced lightweight concrete by 10% was established.
	Yew, M.K., Mahmud, H.B., Ang, B.C., Yew, M.C. [22]	2015	High-strength oil palm shell lightweight concrete with polypropylene fiber in an amount of 0.25–0.5 % by concrete volume.	The concrete strength of high-strength oil palm shell lightweight concrete increased (from 40.9 to 46.6 MPa) with an increase of the reinforcement ratio.

The improvement of the strength characteristics of expanded clay fiber-reinforced concrete is justified in [6, 23] by the formation of a cement-mineral structure. The uneven change in the strength characteristics of self-compacting expanded clay concrete modified with polypropylene fiber is explained in [13] by the uneven distribution of fiber in the concrete mixture.

The fiber length should preferably be commensurate with the grain size of the coarse aggregate, so expanded clay aggregate is in the center of the cell formed by the fibers [8]. The use of polypropylene fiber of different length has a more pronounced positive effect on the strength characteristics of concrete than the addition of polypropylene fiber of the same length; it was concluded in [24].

According to the studies presented in this article, such an ambiguous assessment of the change in strength characteristic resulting from of the addition of polymer fiber to the concrete mixture may be associated with the size of the specimens.

Previously, when conducting our own investigations, we also took the indicated dimensions as standard; however, the cube specimens of both standard sizes (with the edge of 100 mm and with the edge of 150 mm) were made in an amount of at least 9 for each size in each Series. When processing the data, we noticed that for each experimental Series the coefficient of variation turned out to be more than the allowable value of 13.5 %. Then there was an assumption that for lightweight fiber-reinforced concrete the traditional approach should be corrected [25].

In order to test this assumption, we carried out the analysis of the experimental data of various researchers published in open access peer-reviewed sources [3–5, 12, 14–16, 19, 20, 22, 26–28] (Table 2, Fig. 1).

Table 2. Compressive cube strength of fiber-reinforced concrete.

Authors, country	Concrete type, fiber type	Fiber content, %		Mean value of compressive strength with an edge of cube, mm		Remark
		by cement weight	by concrete volume	100	150	
Normal weight concrete						
Ramujee, K [3], India	Concrete, polypropylene fiber	0	0	–	33.7	
		2.96	0.5	–	40.9	
		5.92	1.0	–	44.12	
		8.88	1.5	–	45.25	
		11.84	2.0	–	40.5	
Nkem Ede, A., Oluwabambi Ige, A. [4], Nigeria	Concrete, polypropylene fiber	0	0	–	20.8	
		0.5	0.25	–	22.87	
		1	0.5	–	21.76	
		1.5	0.75	–	20.29	
		2	1	–	20.05	
Pothisiri, T., Soklin, C. [5], Thailand	Concrete, polypropylene fiber	0	0	–	25.5	Fiber was added:
		1.3	0.2	–	26.6	to the finished mix
		1.3	0.2	–	25.1	with coarse aggregate
		1.3	0.2	–	25.5	with fine aggregate
Sun, Z., Xu, Q. [26], China, U.S.A.	Concrete, polypropylene fiber	0	0	50.1	–	
		–	0.45	52.1	–	
		–	0.9	53.6	–	
		–	1.35	46.8	–	
Mazaheripour, H., Ghanbarpour, S., Mirmoradi, S.H., Hosseinpour, I. [27], Iran	Self-compacting concrete, polypropylene fiber	0	0	25.3	–	
		0.18	0.1	24.6	–	
		0.36	0.2	26.3	–	
		0.54	0.3	24.6	–	
Lightweight aggregate concrete						
Qiu, J., Xing, M., Zhang, C., Guan, X. [14], China	Coal gangue ceramsite concrete, polypropylene fiber	0	0	50.8	–	
		0.17	0.07	55.8	–	
		0.25	0.1	48.5	–	
		0.34	0.13	43.8	–	
Ghasemzadeh Mousavinejad, S.H., Shemshad Sara, Y.G. [15], Iran	Lightweight concrete (scoria as coarse aggregate), polypropylene fiber	0	0	22.0	–	Cement 500 kg/m^3
		0.1	0.2	29.0	–	Cement 450 kg/m^3
		0	0	26.5	–	Cement 425 kg/m^3
		0.1	0.2	25.8	–	Cement 425 kg/m^3
Yahaghi, J., Muda, Z.C., Beddu, S.B. [16], Malaysia	Oil palm shells concrete, polypropylene fiber	0	0	47.38	–	
		0.38	0.1	46.29	–	
		0.77	0.2	44.16	–	
		1.15	0.3	43.86	–	
Karamloo, M., Afzali-Naniz, O., Doostmohamadi, A. [12], Iran	Self-compacting lightweight concrete (expanded clay as coarse aggregate), polyolefin macro fibers	0	0	40.77	–	
		0.48	0.1	42.03	–	
		1.45	0.3	40.53	–	
		2.43	0.5	38.9	–	

Authors, country	Concrete type, fiber type	Fiber content, %		Mean value of compressive strength with an edge of cube, mm		Remark
		by cement weight	by concrete volume	100	150	
Yew, M.K., Mahmud, H.B., Ang, B.C., Yew, M.C. [22], Malaysia	Oil palm shell lightweight concrete, monofilament-polypropylene fiber	–	0	–	40.9	
		–	0.25	–	42.4	
		–	0.375	–	44.9	
		–	0.5	–	46.6	
Li, J.J., Niu, J.J., Wan, C.J., Liu, X., Jin, Z. [20], China	Lightweight concrete (lytag as coarse aggregate), high performance polypropylene fiber	0	0	–	39.7	
		0.26	0.53	–	40.7	
		0.36	0.74	–	41.6	
		0.46	0.95	–	43	
		0.57	1.16	–	42.2	
		0.67	1.37	–	40.8	
Li, J.J., Niu, J.G., Wan, C.J., Jin, B., Yin, Y.L. [19], China	Lightweight concrete (lytag as coarse aggregate), high performance polypropylene fiber	0	0	–	37.6	
		0.26	0.53	–	38.3	
		0.36	0.74	–	39.5	
		0.57	1.16	–	38.7	
		0.67	1.37	–	37.2	

a.
b.

