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Fiber concrete for the construction industry

Фибробетон для строительной индустрии

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Ключевые слова: композиционные вяжущие; фибробетон; доменный гранулированный шлак; фибра; армирование

Abstract. The article considers the use of dispersed concrete reinforcement. The efficiency of reinforcing of concrete by a fiber is proved as its strength and deformative characteristics increase. For receiving composite binders were used: Portland cement of TsEM I 42.5H GOST 31108-2003 (Russian State Standard), blast furnace granulated slag with Mo = 1.14 and Ma = 0.2, mineral plasticizer Tricosal 181 softener in essence supplementing particle size distribution knitting, waste of wet magnetic separation of ferruterous quartzites (WMS). Different types of composite binders were developed and their physic-mechanical characteristics are defined. For disperse reinforcing alkaliproof glass fiber was chosen; it is produced in the form of a roving. The analysis of results showed positive influence of the composite binders on mixes strength characteristics. The microstructure of mixes on the basis of composite binders has significant effect on properties of a composite. The conducted researches showed that the most effective length of a glass fiber is 12 mm, percent of reinforcing – 4.5 % on weight at the relation of cement and sand equal 1:3. Optimum selection of filler and also use of fiber glass in an optimum dosage allowed to increase concrete durability by stretching at a bend for 172 % on a Portland cement and to 225 % on composite binders that allows to apply it to designs.

Аннотация. В статье рассмотрено применение дисперсного армирования бетонов. Доказана эффективность армирования бетонов фиброй, поскольку повышаются его прочностные и деформативные характеристики. Для получения композиционных вяжущих были использованы: портландцемент ЦЕМ I 42,5Н ГОСТ 31108–2003, доменный гранулированный шлак с Мо = 1,14 и Ма = 0,2, минеральный пластификатор Tricosal 181, по существу дополняющий гранулометрический состав вяжущего, отходы мокрой магнитной сепарации железистых кварцитов (ММС). Были разработаны различные виды композиционных вяжущих и определены их физико-механические характеристики. Для дисперсного армирования было выбрано щелочестойкое стекловолокно выпускается в виде ровинга. Анализ результатов показал положительное влияние композиционных вяжущих на прочностные характеристики смесей. Микроструктура смесей на основе композиционных вяжущих оказывает существенное влияние на свойства композита. Проведенные исследования показали, что наиболее эффективная длина стеклянной фибры 12 мм, процент армирования 4,5 по массе при отношении цемента и песка 1:3. Оптимальный подбор заполнителя и наполнителя, а также использование стекловолокна в оптимальной дозировке позволили увеличить прочности бетона на растяжение при изгибе на 172 % на портландцементе и до 225 % на композиционном вяжущем, что позволяет применять его для конструкций.

1. Introduction

A promising direction for the production of high-strength concrete is their micro-reinforcement. Dispersed reinforcement provides three-dimensional hardening of composites and allows changing fundamentally the properties of cement stone and other types of artificial composites, providing them with high crack resistance, increasing the resistance to shock and dynamic loads, etc. [1–5]

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The solution to the problem of reducing the cost of such materials is possible through the use of composite binders, the multicomponent composition of which allows not only to reduce the clinker component in the mixture, but also to manage effectively the processes of structure formation, providing high quality of the obtained concretes and products based on them [6–13].

The implementation of fillers, which can be represented as particles of the dispersed phase with other indicators of surface tension than the elementary structural elements of the binder, change the energy state of the dispersed system [14–18]. The choice and purpose of fillers mainly depend on their chemical activity. Effective fillers have a multifunctional value in the synthesis of materials with predetermined properties. In real conditions, there is a compaction of cement stone (reduction in the content of large capillary pores) not only by creating a denser packaging of the initial components, but also by changing the chemistry of the binder hardening [19–23].

2. Materials and methods of research

The research on the impact of the number and type of fillers on the activity of the composite binder, which was obtained by joint grinding of cement and additives, was carried out in the work. The specific surface area was 600 m^2/kg.

To obtain composite binders, the following materials were used: Portland cement CEM I 42.5 N GOST 31108-2003 CJSC “Belgorod cement”, Novolipetsk blast furnace granulated slag with Mo = 1.14 and Ma = 0.2, Tricosal 181 mineral plasticizer, essentially complementing the granulometric composition of the binder, wet magnetic separation waste of ferrous quartzites (WMS) (Tables 1–3).

