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The Effective Reinforcement Ratio of Expanded Clay Concrete by Polypropylene Fiber

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Abstract:

The object of research is the dispersed reinforcement with polypropylene fiber of expanded clay concrete produced by using local raw materials. The purpose of this study is to select the optimal reinforcement ratio of expanded clay concrete containing polypropylene fiber. It is also proposed to investigate which variation of adding fiber is most effective (as an admixture with a constant content of the binding material or instead of cement mass). **Method.** Polymer fiber reinforcement should be added to the dry mix, thoroughly mix all the components and only then add water to the mix. In case of non-observance of this condition, it is impossible to achieve a homogeneous distribution of fiber in the hardened concrete, and therefore, the effect of disperse reinforcement will be reduced to zero. **Results**. As a result of investigations, special attention must be paid to the correct preparation technology at the time of concrete mixture preparation. Otherwise, the polymer fiber introduction will have a negative effect. In this case, the coarse aggregate use is a significant condition. The secant modulus of elasticity will decrease by more than two times if the diameter of expanded clay grains increases. It is recommended to use expanded clay gravel with smaller fractions in accordance with investigations. The maximum and minimum allowable content of polypropylene fiber are 0.5–1.5 %. The compressive cube strength increase of expanded clay concrete by polypropylene fiber is achieved by this allowable content in comparison with unreinforced expanded clay concrete with a similar concrete mixture. The most effective is reinforcement ratio of 1.5 %, and the maximum compressive strength increase by 14 %. The polypropylene fiber should be added in a percentage ratio depending on the cement mass with constant cement content in accordance with investigations. The fiber introduction instead of cement by mass negatively affects the strength characteristics.

1 Introduction

1.1 Efficiency of polymer fiber application for the expanded clay concrete reinforcement

Dispersed reinforcement of the concrete increases the concrete matrix strength and reduces its deformability in comparison with unreinforced concrete as in the hardening stage as in the serviceability stage.

Nowadays, the most common use is domestically produced and imported steel fiber in Belarus. The polymer fiber use has certain advantages over steel fiber (low self-weight load, corrosion resistance, chemical resistance, less tendency to clumping, especially in the case of short fibers usage). According to [1]–[9] fibers promote to eliminate brittle failure of expanded clay concrete.

As a result of polymer fibers application, the concrete resistance to impact loading (blast loading) is significantly increased; it was confirmed experimentally by American scientists and described in [10]. This experiment, from my point of view, is quite interesting. Specimens are with different reinforcement (steel bars; steel fiber; asbestos fiber; and nylon threads were placed in the epicenter of the explosion).

As a result, elements reinforced with bar reinforcement were completely disintegrated, and elements reinforced with nylon threads were less damaged and if necessary, could be restored.

Features of the expanded clay concrete manufacture and behavior

The aggregates used in lightweight concrete manufacture have quite different properties and it is the main feature of all lightweight concrete. There is no opportunity for lightweight concrete to devise clear recommendations for the concrete mix composition. In each case, you must experimentally select the concrete mix proportion and make trial mix [11]–[13]. Usually, only by making trial mix, you can find the optimum water/cement ratio.

Nowadays, it is a perspective to use lightweight concrete with less amount of sand. However, reinforcement with synthetic fibers restricts the coarse aggregate use [10] therefore precondition is the fine and coarse aggregate addition (for example, quartz or river sand, but not expanded clay sand). Whereas using porous fine aggregates, the concrete compressive strength obtained is significantly lower [12]–[14].

1.3 Recommended percentage of polymer fiber reinforcement

All researchers agree on the reinforcement percentage of polymer fiber. It should not exceed 2 % of cement mass, because otherwise the compressive concrete strength will not be increased and may be reduced than for unreinforced specimens [10], [15]–[20]. This is explained by the fact its uniform distribution with increasing fiber content, and it is very difficult to achieve. Thus, the mixture will not be homogeneous, and this will lead to a significant variation in the results of the compressive strength of specimens of different series with the same concrete mix composition [21].