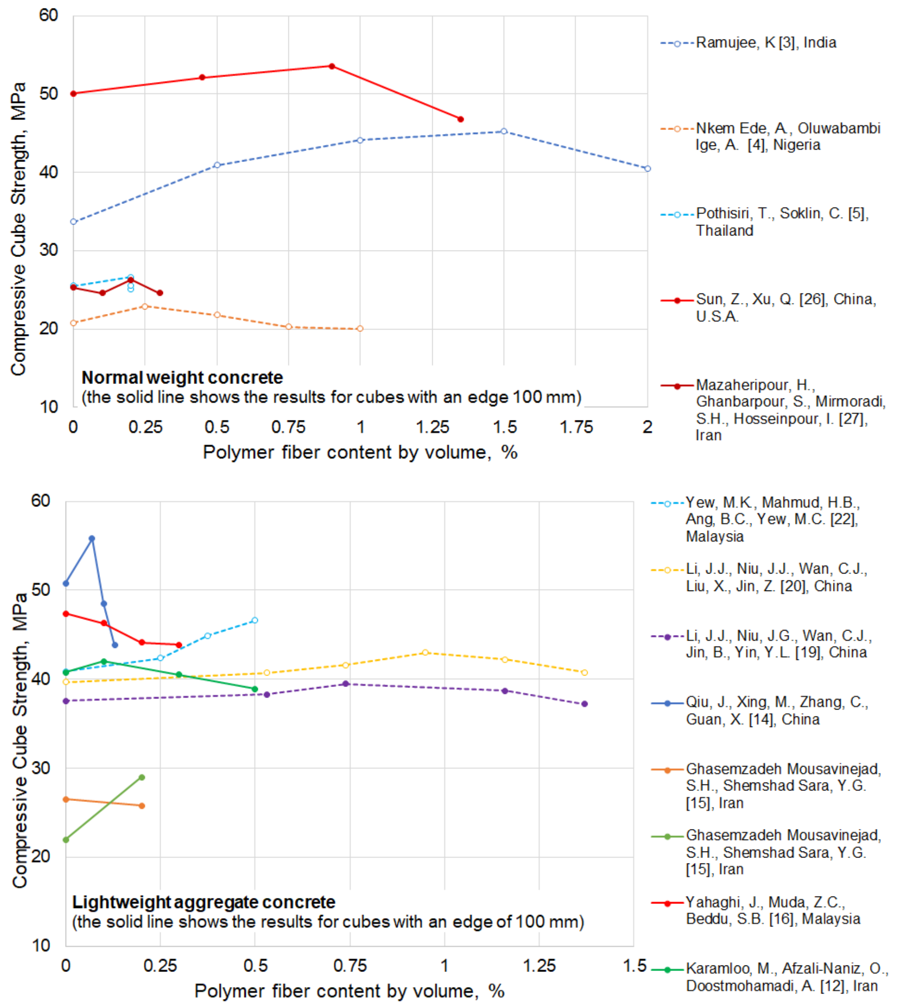


Figure 1. Results of determining the compressive cube strength of lightweight fiber-reinforced concrete (the solid line shows the results for cubes with an edge of 100 mm): (a) curves for normal weight concrete; (b) curves for lightweight aggregate concrete.

Despite the fact that cubes with different sizes were not tested in any considered studies [3–5, 12, 14–16, 19, 20, 22, 26–28] (Table 2, Fig. 1), and the types and classes of concrete differed, the following regularity can be noticed. When testing specimens (cubes) were made of dense aggregate concrete, regardless of specimen size (Fig. 1, (a)), similar (comparable) dependencies of compressive cube strength depending on the fiber content were obtained. When testing specimens (cubes) were made of lightweight concrete (Fig. 1, (b)), no such dependency was found. Thus, the role of the specimen size on the results of the compressive strength test for lightweight fiber-reinforced concrete is more significant than for lightweight concrete without dispersed fibers or dense aggregate concrete compositions.

In addition, in [29] for lightweight fiber-reinforced concrete with fiberglass, the discrepancy between the obtained values of strength was stated when testing specimens of different sizes in the shape of cubes and cylinders. According to [30], when testing cylinders with different heights and diameters (made of lightweight concrete without dispersed reinforcement), dimensions had no significant effect on the obtained strength values.

The determination coefficient was rather low (R^2 = 0.61) in [31] when testing lightweight concrete cubes while the size and shape of the specimens did not affect the results for normal weight concrete.

An analytical review of the studies (Table 2, Fig. 1) also shows that researchers typically produce cubes of only one size for testing (usually 100 mm or 150 mm). It is well known that the size of the specimens depends on the particle size of the aggregate and must be at least seven diameters. This condition is based on the regularities of the mechanics of destruction of heterogeneous building materials. In this regard, the cube edge dimensions of 100 mm and 150 mm are accepted as standard. However, fiber-reinforced concrete is a composite material in which the fiber is not a structural element, but is a reinforcing fiber. The review of studies on lightweight fiber-reinforced concrete [12, 14–16, 19, 20, 22] indirectly confirms that the size can affect the obtained values of compressive cube strength.

At the same time, in studies devoted to the effect of specimen sizes on the obtained strength values [29–32], cylinder sizes (height and diameter) mainly vary, since the design value is determined based on the characteristic compressive strength of concrete. However, control and assessment of concrete strength in laboratory conditions are traditionally carried out on specimens in the shape of cubes; therefore, it is important to evaluate the accuracy of the obtained results when determining not only cylinder strength but also cube strength of concrete.

The investigation of this issue is also relevant because many researchers studying the features of the work of building structures (beams, slabs, columns, etc.) made of fiber-reinforced concrete, often produce specimens of only one type (usually cubes or cylinders) and size.

Thus, for setting the purpose of the study, the key factor is the variability in the size of the specimens of lightweight concrete with fiber. At the same time, the influence of other factors (concrete density and fiber content) on the object of the study should be excluded, which is achieved by using a constant concrete composition.

In accordance with the above, the purpose of the study is to determine the role of the size of the specimen in the shape of the cube (100 and 150 mm) of lightweight fiber-reinforced concrete (based on expanded clay aggregate) on the results of testing strength for short-term uniaxial loading.

The subject of the study is the experimental justification of the use of cubes with an edge size of at least 150 mm to obtain the correct values of the compressive cube strength of expanded clay fiber-reinforced concrete with the addition of micro-reinforcing constructional fiber.

In accordance with the purpose, the task of the study is to establish the effect of the specimen size (cube with an edge of 100 mm and 150 mm) on the mean value of compressive cube strength of expanded clay fiber-reinforced concrete with PPf content of 1.5 % by cement weight (0.36 % by concrete volume). When setting research tasks, the factor of fiber concentration is taken into account. The concrete composition is constant. The variation of the specimen size is binary: 100 and 150 mm.

According to earlier studies, for expanded clay fiber-reinforced concrete with PPf, the percentage of fiber reinforcement of 0.36 % by concrete volume is the most effective among the studied percentages (the PPf contents of 0.12 %, 0.24 % and 0.36 % by volume were studied) [33]. In this regard, to establish the binary variability of the experimental cube dimensions (the edge size of 100 and 150 mm) and the strength of expanded clay fiber-reinforced concrete, the reinforcement percentage ρ_{PPf} = 1.5 % by cement weight (0.36 % by concrete volume) was chosen.

