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COMPRESSIVE CYLINDER STRENGTH AND DEFORMABILITY OF EXPANDED CLAY FIBER-REINFORCED CONCRETE WITH POLYPROPYLENE FIBER

Yulia G. Maskalkova, Valeryia A. Rzhevutskaya

Belarusian-Russian University, Mogilev, BELARUS

Abstract. This article presents the experimental studies results of the reinforcement effect with polypropylene fiber (0.5 %, 1 %, and 1.5 %) on the strength (compressive cylinder strength) and deformation (compressive strain) characteristics for expanded clay concrete. The most effective fiber percentage is the content of 1.5 % by weight of the cement mass, based on obtained experimental results. An increase in the compressive cylinder strength (up to 13 %), a significant increase in the value of ultimate compressive strain in concrete (corresponding to the peak stress) of the stress-strain diagram (up to 50 %), and the plastic failure of expanded clay fiber-reinforced concrete are noted.

Keywords: lightweight concrete, expanded clay concrete, dispersed reinforcement, polypropylene fiber, compressive cylinder strength, compressive strain, stress-strain diagram.

ЦИЛИНДРИЧЕСКАЯ ПРОЧНОСТЬ И ДЕФОРМАТИВНОСТЬ КЕРАМЗИТОФИБРОБЕТОНА НА ОСНОВЕ ПОЛИПРОПИЛЕНОВОЙ ФИБРЫ

Ю.Г. Москалькова, В.А. Ржевуцкая

Белорусско-Российский университет, г. Могилев, БЕЛАРУСЬ

Аннотация: В статье представлены результаты экспериментальных исследований влияния армирования полипропиленовой фиброй (0,5 %, 1 %, 1,5 %) на прочностные (цилиндрическая прочность при сжатии) и деформативные (деформации при сжатии) характеристики керамзитобетона. Наиболее эффективным процентом армирования полипропиленовой фиброй является 1,5 % по массе от массы цемента согласно полученным экспериментальным данным. На диаграмме деформирования отмечено увеличение цилиндрической прочности (до 13 %) и значительное увеличение (до 50 %) предельных относительных деформаций керамзитофибробетона, соответствующих пиковой точке диаграмме, а также пластический характер разрушения керамзитофибробетона.

Ключевые слова: легкий бетон, керамзитобетон, дисперсное армирование, полипропиленовая фибра, цилиндрическая прочность при сжатии, деформации при сжатии, диаграмма деформирования.

1. INTRODUCTION

Nowadays, expanded clay concrete is a promising building material since it can significantly reduce the self-weight in structures. However, the porosity of the coarse aggregate (expanded clay) imposes some restraints on the use of this material for the manufacture of the structure. One of the main features of expanded clay concrete under load is the absence of a descending branch in the stress-strain diagram '$\sigma_c - \varepsilon_c$'.

The specificity of the lightweight concrete deformation is taken into account in Eurocode 2 (Section 11, Table 11.3.1), where the ultimate compressive strain for lightweight aggregate

ε_{lcu1} are recommended to be taken equal to the compressive strain in the concrete at the peak stress ε_{lc1}, i.e. $\varepsilon_{lc1} = \varepsilon_{lcu1}$.

The absence of a descending branch in the stress-strain diagram is evidence of the brittle failure of the material. This negative factor can be eliminated by inclusion fiber to the concrete mix. Many articles are devoted to this topic, but they are often contradictory. This is probably due to the peculiarity of using special materials used to make specimens. According to the results of some investigations, the polymer fiber inclusion increases the compressive strength of LWAC. There are no changes in the compressive strength in other investigations. Following the results of some articles, it is empirically established, the dispersed reinforcement with polymer fibers significantly improves the deformability of lightweight concrete. Fiber promotes to eliminate of brittle failure of LWAC and improve mechanical characteristics, as evidenced in several studies [1–6].