The effective polymer fiber content should be 0.15–0.25 % by weight and 0.4–0.65 % by volume; it was experimentally established in [10].

Nevertheless, the polymer fiber reinforcement ratio, which was equal to 2 %, is already a critical value; it was noted in [15]. This is very problematic to achieve concrete mix homogeneity. The compressive concrete strength in some cases is not higher than the compressive strength of the control unreinforced specimens with this reinforcement ratio. Also, in all cases the efficiency of reinforcement is low. The results are nearly the same for the reinforcement ratio of 2 % and 0.5 %. The reinforcement ratio of 1.5 % is recommended in [15].

The fiber can be put in as an additional reinforcing element without changing the concrete composition. It can also be used instead of cement mass. In the second case (fiber introduction instead of cement mass), the effective reinforcement ratio does not exceed 2 % (2 % of synthetic fiber and 98 % of cement mass), which was empirically justified in [16].

The optimal ratio of reinforcement concrete by polypropylene fiber with coarse aggregates was investigated in [17]. The reinforcement ratio with 0.5 % of cement mass is the most effective, 1 % is less effective, and the polypropylene fiber content higher than 1.5 % adversely affects the compressive concrete strength as the axial compression tests and as the flexural tests.

The synthetic fiber content for lightweight concrete should be in the range of 0.5–1.5 %; it was established in [17].

According to the test results [11], the reinforcement ratio with polymer fiber is below 0.5 % generally is ineffective. The maximum compressive strength was shown by specimens with a polymer reinforcement content of 1.5 %.

Special attention must be paid to the correct technology at the time of concrete mix preparation. Otherwise, the polymer fiber introduction will have a negative effect.

1.4 Options of combined disperse reinforcement

The polymer fiber can be combined with other types of reinforcing fibers; it has shown in the studies analysis of various researchers.

Combined reinforcement of polymer and steel fiber was proposed in [23]. The maximum efficiency of such reinforcement can be achieved with a total fiber content of 1 % by volume instead of coarse aggregate, and 10 % of the steel fiber volume can be replaced by polymer fiber.

The combination of polypropylene and glass fiber reinforcement was considered in [24]. The polypropylene fiber content is 0.1–0.2 % by volume (approximately 0.22–0.45 % of cement mass) and glass fiber content is 0.1–0.2 % by volume (approximately 0.9–1.8 % of cement mass). This variation had a negative effect. The specimens with only polypropylene or glass fiber reinforcement were also ineffective. Perhaps it depends on the low reinforcement ratio. At the same time, the results of test specimens with polypropylene fiber, glass fiber, and combined reinforcement achieve the same compressive strength. There was no point in using two mentioned types of fiber reinforcement simultaneously.

The lightweight concrete reinforcement with carbon fiber and acrylic polymer addition was investigated in [25]. The result turned out to be negative and indicates the unacceptable lightweight concrete combination with dispersed polymer reinforcement and acrylic polymers.

2 Materials and Methods

2.1 Purpose and research aim of the study

The purpose of the study is to select the optimal reinforcement ratio of expanded clay concrete with polypropylene fiber.

The aim of the research is to determine the effective reinforcement ratio of expanded clay concrete with polypropylene fiber. It is also proposed to investigate which variation of adding fiber is most effective (as an admixture with a constant content of the binding material or instead of cement mass).

The research aim of the study is to determine the effect of the dispersed reinforcement with polypropylene fiber on the compressive strength of expanded clay concrete produced by using local raw materials.

2.2 Specimens characteristics

The specimens of the predictable compressive concrete strength LC 8/10 were investigated to determine the characteristic cube strength of expanded clay concrete.

For the manufacture of concrete mixtures, the following materials were used:

– expanded clay gravel produced by OJSC “Plant of expanded clay gravel in Novolukoml” was with fractions in the range of 5–10 mm and bulk density of 343 kg/m^3, specific density of 1670 kg/m^3, particle density of 798 kg/m^3, cylinder compressive strength of 2.68 MPa, total porosity of 82.16 %, water absorption of 15.6 % by weight;

– Portland cement produced by OJSC “Belarusian Cement Plant” was with an activity of 49.0 MPa, bulk density of 1440 kg/m^3, water requirement of normal consistency in the range of 25–28 %;

– dredged sand was with specific density of 2169 kg/m^3, bulk density of 1634 kg/m^3, fineness modulus of 2.27, total porosity of 24.67 %.

