doi: 10.18720/MCE.80.16

Fire resistant fibre reinforced vermiculite concrete with volcanic application

Огнезащитные фибровермикулитобетоны с вулканическими добавками

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Key words: vermiculite; fly ash; pumice; fibre vermiculite concrete composite; ferrocement; fire-resistance

Ключевые слова: вермикулит; пепел; пемза; фибровермикулитобетонный композит; армоцемент; огнестойкость

Abstract. The results of studies on the development of vermiculite concrete composites with application of volcanic ash and pumice are presented. The composition of cement fibre vermiculite concrete fire resistant composites is offered, which allows reducing the consumption of Portland cement and simultaneously increasing their flame retardant properties. The use of basalt fibers in composites can improve the strength, fracture toughness and fire retardant properties of the coating due to the perception of tensile thermal stresses during the fire. Replacement of cement up to 30 % by weight with volcanic pumice fraction d < 0.16 mm significantly improves heat-resisting properties of cement stone with a simultaneous increase in flexural strength and no significant loss of compressive strength. Experimental and theoretical studies of fire resistance of double-layer ferroconcrete constructions showed high fire resistant properties of the developed cement fibre vermiculite concrete fire resistant composites. The algorithm for calculating the fire resistance of multi-layered building constructions with finite-difference implicit scheme for solving the heat conduction problem and the sweep method, providing reasonable agreement with experimental data is offered.

Аннотация. Представлены результаты исследований по разработке фибровермикулитобетонных композитов с применением вулканического пепла и пемзы. Предложены составы цементных фибровермикулитобетонных огнезащитных композитов, позволяющие существенно сократить расход портландцемента и одновременно повысить их огнезащитные свойства. Применение базальтовых волокон в композитах позволяет повысить прочность, трещиностойкость и огнезащитные свойства покрытия за счет восприятия растягивающих температурных напряжений во время пожара. Замена цемента до 30 % от массы вулканической пемзой фракции d < 0,16 мм существенно повышает жаростойкие свойства цементного камня с одновременным увеличением прочности на изгиб и без заметного снижения прочности на сжатие. Экспериментально-теоретические исследования огнестойкости двухслойных армоцементных конструкций показали высокие огнезащитные свойства разработанных цементных фибровермикулитобетонных огнезащитных композитов. Предложен алгоритм расчета огнестойкости многослойных строительных конструкций с использованием конечноразностной неявной схемы решения задачи теплопроводности и метода прогонки, обеспечивающий приемлемое совпадение с экспериментальными данными.

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.

1. Introduction

The increase in the number of fires in our country and abroad is observed every year. About 10 million fires occur annually, as a result more than 65 thousand people die, and 250 thousand are injured. Material damage from the fires is hundreds of billions of rubles.

The collapse of building constructions is the main cause of loss of life and damage from fires. This is due to the fact that in modern construction in the erection of buildings and structures thin-walled concrete constructions of high-strength concrete are increasingly used. Use of dispersed-reinforced concrete in the construction allows reducing material, labor and energy of ferroconcrete constructions while improving quality. Disperse-reinforced concrete is widely used in the manufacture of thin-walled, including spatial, constructions. It is known that the application of spatial ferro cement constructions in building allows reducing material capacity of constructions by 20–50 %, the complexity of their fabrication and installation – by 10–15 % and cost – up to 20 % with mechanized production [1]. Ferro cement constructions have a number of advantages in comparison with reinforced concrete structures: a lower consumption of concrete (by 30–50 %) and steel (up to 15–20 %); higher fracture toughness, density and water resistance; the use of non-deficient filler [2].

Despite significant progress in the development of spatial constructions, their implementation in the construction practice is still insufficient. One of the reasons restraining the use of thin-walled reinforced concrete structures is their low fire resistance [3–5]. With the increasing span of buildings there is a tendency to reduce the thickness and increase the strength of the material structures that lowers their fire resistance. In addition, financial losses from fire increase sharply with the raising of the span of the building. In recent years, the requirements of possible future use after fire exposure in terms of field of fire are made increasingly to constructions. Abroad there is evidence showing the feasibility and efficiency of reinforced concrete structures with a large limit of fire resistance [6–10].

An effective way to improve the fire resistance of building constructions is the application of thermal barrier coatings with the use of expanded vermiculite and perlite. The effectiveness of their use for fire protection of building constructions is increased by the simultaneous implementation of thermal, acoustic and decorative functions.

The disadvantages of flame retardants are high consumption of Portland cement, the relatively high coefficient of thermal conductivity at high temperature and low temperature resistance.

One material that is effective to replace part of Portland cement and aggregate for flame retardants can be volcanic tuff sawing waste, volcanic ash and pumice. To eliminate the harmful effects of secondary hydration of free calcium oxide on the characteristics of fire-resistant and heat-resistant concrete active mineral additives are used.

Thus, overcoming many of the drawbacks of flame retardants is possible in the creation of fibre reinforced composites using effective fillers.

The aim of this work is to develop an effective fire resistant cement fibre reinforced vermiculite composites with application of volcanic rocks. To achieve this goal compositions of vermiculite concrete and fibre vermiculite concrete flame retardant composites with application of volcanic rocks were developed, the flame retardant properties of the developed composites with experimental and computational methods were investigated.

Over the past decade, there has been growth in the use of dispersed reinforced composites. The fiber-reinforced concrete have higher tensile strength, crack resistance, impact resistance, temperature resistance compared to concrete matrix, which allows extending the scope of their effective application [11–18].