The fiber effect on the strength characteristics of expanded clay concrete containing expanded clay aggregate 3–8 mm investigated by Fantilli et al. [7]. According to experimental data, the compressive strength of expanded clay concrete specimens was 21.51 MPa, 23.36 MPa, and 22.91 MPa with the polypropylene fiber contents (ρ_{PPf}) of 0 %, 1.4 %, and 2.0 % by cement mass, respectively. The maximum increase in strength (up to 8.6 %) was corresponded to $\rho_{PPf} = 1.4$ %.

The increase in the fiber content changes insignificantly the compressive strength of self-compacting expanded clay concrete (expanded clay aggregate 3–10 mm); it was experimentally established by Mazaheripour et al. [8]. The fiber percentage for all series investigations is considered sufficiently great ($\rho_{PPf} = 2.3$–2.5 %). It is assumed, the presence of fiber dispersed reinforcement prevents the brittle failure of lightweight concrete.

Similar results were obtained in [9, 10]. The experimental data showed the uneven change in the strength characteristics of the lightweight self-compacting concrete modified with polypropylene fiber as the result of an uneven distribution of fiber in the concrete mixture.

Badogiannis et al. [5] ascertained an increase in strength of 20 % and 29 % for LWAC containing polypropylene fiber of 0.5 % and 1 % by concrete volume, respectively. According to the test results, the following expression (1) was proposed (coefficient of determination $R^2 = 0.85$):

$$f_c^{FRLWC}/f_c^{LWC} = 1 + 1.01 \cdot V_f \cdot (l/d), \qquad (1)$$

where f_c^{FRLWC} – the compressive strength of the fiber-reinforced lightweight concrete, f_c^{LWC} – the compressive strength of the lightweight concrete ($V_f = 0$), V_f – the reinforcement percentage with polypropylene fiber by concrete volume, l/d – the fiber aspect ratio.

Polypropylene fiber content improves the strength and deformability properties of concrete, but exceeding a certain reinforcement percentage will negatively result [11]. Fallah et al. [12] evaluated the mechanical characteristics of concrete containing polypropylene fiber in an amount of 0.1–0.5 % by concrete volume. As a result, the fiber content of 0.1 % had a positive effect on the compressive strength of concrete (the compressive strength increase was up to 11.5 %).

The literature on fiber reinforced lightweight concrete shows that the content of polymer fiber in LWAC should be no more than 2 % of the cement mass [13–18]. Furthermore, if this value is exceeded, the strength of fiber-reinforced concrete is always lower than the strength of lightweight concrete without reinforcement. According to [15], the content of synthetic fibers (carbon fiber) should be in the range of 0.5–1.5 %. A similar conclusion can be derived from the test results of Singh [19], the maximum concrete strength is achieved with a polymer fiber content of 1.5 %, and the percentage of polymer fiber reinforcement of 0.5 % is not effective.

The descending branch of the stress-strain curve is an important keyword parameter for nonlinear structural analysis and design of reinforced concrete structures in compression. The use of fiber affects not only the descending branch but also the ascending one [20].

The use of dispersed reinforcement (steel, metal, plastic, polypropylene fiber, and a mixture of different fibers) slightly increased the compressive strength of expanded clay concrete specimens [3, 21, 22]. The value of the modulus of elasticity increased in all cases, except for the case for LWAC containing polypropylene fiber.

The increase in the value of the modulus of elasticity of LWAC was reported with a polymer fiber content of 0.1–0.3 % by concrete volume, while with higher fiber content, the value of the modulus of elasticity was decreased; it was noted in [12].

In a study [23] the dispersed reinforcement with basalt and polyacrylonitrile fiber (0.5 %, 1.0 %, and 1.5 % by concrete volume) of lightweight aggregate concrete present better compressive stress-strain test results than without reinforcement: the clear pronounced descending branch appears on the stress-strain curve.

2. METHODS

The purpose of the investigation is to evaluate the effect of dispersed reinforcement with polypropylene fiber on the strength and deformation characteristics of expanded clay concrete and to determine the optimal percentage of fiber reinforcement.