2. Methods

Specimens for investigation of mean values of compressive cube strength of expanded clay concrete and expanded clay fiber-reinforced concrete with PPf were made in the shape of cubes in metal molds with an edge size of 150 mm and 100 mm (according to GOST 10180: Concretes. Methods for strength determination using reference specimens).

The following proportion of the expanded clay concrete mixture for the manufacture of specimens (cubes) was:

$$C:S:G = 1:1.84:0.79,\ W/C = 0.52.$$

The following materials were used for preparation of the concrete mix.

1. The coarse aggregate – expanded clay gravel produced by OJSC Plant of expanded clay gravel in Novolukoml (Belarus) with particle size of 4–10 mm (Table 3).

Table 3. Characteristics of expanded clay gravel.

Particle size	Bulk density	Specific density	Mean value of expanded clay grain	Compressive cylinder strength	Porosity	Water absorption by mass (by volume)
4–10 mm	390 kg/m^3	2.35 g/cm^3	0.8 g/cm^3	1.03 MPa	83.23 %	16.7 % (13.4 %)

2. The fine aggregate – medium-sized river sand (according to particle size distribution, the content of particles with a size of more than 0.25 mm by weight is over 50 %) (Table 4). The river sand deposit is Pavlovskoye in the Mogilev region (the floodplain of the Dnieper River, Belarus). The river sand was homogeneous in terms of maximum fine aggregate heterogeneity ($U_{\max}$ = 3.55 < 4).

Table 4. Characteristics of river sand.

Bulk density	Specific density	Average density	Fineness modulus	Porosity
1670 kg/m^3	2.46 g/cm^3	1670 kg/m^3	2.13	32.32 %

3. The Binder – Portland cement (CEM I 42.5N) produced by OJSC Belarusian Cement Plant (Belarus) (Table 5). The chemical and mineralogical composition of the cement clinker is presented in Table 6.

Table 5. Characteristics of Portland cement.

Bulk density	Specific density	Average density	Water requirement of normal consistency	Compressive strength at 28 days	Spread of cement paste
1140 kg/m^3	3.05 g/cm^3	1140 kg/m^3	25–28 %	48.08 MPa	105 mm

Table 6. The chemical and mineralogical composition of the cement clinker.

The chemical composition of the cement clinker	SiO_2, %	21.71
	Al_2O_3, %	5.27
	Fe_2O_3, %	3.74
	CaO, %	66.20
	MgO, %	1.30
	the ratio by mass (CaO)/(SiO_2)	3
The mineralogical composition of the cement clinker	C_3S, %	60.55
	C_2S, %	16.59
	C_3A, %	7.63
	C_4AF, %	11.38

4. The reinforcing polypropylene fiber – constructional micro-fiber (CMF) made of granules of a high-modulus thermoplastic polymer (C_3H_6 polypropylene) by structural modification (Table 7). Polypropylene fiber produced by LLC RUSSEAL (Russia).

Table 7. Characteristics of polypropylene fiber

Property	Value
Length	12 mm
Diameter	50 μm
Shape	round
Density	0.91 g/cm^3 at 20 ºC
Elongation before break	21 %
Melting point	more than 160 ºC
Electrical conduction	low
Chemical resistance	high
Alkali resistance	high

The following percentages of PPf reinforcement were studied:

– ρ_{PPf} = 0 % (control specimens without reinforcement);

– ρ_{PPf} = 1.5 % by cement weight (0.36 % by concrete volume).

According to [5], comparable strength values of the fiber-reinforced concrete specimens were obtained with the same content of polypropylene fiber (0.2 % by concrete volume) although the polymer fiber was introduced into the concrete mixture at different preparation stages (simultaneously with the coarse aggregate; simultaneously with the fine aggregate; into the finished concrete mix) (Table 2). It was also proved in [34] that provided the mix is thoroughly mixed, the moment the polymer fiber is introduced does not significantly affect the strength characteristics.

In this study for the manufacture of specimens, water initially was poured into the concrete mixer drum; next, the required amount of PPf was added to the water in portions; then cement, sand, and expanded clay gravel were added in a sequence. The time of mixing was increased by 15 % compared to the mixing time of expanded clay concrete mixture without fiber reinforcement.

The main technological equipment and measuring instruments were used in this study:

– electronic balance VK-3000 and VE-15T produced by JSC MASSA-K, Russia;
– concrete mixer B-160 produced by Denzel, Germany;
– portable concrete vibrator MVE 1501 produced by LTD Masalta engineering Co., China;
– universal testing machine RGM-1000-M-1 produced by LLC Metrotest, Russia;
– microscreener MS LaboMed-1 produced by LLC Labor-Microscopes, Russia;
– metal measuring rules produced by LTD Tukzar, China.

3. Results and Discussion

All specimens (cubes with dimensions of 100×100×100 mm and 150×150×150 mm) were tested for short-term uniaxial loading on universal testing machine in the laboratory of the Belarusian-Russian University according to GOST 10180. The rate of loading application was 0.4–0.6 MPa/s.

Table 8 shows the test results of experimental expanded clay concrete and expanded clay fiber-reinforced concrete cubes with dimensions of 100×100×100 mm and 150×150×150 mm. The results of testing specimens are without taking into account the data rejected during the processing. The content of polypropylene fiber is given in % by cement weight.

Table 8. Experimental data processing results.

PPf reinfor-cement, %	Nominal edge size of cube, mm	Number of specimens in Group	Mean density, kg/m^3	Mean value of compressive cube strength $f_{lcm,cube}$, MPa	Standard deviation, s, MPa	The coefficient of variation (Var), %	Relative range of variation	Mean value of specific compressive cube strength, $\varphi_{lcm,cube}$, kN·m/kg
0	100	31	1462	13.07	1.33	10.21	0.39	8.94
	150	10	1484	13.13	0.55	4.18	0.11	8.85
1.5	100	42	1445	10.98	1.83	15.50	0.66	7.59

	150	41	1457	13.87	1.56	11.26	0.43	9.49
0	100, 150	41	1467	13.08	1.18	9.06	0.39	8.92
1.5	100, 150	83	1460	12.41	2.18	17.56	0.78	8.25

Table 8 shows the statistics for the mean compressive cube strength. However, due to the heterogeneity of the porous coarse aggregate (expanded clay gravel), even with the same concrete mixture for experimental cubes, the density varies within 1355–1655 kg/m³ (Fig. 2).

