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Compressive Strength of Expanded Clay Fiber-Reinforced Concrete

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Abstract:

The object of research is expanded clay fiber-reinforced concrete based on polypropylene fiber. Dispersed reinforcement with polymer fiber is one of the priority directions for modifying lightweight concrete, in particular, expanded clay concrete. There is no consensus among researchers on the effect of the reinforcement with polypropylene fiber on the strength characteristics of lightweight fiber-reinforced concrete. The influence of the cross-sectional dimensions of the specimens on the values of the compressive cube strength of expanded clay fiber-reinforced concrete has not been studied. **Method.** The article presents the preliminary results of experimental study of the influence on the compressive cube strength of expanded clay fiber-reinforced concrete by the following factors: the reinforcing polypropylene fiber content (0.12 %, 0.24 %, and 0.36 % by concrete volume); the edge size of the testing cubes (100 mm or 150 mm). **Results.** The obtained empirical data and analytical review allowed to state, that it is not ensured to obtain correct values of compressive cube strength if cube specimens are with an edge of 100 mm regardless of the reinforcement percentage. Therefore, it is recommended to test cubes with an edge of 150 mm or more. **Conclusions.** The characteristic values of the strength of expanded clay concrete and expanded clay fiber-reinforced concrete can be obtained on the basis of the test results of both cylinders and cubes. The mean values of the cylindrical and cube strength are comparable.

1 Introduction

The object of the study is expanded clay fiber-reinforced concrete with polymer fiber made from polypropylene C3H6.

The use of lightweight concrete, in particular, expanded clay concrete can considerably reduce the dead weight of structures. The porosity of expanded clay imposes certain restrictions on the usage of this coarse aggregate for the production of bearing structures.

Many researchers' studies are devoted to lightweight concrete modified with polypropylene fiber (PP-fiber). Nevertheless, their results are often contradictory.

According to the analytical review [1]–[7], it was found that the content of polymer fiber in concrete should not be more than 1.5–2 % by concrete volume. If the percentage of fiber reinforcement is higher than the limit value, this leads to a decreasing strength characteristic of concrete, since it is not possible to achieve a uniform distribution of fibers [4]–[6].

However, even if the content of polymer fiber is no more than 2 %, scientists are not in good agreement with the effect of such reinforcement on the strength of fiber-reinforced concrete.

For instance, according to [2], the content of synthetic fiber in concrete should be in the range of 0.5–1.5 %. According to [3], the percentage of fiber reinforcement of 2 % is the upper limit, it is difficult to achieve the homogeneity of the concrete mix if this percentage value is higher. The mechanical properties of concrete with polypropylene fiber in an amount of 0.1–0.5 % by concrete volume (0.46 %, 0.92 %, 1.38 %, 1.85 %, and 2.31 % by cement weight) were evaluated in [8]. As a study result, the reinforcement percentage of 0.1 % by concrete volume had an optimal effect on the compressive strength of concrete; an increase in strength of about 12 % compared to the unreinforced control specimen is noted.

According to [9], the fiber reinforcement prevents brittle failure of concrete, but the fiber content does not have a significant effect on the compressive strength of self-compacting lightweight concrete (3–10 mm particle size of coarse aggregate), and an uneven change in strength properties is observed. Similar results were presented in [10] (5–10 mm particle size of expanded clay, 12 mm PP-fiber long). An insignificant effect of polymer fiber on the compressive strength of shipbuilding expanded clay fiber-reinforced concrete was also noted in [5]. The use of only polypropylene fiber reduces the strength characteristics of lightweight concrete; it was empirically proved in [11]. Similar results were obtained in [12], the compressive strength of the investigated specimens practically did not change; an increase in value of ultimate bending strength of expanded clay fiber-reinforced concrete was noted.

At the same time, according to results established in [4], dispersed reinforcement with PP-fiber is made possible to increase the compressive strength of lightweight concrete from 45.7 to 62.6 MPa (by more than 30 %). Similar results for testing a trial series of specimens were drawn by the authors [13]. In [14], with the addition of PP-fiber to the expanded clay concrete mixture (3–8 mm particle size of expanded clay) in a percentage ratio (by the cement weight) of 0 %, 1.4 %, and 2.0 %, the strength was obtained, 21.51 MPa, 23.36 MPa, and 22.91 MPa respectively. The strength increases of self-compacting expanded clay fiber-reinforced concrete by 10 % was established in [4], [14] with the addition of micro polypropylene fiber.