Table 1. Chemical composition of the additive “TRICOSAL-181”.

Oxide	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	SO_3	K_2O
Tricosal-181, %	1.55	1.66	0.283	89.1	0.629	6.37	0.23

Table 2. Chemical composition of mineral components of binder.

Oxide	SiO_2	Al_2O_3	Fe_2O_3	FeO	CaO	MgO	SO_3	K_2O	Na_2O	MnO	CO_2
Slag	37.1	7.3	0.65	-	41.4	9.4	1.83	0.59	0.35	1.02	-
WMS	77.8	0.57	6.58	7.12	1.5	2.26	0.128	-	-	-	3.63

Table 3. Physical properties of granulated blast furnace slag OJSC “NLMK”.

Parameters	Values
Activity in the age, MPa	
3 days	0.11
7 days	2.5
28 days	19.1
Bulk density in the dry state, kg/m^3	1090
Real density, kg/m^3	2820
Water demand, %	15
Fineness modulus	2.71
Basicity modulus	1.14

The main experimental studies were conducted at the Center of high technologies of BSTU named after V.G. Shukhov, testing center “BSTU-sertis”, in the laboratories of the departments of Architectural and Construction Institute and the Institute of Building Materials, Belgorod State Technological University named after V.G. Shukhov.

Studies of the structural-phase state were carried out using an X-ray diffractometer ARLX´TRA; X-ray fluorescence analysis of the elements-ARL9900 Intellipower Workstation.

High-resolution scanning electron microscope TESCAN MIRA 3 LMU including energy dispersive spectrometer (EMF) X-MAX 50 Oxford Instruments NanoAnalysis for electron-probe microanalysis was used to obtain micrographs of the surface, grain size, microstructure of hardened binders.

The alkali-resistant fiber used in experiments is produced in the form of roving RCR-15-190-2520-9. The figures indicate: the diameter of the elementary fiber in μm is 15; the linear density of the complex thread is 190; the linear density of the roving is 2520; the number of the oiler is 9. Breaking load of roving is 500 N; the limit of the tensile strength is 1600 MPa; the maximum deformation in tensile strength is 2.2 %; modulus of elasticity is 72 GPa; the shear modulus is 29.1 GPa.

The plasticizing additive "Polyplast PREMIUM" was used.

3. Results and Discussion

To detect the action of Tricosal 181 additive and Novolipetsk blast furnace granulated slag on composite binders, compositions with an additive in the amount of 0.5 % of the cement mass were prepared. Additive (AD) in Composition Binder (CB) was implemented from the milling of binders to specific surface area 600 m^2/kg. The compositions with different slag consumption: 10, 20 and 50 % were studied.

Hardening time, day	1	3	7	28
Cem. I 42.5 H, MPa	20.8	43.8	53.3	62.8
Cem. I 42.5 H+25g AD, MPa	21.4	47.0	55.9	64.3
Cem. I 42.5 H+10%Sl +22.5g AD, MPa	19.8	45.6	55.8	64.0
Cem. I 42.5 H+20%Sl +20g AD, MPa	17.0	41.6	56.3	62.1
Cem. I 42.5 H+50%Sl +12.5g AD, MPa	15.8	33.5	45.8	60.5

Figure 1. Kinetics of hardening of CB on the basis of slag.

When comparing the activity of binders, an increase in strength was observed for all compositions (Figure 1). In early terms, the slag slows down the hydration process, and by 28 days the strength indicators of all binders become equal to the strength of the clinker, and in some cases exceed it. The addition of slag 10 and 20 % does not reduce practically the strength parameters of the binders compared to the original clinker in all terms of hardening. CB with 50 % of slag reaches the values of the strength of the ground clinker to 28-day hardening period. This is due to the fact that the high plasticizing effect of the additive is determined by the high dispersion and mineral composition, so when it is mixed with water, it forms colloidal glue and physically binds a large amount of water, compacting the structure. At the same time, its particles, being priming, substrates and centers of crystallization of slag glass, have a catalytic effect on the processes of hydration and hardening of the binder. At the same time, after forming in the initial process of hydration, the particles of the additive adsorb a significant amount of water, thereby reducing the water-binding ratio, and this leads to the activation of the processes of structure formation and synthesis of smaller crystals of calcium hydrosilicates, which undoubtedly affects the optimization of the microstructure of the cement stone compared to the control samples (Figure 2).

