

SPECIFIC DESIGN FEATURES OF PREFABRICATED FIRE-RESISTANT FLOOR SLABS MADE FROM LIGHTWEIGHT CONCRETE

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Abstract

Reinforced concrete roof and floor structures have the highest heating temperatures and are exposed to the most difficult conditions during fires that occur in buildings and structures. The standardized fire resistance of hollow-core slabs made of heavy concrete from Portland cement is regulated as REI 45 or REI 60. The aim of the work is to develop a composition of lightweight fire-resistant concrete and architectural engineering for floor slab devices. The composition of lightweight fire-resistant concrete made from expanded clay aggregates and alumina cement was developed as a result of the work. The degree of fire resistance of the lightweight concrete composition with a bulk density of 1475 kg/m³ has been practically determined; i.e., REI 90. The structural solution of the floor slab has been improved; at the same time, we propose to develop a slab with a flat section made of lightweight fire-resistant concrete. Such floor slabs, along with an increase in the fire resistance limit, improve the heat-insulating ability of a floor due to a significant reduction in the coefficient of the thermal conductivity of lightweight concrete.

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Key words

- Fire,
- Fire-resistant concrete,
- Floor slabs,
- Fire resistance limits.

1 INTRODUCTION

Significant damage to buildings and structures is caused by fires that periodically occur in buildings and structures. It is necessary to pay special attention to the correct determination of the actual fire resistance limit of the reinforced concrete structures used and to establish the possibility of the further operation of the structures after a fire, due to the constantly increasing number of fires.

Reinforced concrete roof and floor structures have the highest heating temperatures and are exposed to the most difficult conditions among all load-bearing structures. According to (DBN V.1.1-7-2002, 2002), for hollow-core slabs of buildings and structures of I-II degrees of fire resistance, the fire resistance limit is regulated as REI 45 or REI 60, which is significantly less than the limits for columns and walls in which the fire resistance limit is regulated as REI 120 – 150.

The value of the heating temperature of the concrete surface in the structure primarily depends on the temperature of the fire

and on the location of the combustion site. When establishing the actual limit of fire resistance of reinforced concrete structures, it is necessary to know the intensity of the fire, since the normalized fire resistance of the structure will depend on the temperatures at which the combustion occurs and the duration of the fire.

2 SURVEY OF THE LITERATURE

According to (Milovanov, A. F., 1986), in the case of fires in residential and office buildings, the temperature on the premises rises to 1000-1100 °C with a fire duration of 1-2 hours. In industrial buildings, shops, and theater buildings, fires lasting 2-3 hours increase the temperature in the building to 1100-1200 °C.

According to (Yakovlev, A. I., 1985), the maximum temperatures that are reached during a fire are established according to a real regime of a “standard fire”. This temperature regime of a “standard fire” can be presented in the form of Tab. 1,

which determines the air temperature in °C for a certain duration of the fire.

Tab. 1 Temperature values

Time τ , min	Temperature t_{θ} , °C
0	20
5	576
10	678
15	739
30	842
45	902
60	945
90	1006

In addition, the values of the maximum heating temperatures can be determined by the color of the concrete and some physical and mechanical effects of the material of structures (NIIŽB, 1987).

For the fire resistance limit of building structures, the duration in hours and minutes from the beginning of a standard fire test to the occurrence of one of the fire resistance limit states is considered the fire resistance limit of building structures. According to (DBN V.1.1-7-2002, 2002), building structures are classified according to their fire resistance and ability to spread fire.

The indicator of fire resistance is the fire resistance limit of a structure, which is determined by the duration (in minutes) from the start of the fire test according to the standard temperature regime to the onset of one of the limiting states of the structure:

- loss of bearing capacity (R);
- loss of integrity (E);
- loss of heat-insulating ability (I).

According to (Milovanov, A. F., 1986), integrity signs (E), which indicate the loss of a structure's ability to block the path of a fire, and the heat insulating ability (I), which indicates the loss of the ability to block the ignition of materials located on an unheated surface, do not require special consideration.

The characteristic of the bearing capacity (R), which indicates the degree of decrease in the strength characteristics of the structure, must be calculated according to (DSTU-N B EN 1992-1-2:2012, 2012) by zonal and tabular methods.