The aim of the investigation is to assign the reinforcement percentage of expanded clay concrete with polypropylene fiber, based on improvements not only in compressive strength but also in deformation characteristics of expanded clay concrete as a result of dispersed reinforcement.

For the manufacture of expanded clay concrete mixtures, the materials with the characteristics were used:

– expanded clay gravel with round shape and a particle size of 4–10 mm; bulk density of 390 kg/m^3; specific density of 2330 kg/m^3; particle density of 800 kg/m^3; cylinder compressive strength of 1.028 MPa; water absorption of 13.03 % (by mass); water absorption of 10.23 % (by volume); porosity of 83.23 %;

– ordinary Portland cement type I (CEM-I 42.5 N) manufactured by OJSC Krichevcementnoshifer; compressive strength at 28 days (the activity of cement) of 42.5 MPa; bulk density of 1136 kg/m^3; specific density of 3050 kg/m^3; water requirement of normal consistency 21–27 %; spread of cement paste of 106 mm;

– river sand was used as the fine aggregate with the fineness modulus of 2.132; specific density of 2460 kg/m^3; bulk density of 1667 kg/m^3; porosity of 32.32 %.

According to STB 943, river sand in terms of grain-size distribution is related to sand of medium size.

Polypropylene microfibers (PP microF) were used in the experimental study.

PP microF are made from granules of a high-modulus thermoplastic polymer by extraction. These polypropylene microfibers manufactured in the Russian Federation according to TU 2272-001-30726220-2015. Main characteristics of PP microF with 12 mm length: diameter of 50 μm; aspect ratio (length/diameter) of 240; shape is round; density of 910 kg/m^3 at 20 ºC; melting point is more than 160 ºC; electrical conduction is low; alkali resistance is high; chemical resistance is high.

Dispersed reinforcement was carried out with a polypropylene fiber contents of 0.5 %, 1 %, and 1.5 % by weight of the binder (cement) for Series 1–2. The percentage reinforcement of polypropylene fiber of 1.5 % by cement weight was considered for Series 3–4 as the most effective in accordance with the results obtained in [25]. The material components of the experimental specimens are shown in Table 1.

Table 1. Material components of the experimental expanded clay fiber-reinforced concrete and expanded clay concrete specimens

PP microF reinforcement percentage ρ_{PPf}, % (by binder weight)	Characteristics of materials (material components referred to 1 m^3 of expanded clay fiber-reinforced concrete, kg)			Mixture proportions of LWAC	
	Binder	Fine aggregate	Coarse aggregate	C : S : G	W/C
Series 1					
0	Portland cement (258)	River sand (716)	Expanded clay aggregate (333)	1 : 2.78 : 1.29	0.85
0.5					
1.0					
1.5					
Series 2					
0	Portland cement (428)	River sand (787)	Expanded clay aggregate (338)	1 : 1.84 : 0.79	0.52
0.5					
1.0					
1.5					
Series 3–4					
0	Portland cement (428)	River sand (787)	Expanded clay aggregate (338)	1 : 1.84 : 0.79	0.52
1.5					

The shape of the specimens for determining the strength and deformation characteristics of expanded clay fiber-reinforced concrete was in a form of a cylinder (diameter of 150 mm and a height of 300 mm). These specimens were tested for short term uniaxial loading on a hydraulic press in the laboratories of Belarusian-Russian University.

The fiber was added to the dry components and then mixed with water in Series 1. Adding polymer fiber to the dry mixture, thoroughly mixing, and then proportionally adding water is applicable for small batches in the laboratory. A batch with a volume of more than 0.3 m^3 using an inclined concrete mixer was used in that case. The strength of expanded clay fiber-reinforced concrete was less in all cases than the strength of expanded clay concrete without reinforcement (Series 1). In this regard, in the next Series of specimen's water was primarily poured into the drum of the concrete mixer, then the required amount of PP microF was added in portions to the water, after cement, sand, and expanded clay gravel were consistently added. Mixing time was increased by 15 %. This method of preparing a fiber-reinforced concrete mixture made it possible to obtain the strength of expanded clay fiber-reinforced concrete not lower than the strength of the expanded clay concrete without fiber (Series 2–4) [24].