Thus, according to the empirically established results of some studies [4], [13], the introduction of polymer fiber increases the strength of lightweight concrete for short term uniaxial loading, according to others [1], [5], [12], the strength value does not change or decreases.

Researchers used standard specimens in the shape of cubes and cylinders for testing; it was found based on analyzing the conditions for conducting experimental studies in [1]–[6], [8]–[12], [14]. In most cases, the conclusions are based on the results of testing cubes with dimensions of 100 × 100 × 100 mm. This size of cubes is generally accepted, and the obtained test results are considered correct a priori.

However, for lightweight concrete, the cross-sectional dimensions of the specimens will influence the result obtained due to the low density; it is justified in [15]. For example, according to GOST 10180, for testing specimens of concrete on porous aggregates, specimens with the smallest size of 150 mm with a characteristic value of the compressive strength of not more than 5 MPa (f_{ck} ≤ 5 MPa) should be used. Furthermore, the minimum specimen size of 150 mm is assigned regardless of the largest nominal grain size of the porous aggregate.

The discrepancy between the obtained strength values for lightweight fiber-reinforced concrete using fiberglass is stated in [16] when testing specimens of different sizes (cubes and cylinders). It is interesting that there was no significant effect of dimensions on the obtained results in [17] for lightweight concrete (without dispersed reinforcement) when testing cylinders with different heights and diameters.

When testing specimens in the shape of cubes made of lightweight concrete in [18], the coefficient of determination was rather low (R^2 = 0.61), while the size and shape of the specimens did not affect the results for concretes on dense aggregates.

The purpose of the study is to determine the effect of the cross-section size of the specimens in the shape of cubes on the compressive cube strength for short-term uniaxial loading.

In accordance with the purpose, **the research task** is to establish the effect of the specimen cube size (cube edge of 100 mm and 150 mm) on the mean value of compressive cube strength of expanded clay-fiber reinforced concrete with different content of PP-fiber (0.5 %, 1.0 %, and 1.5 % by cement weight).

2 Materials and Methods

Specimens for investigations in order to determine the strength characteristics were made in metal molds in the shape of cubes with an edge size of 150 mm and 100 mm and cylinders with a diameter of 150 mm and a height of 300 mm (according to GOST 10180).

The following percentages of PP-fiber reinforcement were investigated:

– ρ_{PPf} = 0 % (control unreinforced specimens);

– ρ_{PPf} = 0.5 % by cement weight (0.12 % by concrete volume);

– ρ_{PPf} = 1.0 % by cement weight (0.24 % by concrete volume);

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

The specimens of different Series with the following proportions of expanded clay concrete mixture were tested:

– Series 1: C : S : G = 1 : 2.78 : 1.29, W/C = 0.76;

– Series 2–3: C : S : G = 1 : 1.84 : 0.79, W/C = 0.52.

The following materials for all Series were used:

– expanded clay gravel produced by OJSC Plant of expanded clay gravel in Novolukoml 5–10 mm particle size with 1.03 MPa cylinder compressive strength, bulk density of 390 kg/m^3, the specific density of 2.35 g/sm^3, the porosity of 83.23 %, and water absorption by mass of 16.69 %;

– Portland cement 48.08 MPa compressive strength at 28 days and 1140 kg/m^3 bulk density;

– river sand with 2.13 fineness modulus, 1670 kg/m^3 bulk density, and 2.46 g/sm^3 specific density.

It has been used constructional micro-fiber (CMF) 12 mm length and 50 µm diameter, as a reinforcing element, made from granules of a high-modulus thermoplastic polymer by structural modification. This polypropylene fiber is made from C3H6 polypropylene.

Special attention was paid to the technology of concrete mix preparation since if it is a disruption to the process, the addition of polymer fiber has a negative effect on the strength and deformation characteristics of lightweight concrete [19].