In addition to calculation methods for determining fire resistance, it is also necessary to consider the structural and technological requirements in relation to various reinforced concrete structures. When designing floor slabs according to (Phan, L. T. et al., (2010), it is necessary to consider the possible layer-by-layer explosive destruction of concrete, which can occur on a concrete surface from the flame side due to tensile stresses arising from the pressure of water in the pores, as well as from a decrease in the strength of the concrete after the loss of bound water.

An analysis of the literature on the effect of various factors on the fire resistance of structures leads us to believe that, along with the effect of high temperatures and the structural features of reinforced concrete elements, one of the factors that significantly affects the fire resistance of structures is the use of concrete component materials that have a high fire resistance.

3 MATERIALS AND METHODS

3.1 Consequences of a fire

Figs. 1-4 show the consequences of the damage to and destruction of hollow-core floor slabs in a room of a residential building during a fire that lasted for 35-40 minutes at a maximum temperature of 850 °C at the epicenter of the fire. The hollow-core floor slabs received significant damage, and their condition was assessed as unsuitable for normal use, although the maximum fire temperatures were not reached.



Fig. 1 Two sections showing the complete destruction of the protective layer of concrete with a length of $l = 2400 \times 1360$ mm and a width of $a = 77 \times 72$ mm, respectively



Fig. 2 Explosive layer-by-layer destruction of the protective layer of concrete on the side of the flames. The through cracks in the concrete bridges between the voids have opening widths of $a = 11.5$ and 21.5 mm, respectively



Fig. 3 An area showing the falling off of the surface layer of the concrete (part of the concrete layer is hanging down), $S_{\text{area}} = 0.32$ m² (pink color of concrete). The crack in the protective layer of the concrete has a length of $l = 1440$ mm and a width of $a = 2.6$ mm



Fig. 4 Areas showing the destruction of the protective layer of the concrete, $S_{area} = 0.04, 0.07$ and 0.065 m^2 , respectively, and the exposure of the working reinforcement (in the middle section, there are traces of soot on the reinforcement)

As can be seen in Figs. 1-4, the floor slab underwent significant damage and destruction in the epicenter of the fire, where temperatures up to 850°C occurred. As a result of the action of the flames and high temperatures, two sections of the slab were completely destroyed, i.e., the concrete collapsed, and through cracks appeared in the concrete lintels between the voids. At a distance from the epicenter of the fire, there are areas showing the falling off of the surface layer of the concrete with pink colored concrete and areas that expose the working reinforcement.

Such floor slabs need to be reinforced or replaced after exposure to a fire.

Our analysis of the consequences of the fire and destruction of the floor slabs allowed us to identify our main tasks, the implementation of which could lead to an increase in the normalized fire resistance of floor slabs. These tasks are:

- 1) The application of fire-resistant materials with a high degree of refractoriness for the manufacture of reinforced concrete structures;
- 2) Lightening the weight of floors, which will lead to an increase in their heat-insulating and sound-insulating capacity;
- 3) Improving the design of floor slabs.

1.2 Characteristics of lightweight fire-resistant concrete compositions and their test procedure

In our opinion, in order to increase the fire resistance and heat-insulating ability of concrete slabs, they should be made of lightweight fire-resistant concrete, the components of which are expanded clay, alumina cement, and water.

The choice of such components of the mixture is dictated primarily by the high fire resistance indicators of expanded clay and 26 mm alumina cement, namely, the refractoriness of expanded clay is $1000-1100^\circ\text{C}$ and that of alumina cement is $1480-1500^\circ\text{C}$. In addition, alumina cement is able to harden when mixed with water without the presence of other active additives, due to the presence in its chemical composition of a significant amount of free oxide Al_2O_3 .

The composition of the mixture components and their fractional composition are shown in Tab. 2, and their chemical composition is shown in Tab. 3.

Since the technical solutions for the compositions of lightweight fire-resistant concretes are new, and the copyright and intellectual property rights for these compositions belong to the authors, Tab. 2 does not list the content of the components of the concrete mixture.

As can be seen in Tab. 2, expanded clay aggregate is classified as light, since it has a poured bulk weight of 550 kg/m^3 , and its fractional composition is 1.25-20 mm. Alumina cement refers to powder additives, since it contains 83 % of a fraction less than 0.14 mm.