In development of science about the fiber concrete the big contribution was made by scientists of Austria, Australia, Belgium, Germany, Holland, Spain, Canada, China, Poland, the USA, France, the Czech Republic, Switzerland, the Republic of South Africa, Japan, and other countries [19–24].

2. Methods and materials

The Kabardino-Balkar Republic has large reserves of volcanic rocks – tuffs, ashes, pumice, ash pumices. They find their use as filler and active mineral additives in the manufacture of binders, mortars and concretes [4, 5]. However, the scope of volcanic rocks application in construction is insufficient. The use of local raw materials for the manufacture of new efficient building materials and products can significantly reduce the cost of construction.

Research was focused on the development of flame retardant composites with the use of ash and pumice.

In experiments there were used: ash fraction 0–0.16 mm; volcanic pumice of Psykhureysk deposits with a bulk density of 700 kg/m^3; expanded vermiculite fraction of 0.16–5 mm; Belgorod Portland cement PTS500-DO; lime; gypsum brand G–4–II–A; air-entraining additive resin wood saponified (RWS), basalt fiber by JSC “Ivotsteklo” brand of RNB-9-1200-4s.

Granulometric compositions of expanded vermiculite and volcanic pumice are given in Table 1.

Table 1. Granulometric composition of aggregates

Name of the material	**Private residues on the sieves, %**					**Passed through a sieve 0.16**
	2.5	1.25	0.63	0.315	0.16	
Vermiculite	26.7	21.9	31.4	14.7	5.3	–
Volcanic pumice	–	1	11	43.5	35	9.5

Preparation of a mixture was produced in the enforcement action mixer, which in water with RWS dry mixture of Portland cement, gypsum, lime, basalt fibers, volcanic ash (pumice) were consistently loaded, then expanded vermiculite, or a pre-mixed dry mixture of Portland cement, gypsum, lime, basalt fibers, volcanic ash (pumice) and expanded vermiculite. Mixing of all components is continued until a homogeneous fire-resistant fibre vermiculite concrete raw mixture. The duration of mixture stirring was 1.5–2 min.

Samples with sizes 4 x 4 x 16 cm from vermiculite concrete composite was compacted on a standard shaking platform. The mobility of the mixture was 3.5 cm of immersion of the cone StroyTSNIL. Samples were stored in air-dry conditions. Before testing, the beams were dried at t = 105 °C to constant weight in a drying cabinet.

3. Results and Discussion

As a result of experiments vermiculite concrete composites with application of volcanic ash were designed (Table 2).

Table 2. The ratio of components in the mixture and physico-mechanical properties of vermiculite concrete composites

No.No. compositions	The ratio of components in the mixture, wt. %					The number of RWS in % by weight of the binder	Average density ρ, kg/m3	The limit of strength, MPa	
	Cement	Vermiculite	Ash	Lime	Gepsum			On compression	On bending
1	2	3	4	5	6	7	8	9	10
1	71.9	29.1	–	–	–	–	750	6.2	2.7
2	50.3	29.1	21.4	–	–	–	762	5.9	2.5
3	22.5	28.3	25.8	22.5	0.9	–	750	6.0	2.4
4	22.5	28.3	25.8	22.5	0.9	0.1	720	6.2	2.6
5	22.5	28.3	25.8	22.5	0.9	0.2	710	6.15	2.5
6	22.5	28.3	25.8	22.5	0.9	0.3	710	6.0	2.4
7	62.1	37.9	–	–	–	–	595	2.9	1.6
8	43.5	37.9	18.4	–	–	–	600	2.7	1.5
9	19.6	38.1	21.9	19.6	0.8	–	590	2.8	1.4
10	19.6	38.1	21.9	19.6	0.8	0.1	570	2.9	1.35
11	19.6	38.1	21.9	19.6	0.8	0.2	560	2.8	1.3
12	19.6	38.1	21.9	19.6	0.8	0.3	540	2.7	1.2
13	56.2	43.8	–	–	–	–	500	1.8	0.65
14	39.3	43.8	16.7	–	–	–	510	1.7	0.6
15	17.9	44.3	19.2	17.9	0.7	–	500	1.7	0.65
16	17.9	44.3	19.2	17.9	0.7	0.1	480	1.8	0.7
17	17.9	44.3	19.2	17.9	0.7	0.2	470	1.7	0.6
18	17.9	44.3	19.2	17.9	0.7	0.3	460	1.6	0.5

The results show that the developed formulations have the same compressive strength and flexural strength compared with the control compositions while reducing the consumption of cement and the density that is provided by the pozzolanic properties of the fly ash and the use of RWS. The use of construction gypsum and lime as the cause of the latent hydraulic activity of volcanic ash significantly reduces the consumption of cement without reducing the strength of fire resistant composite. With the introduction of resin wood saponification of 0.1–0.3 % by weight of the cement the water consumption for mixture is reduced, density of vermiculite concrete composite is decreased by 40–50 kg/m^3.

Developed vermiculite concrete composites have such disadvantages as brittleness, relatively low strength in bending and compression. For obtaining the composites with improved strength and fire resistant characteristics the influence of parameters of the fiber reinforcement by basalt fiber on their properties with the use of rotatable plan of the second order type of a regular hexagon was investigated.

The composition of the original vermiculite concrete matrix and its physico-mechanical properties for reinforcement by the basalt fibers are shown in Table 3.