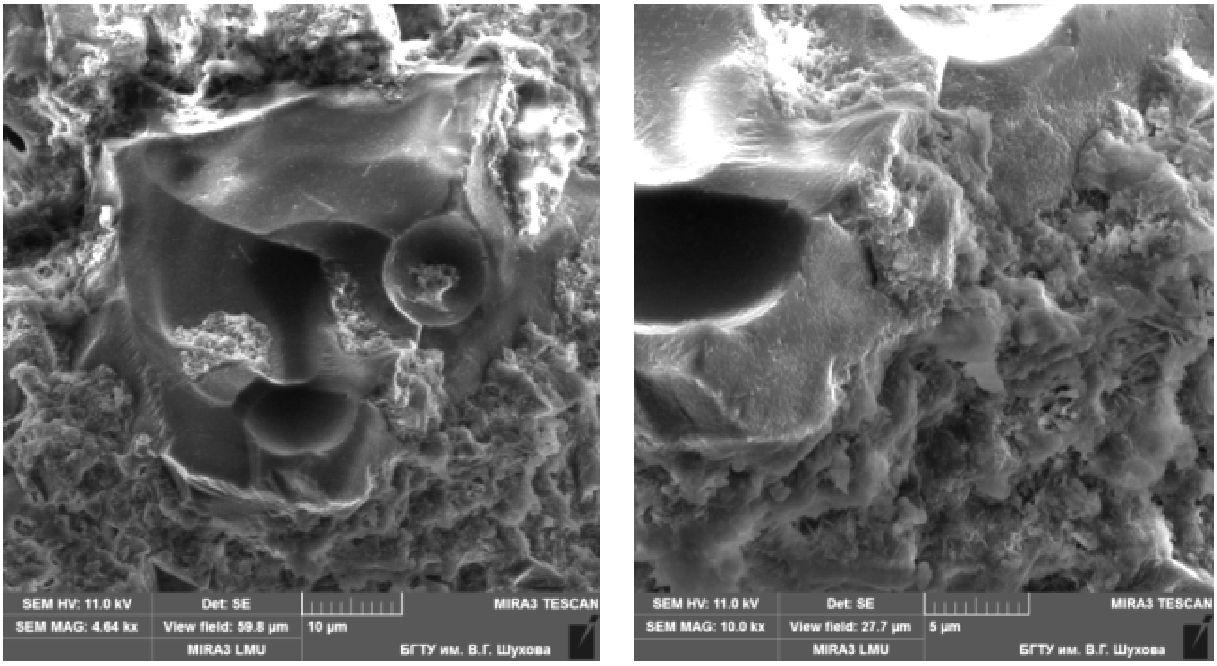

Figure 2. Microstructure of composite binder based on slag.

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The study of the microstructure of samples with the addition of 0.5 % of clinker consumption and 50 % of slag showed that the resulting material is characterized by a dense matrix (Figure 2). Slag filler has good adhesion with cement stone. In this case, the additive particles, being the priming, substrates and crystallization centers of the slag glass, have a catalytic effect on the processes of hydration and hardening of the binder. In addition, the smallest particles of the filler, as well as non-hydrated cement grains, are also additional centers of crystallization, which is clearly visible in micrographs.

The hardened slag-portland cement stone is characterized by a lower content of crystalline portlandite, partially bound by slag grains and a denser hydrosilicate gel structure (Figure 2). These features of the structure explain the high water resistance and resistance to aggressive environments.

Also, various compositions of binders were obtained: fine cement (TMC 100) and composite binders consisting of cement and additives (CB 100 and CB 80 WMS). As a basis for obtaining such binders CEM I 42.5 N made at CJSC "Belgorod cement" (Belgorod) was chosen. The composite binder was obtained by grinding Portland cement with plasticizing additive "Polyplast PREMIUM" in a vibrator mill to a specific surface area of 600 m^2/kg.

