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Research paper

High-Mobility Concrete Mixes for Concrete-Filled Steel Tube Structures of Complex Cross-Section

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Abstract

Currently, in the technology of concrete and reinforced concrete, a period of revolutionary leap is observed, caused mainly by the use of high-strength and composite materials, complex high-performance chemical and mineral admixtures, disperse reinforcement, etc. In conditions of increased requirements for economy, lower consumption of metal, cement and forest materials, Interest in the builders causes concrete-filled steel tubes.
The main requirements for concrete-filled steel tubes and concrete mixtures for its manufacture are considered. The specific features of the selection of the composition of concrete-filled steel tubes are shown. The technique of selection of compositions and results of researches of properties of concrete mixes and concrete-filled steel tubes is presented.
Key words: *concrete-filled steel tubes, concrete mixes, mobility, viscosity, chemical additives, mineral additives, injection.*

1. Introduction

The development of the construction industry is closely related to the development of the entire state economy, which leads to the introduction of unique innovative projects. This process opens up new requirements for building structures, materials and products. Concrete science and technology of concrete and reinforced concrete are experiencing a period of revolutionary leap, caused mainly by the use of high-strength and composite materials, complex high-performance chemical and mineral additives, dispersed reinforcement, etc. builders are interested the concrete-filled steel tubes. When concreting structures by the method of forcing, the main attention is paid to the choice of concrete pumping equipment. The parameters of injection can also be significantly influenced by selecting the composition of the concrete mix. Therefore, the use of highly mobile concrete mixtures for concrete-filled steel tubes structures of complex cross-section is becoming more common.
Concrete-filled steel tubes structures are effectively used in various fields of construction around the world. In particular, in such responsible as bridge construction, construction of the subway, and in recent years - in the construction of high-rise buildings [1, 2].
The reason for the effectiveness of concrete-filled steel tubes structures is a number of positive qualities that they possess.
Their outer steel casing pipe, which simultaneously performs the functions of both longitudinal and transverse reinforcement, is capable of perceiving forces in all directions and at any angle. In addition, the lateral pressure of the pipe prevents the development of fracture microcracks in concrete, which, being insulated, tends to increase its size in the radial direction. This cage effect creates ideal conditions for the operation of the concrete core under load, thereby increasing the load-carrying capacity of the entire array.
The disadvantages of the use of concrete-filled steel tubes structures can be attributed to the possibility of stratification of the concrete mixture when filling pipes; the difficulty of ensuring the joint operation of the concrete core and the shell due to the possible shrinkage of concrete and or the difference in the lateral deformation coefficients of concrete and steel. The most significant of these is the difficulty of ensuring the joint operation of the concrete core and the outer steel shell under operational loads.
The use of highly mobile concrete mixtures with the effect of self-stress in the production of long-span concrete-filled steel tubes structures can solve a number of problems associated with forcing, compaction, ensuring the joint work of the concrete core and metal cage, minimizing the presence of voids and defects, shrinkage, and the like.
Production of long-span concrete-filled steel tubes structures requires the use of special pumping equipment, as well as carefully selected mixture composition, which will ensure uniform and most efficient filling of the entire structure.

2. Materials and methods

Fine-grained mobile concrete mixtures based on Portland cement, used to fill the internal cavity of pipe-concrete structures up to 1 km in length, were investigated.
As a binder used Portland cement CEM 42.5, the characteristics of which are given in Table 1.
Quartz sand of 0.1-0.63 mm fraction was used as an aggregate.
Microsilica with an amorphous silica content of at least 85% and a specific surface area of at least 15 m^2/g was used as an active mineral admixture.
To compensate for shrinking deformations, a mineral admixture PCAM on based sulfoaluminates, was used.
Chemical admixtures Sika ViscoCrete 5-600 SP and Sika Latex were used to regulate the mobility of the concrete mix. Sika Vis-

coCrete 5-600 SP is a superplasticizer with a high water-reducing effect for concrete based on modified polycarboxylate esters. Sika Latex is a synthetic dispersion of styrene-butadiene rubber.

Table 1: Characteristics of Portland cement

Indicators	Unit of measurement	Value
Normal density of cement paste	%	26,0
Setting time of cement Initial Final	minutes	 160 230
Activity	MPa	50,2
Specific surface area	m^2/g	0,338
Mineral composition C_3S C_2S C_4AF C_3A	%	 59,8 15,4 11,1 7,5

Standard methods were used to assess the physical-mechanical properties of concrete and the rheological properties of a concrete mix.
The determination of the carrying capacity of concrete-filled steel tubes samples was carried out in accordance with the schemes presented in Fig. 1.