Studies of the technology of fiber-concrete mixture preparation, presented in [20], testify to the following: firstly, it is necessary to thoroughly mix the dry components, and only then add the required amount of water to the mixture in portions. This method is easily applicable for small laboratory batching; however, it is inconvenient in a technological environment.

At the same time, according to [6], it is effective to add polypropylene fiber in portions to the concrete mixer shortly before the end of mixing the concrete mixture. In the study [3], with the same content of polypropylene fiber (0.2 % by volume concrete), comparable values of the fiber-concrete strength were obtained, although the polymer fiber was introduced into the concrete mixture at different stages of preparation (simultaneously with the fine aggregate; simultaneously with the coarse aggregate; into the finished concrete mixture). The obtained strength was 26.6 MPa, 25.1 MPa, and 25.5 MPa, respectively. The moment of introduction of the polymer fiber does not significantly affect the strength on the condition the mixture is thoroughly mixed; it is also proved in [21].

In this study, for the manufacture of specimens in Series 1 and Series 2, the expanded clay concrete mixture was prepared according to the recommendations [20], so PP-fiber was added to the dry components of the mixture (cement, sand, and expanded clay gravel). The mixture was mixed for 5 minutes, then in parts, water was added (Mix type A). This Mix type was convenient in the laboratory conditions for the manufacture of a trial batching of specimens in the shape of cubes. In the case of batching (with a volume of more than 0.3 m^3), an inclined concrete mixer was used. In all cases adding fiber to dry components followed by mixing with water, the strength of expanded clay fiber-reinforced concrete was obtained less than that of unreinforced expanded clay concrete, since it was not possible to achieve a uniform distribution of fibers in the concrete.

In this connection, in the manufacture of Series 3 water was firstly poured into the concrete mixer drum, then the required amount of polypropylene fiber was added to the water in portions, then cement, sand, and expanded clay gravel were sequentially added (Mix type B). The time of mixing was increased by 15 %. This Mix type of preparing expanded clay fiber-reinforced concrete mixture made it possible to obtain expanded clay-fiber concrete with a strength not lower than that of unreinforced expanded clay concrete (test results of experimental cubes are given below).

Thus, in the presented investigation, different Series of specimens were produced using the following technologies for preparing expanded clay fiber-reinforced concrete mixture:

– Mix type A (traditionally recommended): polymer fiber was added to dry components (cement, sand, expanded clay gravel), the dry mixture was thoroughly mixed, and then water was added in portions;

– Mix type B (alternative): the fiber was pre-mixed with water, then the remaining components of the mixture were added in portions (cement, sand, expanded clay gravel were added sequentially); the time of mixing was increased by 15 % (compared to Mix type A).

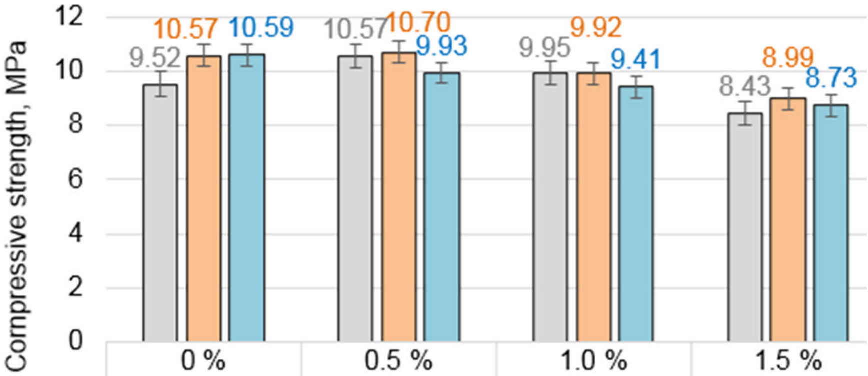
3 Results and Discussion

Experimental cylinders (150 mm diameter, 300 mm height) and cubes (cube edge of 100 mm and 150 mm) were tested for short-term uniaxial loading with the rate of loading application of 0.5 mm/min on hydraulic pressing equipment.