Tab. 3 indicates that silicon and aluminum oxides are the main chemical components that make up expanded clay, and its phase composition is mainly represented by aluminosilicates. Alumina cement is represented by aluminum and calcium oxides, and its phase composition is represented by calcium aluminates.

All the compositions of the lightweight fire-resistant concrete were made in the following order: first, the free-flowing components are thoroughly mixed for 2 minutes; then the resulting mixture and water are mixed for 2-3 minutes until a homogeneous mass is obtained.

The samples of the fire-resistant concrete were made by a vibration-compaction technique of mixtures on a laboratory vibrating platform. The air temperature was $18-20^\circ\text{C}$, and the humidity reached 45-50 % during the manufacture and holding of the samples.

Tab. 2 The composition of the components of the concrete mixture and their characteristics

Component name	Poured Bulk Weight, kg/m^3	Total residue in % in a sieve with a mesh size in the clear, mm								
		20	10	5	2.5	1.25	0.63	0.315	0.14	less 0.14
Expanded clay	550	6.0	63.8	22.2	5.0	3.0	-	-	-	-
Alumina cement	1200	-	-	-	-	-	-	3.2	13.8	83.0
Water	-	-	-	-	-	-	-	-	-	-

Tab. 3 Chemical composition of lightweight fire-resistant concrete components

Component names	Chemical composition, %						
	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	$\text{Na}_2\text{O} + \text{K}_2\text{O}$	Δm_{upk}
Expanded clay	69.5	14.7	6.2	3.7	2.25	1.6	2.05
Alumina cement	3.5	45.0	13.4	36.8	0.3	0.5	0.5

The samples of the concrete mixes were kept for 24 hours before stripping. The concrete compositions on the alumina cement were kept for 4 days under normal conditions after stripping and then dried to a constant weight at a temperature of 105-110 °C.

The physical-mechanical and fire characteristics of the lightweight fire-resistant concrete were investigated. Its physical and mechanical characteristics included its volumetric weight, volumetric shrinkage, thermal conductivity coefficient, cubic and prismatic strength, and modulus of elasticity. These characteristics were determined after drying the samples to a constant weight. The fire characteristics included the strength of the samples and the integrity of the concrete after heating it at a temperature of 1000 °C for 90 min, as well as the thermal conductivity coefficient and bulk density after similar heating.

Concrete specimens with a size of 70 × 70 × 70 mm were produced to study their volumetric weight, shrinkage, and compressive strength. Prisms were produced with a cross-sectional size of 100 × 100 mm and a height of 400 mm to study the prismatic strength and elasticity modulus of the concrete. Samples with dimensions of 140 × 160 × 40 mm were produced to determine the thermal conductivity coefficient and assess the integrity of the concrete when exposed to high temperatures.

The compressive strength of the concrete MPa was determined according to the normative document (DSTU B V.2.7. - 214: 2009, 2009) on samples dried to a constant weight. The samples were brought to failure on a 10-ton UMM-20 press with a load lifting speed of 10 kgf per second. The compressive strength was determined by the ratio of the breaking load to the cross-sectional area of the sample.

The volumetric shrinkage in percentages was determined by fixing the change in the volume of the samples according to the formula:

$$\varepsilon_v = \frac{V_2 - V_1}{V_1} \times 100 \quad (1)$$

where V_1 was the initial volume of the sample after stripping;
 V_2 was the volume of the sample after storage for a specified number of days and drying.

The shrinkage of the concrete samples was determined after drying them after they were stripped.

The thermal conductivity of the concrete after drying and heating to a temperature of 1000 °C (and subsequent cooling) was determined by a surface transducer in accordance with the source (DSTU B.V.2.7 - 41-95, 1995). Samples with dimensions of 140 × 160 × 40 mm were produced; they had smooth flat surfaces for placing the primary transducer and ensuring thermal contact between them.

To determine the prismatic strength and modulus of elasticity of the concrete, the nature of the dependence of the stresses on the concrete deformations was investigated when the prisms were loaded with a stepwise load (DSTU B.V.2.7 - 41-95, 1995). Dial indicators were installed on the four opposing faces of the prisms, and the prism was loaded with a load of 6.25 kN in stages on a P-125 press. The values of the indicators were recorded, and the average deformations of the concrete were determined after each stage of the loading. The load was brought to a destructive level.