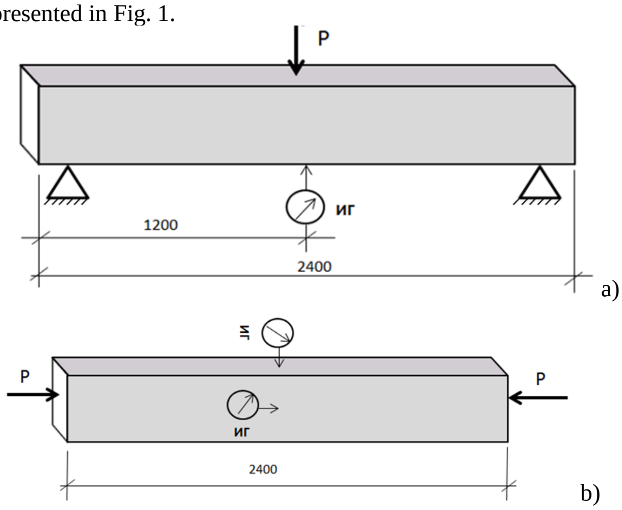

Fig. 1: The determination of the carrying capacity of concrete-filled steel tubes samples: a) bend test pattern; b) compression test pattern

The load of the sample was carried out in accordance with the schemes of Fig. 1, increasing the load P to the loss of stability of the sample with the measurement of deformation. The maximum load P_{max} at which the sample lost its stability was determined. The strain of the sample was shown to depend on the applied force.
When solving the problem of filling a metal truss with a monolithic concrete belt about 840 m long and with a cross section of 160×80×5 mm, it is necessary to develop a highly mobile concrete mixture with the effect of maintaining mobility of at least 6:00.

3. Results

The basic composition of fine-grained concrete included 0.8 m^3 of quartz sand. The density of the concrete mix was 2090 kg/m^3. However, already with the spreading of the standard cone 50cm, water separation is observed. It was found that an increase in the amount of cement reduces water segregation, but at the same time, the tensile strength of the resulting concrete remained unchanged. And also there is a significant shrinkage of concrete.
The introduction of a superplasticizer Sika ViscoCrete 5-600 made it possible to eliminate stratification of the concrete mix and ensure the safety of its mobility for up to 3 hours. The composition of concrete per 1 m^3 was as follows:
Cement - 700 kg, sand - 1080 kg, water - 240 l, chemical admixture - 4.9 kg (0.7% by weight of cement). Flow table test of the resulting concrete mixture was 58 cm with its density of 2010 kg/m^3. The persistence of mobility of the concrete mix at this stage is about 3 hours (Fig. 2).

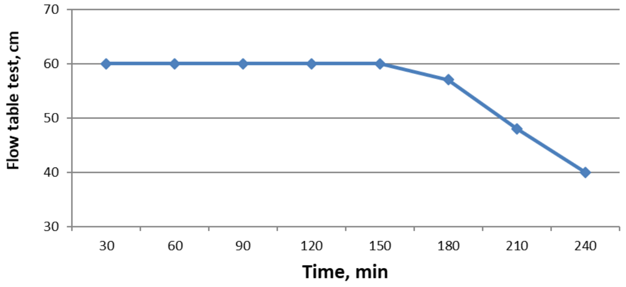

Fig. 2: The mobility of the concrete mix

At the second stage of the modification of the concrete mixture, was added a mineral admixture microsilica. The effect of the admixture of microsilica on the properties of the concrete mix are given in Table. 2.

Table 2: The effect of microsilica on concrete mix properties

No composition	Water / cement ratio	Consumption per 1 m^3 of concrete mix		Flow table test, cm
		Water, l	Microsilica, kg (%)	
1	0.39	300	70 (10%)	91
2	0.39	318	105 (15%)	90
3	0.42	352	140 (20%)	92

In all compositions, cement+ microsilica consumption was 700 kg, sand - 1080 kg, Sika ViscoCrete 5-600 - 4.9 kg. Stratification of the mixture was not observed.
Due to the high specific surface area of silica fume, it is necessary to adjust the amount of the chemical admixture of superplasticizer to obtain the required mobility of the concrete mix. After adjusting the amount of additives Sika ViscoCrete 5-600 was 2% by weight of cement.
At the third stage, to improve the physical mechanical properties of concrete and the rheological properties of the concrete mix, as well as to reduce shrinkage, the chemical admixture Sika Latex was used.
Controlled modification parameters were the greatest spread of the cone without stratification, the limit of compressive strength, the preservation of the properties of the concrete mix. At 20% latex dosage, water separation was observed and part of the additive floated to the surface of the concrete mix.
Butadiene-styrene latex reduces W/C and significantly affects the preservation of the properties of the concrete mix (Fig. 3).