The main characteristics of the developed binders were determined (Table 4).

Table 4. Physical and mechanical characteristics of composite binders.

Name of binder	Specific surface, m^2/kg	Beginning of setting, hours	Ending of setting, hours	Activity	
				In bending, MPa	In compression, MPa
CEM I 42.5N	320	2.30	3.30	7.8	51.3
TMC – 100	600	2.15	3.15	15.2	67.4
CB-100	600	1.50	2.50	18.1	78.9
CB-80 (WMS)	600	2.05	3.00	10.9	56.9
CB-80 (slag)	600	3.20	4.00	15.7	62.1

As it can be seen from the results of studies, the binder CB-100 is characterized by a higher activity compared to cement CEM I 42.5 N and other binders.

Thus, the use of such composite binders allows improving the characteristics of concrete, compared with similar compositions based on cement. That is explained by more dense structure of a cement stone of composite binders, and consequently concretes on their basis, and also smaller porosity.

The interaction between the fibers and the matrix is a fundamental property that affects the quality of fibrous composite material based on the cement. Many factors are involved to understand the interaction between the fibers and the matrix and to predict the behavior of the composite. Here are the most important parameters that affect the interaction of fibers and matrix: matrix condition – without cracks or with cracks; the composition of the matrix; the characteristics of the type, geometry and fiber surface; the hardness of the fibers in comparison with the stiffness of the matrix; the orientation of the fibers; volume fraction of fibers; continuity of the fiber in the composite.

Production practice showed that the reinforcement of concrete with glass fiber, which has high chemical resistance to alkaline medium, became possible due to the directed development of fibers from glass of special compositions.

Available local materials were used to form the samples. The sand used for the manufacture of fine concrete was used. Its characteristics were determined by the methods of GOST 8835-88 "Sand for construction works. Test method". The fineness modulus of sand – 2.56; bulk density – 1700 kg/m^3.

The practice of using optical fiber to dispersed reinforcement of concrete showed that from the point of view of duration of maintaining quality of reinforcing fiber with a diameter of 13-15 microns is accepTable, which is consistent with the used roving.

Studies showed that the most effective fiber length is 12 mm, the percentage of reinforcement is 4.5 by weight with a ratio of cement and sand 1:3. The output parameters were the average density of glass fibre concrete, tensile compressive strength, tensile strength in bending [24]. The results are presented in the Table 5.

Table 5. Test results of glass fibre concrete samples.

Types of samples	fibers		Density, kg/m^3	σ_{bf}		σ_t	
	length, mm	% by weight		value, MPa	growth, %	value, MPa	growth, %
Without fiber			2230	23.0		3.6	
CEM I 42.5	50	4.5	2140	17.0	-26.1	10.0	172.8
CB-80 WMS	50	4.5	2180	23.0		7.5	150
CB-80 slag	50	4.5	2240	25.5	10.8	11.5	219
CB-100	50	4.5	2180	29.3	27.4	11.7	225

Analysis of the results showed a positive effect of composite binders on both compressive strength and tensile strength in bending. The microstructure of the composition based on CB has a significant effect on the composite properties. The solidified body contains pores of variable sizes. A significant change in volume occurs due to creep and shrinkage at temperature and humidity change (Figure 3).

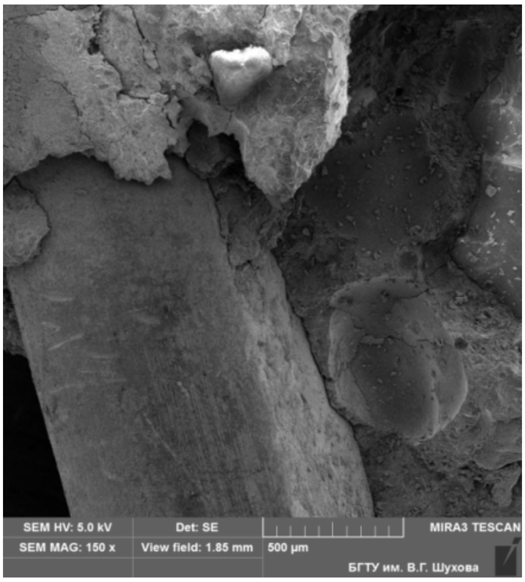

Figure 3. The contact area of fiber with composite binder CB100.