Table 3. The ratio of components in the mixture and physico-mechanical properties of the vermiculite concrete composite

The ratio of components in the mixture, wt. %					The number of RWS in % by weight of the binder	Average density, ρ, kg/m^3	The limit of strength, MPa	
Cement	Vermic ulite	Ash	Lime	Gypsum			On compression	On bending
1	2	3	4	5	6	7	8	9
19.6	38.1	21.9	19.6	0.8	0.1	570	2.8	1.4

As the investigated factors the main parameters of dispersed reinforcement were adopted: X_1 – the reinforcement ratio by volume μ_v, %; X_2 – the ratio of the length of the fibers to their diameter l/d. As the optimization parameters there were considered: Y_1 – the limit of strength in compression R_b, MPa; Y_2 – tensile strength at bending R_f, MPa.

The matrix of the experiment is as follows (Table 4).

Table 4. The matrix of the experiment

Ordering No.	Natural variables		The matrix of the experiment				
	x_1	x_2	X_1	X_2	X_1^2	X_2^2	X_1X_2
1	0.30	1444	-1	0	+1	0	0
2	0.9	1444	+1	0	-1	0	0
3	0.75	2221	+0.5	+0.87	+0.25	+0.75	+0.43
4	0.75	667	+0.5	-0.87	+0.25	+0.75	-0.43
5	0.45	2221	-0.5	+0.87	+0.25	+0.75	-0.43
6	0.45	667	-0.5	-0.87	+0.25	+0.75	+0.43
7	0.6	1444	0	0	0	0	0

After processing the experimental data the following regression equations in coded form were obtained:

$$Y_1 = 3.6 - 0.2X_1 - 0.3X_1^2 - 0.9X_2^2 + 0.12X_1X_2\ ;$$

$$Y_2 = 2.6 + 0.2X_1 - 0.65X_1^2 - 0.65X_2^2.$$

The regression equations are made on response surface (Fig. 1).

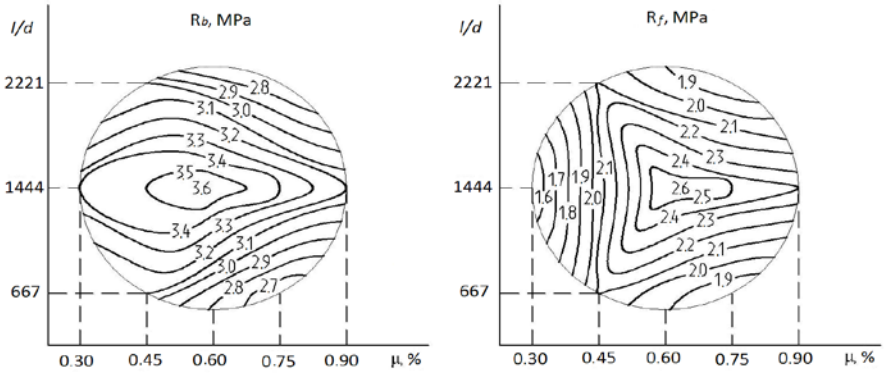


Figure 1. Response surfaces:
R_b – the limit of compressive strength, MPa; R_f – the limit of strength in bending, MPa;
l/d – the ratio of the length of the fibers to their diameter;
μ_v – the percentage of reinforcement by volume

Analysis of the obtained equations and response surfaces showed that the highest values of compressive strength are observed in the plan area with $\mu_v \approx 0.35 - 0.65\%$ and $l/d = 1444$, but flexural strength – $\mu_v \approx 0.6 - 0.85\%$ and $l/d = 1444$. Further increase in reinforcement ratio leads to a decrease in strength, due to violation of the structure of fibre vermiculite concrete composite.

To study the flame retardant properties of the proposed compositions ferro cement slabs with fire-resistant layer with a thickness of 25 mm were made. Studies on the fire resistance were conducted by testing samples with dimensions of 190 × 190 mm in an electric furnace in a horizontal position at temperature mode "standard" fire, regulated by Russian State Standard GOST 30247.1–94. The fire resistance rating for load-bearing capacity (R) of ferro cement slabs was evaluated by heating the woven mesh in the structural layers (on the boundary of layers) to 300 ° C. Humidity of fine-grained concrete ferro cement layer and a flame retardant to the time of testing were respectively 3–4% and 8–10 %. During the fire tests of two-layer elements of violations of their integrity is not detected.

The results of fire tests of ferro cement slabs 20 mm thick with fire resistant layer with a thickness of 25 mm is shown in Figures 2 and 3.