Initially, in each Series, cubes with an edge of 150 mm and 100 mm were made in total number at least of 5 (standard specimens for determining compressive cube strength in accordance with GOST 10180). However, during the statistical data manipulation, it was found out that for all Series the values of the coefficients of variation exceed 20 %, and the data outburst of the results does not significantly affect the value of the coefficient of variation until the specimens of the same size remain in the data sample. Then we realized that it was necessary to separate the data sample into two groups. The size of the edge of the cube was chosen as the criterion for data separation.

As a result of data separation, regardless of the preparing technology and the proportions of the concrete mixture, the following regularity was established. When testing cubes with an edge size of 100 mm, the cube strength of expanded clay fiber-reinforced concrete with all investigated PP-fiber reinforcement percentages turned out to be less than the obtained cube strength of testing cubes with an edge size of 150 mm and also less cylindrical strength (Fig. 1). Such a phenomenon for control unreinforced cubes was not observed.

The bar chart in Fig. 1 visually demonstrates the size effect of the experimental cubes on the mean value of compressive cube strength of expanded clay fiber-reinforced concrete.



	0 %	0.5 %	1.0 %	1.5 %
Cylinder strength, diameter of 150 mm	9.52	10.57	9.95	8.43
Cube strength, cube edge of 150 mm	10.57	10.70	9.92	8.99
Cube trength, cube edge of 100 mm	10.59	9.93	9.41	8.73

Fig. 1 - Comparison of mean values of cube and cylinder strengths for specimens of Series 1 (Mix type A)

Similar results were obtained in [17]. The strength of concrete on a lightweight coarse aggregate, determined on standard cylinders, in some cases may be higher than the strength obtained on standard cubes. The authors attribute this phenomenon to a less pronounced size effect for lightweight concrete compared to normal weight concrete. However, in this case, they focus on the ratio of the specimen height and the dimensions of the cross-section. The influence on the results of the cross-sectional dimensions is not considered in their study. The authors [17] tested cubes with an edge of 150 mm and cylinders with a diameter of 80, 100, 125, 150 mm with slenderness λ equal to 1.0, 1.5, 2.0. At the same time, the largest scatter of test results is noted for cylinders with a diameter of 80 and 100 mm.

At the same time for lightweight concrete, in particular, expanded clay concrete, the ratio of cylindrical strength to cube strength is rather high and amounts to 0.9 or more ($f_{lc,cyl,m} / f_{lc,cube,m}$ ≥ 0.9); it was noted in [17], [18].

Table 1 and Table 2 shows the test results of expanded clay concrete and expanded clay fiber-reinforced concrete (cubes with an edge of 100 × 100 × 100 mm and 150 × 150 × 150 mm for all Series).

Table 1. Results of testing specimens of expanded clay concrete and expanded clay fiber-reinforced concrete