3. RESULTS AND DISCUSSION

The characteristic compressive cylinder strength of expanded clay fiber-reinforced concrete at 28 days was determined from the test results taking into account the coefficient of variation $V < 13.5$ % with a confidence probability of 95 %. Characteristics of the experimental specimens are shown in Table 2.

The actual change in the characteristic compressive cylinder strength of expanded clay fiber-reinforced concrete at 28 days depending on PP microF reinforcement percentage is shown in Fig. 1 (the data are based on Table 1).

Table 2. Characteristics of the experimental cylinder specimens

ρ_{PPf} (by cement weight)	Mean value of density, kg/m^3	Cylinder compressive strength $f_{lc.cyl}$, MPa			The relative value of cylinder compressive strength in comparison with the control specimen	Remark
		Mean value f_{lcm}	The coefficient of variation *Var*, %	Characteristic value at 28 days f_{lck}		
Series 1						
0	1387	13.79	5.35	12.31	1.00	Fiber was added to dry mix
0.5	1412	11.92	5.64	10.57	0.86	
1.0	1398	9.48	6.98	8.15	0.69	
1.5	1363	10.57	10.05	8.43	0.77	
Series 2						
0	1387	11.62	5.10	10.50	1.00	Fiber was added to water
0.5	1567	11.83	4.44	10.83	1.02	
1.0	1475	11.61	5.28	10.45	1.00	
1.5	1421	13.12	7.09	11.47	1.13	
Series 3						
0	1536	11.76	5.41	10.56	1.00	Fiber was added to water
1.5	1413	12.65	4.67	11.57	1.10	
Series 4						
0	1475	11.45	4.84	10.44	1.00	Fiber was added to water
1.5	1474	12.39	4.53	11.40	1.09	

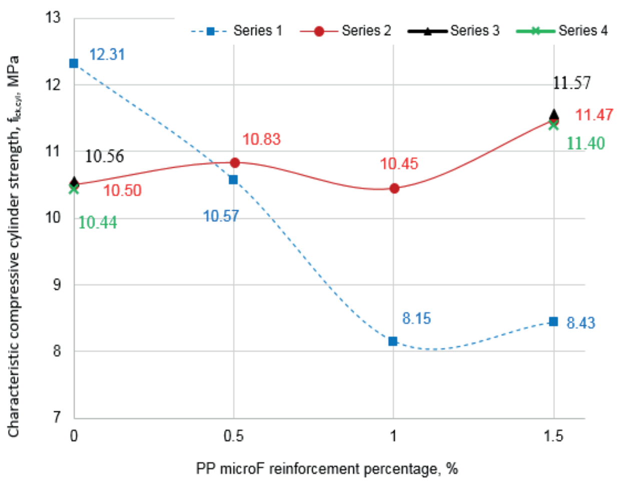


Figure 1. The change in the cylinder strength of expanded clay fiber-reinforced concrete depending on reinforcement percentage

The obtained results are in a good agreement with the results obtained earlier in the study of the cube compressive strength of expanded clay fiber-reinforced concrete [24, 25].

Compressive strength of expanded clay fiber-reinforced concrete can be determined based on the compressive strength of expanded clay concrete by introducing a partial safety factor k_{PPf}, taking into account the reinforcement percentage of polypropylene fiber ρ_{PPf}:

$$f_{lc,PPf} = f_{lc} \cdot k_{PPf}, \qquad (2)$$

where $f_{lc,PPf}$ – compressive strength of expanded clay fiber-reinforced concrete, MPa, f_{lc} –

compressive strength of expanded clay concrete, MPa, k_{PPf} – partial safety factor for accounting the percentage of fiber reinforcement.

According to the data presented in Fig. 1, the relation between the characteristic compressive cylinder strength of expanded clay fiber-reinforced concrete at 28 days and the reinforcement percentage is not linear, but it can be expressed by a 2nd degree polynomial. This statement does not contradict the data obtained in [8–10].