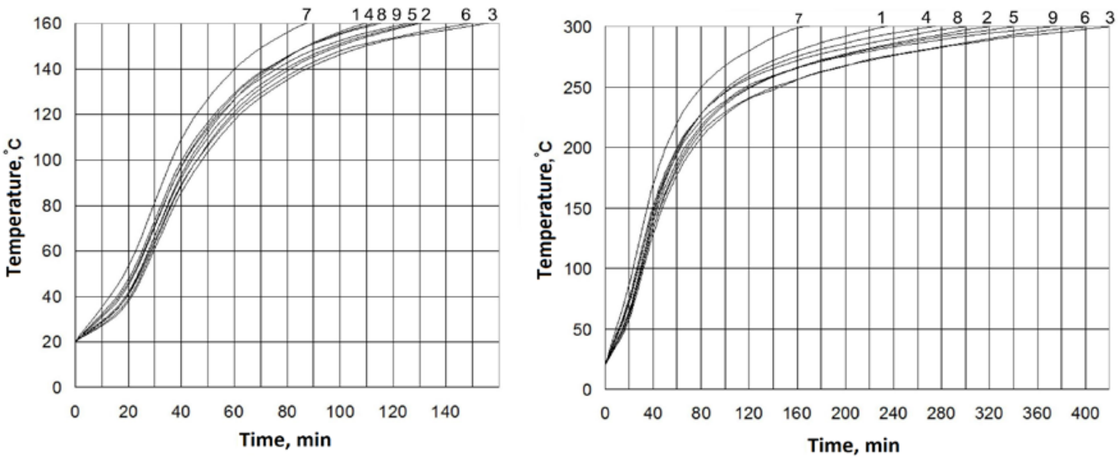
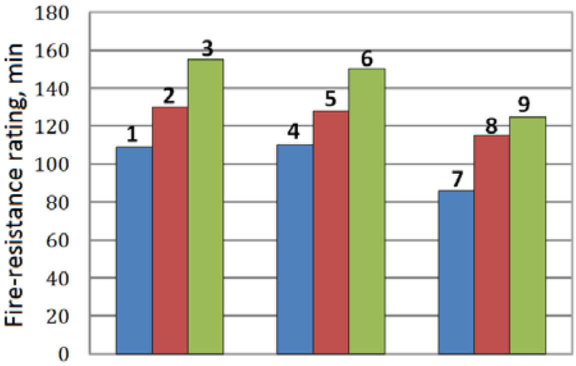
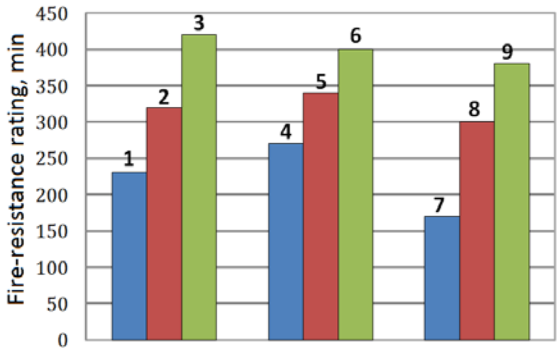


Figure 2. Experimental curves of temperature change on the unheated surface (a) and at the level of the woven mesh (b) double-layer ferro cement samples:
1, 4, 7 – cement vermiculite concrete with average density 500 kg/m^3, 595 kg/m^3 and 740 kg/m^3 respectively;
2, 5, 8 – vermiculite concrete composite with an average density of 480 kg/m^3, 570 kg/m^3 and 730 kg/m^3 respectively;
3, 6, 9 – fibre vermiculite concrete composite with an average density of 470 kg/m^{3,} 560 kg/m^3 and 720 kg/m^3 respectively



a)



b)

Figures 3. The limit of fire resistance of double-layered ferro cement elements in heat-insulating ability (a) and bearing capacity (b)
Symbols 1-9 look at Figure 2

From Figures 2 and 3 it is followed that the developed fibre vermiculite concrete composites provide higher fire resistance of ferro cement plates in comparison with cement vermiculite concrete. This is due to the better preservation of the flame retardant layer under the influence of high temperatures as a result of dispersal reinforcement with basalt fibers. Furthermore, the addition of RWS additionally forms pores on fibre vermiculite concrete composite, that improving flame retardant properties. The compositions with an average density of 480 kg/m^3 have the highest fire resistant properties.

The study of fire resistance of building constructions with tests for the "standard" temperature is a time-consuming task, which requires expensive equipment. In this regard, the calculation methods determining fire resistance of constructions are of great importance.

For the calculation of fire resistance of building constructions in our country numerical and analytical methods are developed. The greatest preference is for numerical methods because of their simple implementation using modern computer technology.

We developed an algorithm of thermal and technical calculation of the fire resistance of multi-layered building constructions, providing acceptable coincidence of calculated values with experimental data. The algorithm for calculating the fire resistance of building constructions with fire resistant layer is reduced to the solution of the thermal and physical problem. The temperature distribution $t(x, \tau)$ on the thickness of the multilayer structure is described by the Fourier equation

$$\rho(x)\,c(t,x)\frac{\partial t}{\partial \tau} = \frac{\partial}{\partial x}\left(\lambda(t,x)\frac{\partial t}{\partial x}\right)$$
$$(x,\tau)\in Q \equiv \{(x,\tau): x\in(0,l), \tau\in(0,T)\}, \qquad (1)$$

where x, τ – coordinates in space and time; $c(t, x)$, $\lambda(t, x)$, $\rho(x)$ – specific heat, thermal conductivity and material density; l – the thickness of the construction; T – some finite value of time. Not odnoclasnichi design causes a dependence of c and λ on the spatial coordinates x, in addition, they are also functions of time indirectly via t(x, τ). Vermiculations density of the composite is adopted unchanged, as during a fire will not change significantly. Because of the layered design, the density of the material depends on spatial coordinates.

Multi-layer construction determines the dependence of c and λ on the spatial coordinate x; in addition, they are also functions of time indirectly via $t(x, \tau)$. Density of the vermiculite concrete composite is adopted unchanged, as during a fire it will not change significantly. Because of the layered construction, the density of the material depends on spatial coordinates.

To solve the above problem in the work numerical methods were used, found application in various fields of science and technology.