Series number, Mix type	PP-fiber reinforcement	Mix ID	Sizes of testing cubes, mm $(a \times b \times h)$	Mass, kg	Density, kg/m^3	Breaking load, kN	Cube strength, $f_{lc,cube,i}$, MPa	Mean value of compressive cube strength $f_{lc,cube,m}$, MPa, cube edge of 150 mm	100 mm
Series 1 (Mix type A)	0 %	K1-1-0 %	149×149×148	5.4	1583	239.1	10.84	10.57	10.59
		K1-2-0 %	147×151×151	5.3	1581	223.9	10.09		
		K1-3-0 %	150×149×149	5.2	1561	240.9	10.78		
		K1-2-0 %	101×100×100	1.45	1436	112.6	10.59		
	0.5 %	K1-1-0.5 %	149×149×150	5.4	1622	249.8	11.25	10.70	9.93
		K1-2-0.5 %	149×150×150	5.3	1581	226.7	10.14		
		K1-1-0.5 %	101×98×100	1.506	1522	104.1	9.99		
		K1-2-0.5 %	99×99×100	1.497	1527	101.9	9.88		
	1.0 %	K2-1-1 %	151×150×150	5.4	1589	203.9	9.00	9.92	9.41
		K2-2-1 %	146×150×152	5.3	1592	237.4	10.84		
		K2-1-1 %	99×100×100	1.528	1543	103.0	9.88		
		K2-2-1 %	101×102×101	1.584	1522	96.9	8.93		
	1.5 %	K2-1-1.5 %	150×150×150	5.3	1570	192.6	8.56	8.99	8.73
		K2-2-1.5 %	150×147×150	5.2	1572	207.6	9.41		
		K2-1-1.5 %	99×100×100	1.573	1589	93.1	8.93		
		K2-2-1.5 %	100×101×101	1.593	1562	90.7	8.53		
Series 2 (Mix type A)	0 %	K2-1-0 %	149×149×147	5.3	1624	369.1	16.63	16.43	–
		K2-2-0 %	149×150×150	4.8	1437	369.0	16.57		
		K2-3-0 %	148×149×150	5.1	1542	357.2	16.20		
		K2-4-0 %	151×152×150	5.2	1510	374.9	16.33		
	0.5 %	K2-1-0.5 %	149×153×149	5.3	1560	362.1	15.88	16.03	–
		K2-2-0.5 %	149×150×152	5.1	1501	344.9	15.43		
		K2-3-0.5 %	150×150×150	5.2	1541	377.2	16.76		
	1.0 %	K2-4-1 %	152×151×150	5.2	1510	305.7	13.32	13.32	12.82
		K2-1-1 %	104×100×100	1.551	1491	144.1	13.16		
		K2-2-1 %	100×101×100	1.5	1485	142.2	13.38		
		K2-3-1 %	100×102×100	1.527	1497	141.6	13.19		
		K2-4-1 %	103×100×100	1.564	1518	138.8	12.80		
		K2-5-1 %	102×100×100	1.52	1490	134.4	12.52		
		K2-6-1 %	100×100×101	1.467	1453	134.9	12.82		
		K2-7-1 %	100×100×102	1.52	1490	127.8	11.90		
	1.5 %	K2-1-1.5 %	149×152×150	4.9	1442	300.8	13.28	13.28	12.59
		K2-1-1.5 %	100×100×100	1.449	1449	133.2	12.65		
		K2-2-1.5 %	101×99×100	1.472	1472	132.3	12.51		
		K2-3-1.5 %	100×100×100	1.513	1513	159.9	15.19		
		K2-4-1.5 %	101×99×100	1.457	1457	147.6	14.02		
		K2-5-1.5 %	100×99×101	1.42	1420	128.4	12.32		
		K2-6-1.5 %	104×100×100	1.449	1393	138.0	12.61		
		K2-7-1.5 %	101×101×101	1.507	1463	126.0	11.62		
		K2-8-1.5 %	101×102×101	1.451	1415	124.9	11.63		
		K2-9-1.5 %	100×100×100	1.511	1511	112.9	10.73		
Series 3 (Mix type B)	0 %	K3-1-0 %	100×100×101	1.606	1585.3	173.9	16.47	16.44	16.47
		K3-1-0 %	149×151×152	4.98	1459.1	379	16.85		
		K3-2-0 %	151×143×153	5.048	1524.6	377.4	17.44		
		K3-3-0 %	153×147×152	4.856	1420.4	339	15.04		
	1.5 %	K3-1-1.5 %	102×105×100	1.38	1428.6	139	9.74	16.59	12.33
		K3-1-1.5 %	151×149×151	4.736	1398.7	376.7	16.77		
		K3-2-1.5 %	150×151×151	4.862	1426.3	389.2	17.18		
		K3-3-1.5 %	149×151×152	4.776	1402.2	353.4	15.77		
		K3-4-1.5 %	146×147×150	4.774	1482.7	378.8	17.65		
		K3-5-1.5 %	146×151×148	4.996	1532.9	354.2	16.12		
		K3-6-1.5 %	148×151×148	4.466	1362.1	356.3	16.03		

The number of specimens in Table 1 in each Series was corresponded to the minimum according to GOST 10180. However, due to the established effect of the cross-sectional size on the compressive cube strength of expanded clay fiber-reinforced concrete and the separation of a total number of specimens into two groups (with a cube edge of 150 and 100 mm), the number of test results for some of the considered groups was less than three. In connection with this, it was not possible to determine the values of characteristic compressive cube strength of concrete, and the comparison was carried out according to the average values.