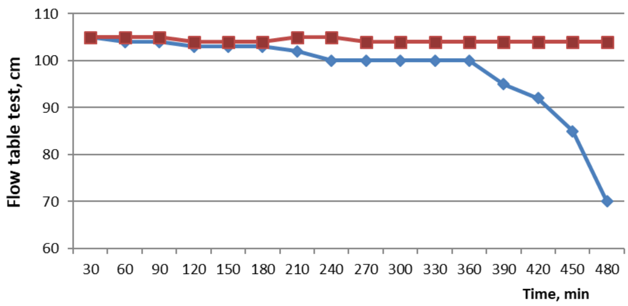

Fig. 3: The mobility of the concrete mix with Sika Latex

The introduction of Sika Latex has reduced the consumption of sand to 930 kg/m^3 and silica fume to 10% by weight of cement. At the same time, the mobility of the concrete mix significantly increased without exfoliation (Table. 3).
When dosing Sika Latex 15%, the compressive strength was 62.8 MPa, and the mobility of the concrete mixture was maintained at least 8:00. However, at this dosage, a significant shrinkage of concrete was observed, which was the criterion for choosing the consumption of the admixture - 10% by weight of cement.

Table 3: The effect of Sika Latex on concrete mix properties

No composition	Water / cement ratio	Consumption per 1 m^3 of concrete mix		Flow table test, cm	Concrete compressive strength, MPa
		Water, l	Sika Latex, кг (%)		
1	0.33	240	35 (5)	100	56.0
2	0.32	210	70 (10)	105	60.2
3	0.31	190	105 (15)	105	62.8
4	0.31	170	140 (20)	104	59.0

As can be seen from the Table. 3, an increase in the dosage of Sika Latex to 20% by weight of cement leads to a decrease in the strength characteristics of concrete, the mobility of the concrete mix decreases, and its separation is observed.
To compensate for shrinkage of concrete in the fourth stage, the expanding sulfoaluminate modifier PCAM was used.
Consumption of the admixture was 105 kg/m^3. At the same time, the preservation of the mobility of the concrete mixture was 300 minutes, the strength of concrete in compression - 55.7 MPa. Hardened concrete samples had no shrinkage cracks.
The final composition of the concrete mix is presented in Table. 4. The resulting concrete corresponds to class C55/67, the density of the concrete mix is 1900 kg/m^3, the strength of concrete in compression - 55.7 MPa. When the cone was spreading out at 105 cm, the water-cement ratio was 0.33.

Table 4: The final composition per 1 m^3 of the concrete mix

Material	Unit of measurement	Consumption
Cement	kg	700
Sand	kg	760
Water	l	210
Sika ViscoCrete 5-600	kg	14
Sika Latex	kg	70
Microsilica	kg	100
PCAM	kg	70

The mobility of the resulting concrete mixture was maintained for 6 hours (Fig. 4), but after 8 hours it possessed sufficient mobility (Flow table test = 70 cm).

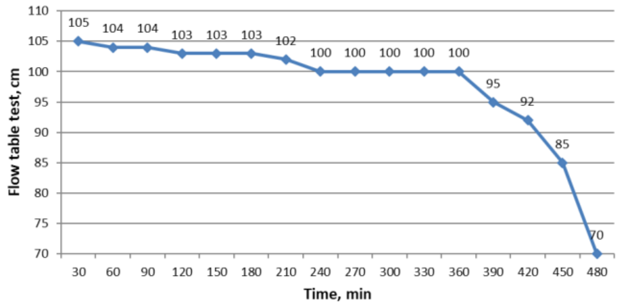

Fig. 4: The mobility of the final concrete mix

To determine the dynamic viscosity of the concrete mixture, correspondences between workability and viscosity were established (Table 5).