The average elastic moduli, which were used in the calculations at loads that were 30 % of the destructive ones, were determined.

The compressive strength of the concrete after heating was determined in accordance with the source (DSTU B.V.2.7 – 217:2009, 2009). The samples were heated in an electric heating furnace to a temperature of 1000 °C according to the temperature rise mode in accordance with the normative document (GOST 20910-90, 1990). After heating to temperatures of 1000 °C, the samples were kept for 90 min and then cooled, together with the furnace.

To assess the integrity of the concrete, the samples were placed in a heated furnace in such a way as to provide one-sided heating of one of the surfaces. The temperature from the side of the heated surface was raised to 1000 °C according to the temperature rise mode in accordance with the normative document (Standard GOST 20910-90, 1990), and then the sample was kept at the given temperature for 90 min. Fig. 5 shows a general view of the furnace and the sample after the one-sided heating in the inside of the furnace to a temperature of 1000 °C.



Fig. 5 General view of the furnace and the sample after one-sided heating in the inside of the furnace to a temperature of 1000 °C

The integrity of the samples was assessed by the presence of through cracks and the presence of flames on the unheated surface of the sample, which could arise from the penetration of fire through these cracks. In addition, 9 characteristic points were distinguished on the surface of the sample heated in accordance with the requirements of the normative document (DSTU B V.1.1-4-98, 1998), according to which the deformations after heating were measured. The general view of the sample after the integrity test is shown in Fig. 6.



Fig. 6 General view of the concrete specimen after the integrity test

3.3 Design features of the floor slab

Currently, most of the floors of residential and public buildings are made of precast hollow-core slabs. These slabs are manufactured in precast factories and delivered directly to construction sites. Hollow core slabs are manufactured up to 9.0 m long and could have widths of 1.0, 1.2, 1.5, and 1.8 m.

The use of such concrete floor slabs is technologically advanced, since it permits the exclusion of the assembly process, i.e., dismantling of the formwork and the process of monitoring the concrete with respect to gaining the necessary strength in a certain climatic period of the year.

Fig. 7 shows a cross-section of a 6.0 m long and 1.5 m wide hollow-core floor slab.

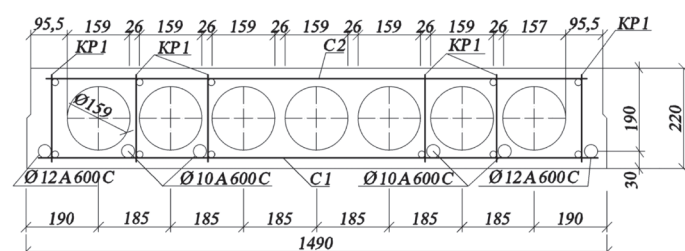


Fig. 7 Cross-section of a hollow-core floor slab with a width of 1.5 m

According to the calculations for the first and second groups of limit states, a floor slab for office buildings is reinforced with 6 rods (two rods with a diameter of 12 mm and four rods with a diameter of 10 mm) of prestressed class A600C reinforcement. In addition to the prestressed reinforcement, the slab is reinforced with C1 and C2 reinforcement meshes made of a Bp-I class reinforcement with a diameter of 3-4 mm, which are located in the lower and upper parts of the slab, as well as 6 Kr1 reinforcement cages made of a class A240C reinforcement with a diameter of 6-8 mm. The total mass of the slab is 2.56 tons; the volume of concrete is 1.125 m³; and the consumption of steel is 89.1 kg.

The standardized fire resistance of such a hollow-core slab, as determined by the source (DSTU-N B EN 1992-1-2:2012, 2012), is REI 60.

The weakest structural points of such plates are:

- relatively small sections of concrete from the lower and upper surfaces of the slab to the voids, which are 30.5 mm;
- the thickness of the wall between the voids, which is 26 mm;
- the composition of the concrete from a binder made of Portland cement in monolithic reinforced concrete structures is limited by the maximum temperature applied, which is 1100 °C (DSTU B V.1.1-6-2001, 2002).

The listed disadvantages of the hollow-core floor slabs are practically confirmed after examining the slabs exposed to the fire (Fig. 1-4).