Table 2. Characteristics of the experimental specimens in the shape of cubes

Series number, Mix type	Polypropylene fiber content (by cement weight)	Mean value of compressive cube strength $f_{lc,cube,m}$, MPa	Standard deviation S, MPa	The coefficient of variation Var, %	The relative value of cube compressive strength in comparison with the control unreinforced specimen
Cube edge of 150 mm					
Series 1 (Mix type A)	0 %	10.57	0.42	3.96	1.00
	0.5 %	10.70	0.78	7.33	1.01
	1 %	9.92	1.30	13.10	0.94
	1.5 %	8.99	0.60	6.73	0.85
Series 2 (Mix type A)	0 %	16.43	0.20	1.21	1.00
	0.5 %	16.03	0.68	4.23	0.98
	1 %	13.32	–	–	0.81
	1.5 %	13.28	–	–	0.81
Series 3 (Mix type B)	0 %	16.44	1.25	7.59	1.00
	1.5 %	16.59	0.74	4.44	1.01
Cube edge of 100 mm					
Series 1 (Mix type A)	0 %	10.59	–	–	1.00
	0.5 %	9.93	0.08	0.81	0.94
	1 %	9.41	0.67	7.15	0.89
	1.5 %	8.73	0.28	3.22	0.82
Series 2 (Mix type A)	0 %	–	–	–	–
	0.5 %	–	–	–	–
	1 %	12.82	0.50	3.89	–
	1.5 %	12.59	1.33	10.60	–
Series 3 (Mix type B)	0 %	16.47	–	–	1.00
	1.5 %	12.33	–	–	0.75

The mean values of the compressive cube strength of expanded clay concrete and expanded clay fiber-reinforced concrete were determined with a confidence probability of 95 % (Table 2) and the value of the coefficient of variation was less than 13.5 %.

The graphs (Fig. 2) demonstrably show the influence of the preparing technology of concrete mixture with PP-fiber on the cube strength of expanded clay fiber-reinforced concrete. In the case of dry components being mixed and water being subsequently poured (Mix type A), a tendency of strength decrease with an increase of the PP-fiber content is noted. On condition that the introduction of polypropylene fibers into the water with the subsequent addition of the remaining components (Mix type B) this tendency is not noted.