Table 5: Correspondences between workability and viscosity of the concrete mixture

Standard slump test, cm	Suttard's viscometer, cm	Viscosity by rotational viscometer, Poise
52	10	46
78	15	34
104	20	24
130	25	16
156	30	8

The dependence of the viscosity of the concrete mixture on the speed of rotation of the spindle rotational viscometer is shown in Fig. 5.

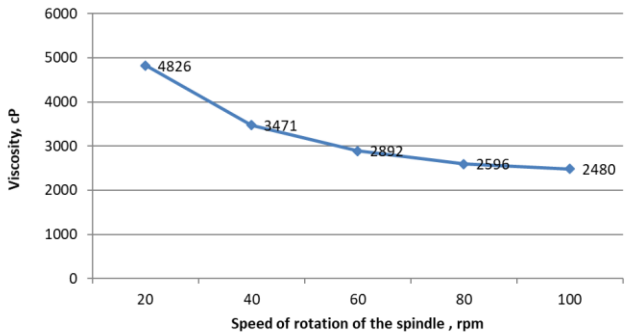

Fig. 5: The dependence of the viscosity of the concrete mixture on the speed of rotation of the spindle rotational viscometer

When concrete hardened under normal conditions, its compressive strength at the age of 28 days was 61.2 MPa, at the age of 56 days - 74.8 MPa. Thus, the resulting concrete meets the class C55/67 (B55).
The strength of concrete tensile at the age of 28 days was 4.1 MPa, which corresponds to the class Btb 4.0.
To determine the bearing capacity for compression and bending of the pipe-concrete elements of trusses of elevated transport systems (2400 mm long, rectangular section 80x60x4 mm), tests were carried out using concrete developed.
The tensile strength of concrete-filled steel tubes during bending was 25.84 kN (average for two samples), which is 11.4% more than the bending strength of a hollow pipe. The compressive strength of the concrete was 279.25 kN (average for two samples), which is 35% more than the compressive strength of a hollow pipe.

4. Discussion

In concretes obtained from a high-mobility mixture, significant shrinkage may occur. And this mechanism has not been studied enough. However, to reduce this effect, it is necessary to choose the right composition of concrete with the optimal amount of cement, aggregates, mineral and chemical additives, as well as the value of W / C. The amount of primary shrinkage is also influenced by the slow setting of the mixture [3], but in our case, the viability of the mixture plays a more important role.
The formation of the structure of concrete, which provides its physical mechanical and technological properties, is largely determined by the rheological properties of concrete mixtures. Indicators of precipitation or cone melting do not give a complete picture of the physical and structural processes occurring in the mixture. Therefore, for a wide range of technological problems, it is necessary to express the rheological characteristics of building mixtures in physical units.
Concrete mixtures are multiphase systems, where water acts as a dispersion medium, and aggregate particles, a binder, act as a dispersed phase [4].
One of the factors influencing the processes of structure formation in dispersed systems is the interaction of the dispersed phase with the dispersion medium. The properties of the system can be controlled using surfactants [4, 5]. The surfactant molecules are sorbed on the surface of the particles and create a gel-like shell around it, thereby changing the nature of the contacts. A contact of the sorption shells of the surfactant makes the mass more mobile and easily deformable, that is, less viscous.
The extremely high recovery rate of the structure, exceeding the rate of its destruction in the flow, is a characteristic feature of non-plasticized systems, distinguishes them from dispersed systems with superplasticizer [6]. One of the characteristic properties of highly concentrated cement systems with superplasticizers is their ability to flow at low shear stresses, in particular, under the action of a gravity.

To obtain an effective concrete mix for filling pipe-concrete structures, it is first necessary to determine the maximum size of aggregates.
According to the authors [7, 8], the plastic viscosity of the concrete mix increases with increasing amount of coarse aggregate. This is due to the growth of interparticle contacts.
The dimensions and the device used in this work of the concrete-filled steel tubes structure are shown in Fig. 6.