To determine the grain composition of sand from a laboratory specimen, weighed 2.0 kg of sand, preliminarily dried to constant weight, and sieved through holes diameter in a range of 10 and 5 mm. Then, sieve residues on these sieves were calculated by weight as a percentage of accuracy of up to 0.1 %. The sand passed through a sieve with holes of 5 mm diameter, weighed 1000 g, and sieved through a standard sieve set with holes of 2.5; 1.25; 0.63; 0.315; 0.16 mm, arranged in sequence as the diameter of holes is reduced. Partial residues a_i were determined.

The grain composition is presented in table 1.

Table 1. The grain composition of sand

Sieve size, mm	Partial sieve residues, a_i, g	Partial residues, a_i, %	Total residues, A_i, %
2.5	94	9.4	9.4
1.25	84	8.4	17.8
0.63	204	20.4	38.2
0.315	300	30.0	68.2
0.16	252	25.2	93.4

The concrete mix design was carried out in accordance with the recommendations for the expanded clay concrete mix design, which was developed by the Institute BelNIIS [26].

As a reinforcing element, constructional micro-fiber (CMF) was used. CMF was made from granules of a high-modulus thermoplastic polymer by means of a structural modification (extraction). This polypropylene fiber is an analog of the British fiber “Fibrin” (“Adfil”), produced in the Russian Federation according to TU 2272-006-13429727 of C3H6 polypropylene.

General properties of the CMF were:

– fiber length of 6 mm;

– fiber diameter in the range of 10–15 micrometers;

– round shape;

– the surface is covered with a special composition, and stimulates dispersion and adhesion with cement mortar;

– density of 0.91 g/cm^3 at 20 ºC;

– Modulus of elasticity of 5.7 GPa.

The fiber was added to the dry mix. All components were thoroughly mixed in the concrete mixer, then water was added portion-wise to the mixture.

Reinforcement was carried out with a fiber content of 0.5 %, 1 %, and 1.5 % by weight of the cement mass.

Specimens of the geometric shapes of cubes with a height of 100 mm were molded from the resulting mixture.

The characteristic values of the compressive cube strength of expanded clay concrete were determined by taking into account the coefficient of variation (V ≤ 13.5 %) with a confidence probability of 95 %.

Characteristics of the specimens are given in table 2.

Table 2. Characteristics of expanded clay concrete specimens

Strength class		CMF reinforcement ratio ρ_{pf}, % (of cement mass)	Characteristics of materials			Concrete mix proportion	
Predictable	Actual		Coarse aggregate	Fine aggregate	Binding material	G:S:C	W/C
LC 8/10	LC 6.5/7.1	0	Expanded clay gravel with a fraction 5–10 mm	River sand with fineness modulus of 1.64	Portland cement	0.83:1.72:1	0.49
	LC 9.3/10.1	0.5					
	LC 8.5/9.2	1.0					
	LC 8.6/9.3	1.5					

The expanded clay gravel fraction was accepted of up to 10 mm for the preparation of specimens. The earlier studies of the maximum particle size effect of coarse aggregate on the expanded clay concrete deformability are showed significantly decrease of the modulus of elasticity with an increase of the grain size. It is not depending on strength classes of expanded clay concrete. The test results are shown in table 3 and in figure 1.