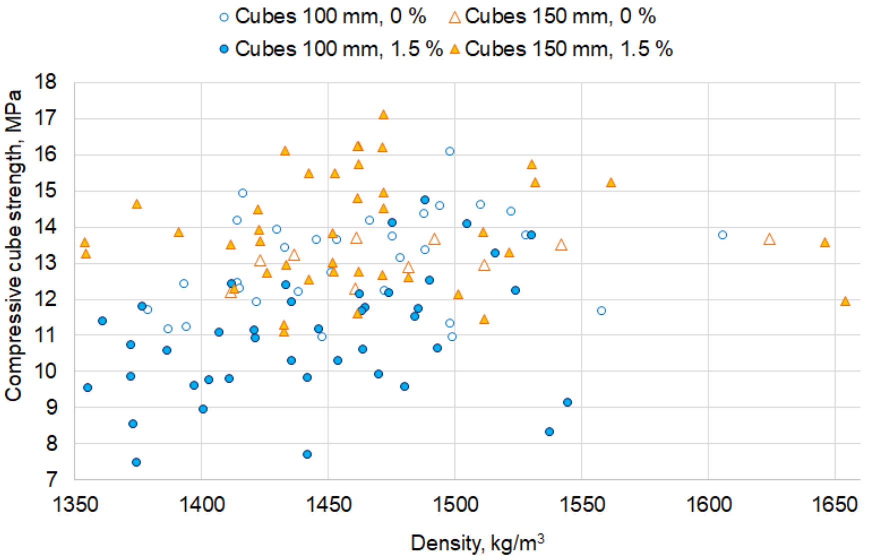


Figure 2. Actual values of the main physical and mechanical characteristics of experimental cubes: density (kg/m³) and compressive cube strength, $f_{lc,cube,i}$ (MPa).

However, it is important that the non-variability of the specimens, which is generally controlled by constant consumption of lightweight aggregate, should be taken into account when analyzing the strength, i.e., use a criterion that would take into account the spread in strength values caused by a change in the density of the specimens due to the heterogeneity of the aggregate. Such criterion can be, for example, specific strength (Table 8).

Specific strength is usually used to reflect the ratio of strength characteristics and density of lightweight concrete: the higher this value, the lower the density and higher the strength of lightweight concrete. The trend of specific compressive strength corresponds to the trend of compressive strength, which was established by other researchers [19] and is shown in Fig. 3.

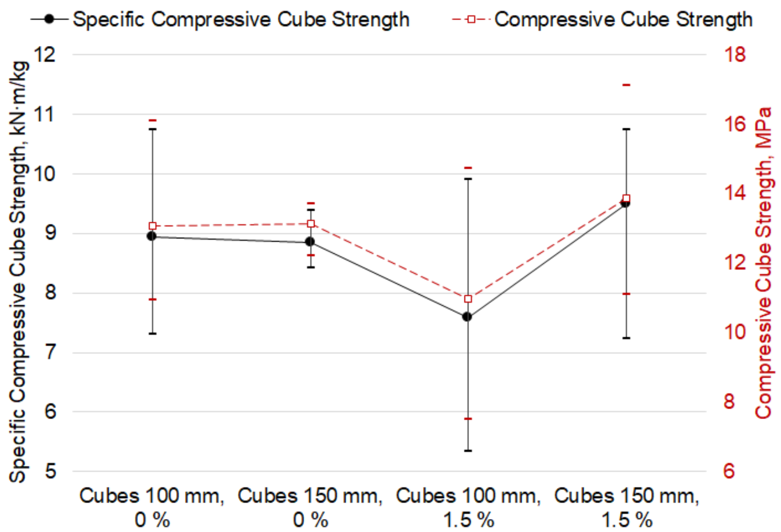


Figure 3. The values of the specific compressive cube strength and compressive cube strength for the studied Groups of experimental cubes.

Further in the article, the statistical analysis of the data is based on the values of the specific compressive cube strength. The use of values of specific compressive cube strength instead of the mean for statistical processing makes it possible to exclude the effect of scatter in the density values of the specimens and establish only the influence of the key parameter (the edge size of the experimental cubes).

Basic statistics for cube-shaped specimens are presented in Table 9.

Table 9. Basic statistics for Groups of specimens

Group of specimens	Group 1	Group 2	Group 3	Group 4
Characteristics of Group	Edge size of 100 mm, ρ_{PPf} = 0 %	Edge size of 150 mm, ρ_{PPf} = 0 %	Edge size of 100 mm, ρ_{PPf} = 1.5 %	Edge size of 150 mm, ρ_{PPf} = 1.5 %
Sample size, n	31	10	42	41
Expectation (Sample Mean), m, kN·m/kg	8.94	8.85	7.59	9.49
Standard Error of the Mean (SEM), δ_m	0.16	0.11	0.17	0.17
Median, kN·m/kg	8.92	8.74	7.74	9.57
Standard Deviation, s, kN·m/kg	0.87	0.36	1.09	1.12
Sample Variance, s^2, kN·m/kg ^{2}	0.75	0.13	1.19	1.25
Minimum, $f_{lcm,cube,\min}$, kN·m/kg	7.30	8.41	5.34	7.23
Maximum, $f_{lcm,cube,\max}$, kN·m/kg	10,74	9,38	9,90	11,63
Range, kN·m/kg	3.44	0.97	4.56	4.40
Skewness	–0.04	0.25	–0.17	–0.08
The coefficient of variation (Var)	10 %	4 %	14 %	12 %
Relative range of variation	0.38	0.11	0.60	0.46
95 % Confidence Interval of the Mean (α = 0.05), kN·m/kg	±0.32	±0.26	±0.34	±0.35
Upper Confidence Limit, kN·m/kg	9.26	9.11	7.93	9.85
Lower Confidence Limit, kN·m/kg	8.62	8.59	7.25	9.14

According to Table 9, it is obvious that for expanded clay concrete (without fiber reinforcement) the size of the cube does not affect the obtained values of the mean specific compressive cube strength (on condition the edge size is at least 7 times greater than the maximum aggregate grain size). This way, $\varphi_{cm,cube,100}$ = 8.94 kN m/kg and $\varphi_{cm,cube,150}$ = 8.85 kN·m/kg.

However, for expanded clay fiber-reinforced concrete with a polypropylene fiber content of 1.5 % by cement weight, the discrepancy between the mean values is obvious: $\varphi_{lcm,PPf,cube,m,100}$ = 7.59 kN·m/kg, $\varphi_{lcm,PPf,cube,m,150}$ = 9.49 kN·m/kg. At the same time, judging by cubes with an edge size of 100 mm, as a result of the addition of PPf, the mean value of specific compressive cube strength of expanded clay concrete decreased by 15 %. According to tests of cubes with an edge size of 150 mm, the specific compressive strength increased slightly by 7 %.