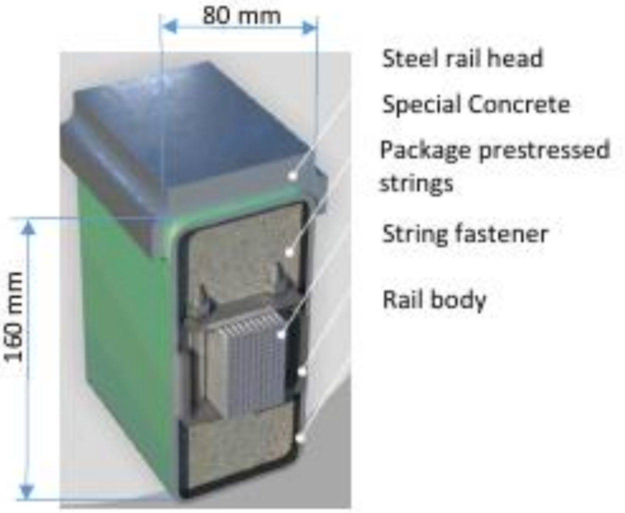

Fig. 6: General view of the string rail

Proceeding from presented on fig. 6 sizes, use of fine-grained concrete is possible. Taking into account the length of the structure (about 1 km) and the impossibility of using efficient compaction, it is necessary to use highly mobile self-compacting concrete SCC mixtures.
To effectively control the process of filling the shell with a concrete mixture, an automation system was used.
Technically, the control system is implemented in a two-level version based on I-7000 series microcontrollers (ICPDAS, Taiwan). At the top level, a personal computer (PC) is used with an I-7520 module - an RS-232 to RS-485 interface converter. The lower level is represented by the I-7018 8-channel information input module, which collects data from the pressure sensors of a concrete pump, a conductometric filling sensor, and a 4-channel output module I-7024, which controls the concrete pumps. The structure of the control system and the technological control object is presented in Figure 7.

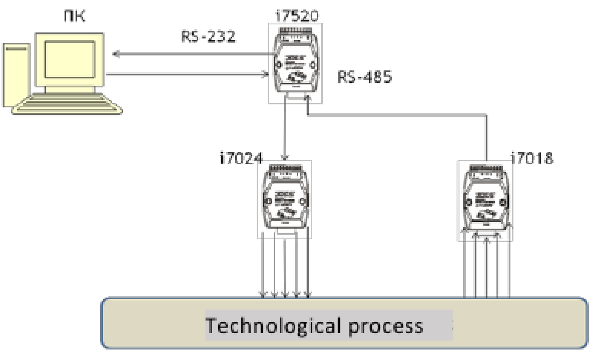

Fig. 7: Automation block diagram

This structure allows for an increase in the number of control and regulation channels, which make it possible to use it both when expanding functions and when integrating into a more extensive hierarchical structure. One of the features of the proposed system is the possibility of its work without the top level of the hierarchy - a personal computer. Changes in the values of the basic system parameters, control laws, and control of the values of different parameters at the control points of the system can be adjusted manually.
When filling a self-compacting concrete mix of this design, it is necessary to consider that the discharge pressure depends on the viscosity of the mixture [9, 10]. In work [11] it is emphasized that the determining factor in pumping a mixture is its composition.
The effectiveness of such concrete mixtures can be enhanced by modifying their compositions, reducing viscosity and maintaining homogeneity.
The elimination of coarse aggregate will allow solving a number of problems related to the segregation of the mixture under pressure, while the introduction of organic and fine mineral additives will ensure the homogeneity of the mixture and high final characteristics of the concrete. The use of powder concretes with high mobility during the filling of long-span metal or bridge structures, concreting in tunnels where the discharge pressure is limited, may be the only solution in the implementation of these tasks.
When determining the water consumption in the concrete mix, it is necessary to take into account the water-holding capacity of cement and the amount of water absorption of aggregates.
When determining the consumption of cement, it is necessary to proceed from the condition of the need to ensure the necessary physical mechanical characteristics, the minimum amount of shrinkage or expansion, as well as workability. The latter is achieved by the optimum content in the concrete mix of cement, dust-like particles of sand up to 0.14 mm in size and mineral additives. Cement consumption in concrete mix should be at least 250 kg/m^3.
The increase in the cement content of more than 500 kg/m^3 and dust particles dramatically increases the viscosity of the mixture and, accordingly, its resistance to movement in the concrete. However, the increased viscosity can be adjusted by introducing organic additives of the new generation based on polycarboxylate ethers.
The most favorable is the use of high grade cements with finer grinding.
Sand for such concrete mixtures should contain up to 3–7% of dust particles less than 0.14 mm in size and 15–20% of fine particles less than 0.31 mm in size. In the absence or lack of natural or fragmented sand of its finest fraction, the latter is replaced by stone or quartz flour, microsilica, fly ash, trass, etc. However, an increase in the content of fine-ground additives of more than 20% by weight of cement is not recommended, since in this case the concrete mix, due to its leanness, does not hold water well and can easily be stratified.
The components of a concrete mix affect its rheological properties in different ways [12].
Due to the presence of a large number of non-ionized groups, additives based on polycarboxylates are characterized by lower adsorption activity [4, 13, 14]. Therefore, with a significant content of free alkali in cement, the adsorption of polycarboxylates on hydrated neoplasms becomes insufficient for the required plasticization of the system. And at a high concentration of sulfate ions, the side chains of the additive molecules coagulate, which also reduces its plasticizing effect [15]. The main difference between polycarboxylate superplasticizers is the more efficient dispersion of particles. Therefore, self-compacting and cast concrete mixes suggest the use of superplasticizers.
Polycarboxylates are molecules with a comb structure and the ability to change the length of the main chain (therefore, molecular weight) and the length of the side chain (therefore, the thickness of the adsorbed layer). Anionic carboxylic acid groups are adsorbed on hydrated neoplasms, while non-ionic ester groups are not adsorbed, but can be freely in solution. The combination of a short polymer base and a long ether side chain leads to a more prolonged increase in workability [16].
The introduction of latex into a concrete mix improves tensile and flexural strength, improves plasticity, reduces the modulus of elasticity, improves the adhesion strength with metals and improves