Table 3. The largest nominal maximum aggregate size dg and the secant modulus of elasticity of expanded clay concrete for various trial series

Predictable strength classes of expanded clay concrete	The largest nominal maximum aggregate size, d_g, mm	The secant modulus of elasticity, E_{lcm}, GPa	
LC 25/28	10	23.9	27.2
LC 30/33		30.5	
LC 25/28		27.2	
LC 12/15	15	14.5	14.3
LC 16/18		15.4	
LC 8/10		13.0	
LC 10/12	20	10.4	10.5
LC 10/12		10.5	

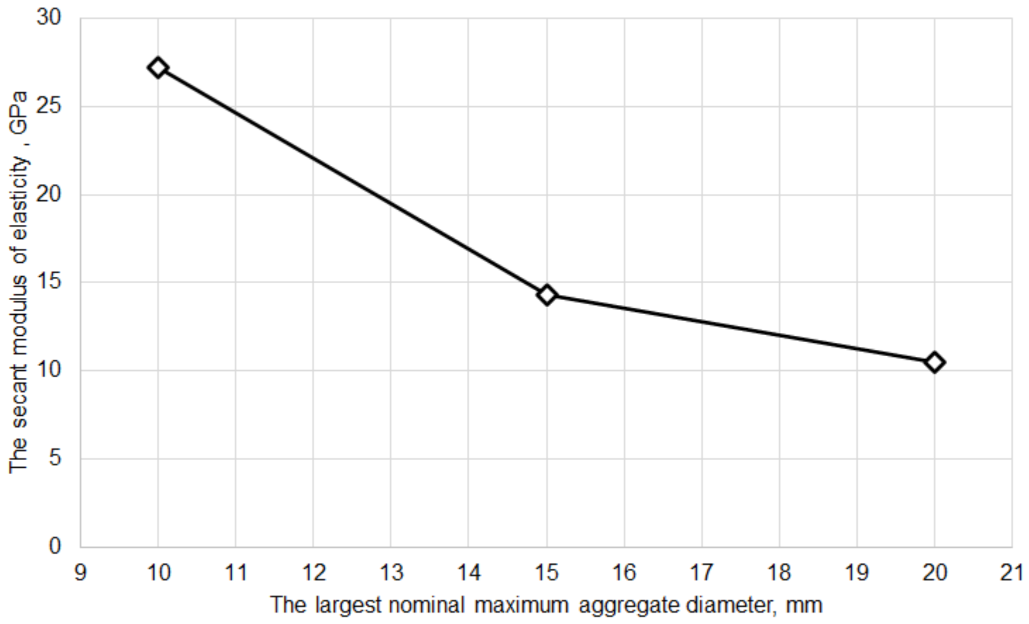

Fig. 1 – The dependence of the secant modulus of elasticity of the expanded clay concrete strength classes LC 8/10 – LC 30/33 on the aggregate diameter dg

According to the tests results of several series of standard specimens, if the expanded clay fraction used as coarse aggregate is finer, the secant modulus of elasticity of the expanded clay concrete will be higher regardless of the expanded clay concrete strength class. The test results are shown in figure 1. The secant modulus of elasticity will decrease by more than 2 times if the diameter of expanded clay grains increases. The opposite dependence was shown in [27]. However, if use expanded clay gravel with a finer fraction, the structure will be more homogeneous. Expanded clay is a porous material, so the elastic properties of expanded clay concrete will be primarily due to the homogeneity of its structure.

The dependence of the secant modulus of elasticity of the expanded clay concrete on the aggregate diameter (expanded clay) can be described using a power function or a 2nd degree polynomial. This dependence is shown in figure 1. In this case, the coefficient of determination will be approximately equal to 1. However, the optimal data are insufficiently yet for the derivation of the formula. This conclusion determines the expediency of further investigations.

2.3 Manufacturing technique of specimens.

It is necessary to adhere to the technology of concrete mix preparation, when reinforcing concrete with polymer fiber.

Polymer fiber reinforcement should be added to the dry mix, thoroughly mix all the components and only then add water to the mix. In case of non-observance of this condition, it is impossible to achieve a homogeneous distribution of fiber in the hardened concrete, and therefore, the effect of disperse reinforcement will be reduced to zero. The study [22] is devoted to the issues of modeling the process of preparing a concrete mix with polypropylene fiber.

This statement was confirmed experimentally. Test specimens were molded of geometric shape of cube of expanded clay concrete with polypropylene fiber reinforcement, which was added after mixing the concrete mix. As a result, the compressive strength of these specimens was lower in a comparison with the control (unreinforced) specimens.