The following expression (3) for the analytical determination of the coefficient k_{PPf} was obtained, based on the test results of Series 2–4:

$$k_{PPf} = 1.2 + 0.27\rho_{PPf} \cdot (\rho_{PPf} - 1.77), \qquad (3)$$

where ρ_{PPf} – the percentage of polypropylene fiber content in the concrete mixture by cement weight, %.

A comparison of the experimental r_e and theoretical r_t values is shown in Fig. 2. All points are located close to the straight line $r_e = b \cdot r_t$ on the '$r_e - r_t$' diagram. Inclination of line is arctan1.0015 = 45.04° ≈ 45° (coefficient of determination R^2 = 0.9969).

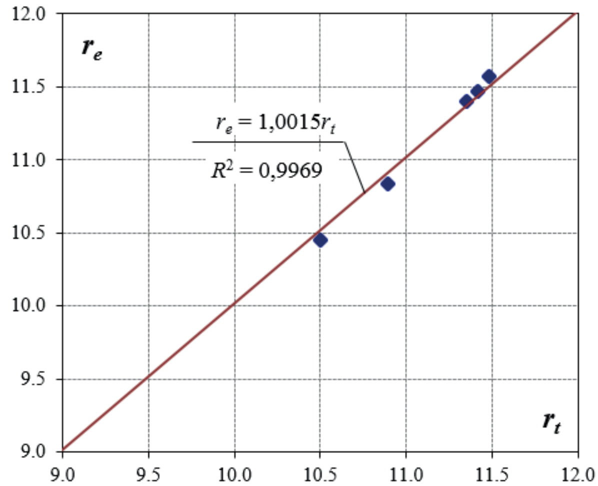


Figure 2. The '$r_e - r_t$' diagram

The proposed expression (3) is required elaboration based on the accumulated empirical data.

Plastic fracture in specimens reinforced by PP microF with a fiber contents of 1 % and 1.5 % by cement weight was observed (Fig. 3).

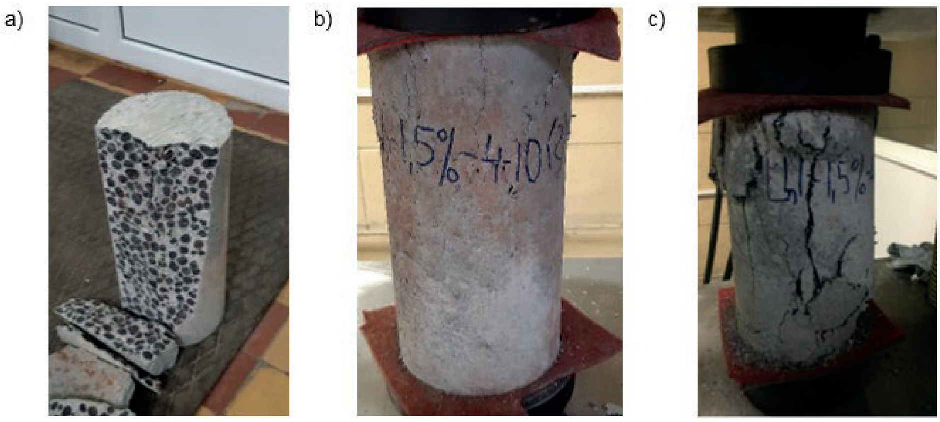
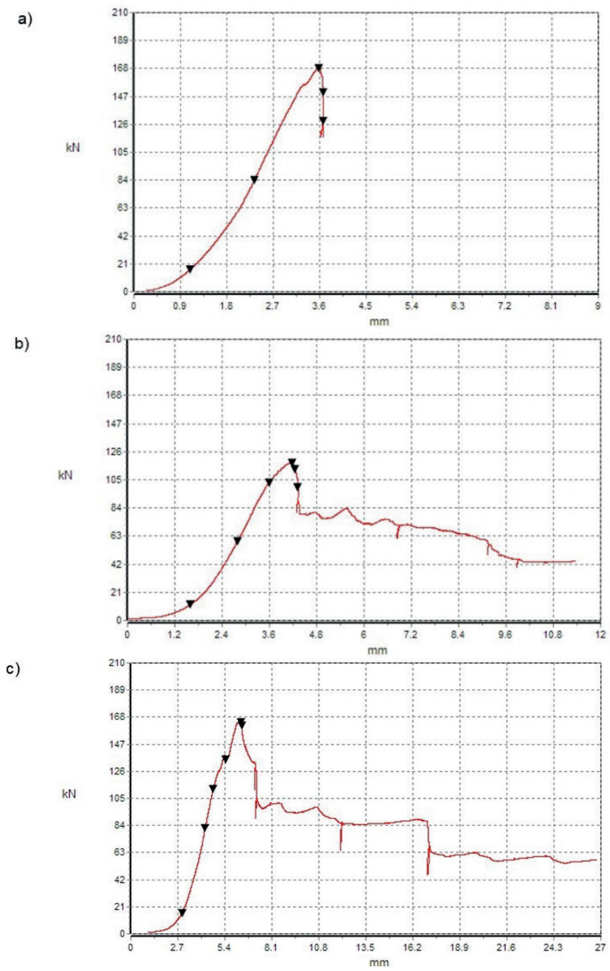


