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The effect of three–stage ionization on the structure formation of a concrete mixture during shotcrete

The article deals with the problem of reducing rebound and dust formation, as well as increasing the strength of shotcrete. It is known that with “dry” shotcrete, the rebound is especially significant, since the mixture does not have time to acquire sufficient adhesive properties when mixing different phases. As a result, there is an irreparable loss of a significant part of the applied material. The formation of crystal centers that ensure the strength of concrete also occurs slower than with “wet” shotcrete, since the contact of the binder with water in the nozzle of the shotcrete machine is too short. This leads to a decrease in strength characteristics, slowing down the setting of shotcrete. To solve this problem, a method was developed for applying a concrete mixture to enclosing structures using a previously patented experimental nozzle and electrostatic treatment. This method, for a long time, has been successfully used for painting various surfaces, and its modernization will allow the introduction of electrostatics in shotcrete. A systematic ionization of the binder and then the finished mixture is proposed, as a result of which the shotcrete will be attracted to the shotcrete structure along the power lines. To obtain empirical data and confirm theoretical calculations, laboratory tests were carried out, during which the samples of both the initial shotcrete and those exposed to electrostatics were formed. During the application of the mixture, the magnitude of the rebound was recorded at various distances of the nozzle with the nozzle fixed on it from the shotcrete surface. Samples of the resulting concrete were examined on universal testing machines in order to determine the specific heat release, as well as the compressive and bending strength. The experiments showed that electrostatic treatment allows to speed up the time of the initial setting of the cement dough due to faster hydration of the mixture. An improvement in the strength of shotcrete and a significant reduction in rebound were recorded.
Keywords: *shotcrete, electrostatics, ionization, corona electrode, material rebound, particle charging, shotcrete density, shotcrete strength*

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INTRODUCTION

When shotcreting by the “dry” method, a ready-made factory mixture is often used, delivered in bags, or by dump truck, where the ratio of “cement – filler” is on average 300 kg per 1,000 liters. With this composition, you will get about 350–360 kg. per cubic meter of shotcrete concrete. This is due to taking into account the rebound, that is, the loss of the mixture during the production of works. Moreover, the shotcrete of enclosing structures varies in the degree of losses: applying shotcrete to walls with maximum compliance with technology makes it possible to reduce losses by up to 15 %, and working with the ceiling can lead to losses of up to 35 %. If we take into account that manufacturers of ready-made mixtures do not recommend reusing the rebound material, which is fully justified by a sharp decrease in strength characteristics, then the still unresolved problem of irretrievable losses of the finished shotcrete mixture is relevant, and the search for its solution is economically more than justified.

One of the ways to regulate the properties of shotcrete is the use of alkali-free setting accelerators based on aluminum sulfates and hydroxosulfates. It is proposed to mix such additives in a ratio of 1–5 % of the binder weight, which makes it possible to increase the rate of formation of the primary structure by a factor of 2–3.5 (such data is given, for example, by the manufacturer) [1]. However, manufacturers everywhere recommend using a plasticizer to achieve the most optimal result. In addition, these additives are toxic to humans, especially in the form of powder and dust, fire and explosion hazardous, the effect on metal in the presence of water is also negative [2]. Taking into account the cost of such additives, the issue certainly remains unresolved and open.

There is another problem of “dry” shotcrete, as the water-cement ratio and workability of the mixture are, in fact, under the control of the nozzle operator: because he directly regulates the water supply and, by his own decision, its volume can be increased or decreased[1]. It is easy to make a mistake here: too liquid shotcrete concrete, when applied, will not achieve sufficient adhesion to the shotcrete surface and will begin to slip; too thick concrete will not have enough water for hydration, which is discussed in detail by A. Neville in an extensive work on the properties of concrete and further in the Jensen-Hansen model [3]. Of course, this is more relevant when using a filler of larger sizes, but it is also true for shotcrete. It is believed that the structure formation of concrete ends on the 28th day after application, but in fact, even under normal conditions of sealing and application of shotcrete, samples can often contain non-hydrated cement grains containing calcium silicates of both C_3S and C_2S [4, 5]. In such cases, the amount of

1 Guidelines for the use of shotcrete in the construction, repair and restoration of building structures of buildings and structures. Moscow, Tsniipromzdaniy Publ., 2007; 31.