In addition, for all groups of specimens (cubes), except for Group 3 (edge size of 100 mm, ρ_{PPf} = 1.5 %), the coefficient of variation does not exceed 13.5 %, and only for Group 3 the coefficient of variation is more than 13.5 %. Group 3 also demonstrates the largest value of relative range of variation.

Thus, as a result of the investigation, a difference was revealed in the mean values of the specific strength of expanded clay fiber-reinforced concrete, obtained according to experimental data for cubes with an edge size of 100 mm and 150 mm. It is necessary to establish how significant this difference is. In addition, the difference in the strength of specimens of the same composition but of different sizes can be associated with the objective error of mechanical tests of concrete strength or such difference indicates a correlation between the strength of the concrete and the dimensions of the specimens.

Visually, the differences in the test results of cubes are presented on box-and-whisker chart (Fig. 4).

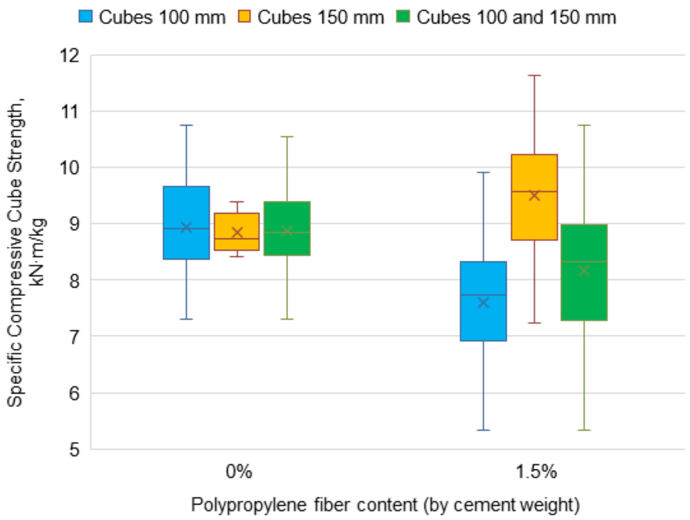


Figure 4. Box-and-whisker chart for testing cubes.

The chart in Fig. 4 clearly demonstrates the significant effect of the size of the cubes on the obtained specific strength when PPf is added, i.e., the size effect is observed. Such dependence was not established for expanded clay concrete without fiber reinforcement.

When testing the hypothesis by the method of the confidence interval (data based on one-sample *t*-test), the following was established. Based on the data obtained in Table 9, for the sample of Group 1, the mathematical expectation of 8.94 kN·m/kg falls into the confidence interval of Group 2; thus, the null hypothesis of equality of means is not rejected. For the sample of Group 3, the mathematical expectation of 7.59 kN·m/kg does not fall into the confidence interval of Group 4, therefore the null hypothesis is rejected (Fig. 5).

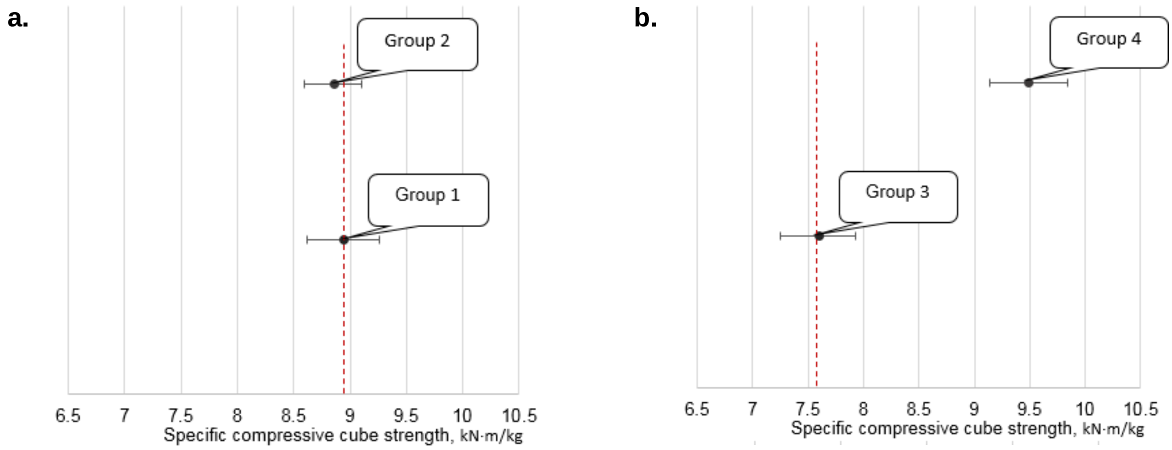


Figure 5. Upper and lower confidence limit for: (a) Group 1 and Group 2; (b) Group 3 and Group 4.

To clarify the obtained results, first, it is necessary to test the statistical hypothesis of the correspondence of the empirical distribution (frequency histogram) of the controlled parameter (specific compressive cube strength) to the normal distribution.

The number of class-intervals for plotting a frequency histogram was assigned based on the sample size according to the Sturges rule:

$$k = 1 + 3.322 \lg n. \quad (1)$$

The largest number of results (sample size) was n = 42, then k = 6. The maximum range was (11.63 – 5.34) = 6.30 kN·m/kg, then 'height' of class-interval was h = 6.30 / 6 = 1.05 kN·m/kg. For the convenience of plotting h = 1.1 kN·m/kg was taken.

Observed frequencies were determined according to the initial data (Table 9). Expected frequencies were determined according to the traditional method based on the sample mean and sample variance using the Gaussian function.

The null hypothesis that observed frequency distribution in a sample is consistent with theoretical frequency distribution; it was tested by Pearson's chi-squared test. The level of significance was accepted as $\alpha = 0.05$.

The calculation results are summarized in Table 10.

Table 10. Results of Pearson's chi-squared test (χ^2).