Figure 3. The failure behavior of expanded clay concrete cylinders: a) unreinforced $\sigma_c = f_{lc}$ (the peak stress in the stress-strain diagram), b) reinforced by PP microF $\sigma_c = f_{lc}$ (the peak stress in the stress-strain diagram), c) reinforced by PP microF $\sigma_c > f_{lc}$ (a descending branch in the stress-strain diagram)

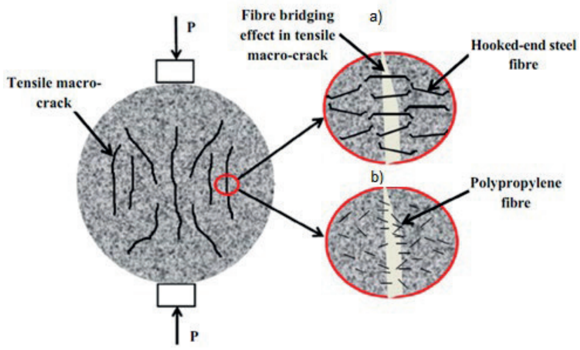
In these cases, a descending branch appears in the stress-strain diagram (Fig. 4). Moreover, the actual recorded ultimate compressive strain increases with raising the fiber content. The appearance of a descending branch was not observed at a fiber content of 0.5 % by cement weight (Fig. 4).



<u>Figure 4.</u> The actual stress-strain diagram of expanded clay fiber-reinforced concrete specimens containing polypropylene fiber: a) 0.5 %, b) 1 %, c) 1.5 %

Fiber forms structural bonds in the concrete mix and prevents segregation when mixing. The use of fiber enables to reduce the crack width and crack spacing, especially at an early age [20, 21]. The optimal effect of dispersed reinforcement is achieved when fibers are located in the sample in the direction perpendicular to the force [4]. As our investigations have shown, polypropylene fibers are predominantly located perpendicular to the vertical axis in cylindrical specimens in case of adherence to the technology of concrete mix preparation with the fiber addition and sufficient mixing time.

The influence of polypropylene and steel fiber (0.1 %, 0.2 %, and 0.3 % by concrete volume) on the deformation characteristics of expanded clay concrete was studied in [26]; it was noted the failure occurs as a result of pulling out or discontinuity of polymer fiber within the crack width (Fig. 5).



<u>Figure 5.</u> The effect of fibers on cracks in expanded clay concrete: a) steel fiber, b) polypropylene fiber [26]

However, our investigations contradict this statement. Polypropylene fibers restrained cracking, preventing brittle fracture of specimens. The fibers were stretched within the crack, but fiber discontinuity was not noted (Fig. 6).