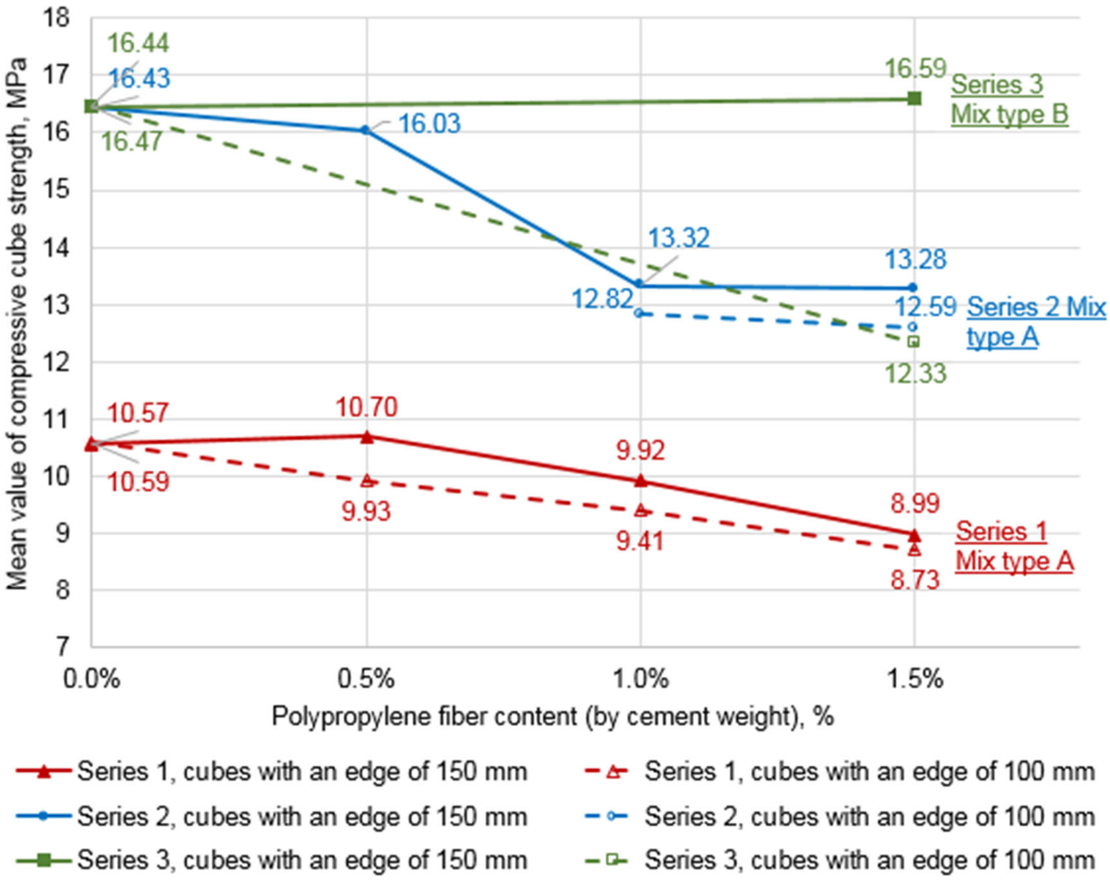


Fig. 2 - The mean values of compressive cube strength depending on the percentage of PP-fiber reinforcement and the cross-sectional size of cube specimen

Thus, our experimental data and the experimental data of other researchers, published by them in the open press in peer-reviewed publications [1]–[3], [9], [11], [22]–[27], indicate the following:

1. the values of compressive cube strength of concretes on dense aggregate containing fiber are comparable regardless of the cube specimen size (Table 3);

2. the results of testing cubes with an edge of 150 mm and 100 mm demonstrate fundamentally different effects for lightweight fiber-reinforced concrete (Table 3), while the results of testing cubes with an edge size of 100 mm are not comparable.

Table 3. The established effect of polymer fiber on the compressive cube strength

Type of fiber-reinforced concrete	The change in the value of cube compressive strength in comparison with the control unreinforced concrete when testing cubes with dimensions		Recommendations for determining the cube compressive strength of fiber-reinforced concrete for cubes with dimensions	
	150×150×150 mm	100×100×100 mm	150×150×150 mm	100×100×100 mm
Normal weight fiber-reinforced concrete	The value of strength increases slightly or does not change	The value of strength increases slightly or does not change	Recommended	Recommended
Lightweight fiber-reinforced concrete	The value of strength increases or does not change	The value of strength decreases does not change or increase. ‘Overshots’ may occur, showing a significant increase or decrease in strength	Recommended	Not recommended

The obtained results are in good agreement with the conclusions made in [16]–[18] and complement them.

4 Conclusions

The results obtained in this study are preliminary. The presented conclusions based on the results require additional experimental confirmation since the number of specimens in this study was insufficient for statistical evaluation. Nevertheless, the conclusions are in good agreement with the results of other researchers published in the scientific literature.

1. It is permissible to evaluate the characteristic value of the compressive strength of expanded clay concrete and expanded clay fiber-reinforced concrete both on specimens in the shape of cylinders and on specimens in the shape of cubes. This is due to the fact that the cylindrical and cube strength for expanded clay concrete have comparable values.

2. It is recommended to use standard specimens in the shape of cubes with an edge size of 150 mm or more to obtain the mean values of compressive cube strength of expanded clay concrete reinforced with polypropylene fiber. If the dimensions of the specimens are comparable to the dimensions of the characteristic elements of the structure of expanded clay concrete (about 100 mm), polypropylene fiber does not provide the effect of crack stopping; it was found in accordance with the obtained empirical study. Therefore, testing cubes with an edge size of 100 mm does not guarantee correct results.

3. It is a perspective to investigate and refine the technology for preparing expanded clay fiber-reinforced concrete mixture. It is proposed to pour firstly the required amount of water into the concrete mixer, and then add in portions polypropylene fiber, then binder (cement), and aggregates (sand and expanded clay). It is required to increase the mixing time by at least 15 % (compared to expanded clay concrete without fiber reinforcement). This option is more adapted to the technological environment and, according to preliminary data, ensures the production of expanded clay fiber-reinforced concrete with a strength not lower than unreinforced expanded clay concrete.

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