4. Conclusion

1. Matrix and fibers form a microstructure, which is fundamentally different from the microstructure of the matrix. The interaction zone exists up to 50 microns deep into the fiber surface. This zone contains a double film with a thickness of about 1-2 microns, which surrounds the fiber, the area of large CH crystals, having a depth of up to 30 microns, and an area that has sufficient porosity. The contribution of the interaction zone to the mechanical properties of the composite is determined by the process of fiber binding and peeling.

2. Thus, the granulometric composition of mineral components of binders was optimized taking into account the genesis and morphology of the surface of the particles. It is found that the optimization of the structure formation of composite binders occurs due to the consistent growth of tumors during the hardening of the system "clinker minerals-filler-water-superplasticizer", determined by the different intensity and time of interaction of filler particles with the products of hydration of clinker minerals.

3. Rational selection of aggregate and filler, as well as the use of glass fiber in the optimal dosage allowed increasing the tensile strength of concrete in bending by 172 % on Portland cement and up to 225 % on the composite binder.

References

1. Wischers, G. Faserbewehrter Beton. Beton-Verlag. Düsseldorf 1975. Pp. 95–99.
2. Wörner, J.-D. Faserarten und – eigenschaften. Darmstädter Massivbau-Seminar. Darmstadt, 1990. Pp.75–81.
3. Alfes, Ch., Wiens, U. Stahlfaserbeton nach DAfStb-Richtlinie. Beton, Heft 4. 2010. Pp. 128–135.
4. Alfes, Ch. Qualitätssicherung von Stahlfaserbeton im Transportbetonwerk. BWI - Betonwerk International Heft 6. 2006. Pp. 212–218.
5. Grübl, P., Weigler, H., Karl, S. Beton. Art, Herstellung und Eigenschaften. Verlag Ernst & Sohn. 2001. Pp. 98–112.
6. Vatin, N.I., Barabanshchikov, Yu.G., Komarinskiy, M.V., Smirnov S.I. Modification of the cast concrete mixture by air-entraining agents. Magazine of Civil Engineering. 2015. 56(4). Pp. 1–10. (rus)
7. Dudin, M.O., Vatin, N.I., Barabanshchikov, Y.G. Modeling a set of concrete strength in the program ELCUT at warming of monolithic structures by wire. Magazine of Civil Engineering. 2015. 54(2). Pp. 33–45. (rus)
8. Dmitrieva, T.V., Strokova, V.V., Bezrodnykh, A.A. Influence of the genetic features of soils on the properties of soil-concretes on their basis. Construction Materials and Products. 2018. Vol. 1. No. 1. Pp. 69–77.
9. Klyuev, S.V., Klyuev, A.V., Abakarov, A.D., Shorstova, E.S., Gafarova, N.G. The effect of particulate reinforcement on strength and deformation characteristics of fine-grained concrete. Magazine of Civil Engineering. 2017. 75(7). Pp. 66–75.
10. Klyuyev, S.V., Klyuyev, A.V., Lesovik, R.V., Netrebenko, A.V. High Strength Fiber Concrete for Industrial and Civil Engineering. World Applied Sciences Journal. 2013. 24(10). Pp. 1280–1285.
11. Lesovik, R.V., Klyuyev, S.V., Klyuyev, A.V., Netrebenko, A.V., Kalashnikov, N.V. Fiber Concrete on Composite Knitting and Industrialsand KMA for Bent Designs. World Applied Sciences Journal. 2014. 30(8). Pp. 964–969.
12. Elistratkin, M.Yu., Kozhukhova, M.I. Analysis of the factors of increasing the strength of the non-autoclave aerated concrete. Construction Materials and Products. 2018. Vol. 1. No. 1. Pp. 59–68.
13. Morozov, V.I., Pukharenko, Yu.V., Yushin, A.V. The numerical investigations of double-span concrete beams strengthened with fiber reinforced plastics across the oblique section. Materials Physics and Mechanics.2017. Vol. 31. No. 1-2. Pp. 40–43.
14. Zharikov, I.S., Laketich, A., Laketich, N. Impact of concrete quality works on concrete strength of monolithic constructions. Construction Materials and Products. 2018. Vol.1. No. 1. Po. 51–58.
15. Zagorodnyuk, L.Kh., Lesovik, V.S., Sumskoy, D.A. Thermal insulation solutions of the reduced density. Construction Materials and Products. 2018. Vol. 1. No. 1. Pp. 40–50.
16. Klyuev, S.V., Klyuev, A.V., Vatin, N.I. Fine-grained concrete with combined reinforcement by different types of fibers. MATEC Web of Conferences. 2018. 245. 03006.
17. Klyuev, S.V., Khezhev, T.A., Pukharenko, Yu.V., Klyuev, A.V.The Fiber-Reinforced Concrete Constructions Experimental Research. Materials Science Forum. 2018. Vol. 931. Pp. 598–602.
18. Klyuev, S.V., Khezhev, T.A., Pukharenko, Yu.V., Klyuev, A.V. Fiber Concrete on the Basis of Composite Binder and Technogenic Raw Materials. Materials Science Forum. 2018. Vol. 931. Pp. 603–607.
19. Yu, R., Spiesz, P., Brouwers, H.J.H. Development of an ecofriendly Ultra-High Performance Concrete (UHPC) with efficient cement and mineral admixtures uses. Cement and Concrete Composites. 2015. Vol. 55. Pp. 383–394.