Dry raw materials (cement, sand, gravel, polypropylene fiber) were bulk into the concrete mixer. Water was added in accordance with the accepted proportions.

The total required volume of a specified type of concrete was made in one batching.

For the specimen's manufacture was used metal prefabricated demountable forms. Before concrete casting, the interior surfaces of the mold were smeared with mineral oil, which prevents the sides of the molds from hanging-up of concrete and from corrosion.

The concrete mixture was laid in one or two layers by ramming, compacting with a plain reinforcing bar 10–20 times from the edges to the middle. The mixture was compacted until laitance appeared on its surface. Then the concrete mix was compacted on a vibration exciter. At the end of compaction, the surface was smoothed out with a trowel and cutting off the excess mixture. Concrete hardening was carried out in a temperature-humidity conditions (T = 20 ± 2 ºC; H = 95 ± 5 %). On the sixth day the demountable forms were remove.

2.4 Testing technique

Before each investigation, the specimens were inspected, measured, and weighed to determine the average density.

All tests of the cubes were carried out on a hydraulic press PGM-500MG4-A. This hydraulic press is intended for compressive and flexural strength of test specimens at the rate of load application. The load is normalized by the relevant standard. The press is supplied with an electric drive (220 V, 50 Hz) and tensometric force measure device.

The specimen was aligned along the axis of the upper and lower fixed table. The gap between the top fixed table and the specimen ranged from 3 to 4 mm. The loading of the specimens before their failure was carried out with a constant growth rate of stresses of 0.6 MPa/s. The tests were carried out on the 28th day.

3 Results and Discussion

3.1 Results of experimental investigations

Correction coefficient of 0.91 was used in connection with size cube face of 100 mm in determining the compressive cube strength according to the tests results.

The results of testing specimens of geometric shape of cubes are shown in Table 4.

Table 4. The results of testing specimens

Testing specimens		Mass, m, g	Cross-section area, sm^2	Volume, sm^3	Density, g/cm^3	Thermal conductivity coefficient, λ, W/(m·°C)	Breaking load, kN	Compressive cube strength, MPa		
CMF reinforcement ratio, ρ_{pf}, %	Code							According to the test results, $f_{lc,cube,i}$	Average value, $f_{lc,cube,m}$	Characteristi value, $f_{lc,cube}$
Series 1 – Fiber was introduced as an admixture without changing the concrete mix composition										
0	К1$_{0\ \%}$-1	1360	104	1040	1.307	0.569	115.9	10.14	11.11	9.3
	К1$_{0\ \%}$-2	1384	101	960	1.441	0.641	133.6	12.04		
	К1$_{0\ \%}$-3	out-of-control								
	К1$_{0\ \%}$-4	1304	102	1060	1.229	0.528	125	11.15		
0.5	К1$_{0,5\ \%}$-1	1384	102	1010	1.370	0.603	132.3	11.80	13.70	10.3
	К1$_{0,5\ \%}$-2	1458	99	970	1.503	0.674	152.1	13.98		
	К1$_{0,5\ \%}$-3	1486	96	990	1.501	0.673	167.1			
	К1$_{0,5\ \%}$-4	1554	99	960	1.619	0.736	166.7	15.32		
1	К1$_{1\ \%}$-1	1360	99	990	1.374	0.605	129.2	11.88	13.02	9.7
	К1$_{1\ \%}$-2	1484	104	1050	1.413	0.626	167.3	14.64		
	К1$_{1\ \%}$-3	1428	102	1030	1.387	0.612	162.4	14.49		
	К1$_{1\ \%}$-4	1380	107	1080	1.380	0.608	130.2	11.07		
1.5	К1$_{1,5\ \%}$-1	1422	99	990	1.457	0.649	132.1	12.14	13.14	10.7
	К1$_{1,5\ \%}$-2	1480	103	1050	1.410	0.624	163.2	14.42		
	К1$_{1,5\ \%}$-3	1466	102	1030	1.423	0.631	158.7	14.16		