Considering the above design disadvantages of hollow-core floor slabs when exposed to fire, we put forward the following assumptions:

- structurally, a slab can be made of a solid section without voids, which is much more technologically advanced in its manufacture;
- due to the use of lightweight concrete components with a high degree of refractoriness, the normalized fire resistance of slabs can be increased;
- due to the use of lightweight concrete, the heat-insulating and sound-insulating ability of slabs and floors as a whole can be improved.

4 RESULTS AND DISCUSSION

4.1 Study results of lightweight fire-resistant concrete characteristics

The study results of the physical and mechanical characteristics of the lightweight fire-resistant concrete are given in Tab. 4, and the fire characteristics are in Tab. 5.

Tab. 4 Basic physical and mechanical characteristics of lightweight fire-resistant concrete (DBN V.1.1-7-2002, 2002)

Product name	Name of indicators						
	Bulk weight kg/m ³	Volume shrinkage, %	Thermal conductivity coefficient, W/m·K	Cubic strength, MPa	Prismatic strength, MPa characteristic estimated	Elastic modulus, MPa	Concrete class, C(B)
Lightweight fire-resistant concrete	1475	0.58	0.68	18.36	$\frac{12.0}{9.25}$	14.2·10 ³	C16/20 (B15)

Tab. 5 Fire characteristics of lightweight concrete

Product name	Name of indicators							
	After heating to 1000 °C							
	Bulk weight kg/m ³	Volume shrinkage, %	Thermal conductivity coefficient, W/m · K	Cubic strength, MPa	Through cracks	Cracks and other defects	Deflections	Fire resistance limit
Lightweight fire-resistant concrete	1400	0.86	0.62	14.58	No	Mesh of cracks in depth to 2.5 mm and width a _{max} = 0.15-0.2 mm	0.1 – 0.2	REI 90

As can be seen in Tab. 4, the composition of the lightweight fire-resistant concrete developed has a volumetric weight of 1475 kg/m^3 , which is significantly less than the volumetric weight of the heavy concrete ($2200\text{--}2300 \text{ kg/m}^3$) that is used for the manufacture of hollow-core slabs; it has a relatively small volumetric shrinkage of 0.58% and a thermal conductivity coefficient of $0.68 \text{ W/m} \cdot \text{K}$ versus $1.86 \text{ W/m} \cdot \text{K}$ for heavy concrete.

In terms of its strength and deformation characteristics, this concrete has a cubic strength of 18.36 MPa , a prismatic strength of 12.0 MPa , and a modulus of elasticity of $14.2 \cdot 10^3 \text{ MPa}$.

Based on the strength and deformability characteristics of this fire-resistant concrete, it can be classified as C16/20 (B15).

As can be seen in the Tab. 5, the volumetric weight of the lightweight fire-resistant concrete C decreases to 1400 kg/m^3 after heating to 1000°C , and the volumetric shrinkage increases to 0.86% , which is associated with the evaporation of the physically bound water and compaction of the concrete structure. There is also a decrease in the strength of the concrete to 14.52 MPa and the thermal conductivity coefficient to $0.62 \text{ W/m} \cdot \text{K}$. There are no through cracks in the samples after the one-sided heating of the concrete samples to 1000°C , which means that there is no flame on the unheated surface of the sample. A network of cracks along the binder with a depth of 2.5 mm and a maximum width of $0.1\text{--}0.2 \text{ mm}$ was observed after cooling the samples from the side of the heated concrete surface.

The deformations of the concrete specimens, which were measured at characteristic points on the heated surface, indicate the presence of deflections, which amounted to $0.1\text{--}0.2 \text{ mm}$, and which are less than the maximum allowable deflections equal to 1.07 mm , determined according to the source (Nekrasov, K. D., 1957).

Thus, according to the fire characteristics, which were investigated after heating the lightweight concrete to a temperature of 1000°C , the fire resistance limit of the concrete, i.e., REI 90, was practically determined.

4.2 Design engineering of a lightweight fire-resistant concrete floor slab

Considering the characteristics of the composition developed of the lightweight fire-resistant concrete of a binder made of alumina cement and having a fire resistance limit of REI 90, we consider it possible to use floor slabs on a large section with a height of 200 mm .