Литература

1. Wischers G. Faserbewehrter Beton // Beton-Verlag. Düsseldorf 1975. Pp. 95–99.
2. Wörner J.-D. Faserarten und – eigenschaften // Darmstädter Massivbau-Seminar. Darmstadt, 1990. Pp. 75–81.
3. Alfes Ch., Wiens U. Stahlfaserbeton nach DAfStb-Richtlinie // Beton, Heft 4. 2010. Pp. 128–135.
4. Alfes Ch. Qualitätssicherung von Stahlfaserbeton im Transportbetonwerk // BWI - Betonwerk International Heft 6. 2006. Pp. 212 – 218.
5. Grübl P., Weigler H., Karl S. Beton. Art, Herstellung und Eigenschaften // Verlag Ernst & Sohn. 2001. Pp. 98–112.
6. Ватин Н.И., Барабанщиков Ю.Г., Комаринский М.В., Смирнов С.И. Модификация литой бетонной смеси воздухововлекающей добавкой // Инженерно-строительный журнал. 2015. №4(56). С. 3–10.
7. Дудин М.О., Ватин Н.И., Барабанщиков Ю.Г. Моделирование набора прочности бетона в программе ELCUT при прогреве монолитных конструкций проводом // Инженерно-строительный журнал. 2015. №2(54). С. 33–45.
8. Dmitrieva T.V., Strokova V.V., Bezrodnykh A.A. Influence of the genetic features of soils on the properties of soil-concretes on their basis // Construction Materials and Products. 2018. Volume 1. Issue 1. Pp. 69–77.
9. Клюев С.В., Клюев А.В., Абакаров А.Д., Шорстова Е.С., Гафарова Н.Е. Влияние дисперсного армирования на прочностные и деформативые характеристики мелкозернистого бетона // Инженерно-строительный журнал. 2017. № 7(75). С. 66–75.
10. Klyuyev S.V., Klyuyev A.V., Lesovik R.V., Netrebenko A.V. High Strength Fiber Concrete for Industrial and Civil Engineering // World Applied Sciences Journal. 2013. 24(10). Pp. 1280–1285.
11. Lesovik R.V., Klyuyev S.V., Klyuyev A.V., Netrebenko A.V., Kalashnikov N.V. Fiber Concrete on Composite Knitting and Industrialsand KMA for Bent Designs // World Applied Sciences Journal. 2014. 30(8). Pp. 964–969.
12. Elistratkin M.Yu., Kozhukhova M.I. Analysis of the factors of increasing the strength of the non-autoclave aerated concrete // Construction Materials and Products. 2018. Vol. 1. № 1. Pp. 59–68.
13. Morozov V.I., Pukharenko Yu.V., Yushin A.V. The numerical investigations of double-span concrete beams strengthened with fiber reinforced plastics across the oblique section // Materials Physics and Mechanics.2017. Т. 31. № 1-2. Pp. 40–43.
14. Zharikov I.S., Laketich A., Laketich N. Impact of concrete quality works on concrete strength of monolithic constructions // Construction Materials and Products. 2018. Vol. 1. № 1. Pp. 51 – 58.
15. Zagorodnyuk L.Kh., Lesovik V.S., Sumskoy D.A. Thermal insulation solutions of the reduced density // Construction Materials and Products. 2018. Vol. 1. № 1. Pp. 40–50.
16. Klyuev S.V., Klyuev A.V., Vatin N.I. Fine-grained concrete with combined reinforcement by different types of fibers // MATEC Web of Conferences. 2018. 245. 03006.
17. Klyuev S.V., Khezhev T.A., Pukharenko Yu.V., Klyuev A.V.The Fiber-Reinforced Concrete Constructions Experimental Research // Materials Science Forum. 2018. Vol. 931. Pp. 598–602.
18. Klyuev S.V., Khezhev T.A., Pukharenko Yu.V., Klyuev A.V. Fiber Concrete on the Basis of Composite Binder and Technogenic Raw Materials // Materials Science Forum. 2018. Vol. 931. Pp. 603–607.
19. Yu R., Spiesz P., Brouwers, H.J.H. Development of an ecofriendly Ultra-High Performance Concrete (UHPC) with efficient cement and mineral admixtures uses // Cement and Concrete Composites. 2015. Vol. 55. Pp. 383–394.