	K1$_{1,5\%}$-4	1362	102	1040	1.310	0.571	132.7	11.84		
Series 2 – Fiber was introduced instead of cement mass according to the recommendations [16]										
0	K2$_{0\%}$-1	1402	103	1020	1.307	0.569	155.3	13.72	14.51	11.7
	K2$_{0\%}$-2	1408	103	982	1.441	0.641	158.8	14.03		
	K2$_{0\%}$-3	1420	100	985	1.216	0.521	184.3	16.77		
	K2$_{0\%}$-4	1422	104	994	1.229	0.528	153.7	13.51		
0.5	K2$_{0,5\%}$-1	out-of-control							12.86	11.7
	K2$_{0,5\%}$-2	1418	100	970	1.503	0.674	149.3	13.52		
	K2$_{0,5\%}$-3	1376	102	972	1.501	0.673	143.6	12.81		
	K2$_{0,5\%}$-4	1462	102	1025	1.619	0.736	136.7	12.26		
1	K2$_{1\%}$-1	out-of-control							11.29	10.8
	K2$_{1\%}$-2	1372	99	948	1.413	0.626	119.5	10.98		
	K2$_{1\%}$-3	1304	97	939	1.387	0.612	122.9	11.53		
	K2$_{1\%}$-4	1474	101	995	1.380	0.608	126.2	11.37		
1.5	K2$_{1,5\%}$-1	1438	100	888	1.457	0.649	129	11.80	10.64	8.7
	K2$_{1,5\%}$-2	1384	98	926	1.410	0.624	109.4	10.21		
	K2$_{1,5\%}$-3	out-of-control								
	K2$_{1,5\%}$-4	1288	98	965	1.310	0.571	106.7	9.91		

The value of the thermal conductivity coefficient was determined by the formula:

$$\lambda = 1.16\sqrt{0.0196 + 0.22\rho^2} - 0.16. \qquad (1)$$

The correctness of the obtained experimental results was verified by means of an express statistical estimate:

$$\frac{f_{lc,cume,max} - f_{lc,cume,min}}{f_{lc,cume,m}} \leq q, \qquad (2)$$

where q is a statistical coefficient depending on the amount of test series.

3.2 Evaluation of the effectiveness of dispersed reinforcement

Comparison of the obtained experimental data is shown in the histogram (Figure 2).