Number of class-interval	Class interval, kN·m/kg	Observed frequency O_i	Relative observed frequency O_i / N	Expected frequency E_i	χ^2	Results of chi-squared test
			Cubes with edge size of 100 mm, $\rho_{PPf} = 0$ %			
1	6…7.09	0	0.000	0.01	0.01	$\chi^2 = 1.1$;
2	7.1…8.19	0	0.000	0.39	0.39	$\chi^2_{0.05;30} = 43.8$;
3	8.2…9.29	6	0.194	4.60	0.43	$\chi^2 << \chi^2_{0.05;30}$;
4	9.3…10.39	12	0.387	13.73	0.22	*p-value* = 0.95452;
5	10.4…11.49	11	0.355	10.27	0.05	*p-value* >> $\alpha = 0.05$.
6	11.5…12.59	2	0.065	1.92	0.00	
	$\sum$	31	1.000	30.91	1.1	
			Cubes with edge size of 150 mm, $\rho_{PPf} = 0$ %			
1	8.3…8.59	0	0.000	0.41	0.41	$\chi^2 = 2.3$;
2	8.6…8.89	3	0.300	1.80	0.79	$\chi^2_{0.05;9} = 16.9$;
3	8.9…9.19	3	0.300	3.49	0.07	$\chi^2 < \chi^2_{0.05;9}$;
4	9.2…9.49	2	0.200	2.96	0.31	*p-value* = 0.67672;
5	9.5…9.79	2	0.200	1.10	0.74	*p-value* > $\alpha = 0.05$.
	$\sum$	10	1.000	9.77	2.3	
			Cubes with edge size of 100 mm, $\rho_{PPf} = 1.5$ %			
1	6…7.09	4	0.095	2.95	0.37	$\chi^2 = 0.8$;
2	7.1…8.19	10	0.238	10.54	0.03	$\chi^2_{0.05;41} = 56.9$;
3	8.2…9.29	15	0.357	15.67	0.03	$\chi^2 << \chi^2_{0.05;41}$;
4	9.3…10.39	10	0.238	9.70	0.01	*p-value* = 0.97649;
5	10.4…11.49	3	0.071	2.50	0.10	*p-value* >> $\alpha = 0.05$.
6	11.5…12.59	0	0.000	0.27	0.27	
	$\sum$	42	1.000	41.63	0.8	
			Cubes with edge size of 150 mm, $\rho_{PPf} = 1.5$ %			
1	7.1…8.19	0	0.000	0.56	0.56	$\chi^2 = 1.6$;
2	8.2…9.29	6	0.146	4.32	0.65	$\chi^2_{0.05;40} = 55.8$;
3	9.3…10.39	12	0.293	12.97	0.07	$\chi^2 << \chi^2_{0.05;40}$;
4	10.4…11.49	14	0.341	15.07	0.08	*p-value* = 0.90070;
5	11.5…12.59	8	0.195	6.79	0.22	*p-value* >> $\alpha = 0.05$.
6	12.6…13.69	1	0.024	1.18	0.03	
	$\sum$	41	1.000	40.89	1.6	

Since in all cases the value of χ^2 (Table 10) is significantly less than its critical value ($\chi^2 << \chi^2_{crit}$) and the *p-value* for the chi-square distribution (χ^2) significantly exceeds the established level of significance

(p-$value$ >>α = 0.05); therefore, there is no reason to reject the hypothesis that the random variable is normally distributed.

Experimental data were used to plot relative frequency histograms and polygons (Fig. 6) for expanded clay fiber-reinforced concrete (with PPf). For clarity, histograms and polygons for cubes with an edge size of 150 mm and 100 mm are shown in one figure. The histograms and polygons show that although both values are normally distributed, their mathematical expectations are different.

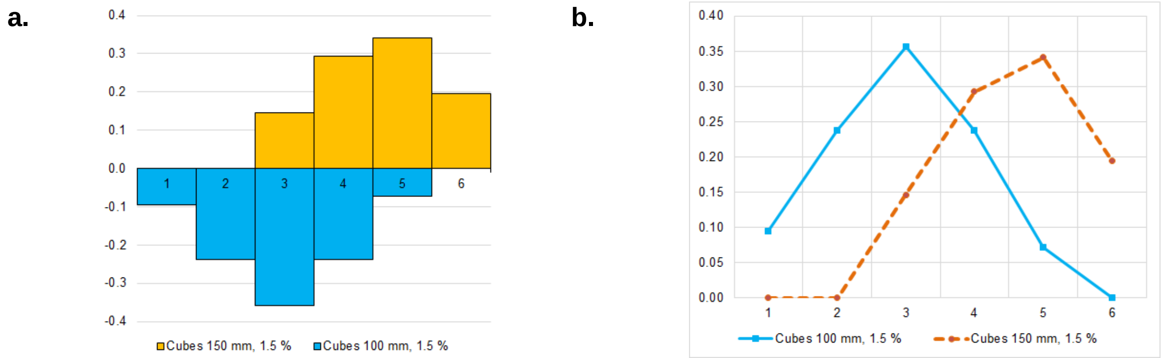


Figure 6. Relative frequency: (a) histogram; (b) polygons for the test results for short term uniaxial loading of expanded clay fiber-reinforced concrete cubes with edge size of 150 mm and 100 mm (ρ_{PPf} = 1.5% by cement weight).

Two-sample *F*-test for variances was chosen to determine the statistical significance of the difference in the variances of the samples. The analysis results are shown in Table 11.

Table 11. Results of F-test for hypothesis test for equality of variances

Group of specimens	Results of F-test
Group 1 (edge size of 100 mm, ρ_{PPf} = 0 %) and Group 2 (edge size of 150 mm, ρ_{PPf} = 0 %)	F = 5.814; $F_{0.05;30;9}$ = 2.864 (α = 0.05); $F > F_{0.05;30;9}$; p-$value$ = 0.004 < α = 0.05. Sample variances are significantly different.
Group 3 (edge size of 100 mm, ρ_{PPf} = 1.5 %) and Group 4 (edge size of 150 mm, ρ_{PPf} = 1.5 %)	F = 1.058; $F_{0.05;40;41}$ = 1.686 (α = 0.05); $F < F_{0.05;40;41}$; p-$value$ = 0.429 > α = 0.05. Sample variances are not significantly different.

According to the performed analysis, there is no reason to reject the null hypothesis of the equality of the variances of Group 3 and Group 4 since $F < F_{crit}$ and the p-$value$ significantly exceeded the established level of significance (α = 0.05).

T-test for two-sample assuming unequal variances was used to assess the significance of the difference in the mean values of Group 1 and Group 2 obtained from the presented samples. This test was chosen due to assessing the differences in the mean values of two unrelated samples, which are normally distributed, and the samples may be unequal in size and with different variances.

In the case of assessing the significance of the difference between the mean values of Group 3 and Group 4, a *t*-test for two-sample assuming equal variances was selected according to the minimum difference in variances (Table 11). The results are shown in Table 12 (basic statistics for samples are presented in Table 9).

Table 12. Results of t-test for hypothesis test for difference of sample means.