the frost resistance of concrete. Water resistance increases and shrinkage of concrete decreases.

When cement hydrates, latex particles fill voids and capillaries [17]. As water participates in hydration reactions and partial evaporation, the latex particles merge into a continuous film, which gives the necessary properties to obtain the final characteristics of the concrete. However, unlike conventional mortar and concrete, curing in water will prevent the formation of a film.

Replacing coarse aggregate with fine particles in the mixture leads to a more uniform concrete structure [18], which eliminates the formation of macrodefects and reduces the number of microdefects. The use of microfillers instead of coarse aggregate has led to the emergence of modern reaction powder RPC concretes [19, 6]. Separate components of such concrete go to the micro and nano level (microsilica, microfibers, carbon nanotubes, metakaolin). The large specific surface area of microfillers also reduces the amount of water separation and stratification of the mixture using powder concretes.

By adding chemically and rheologically active powders with cement, the plasticizing effect of plasticizer additives can be enhanced. This approach has been implemented in reaction-powder concretes [20]. The use of fine sand with a fraction of 0.1-0.5 mm allows to obtain fine-grained, self-compacting and self-flowing concrete [21].

The introduction of mineral additives is advisable only in combination with surfactants [22]. The presence of surfactants prevents the aggregation of fine particles of the mineral additive and provides stabilization of its properties. Mineral additives reduce the consumption of the binder and provide an increase in the density of concrete and the water-holding capacity of the concrete mix [23].

Fine-ground mineral additives play an important role in reducing delamination when using high-mobility and cast mixtures, as well as self-compacting concretes [24].

According to [25], the addition of microsilica increases the yield strength of the cement slurry and reduces its viscosity with an increase in its content in the slurry.

Thus, an analysis of the literature data shows that obtaining highly mobile concrete mixtures for pipe-concrete structures requires careful preliminary studies of the influence of each component of the mixture on their rheological properties and the final properties of concrete.

5. Conclusions

1. The principles of designing concrete mixes for concrete-filled steel tubes structures of complex cross-section have been developed, which consist in optimizing the structure of concrete mix at the micro and macro levels, reducing the viscosity of the mixture, increasing its viability. This allows the use of such concrete mixes when filling in long-span metal or bridge structures, concreting in tunnels where the discharge pressure is limited.
2. The results of studies of the influence of chemical and mineral additives on the rheological properties of concrete mixtures and the physical mechanical properties of concrete are presented.
3. It is shown that the introduction of chemically and rheologically active powders significantly enhances the plasticizing effect of additives of plasticizers, provides a increase in the density of concrete and water holding capacity of the concrete mix.
4. It has been established that the developed compositions of concrete-filled steel tubes allow to increase the bearing capacity of structures based on it under the action of compressive (by 2%) and tensile (by 2%) loads.
5. To improve the efficiency of filling concrete structures with concrete mix, a system of automatic control of a concrete pump has been developed, which made it possible to regulate the mixture discharge pressure in order to avoid the formation of traffic jams.

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