To solve the thermal and physical problem of fire resistance of double-layer building construction from fire resistant and ferro cement layers to the equation (1) the initial and boundary conditions are joined. The initial conditions are set by formula

$$t(x,0) = \varphi(x), \quad x\in[0,l], \qquad (2)$$

where $\varphi(x)$ – a function of the temperature distribution along the thickness of the construction. Through the outer surface of the construction there is a heat exchange with the surrounding media, the temperature of which: $T_f(\tau)$ – the temperature of the fire, $T_c(\tau)$ – the outside air temperature, are known. Then the boundary conditions take the form of:

$$\lambda_{в}(t)\frac{\partial t(0,\tau)}{\partial x}=\alpha_{в}(t)[t(0,\tau)-T_n(\tau)],\quad \tau>0, \tag{3}$$

$$-\lambda_a(t)\frac{\partial t(l,\tau)}{\partial x}=\alpha_a(t)\,[t(l,\tau)-T_c(\tau)],\quad \tau>0. \tag{4}$$

Here $\lambda_{в}(t)$ = (t, 0), $\lambda_{a}(t) = \lambda(t, l)$ – the conductivity coefficients of vermiculite concrete composite and ferrocement, respectively; $\alpha_{в}$ – the heat transfer coefficient from the heated medium (the firing chamber) to construction surface (vermiculite concrete layer); α_a – the coefficient of heat transfer from the unheated surface (ferro cement layer) to the environment. In this model $T_c(\tau)$ and $\varphi(x)$, as a rule, in practical calculations are constants.

Equation (1), initial and boundary conditions (2) – (4) constitute the problem of the temperature distribution through the thickness of the construction. Coefficients included in the equation and the additional conditions are determined from the known formulas for two-layer construction:

$$\lambda_{в}(t)=\lambda_1+k_1t,\quad c_{в}(t)=c_1+k_2t,\quad \lambda_a(t)=\lambda_2+k_3t,\quad c_a(t)=c_2+k_4t,$$

$$\alpha_{в}(t)=29+\frac{5{,}77\varepsilon_{в}}{t(0,\tau)-T_n}\left[\left(\frac{T_n+273}{100}\right)^4-\left(\frac{t(0,\tau)+273}{100}\right)^4\right],$$

$$\alpha_a=1{,}5\sqrt{t(l,\tau)-T_c}+\frac{5{,}77\varepsilon_{в}}{t(l,\tau)-T_c}\left[\left(\frac{t(l,\tau)+273}{100}\right)^4-\left(\frac{T_c+273}{100}\right)^4\right], \tag{5}$$

where λ_1, λ_2, c_1, c_2 – the initial characteristics of the coefficients of thermal conductivity and heat capacity, respectively vermiculite concrete composite and ferrocement; k_1, k_2, k_3, k_4 – coefficients, the numerical values which are determined from the criterion of the satisfactory coincidence of experimental and calculated curves of heating plates; $\varepsilon_{в}$, ε_a – degree of black vermiculite concrete composite and ferrocement respectively.

Due to the dependence of the specific heat capacities and thermal conductivity coefficients from temperature the equation (1) and boundary conditions (3) – (4) are nonlinear. Therefore, to solve problem (1) – (4) numerical methods are used. In the work [17] the course differential implicit two-layer scheme of calculations combined with the Thomas method and iteration are used. While derivatives included in the heat equation and the boundary conditions are replaced by the known differential relationships.

Then the system of algebraic equations with a tridiagonal coefficient matrix on each upper layer in time is solved. The nonlinearity of the algebraic equations is overcome by using the method of iteration and sweep.

We developed software for thermal and technical calculation of the fire resistance of ferroconcrete construction with fire-resistant layer from vermiculite concrete. With the use of PC calculations with a precision equal to 0.001 were conducted and the coefficients k_1, k_2, k_3, k_4 of formula (5) providing a reasonable correlation between theoretical and experimental curves, in which expressions for the coefficients of thermal conductivity and heat capacity were determined:

ferrocement – $\lambda_a(t)=0.83-0.0004t,\quad c_a(t)=770+0.8t$;

cement vermiculite concrete with density 500 kg/m^3 – $\lambda_o(t)=0.09+0.000093t,\quad c_o(t)=920+0.51t$;

cement vermiculite concrete composite with density of 480 kg/m^3 –

$\lambda_o(t)=0.087+0.00008t,\quad c_o(t)=920+0.51t$;

cement fibre vermiculite concrete composites with density 470 kg/m^3 –

$\lambda_o(t)=0.086+0.00007t,\quad c_o(t)=920+0.51t$;

cement vermiculite concrete with density of 595 kg/m^3 – $\lambda_o(t) = 0.11 + 0.000057t, \quad c_o(t) = 920 + 0.51t$;

cement vermiculite concrete composite with density of 570 kg/m^3 –

$\lambda_o(t) = 0.1 + 0.00006t, \quad c_o(t) = 920 + 0.51t$;

cement fibre vermiculite concrete composite with density of 560 kg/m^3 –

$\lambda_o(t) = 0.099 + 0.00005t, \quad c_o(t) = 920 + 0.51t$;

cement vermiculite concrete with density 740 kg/m^3 – $\lambda_o(t) = 0.14 + 0.00004t, \quad c_o(t) = 920 + 0.61t$;

cement vermiculite tuff concrete with density of 730 kg/m^3 –

$\lambda_o(t) = 0.125 + 0.00003t, \quad c_o(t) = 920 + 0.61t$;

cement fibre vermiculite concret composite with density of 720 kg/m^3

$\lambda_o(t) = 0.120 + 0.00003t, \quad c_o(t) = 920 + 0.61t$;

The dependence of the fire resistance of ferroconcrete constructions on the thickness and composition of the composite obtained by the calculation method is shown in Figure 4.