Characteristics of specimens	Results of *t*-test
Expanded clay concrete (without reinforcement), cubes with the edge size of 100 mm; Expanded clay concrete (without reinforcement), cubes with the edge size of 150 mm	Two-tailed test at α = 0.05; t = 0.477; $t_{0.05;36}$ = 2.028; $t < t_{0.05;36}$; p-$value$ = 0.636. Sample means are not significantly different.
Expanded clay fiber-reinforced concrete (with PPf;	

ρ_{PPf} = 1.5 %), cubes with the edge size of 100 mm Expanded clay fiber-reinforced concrete (with PPf; ρ_{PPf} = 1.5 %), cubes with the edge size of 150 mm	Two-tailed test at α = 0.05; t = 7.832; $t_{0.05;81}$ = 1.99; $t > t_{0.05;81}$; $p\text{-}value = 1.606 \cdot 10^{-11} \approx 0$. Sample means are significantly different.

According to the data analysis, for expanded clay fiber-reinforced concrete, the differences in mean values of the specific compressive cube strength of specimens with the same composition but different sizes (100 mm and 150 mm) are statistically significant.

A single factor analysis of variance (ANOVA) was chosen to confirm the significance of the difference in mean values obtained from the results of testing cubes with an edge of 100 mm and an edge of 150 mm. This analysis was selected based on the normal distribution of data from two unrelated samples with minimal differences in the variances. The analysis results are shown in Table 13.

Table 13. Data results of ANOVA: Single Factor (MS Excel)

ANOVA: Single Factor						
SUMMARY						
Groups	Count	Sum	Mean	Variance		
Cubes, edge size of 100 mm	42	318.9357	7.593708	1.18597		
Cubes, edge size of 150 mm	41	389.2111	9.492953	1.254728		
Analysis of Variance						
Source of Variation	SS	df	MS	F	p-$value$	F_{crit}
Between Groups	74.83714	1	74.83714	61.34573	1.6057E-11	3.95885
Within Groups	98.81386	81	1.219924			
Total	173.651	82				

According to the performed analysis (Table 13) at the level of significance α = 0.05, the F-test significantly exceeds its critical value (F = 61.35 >> $F_{0.05;1;81}$ = 3.96); therefore, the null hypothesis is rejected

Thus, it is possible to state a significant influence of the factor on the study results (size of cubes), i.e., the sizes of the samples have a significant effect on the obtained values of the specific compressive cube strength of expanded clay fiber-reinforced concrete, and this fact should be taken into account when planning experimental studies.

It should be noted that when calculating the mean values of compressive cube strength of expanded clay fiber-reinforced concrete using cubes with dimensions of 100 × 100 × 100 mm, as well as cubes with dimensions of 100 × 100 × 100 mm and 150 × 150 × 150 mm at the same time, the cube strength in both cases turned out to be lower in comparison with the control specimens (without fiber). According to the data test only of cubes with dimensions of 150 × 150 × 150 mm, the strength increased due to the addition of fiber.

Getting lower mean value of cube strength is not critical. A downward deviation in the subsequent design of structures will provide an additional margin of safety. However, when assessing the effectiveness of fiber reinforcement, this deviation is significant. According to the chart in Fig. 3, based on the results of testing cubes with an edge of 100 mm, the strength of expanded clay concrete decreases with the addition of polypropylene fiber (ρ_{PPf} = 1.5 %), i.e., fiber reinforcement negatively affects the strength characteristics. At the same time, according to the results of testing cubes with an edge of 150 mm, the strength of expanded clay concrete does not decrease as a result of the fiber addition, i.e., the negative effect of fiber reinforcement on strength is not noted.

In connection with the above, it is advisable to evaluate the correctness of the obtained data and to establish the recommended size of cubes for determining the cube strength of expanded clay fiber-reinforced concrete. This can be done by testing the strength of specimens in shape of cylinders.

Cylinders (with a diameter of 150 mm and a height of 300 mm) made in the same series with cubes were tested. The results of determining the mean value of cylinder compressive strength and comparison with the mean value of compressive cube strength are shown in Table 14.

Table 14. Mean values of compressive strength for cube and cylinder of expanded clay fiber-

reinforced specimens.

PPf reinforcement by cement weight, %	Mean value of compressive cube strength $f_{lcm,PPf,cube}$, MPa, with edge size of, mm		Mean value of compressive cylinder strength $f_{lcm,PPf,cyl}$, MPa (cylinder diameter of 150 mm, height of 300 mm)	Ratio $\frac{f_{lcm,PPf,cyl}}{f_{lcm,PPf,cube}}$ with edge size of, mm	
	100	150		100	150
1.5	10.98	13.87	12.6	1.15	0.91

Table 14 shows that the mean value of cube strength $f_{lcm,cube}$ is lower than the mean value of cylinder strength $f_{lcm,cyl}$ (when testing cubes with dimensions of 100 × 100 × 100 mm). This is unlikely due to the significant influence of friction forces between the press plates and surfaces of the specimen, which, as is known, prevent the free development of transverse deformations and causes the so-called 'jacketing effect'.

In accordance with Saint-Venant's principle, the stresses caused by the forces of friction on the support surface are significant only in the area, dimensions of which are commensurate with the dimensions of the loaded surface area. Thus, the middle part in prisms and cylinders (with a height exceeding double cross-sectional size) is free from the influence of friction forces, and longitudinal cracks appear in the middle part of the prisms before failure, propagating up and down to the support surface area. For this reason, with a correctly performed investigation, the cube strength cannot be lower than the cylinder strength. When testing cubes with dimensions of 150 × 150 × 150 mm, the cube strength is greater than the cylinder strength.

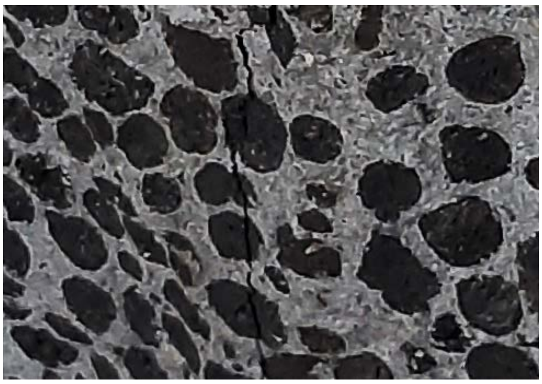
On this basis, it can be concluded that in order to assess the strength of expanded clay fiber-reinforced concrete, cubes with an edge size of at least 150 mm should be tested. Tests on cubes with an edge of 100 mm may demonstrate underestimated strength values.

Lower values of the cube strength compared to the cylinder strength of expanded clay concrete (without fiber) were also noted in [30]. The authors connected this fact to a much less expressed size effect for lightweight concrete in comparison with normal weight concrete. Authors of [30] tested cubes with an edge of 150 mm, the diameter of the cylinders was varied from 80 to 150 mm (diameters of 80, 100, 125, and 150 mm), and the number of twin specimens was taken as 6 or 7. At the same time, for control specimens (cube with dimensions of 150 × 150 × 150 mm, cylinder with the diameter of 150 mm and the height of 300 mm), the cube strength turned out to be greater than the cylinder strength.