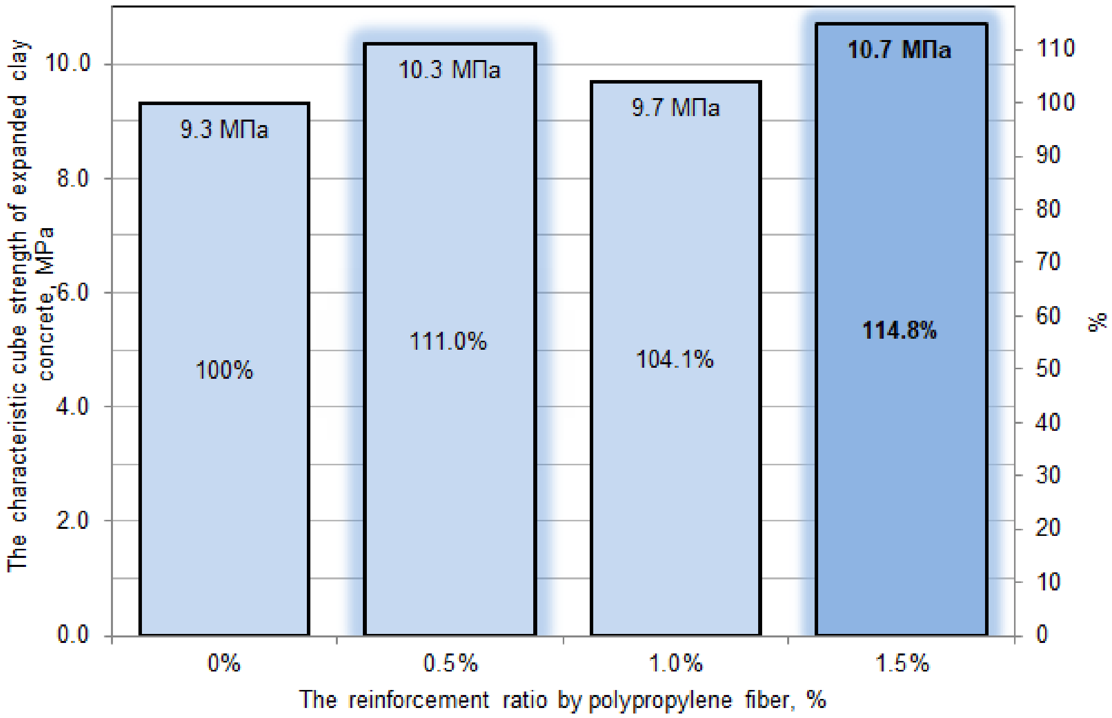

Fig. 2 – Change in the characteristic cube strength of expanded clay concrete according to the reinforcement ratio by polypropylene fiber for Series 1 of test specimens

According to Table 3 and the comparison histogram of experimental data (Fig. 2), dispersed reinforcement of expanded clay concrete by polypropylene fiber is effective at recommended values of reinforcement ratio (ρ_{pf} = 0.5–1.5 % by cement mass). An increase in the compressive strength of expanded clay concrete was detected in a range of 4.1–14.8 % as a result of reinforcement. The maximum growth of strength (14.8 %) was noted at ρ_{pf} = 1.5 %. According to the data from the Table 3, the introduction of polypropylene fiber instead of cement, as recommended in [16], had negative effect in all cases. The compressive cube strength decreased by 0.5–25 % whiles the reinforcement ratio was higher, the compressive strength decreased significantly.

4 Conclusions

The optimum content of the reinforcing polymer fiber is 0.5–1.5 % by cement mass, based on an analytical survey of the studies of various researchers. If the reinforcement ratio is lower than 0.5 % or higher than 1.5 %, the introduction of the fiber is ineffective for several reasons. Firstly, it is difficult to achieve a uniform distribution of the fiber in the concrete. Secondly, according to the low modulus of elasticity of polypropylene fiber (5.7 MPa), it influences on a reinforcing element only with low content, increasing the viscosity of concrete disintegration. As a result, the strength and deformation characteristics are increase. However, there is no consensus on the most effective reinforcement ratio. This is condition for conducting research in this direction.

The growth of the expanded clay concrete compressive strength exceeds 10 % with the percentage of dispersed reinforcement by polypropylene fiber ρ_{pf} = 0.5 % and ρ_{pf} = 1.5 %. The most effective reinforcement ratio is ρ_{pf} = 1.5 % by cement mass (the growth of compressive cube strength exceeds 14 %). The reinforcement percentage ρ_{pf} = 1.0 % is ineffective, the compressive cube strength increases by 4 %.

According to the recommendations [16], polypropylene fiber can be added instead of binding material (cement), however, the results of the tests disprove this statement. As a result of investigations, the introduction of polypropylene fiber reinforcement instead of cement negatively effects on the strength characteristics (a decrease of the compressive strength up to 25 % was recorded).

The obtained results are consistent with the results of [17] and different from the results of [11], [15], it is indicating the most effective reinforcement ratio of 1.5 %. In this regard, it seems appropriate to undertake additional research.

The efficiency of reinforcement by polymer fiber for expanded clay concrete should be rather higher than for normal weight concrete, since there is no clear boundary on the contact of coarse aggregate and cement matrix [12], [13]. Therefore, the limits of microcrack formation will have higher values compared with normal weight concrete [28], and hypothetically, the introduction of polymeric fiber will improve these values. This assumption requires experimental confirmation or disproof.

The investigation results of the aggregate size effect on the secant modulus of elasticity of the expanded clay concrete are also interesting. It is possible to predict the secant modulus of elasticity at the designing stage of the concrete mixture with sufficient accumulation of experimental data.

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