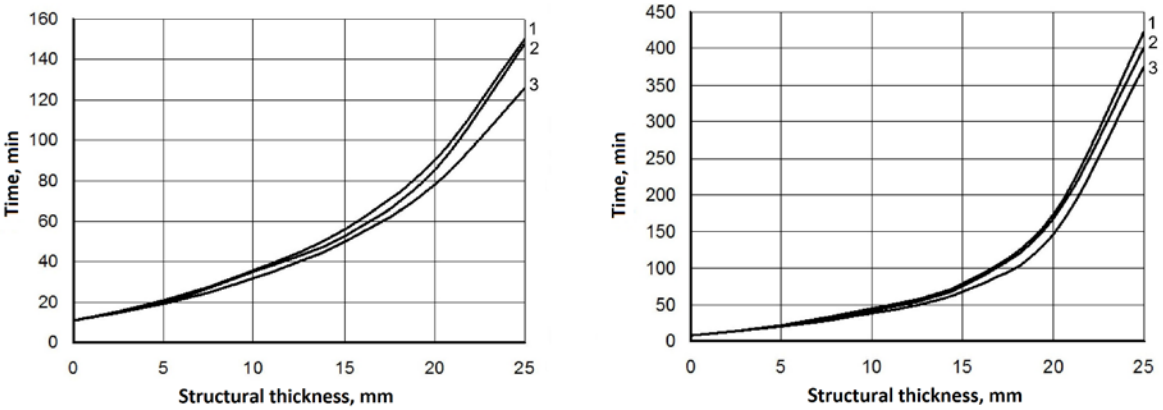


Figure 4. The dependence of the limit of fire resistance of double-layered ferro cement elements on the basis of the loss of insulating ability (a) and the loss of bearing capacity (b) on the thickness and composition of the fire resistant layer:
1, 2, 3 – fibre vermiculite concrete composite with an average density of 470 kg/m^3, 560 kg/m^3 and 720 kg/m^3 respectively

Figure 5 shows the results of calculation of the limit of fire resistance of fibre vermiculite concrete plates on the grounds of loss of insulating ability.

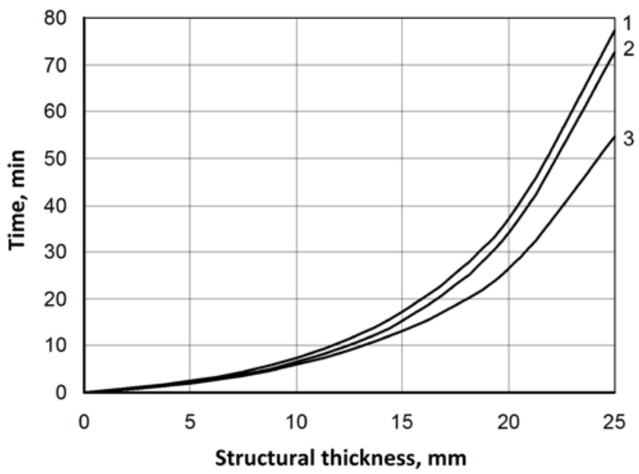


Figure 5. The dependence of the fire resistance of fibre vermiculite concrete plates on the grounds of loss of insulating ability on the thickness and composition of layer:
1, 2, 3 – fibre vermiculite concrete composite with an average density of 470 kg/m^3, 560 kg/m^3 and 720 kg/m^3 respectively

In further experiments to produce flame retardant composites volcanic pumice of Psykhureysk field was used.

The results of studies of the properties of the composites on Portland cement PTS500-DO without additives and with additives of volcanic pumice are given in Table 5.

Table 5. The properties of cement stone and concrete on cement with pumice

The addition of pumice in % by mass of cement	The properties of cement stone (concrete)								
	the average density (kg/m^3), age, days			the limit of flexural strength (MPa) age, days			the limit of compressive strength (MPa) age, days		
	28			28			28		
	heating temperature, ^{o}C			heating temperature, ^{o}C			heating temperature, ^{o}C		
	105	600	800	105	600	800	105	600	800
PTS500-DO, without additives									
0	1788	1769	1760	5.8	5.3	4.4	46.0	26.7	23.2
PTS500-DO, the addition of pumice with a grain size of 0<d<0.16 mm									
30	1609	1538	1528	6.4	6.3	6.3	39.5	25.4	24.2
PTS500-DO, the addition of pumice with a grain size of 0<d<0.31 mm									
20	1764	1746	1717	7.6	7.4	6.2	32.2	31.4	27.6
40	1787	1753	1733	5.4	5.0	3.6	28.5	24.0	23.3
60	1725	1700	1680	4.9	4.6	3.5	16.2	15.5	14.7
PTS500-DO, the addition of pumice with a grain size of 0<d<0.63 mm									
20	1750	1692	1682	7.4	7.0	6.1	35.5	32.8	32.4
40	1656	1623	1606	6.8	6.3	6.2	25.1	23.1	21.7
60	1511	1490	1469	4.6	4.2	3.7	13.7	12.8	12.5
PTS500-DO, the addition of pumice with a grain size of 0<d<1.25 mm									
20	1711	1684	1673	7.1	6.5	5.3	30.7	27.6	22.4
40	1630	1607	1534	7.4	6.6	6.1	20.8	18.9	15.6
60	1423	1392	1385	3.9	3.7	3.3	10.8	8.2	8.0

From Table 5 it follows that the additive of volcanic pumice fraction d < 0.16 mm up to 30 % by weight of cement significantly improves heat-resisting properties of cement stone with a simultaneous increase in flexural strength and no significant loss of compressive strength that is associated with the hydraulic activity of the fraction of pulverized volcanic pumice. The use of pumice with large grain size largely reduces the compressive strength of the composite, but significantly increases heat resistant properties and average density of the composite decreases slightly.