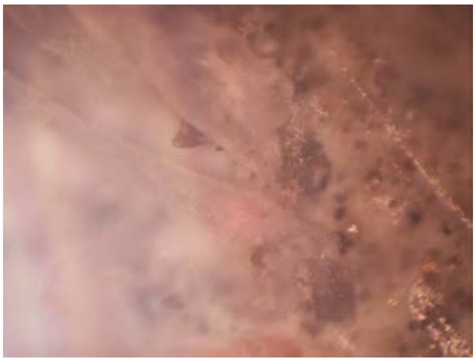
It is also indicated in [15] that due to an increase of polymer fiber content, the air is entrained and an empty space is formed, leading to a decrease in strength. The reason for the decrease in the compressive cube strength of expanded clay concrete containing polypropylene fiber may be the uneven distribution of PP-fibers in the hardened concrete leading to an increase in porosity. The noted effects have a significant influence on the test results of specimens with small sizes (cubes with an edge of 100 mm).

In this study expanded clay gravel with a maximum grain size of d_g = 10 mm was used, the average layer of the cement matrix width was approximately a_m ≈ 10 mm (Fig. 7 (a)). Polypropylene fibers are ‘included’ in the hardened cement (Fig. 7 (b, c)); it is clearly visible when examining the slices of the specimen using the microscreener.

a.



b.



c.

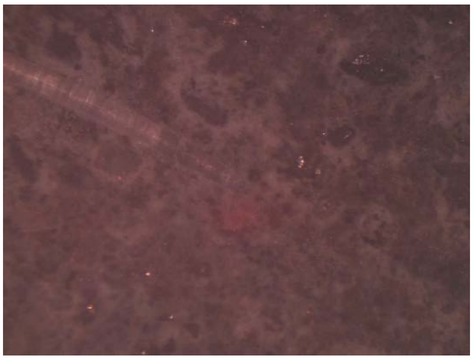


Figure 7. Slices of expanded clay concrete specimen: (a) without magnification; (b) magnification 10x; (c) magnification 4x.

The value of a characteristic element of the expanded clay concrete structure (the minimum element during the material properties test will appear but not of particular elements of the macrostructure) is:

$$l_0 = 5 \cdot \left(d_g + a_m\right) = 5 \cdot (10 + 10) = 100 \text{ mm}.$$

Since grains of coarse aggregate (expanded clay) with a properly selected fiber length are in the center of the cell formed by reinforcing fibers [8, 24], the dimensions of the characteristic element obviously increase. Then in all cases l_0 > 100 mm.

It is necessary to take the minimum specimen size $h_{\min}$ not less than the size of the characteristic element l_0, to obtain correct data, i.e., $h_{\min} \geq l_0$. In this way, $h_{\min}$ > 100 mm.

The main crack initiation with an intragranular mechanism of expanded clay concrete failure can lead to momentary failure since tensile stresses at the crack tip quickly reach critical values. Momentary failure is associated with a high upper limit of microcracks formation for lightweight concrete [35].

The dangerous cracks are less likely to develop for small specimens than large ones due to the use of scale factors. However, Kholmyanskiy M. M. [36] proposed to assign a scale factor depending not only on the specimen size, but also taking into account the effects of dangerous crack stopping.

Evenly distributed fibers throughout the concrete volume provide the effect of crack stopping, regardless of the fiber type and the concrete type. Experimental verification of this can be found in many studies, for example, in [3–5, 37, 38]. Moreover, this effect becomes more evident as the specimen volume increases. At the same time in [36], the author noted that the stopping effect does not appear if the volume of concrete is too small.

Since the volume of the testing cubes (100 × 100 × 100 mm) is small (comparable to l_0), the introduction of fiber does not provide the effect of crack stopping. This statement is in good agreement with the classical theory of Kholmyanskiy M. M. [36].

Summarizing the above, in order to determine the cube strength of lightweight concrete with polymer fiber content, it is recommended to test specimens (cubes) with an edge of at least 150 mm for short-term uniaxial loading test.

Obviously, the effect of fiber reinforcement on the strength characteristics of lightweight aggregate concrete depends on the type of aggregate and reinforcing fiber. Results may also differ with other fiber content. This justifies additional research.

4. Conclusions

1. In the study, based on the tests carried out on standard cube-shaped specimens with an edge size of 100 mm and 150 mm, the size effect of cubes on the obtained values of the mean compressive cube strength of expanded clay fiber-reinforced concrete was established. This statement contradicts the established world practice since the cube dimensions of 100 × 100 × 100 mm are considered generally accepted. Nevertheless, these sizes of cube specimens were originally used to assess the cube strength of dense aggregate concrete, and lightweight fiber-reinforced concrete cubes with dimensions of 100 × 100 × 100 mm were taken as standard for testing without sufficient justification for the possibility of their correct application. Statistical analysis of experimental data allows us to conclude that for specimens of the same composition but different sizes, the differences in the mean values of specific compressive cube strength of expanded clay fiber-reinforced concrete are statistically significant. Thus, the binary variability of the key factor (cube edge size: 100 and 150 mm) and mean values of compressive cube

strength of expanded clay fiber-reinforced concrete (polypropylene fiber with content of 1.5 % by cement weight) were established.

2. The use of cubes with an edge size of 100 mm is incorrect to determine the strength of expanded clay fiber-reinforced concrete since, in this case, the mean value of compressive cube strength is less than the mean value of cylinder compressive strength, and it contradicts the mechanics of concrete failure. In addition, polypropylene fibers do not provide effect of crack stopping if specimen sizes are comparable to the dimensions of a characteristic element of the expanded clay concrete structure. Consequently, the use of cubes with an edge size of 100 mm for testing does not guarantee correct results for lightweight concrete reinforced by polypropylene fiber. In connection with the above, it is recommended to use standard cube specimens with an edge size of 150 mm or more to obtain the mean value of compressive cube strength for expanded clay fiber-reinforced concrete with polypropylene fiber.

3. It is necessary to change the size of the cube by at least three values to establish the relationship between the size of the specimen and the compressive cube strength of lightweight fiber-reinforced concrete. For further analysis, the choice of cubes with the edge size of 70, 100, 150, and 200 mm seems sufficient. In addition, it is possible to change the fiber content (polypropylene and others) for justification of this study results. If the results of further studies with varying sizes of cube specimens and fiber content are statistically significant, it seems appropriate to amend the standard documents regulating the method for determining the compressive cube strength for lightweight fiber-reinforced concrete.

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