Klyuev, S.V., Klyuev, A.V., Vatin, N.I. Fiber concrete for the construction industry. Magazine of Civil Engineering. 2018. 84(8). Pp. 41–47. doi: 10.18720/MCE.84.4.

20. Hezhev, T.A., Zhurtov, A.V., Tsipinov, A.S., Klyuev, S.V. Fire resistant fibre reinforced vermiculite concrete with volcanic application. Magazine of Civil Engineering. 2018. 80(4). Pp. 181–194.
21. Khezhev, T.A., Pukharenko, Yu.V., Khezhev, Kh.A., Klyuev, S.V. Fiber Gypsum Concrete Composites with Using Volcanic Tuff Sawing Waste. ARPN Journal of Engineering and Applied Sciences. 2018. Vol. 13. No. 8. Pp. 2935–2946.
22. Sivakumar, N., Muthukumar, S., Sivakumar, V., Gowtham, D., Muthuraj, V. Experimental studies on High Strength Concrete by Using Recycled Coarse aggregate. Research Inventy: International Journal of Engineering and Science. 2014. Vol. 4. No. 1. Pp. 27–36.
23. Brouwers, H.J.H., Radix, H.J. Self-Compacting Concrete: Theoretical and experimental study. Cement and Concrete Research. 2005. Vol. 35. Pp. 2116–2136.
24. Klyuev, S.V., Klyuev, A.V., Khezhev, T.A., Pucharenko, Yu.V. Technogenic sands as effective filler for fine-grained fibre concrete. Journal of Physics: Conference Series. 2018. 1118. 012020.

20. Хежев Т.А., Журтов А.В., Ципинов А.С., Клюев С.В. Огнезащитные фибровермикулитобетоны с вулканическими добавками // Инженерно-строительный журнал. 2018. № 4(80). С. 181–194.
21. Khezhev T.A., Pukharenko Yu.V., Khezhev Kh.A., Klyuev S.V. Fiber Gypsum Concrete Composites with Using Volcanic Tuff Sawing Waste // ARPN Journal of Engineering and Applied Sciences. 2018. Vol. 13. № 8. Pp. 2935–2946.
22. Sivakumar N., Muthukumar S., Sivakumar V., Gowtham D., Muthuraj V. Experimental studies on High Strength Concrete by Using Recycled Coarse aggregate // Research Inventy: International Journal of Engineering and Science. 2014. Vol. 4. № 1. Pp. 27–36.
23. Brouwers H.J.H., Radix H.J. Self-Compacting Concrete: Theoretical and experimental study // Cement and Concrete Research. 2005. Vol. 35. Pp. 2116–2136.
24. Klyuev S.V., Klyuev A.V., Khezhev T.A., Pucharenko Yu.V. Technogenic sands as effective filler for fine-grained fibre concrete // Journal of Physics: Conference Series. 2018. 1118. 012020.

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