Expanded vermiculite is an expensive material, therefore the possibility of replacing parts of vermiculite fraction of 0.16–5 mm with volcanic pumice was considered.

Further studies were conducted on the development of flame retardant vermiculite concrete with the use of volcanic pumice; the results of the experiments are given in Table 6.

Studies showed that the insertion of up to 30 % pumice fraction 0-0.16 mm by mass of cement strength characteristics of vermiculite concrete decrease slightly, but their heat-resistant properties increase. Replacement of volcanic pumice parts with expanded vermiculite reduces the average density of the vermiculite concrete composite and enhances their heat-resistant properties.

Further research focuses on the study of flame retardant properties of the developed composites with the use of volcanic pumice.

Table 6. Physico-mechanical properties of vermiculite concrete with the use of volcanic pumice

№№ compositions	Features of vermiculite concrete composite								
	average density, kg/m^3			the limit of flexural strength (MPa) at the age of 28 days			the limit of compressive strength (MPa) at the age of 28 days		
	heating temperature, °C			heating temperature, °C			heating temperature, °C		
	105	600	800	105	600	800	105	600	800
1	2	3	4	5	6	7	8	9	10
Cement: vermiculite by volume – 1:3									
1	720	715	710	1.6	1.3	1.0	2.9	2.2	2.1
Cement: vermiculite by volume – 1:3 with the addition of pumice fractions 0-0.16 mm by weight from cement									
2	723	712	707	1.4	1.26	0.9	2.4	1.8	1.7
Cement: pumice (fractions 0-1.25 mm) by volume – 1:3									
3	1461	1436	1426	3.2	2.2	1.9	11.9	7.4	6.7
Cement: pumice (fraction 0.16–0.315 mm)+vermiculite fraction 0.315–5 mm instead of pumice fraction 0.315–1.25 by volume – 1:3									
4	1676	1657	1650	3.6	2.9	1.9	14.0	10.7	8.5
Cement: pumice (fraction 0.16–0.63 mm)+vermiculite fraction of 0.63–5 mm instead of pumice fraction 0.63–1.25 by volume – 1:3									
5	1303	1288	1280	2.1	1.9	1.9	8.8	6.5	6.4

Table 7 presents the results of studies on the fire resistance of ferro cement elements with a thickness of 20 mm, with fire resistant layer with a thickness of 20 mm based on control and proposed compositions of vermiculite concrete composites with volcanic pumice application.

Table 7. The results of studies on the fire resistance of double-layered ferro cement elements

№№ compositions	The composition of the fire resistant layer				Average density, kg/m^3	The limit of fire resistance of slabs, min.	
	Cement: vermiculite by volume	Replacement of vermiculite part with pumice by volume	RWS in % by weight of cement	The reinforcing percentage of fibers by volume		on bearing capacity (*R*)	on the heat-insulating capacity (*E*)
1	2	3	4	5	6	7	8
1	1:2	–	–	–	750	82	57
2	1:3	pumice fraction 0.16–0.315 mm	–	–	847	68	44
3	1:3	pumice fraction 0.16–0.315 mm	0.3	0.6	805	73	48
4	1:4	pumice fraction 0.16–0.63 mm	–	–	855	66	43
5	1:4	pumice fraction 0.16–0.63 mm	0.3	0.6	812	65	46

Developed vermiculite concrete composites using volcanic pumice, air-entraining additives RWS and basalt fibers with higher density in comparison with the reference vermiculite concrete have higher flame retardant properties due to the better preservation of the flame retardant layer as a result of dispersal reinforcement with basalt fiber and additional pore of RWS.

With the use of PC calculations with a precision equal to 0.001 were conducted and the coefficients k_1, k_2, k_3, k_4 of formula (5) providing a reasonable correlation between theoretical and experimental curves, in which expressions for the coefficients of thermal conductivity and heat capacity of developed fibre vermiculite pumice concrete composite with density of 810 kg/m^3 (tab. 7, the composition No. 5) were determined:

$$\lambda_o(t) = 0.180 + 0.00003t, \quad c_o(t) = 920 + 0.63t\,;$$

Figure 6 shows the results of calculating the fire resistance of ferro cement elements, depending on the thickness and composition of fibre vermiculite pumice concrete composite.