<u>Figure 6.</u> Location of fibers within the crack at the moment of complete failure (see Fig. 3, c)

The investigation results of the effect of dispersed reinforcement with polypropylene fiber on the compressive strength and deformability of expanded clay concrete are shown in Table 3.

Table 3. The effect of the fiber reinforcement percentage on the compressive strength and deformability of expanded clay fiber-reinforced concrete

ρ_{PPf}	The effect on the compressive strength	Change in deformability	Justification
0.5 %	Compressive strength practically does not change.	The brittle failure. The value of compressive strain in the concrete at the peak stress ε_{lc1} practically does not change.	The fiber content is too low to have an appreciable effect on compressive strength and deformability.
1.0 %	Compressive strength decreases.	The plastic failure. The value of ε_{lc1} increases slightly (up to 10 %).	The fiber content is sufficient to prevent brittle failure, but not enough to inhibit the development of micro cracks. The fiber with low strength negatively affects the compressive strength.
1.5 %	Compressive strength increases (up to 13 %).	The plastic failure. The value of ε_{lc1} increases significantly (more than 50 %).	The fiber content is sufficient to prevent brittle fracture and inhibit the formation and internal micro crack development. The compressive strength of expanded clay concrete increases due to a later crippling of the cement stone

4. CONCLUSIONS

1. According to the obtained experimental data, dispersed reinforcement with polypropylene fiber does not have a significant effect on the strength of expanded clay fiber-reinforced concrete. When the content of polypropylene fiber is 1.5 % (by cement weight), the cylinder strength of expanded clay fiber-reinforced concrete increases up to 13 %. However, the increase of the strength can be due to the error of the testing machine during investigations.
2. The failure of expanded clay fiber-reinforced concrete occurs as a result of the failure of the expanded clay concrete matrix, and not as a result of pulling out or discontinuity of polypropylene fibers at all investigated percentages of reinforcement (0.5 %, 1 %, and 1.5 %).
3. Expanded clay concrete reinforced by polypropylene fiber with a reinforcement percentage of 1 % and 1.5 % by cement weight has a positive effect on the deformability of concrete. A pronounced descending branch appears on the stress-strain diagram; it is determined the plastic failure of expanded clay fiber reinforced concrete.
4. It is recommended to assign the percentage reinforcement of expanded clay concrete containing polypropylene fiber of 1.5 % by cement weight. In this case, it is possible to obtain the required compressive strength with a significant improvement in deformation characteristics, eliminating the brittle failure.
5. The technology of concrete mix preparation with the fiber addition requires clarification. Adding fiber to a dry mix and then mixing with water has a negative effect.
6. The compressive strength of expanded clay fiber-reinforced concrete $f_{lc,PPf}$ can be calculated based on the compressive strength of expanded clay concrete (unreinforced) f_{lc} by multiplying it by the partial safety factor for accounting the percentage of fiber reinforcement k_{PPf}.

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Yulia G. Maskalkova. PhD. in Engineering, Associate Professor, Associate Professor at the Department of Industrial and Civil Construction, Belarusian-Russian University, Mira Ave, 43, Mogilev, 212000, Belarus, e-mail: julia43@tut.by; ORCID ID: 0000-0002-4107-2452

Valeryia A. Rzhevutskaya. Postgraduate student at the Department of Industrial and Civil Construction, Belarusian-Russian University, Mira Ave, 43, Mogilev, 212000, Belarus, e-mail: valeriarzhevuckaya@gmail.com; ORCID ID: 0000-0001-8854-5408

Москалькова Юлия Георгиевна. К.т.н, доцент, доцент кафедры «Промышленное и гражданское строительство», Белорусско-Российский университет, пр. Мира, 43, Могилев, 212000, Беларусь, e-mail: julia43@tut.by; ORCID ID: 0000-0002-4107-2452

Ржевуцкая Валерия Андреевна. Аспирант кафедры «Промышленное и гражданское строительство», Белорусско-Российский университет, пр. Мира, 43, Могилев, 212000, Беларусь, e-mail: valeriarzhevuckaya@gmail.com; ORCID ID: 0000-0001-8854-5408