Such slabs are much less labor-intensive to manufacture, since they do not require the use of hollow formers, and the weight of a $6.0 \times 1.5 \text{ m}$ slab will be 2.73 tons , which slightly exceeds the weight of a hollow-core slab, which is 2.56 tons .

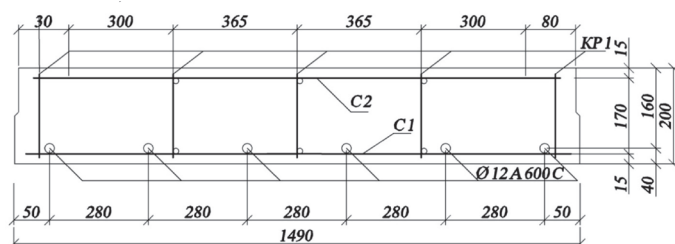


Fig.8 Cross-section of a solid floor slab with a length of 6.0 m and a width of 1.5 m

As a result of the selection of the lightweight fire-resistant concrete composition and the calculation and design of a solid floor slab with dimensions of $6.0 \times 1.5 \text{ m}$, the following results were achieved:

- to reduce the labor intensity of the slab due to the use of a solid cross-section of the slab instead of a hollow section;
- to exclude the destruction of thin concrete walls between the voids in the case of a fire;
- to increase the distance to the axis of the prestressed reinforcement to 40 mm instead of 30 mm for hollow-core slabs and thereby increase the thickness of the concrete cover to 35 mm ;
- to increase the normalized fire resistance of the slabs to REI 90, which is 30 minutes higher than the fire resistance of hollow-core floor slabs due to the use of components with a high degree of refractoriness in the composition of fire-resistant concrete;
- to significantly increase the heat-insulating ability of the slab, since the thermal conductivity coefficient of the concrete of a light fire-resistant slab is $\lambda = 0.68 \text{ W/(m} \cdot \text{K)}$, which is significantly less than the thermal conductivity coefficient of heavy concrete equal to $\lambda = 1.86 \text{ W/(m} \cdot \text{K)}$;
- in addition, to significantly improve the sound-insulating properties of the structure of the floor slab developed.

5 CONCLUSIONS

The article analyses the impact of fire on the structures of buildings and other constructions. It has been established that floor slabs, the standardized fire resistance of which is REI 45-60, are the most vulnerable to fire.

The main disadvantages of the use of hollow-core floor slabs made of heavy concrete from Portland cement when exposed to fire include the limitation of the maximum temperature applied for concrete compositions with a binder made of Portland cement, which is 1100°C ; the thinness of the wall between the voids, which is 26 mm , and which is destroyed even at temperatures below 1000°C ; the relatively small thickness of the areas of the concrete from the lower and upper surfaces of the slab to the voids, which are 30.5 mm , and in which the reinforcement is placed; and the insufficient thickness of the concrete's protective layer to reliably protect the reinforcement from fire.

The noted disadvantages of hollow-core floor slabs incentivize discussing the possibility of increasing the fire-retardant properties of concrete due to the use of light materials with a high degree of refractoriness and of a constructive solution whereby solid floor slabs can be used.

To solve the above problems, a composition of lightweight fire-retardant concrete with a bulk density of 1475 kg/m^3 has been developed, where expanded clay is used as a filler; alumina cement is used as a binder; and water is the grout. The normalized fire resistance of such concrete, which was REI 90, has been practically investigated, it is higher than the fire resistance of hollow-core slabs, which is REI 60.

In a construction sense, manufacturing such solid floor slabs, without any voids, is proposed. In this case, due to the use of lightweight concrete, the weight of the solid floor slabs will be minimally different from the weight of hollow-core slabs. The use of solid floor slabs will eliminate the destruction of thin concrete walls (as occurs in hollow-core slabs) and will increase

the thickness of the protective concrete layer to reliably protect the reinforcement from fire. In addition, the heat-insulating and sound-insulating ability of the solid floor slabs will be significantly improved, since the thermal conductivity coefficient of the lightweight concrete developed is 2.74 times lower than the thermal conductivity coefficient of the heavy concrete of the hollow-core floor slabs.

Since the concrete composition developed has good fire resistance, it can be recommended for construction devices for various fire barriers, such as walls, partitions and doors.

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