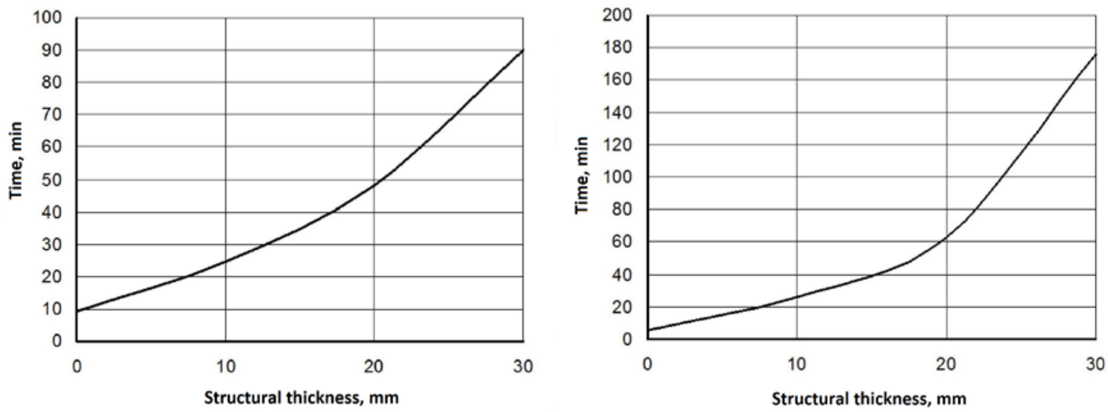


Figure 6. The dependence of the limit of fire resistance of double-layered ferro cement elements on the basis of the loss of insulating ability (a) and the loss of bearing capacity (b) on the thickness of the fibre vermiculite pumice concrete layer

Figure 7 shows the results of calculation of fire resistance of fibre vermiculite pumice concrete plates on the grounds of loss of insulating ability.

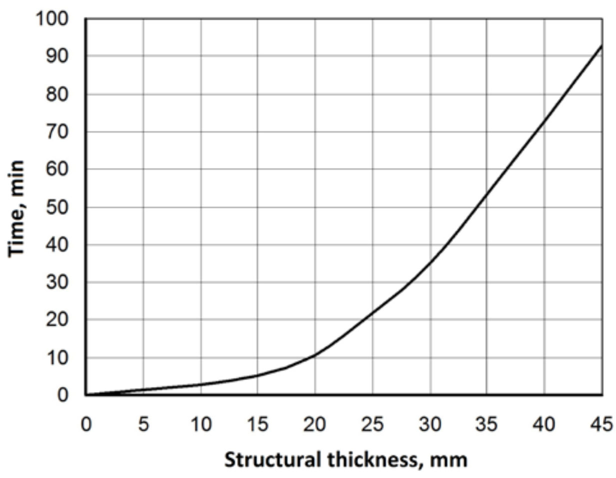


Figure 7. The dependence of the fire resistance of fibre vermiculite pumice concrete plates on the grounds of loss of insulating ability on the layer thickness

Thus, the developed fibre vermiculite concrete and fibre vermiculite pumice concrete composites have high fire retardant properties and improved strength characteristics with less consumption of Portland cement. Using the obtained expressions for the coefficients of thermal conductivity and thermal capacity of flame retardant composites, it is possible to calculate the fire resistance of two-layer structures by numerical methods with application of the developed software.

Thus, the developed fibre vermiculite concrete composites with application of volcanic ash have higher heat resistant properties, thus reducing the consumption of Portland cement without compromising strength characteristics. High flame retardant properties of fibre vermiculite concrete composites are ensured by using RWS, ash and basalt fiber. The use of consrtuction gypsum and lime as the cause of the latent hydraulic activity of volcanic ash reduces significantly the consumption of cement without reducing the strength of fire resistant composite.

Dispersed reinforcement with basalt fiber increases composite fire-resistant and strength characteristics of the original matrix. With the use of rotatable plan of the second order type of a regular hexagon it is found that the highest values of compressive strength are observed in the area plan with $\mu_v \approx 0.35 - 0.65\%$, and flexural strength – $\mu_v \approx 0.6 - 0.85\%$ and $l/d = 1444$.

Experimental studies of fire resistance of double-layer ferroconcrete structures showed high fire resistant properties of the developed cement fibre vermiculite concrete fire resistant composites.

The course differencing implicit scheme of solving the problem of thermal conductivity and sweep method in conjunction with the iteration method gives a universal algorithm for determining the temperature across the thickness of the construction, not associated with restrictions on the number of layers on the smallness of the grid and does not require linearization of the basic differential equations of heat conduction and boundary conditions. The proposed algorithm allows selecting and specifying the coefficients and the functional dependencies included in the mathematical model and known a priori only approximately.

Fibre vermiculite concrete composites using volcanic pumice, air-entraining additives RWS and basalt fibres with a higher fire resistant properties in comparison with the reference vermiculite concrete that reduce the consumption of expensive expanded vermiculite were developed.

The expressions of the coefficients of thermal conductivity and heat capacity of fibre vermiculite concrete composites with the use of volcanic pumice and ash for thermal and technical calculation of fire resistance of building constructions by numerical methods were obtained.

The received results are coordinated with the theoretical and pilot studies conducted in the works [6, 10–12].

4. Conclusions

1. Thus, the article considers a number of fundamental issues related to obtaining effective cement fibre vermiculite concrete composites with application of volcanic rocks. It is revealed that the use of volcanic rocks reduces the consumption of Portland cement and improves flame retardant properties of vermiculite concrete composites.

2. Dispersed reinforcement with basalt fiber of source matrix allows improving significantly strength properties while improving the fire retardant properties due to the perception of the tensile forces impacted by fire.

3. The proposed algorithm with the use of finite-difference implicit scheme for solving the heat conduction problem and the sweep method allows selecting and specifying the coefficients and the functional dependencies included in the mathematical model and known a priori only approximately.

4. Using the proposed algorithm the expression for the coefficients of thermal conductivity and heat capacity of fibre vermiculite concrete composites with the use of volcanic pumice and ash for thermal and technical calculation of fire resistance limit of building constructions by numerical methods was obtained. The proposed calculated method of determination of fire resistance limits of constructions provides an acceptable coincidence with the experimental data.

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