$Ca(OH)_2$ is not enough, and the strength may not correspond to the vintage.

In addition, lack of water leads to increased dust formation, which again (especially in the presence of fiber and accelerators) can lead to negative consequences up to poisoning the operator.

The solution to the rebound problem is also important on the other hand: "dry" shotcrete does not allow applying large volumes of the mixture (up to 4 m^3/h), the work can be significantly delayed by the execution time [6]. It is also necessary to take into account the factor that shotcrete contains more binder for better workability, so, it is more expensive than conventional mixtures. Thus, the loss of material is more noticeable here.

Improving the strength of concrete is an equally urgent task that has been studied for a long time. There are many ways to activate the binder and concrete mixtures of solution methods, which are described in detail in one of the review articles [7].

First of all, we note that, as it was already mentioned above, in order to increase the strength characteristics, the importance of the water content in the shotcrete mixture cannot be overestimated, since it is the water molecules that lead to the formation of calcium hydroxide, whose crystal structures are comparable in size to the crystal lattice of the main minerals. As a result, the destruction of the surface layers of the initial cement occurs during the formation of the cement dough and the formation of its structure. On the other hand, water molecules create hydrate shells. The active centers of the particles are separated by energy barriers on the surface of these particles, so it is already obvious that it is necessary to influence various activating technologies that would speed up the process of joining water molecules and hydration of cement in order to increase strength characteristics.

In addition, the shotcrete process itself requires improvement to reduce rebound and dust formation, as well as overall material savings.

GENERAL PRINCIPLE OF ELECTROSTATIC TREATMENT OF SHOTCRETE

One of the solutions to the problem is the three-stage ionization of the shotcrete mixture in the technological scheme created using the previously developed experimental nozzle (Fig. 1) and completed on the basis of the "Duo-mix 2000" mixer pump [8]. This

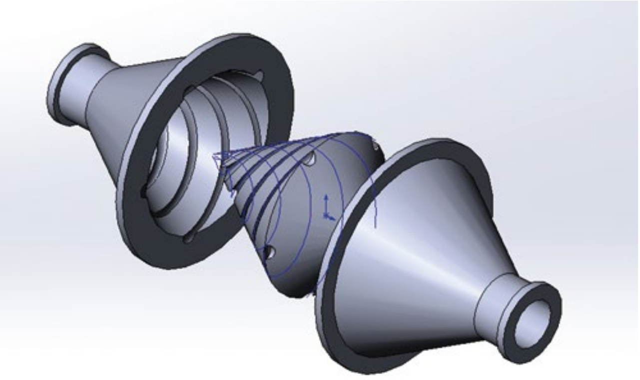

Fig. 1. Scheme of the experimental nozzle for the mixing pump "Duo-mix 2000"

invention was based on the principles of a long-established and successfully proven electrostatic painting, based on the discoveries of the American scientist Gerald Ransburg. With this method of application, the paint and varnish material passes through an electrostatic field formed by the electrodes and receives a negative charge. As a result, the sprayed material moves along the force lines between the spraying device and the surface to be painted, it is attracted to the latter, which allows to sharply reduce the rebound and loss of paint particles of the precipitating paint-air mixture. Moreover, this technology has been recently used for liquid paint material.

Of course, the principle of shotcrete has similarities with staining, but also numerous differences that need to be taken into account. Let us consider in detail the developed technological scheme for the application of shotcrete using electrostatics (Fig. 2). For convenience and simplification, we will take for 100 % charging during electrostatic painting, comparing similar processes in the processing of sand-cement suspension.

The first stage. The dry shotcrete mixture enters the receiving hopper of the "Duo-mix 2000" mixer pump *1*, where compressed air is supplied from the compressor *2*. Then the air-powder fraction is sent to the ejector pump *3*, where, according to the Bernoulli principle, ionized negative ionized air is supplied from the ionizer *4*, equipped with a crane *5*. It is experimentally determined that at

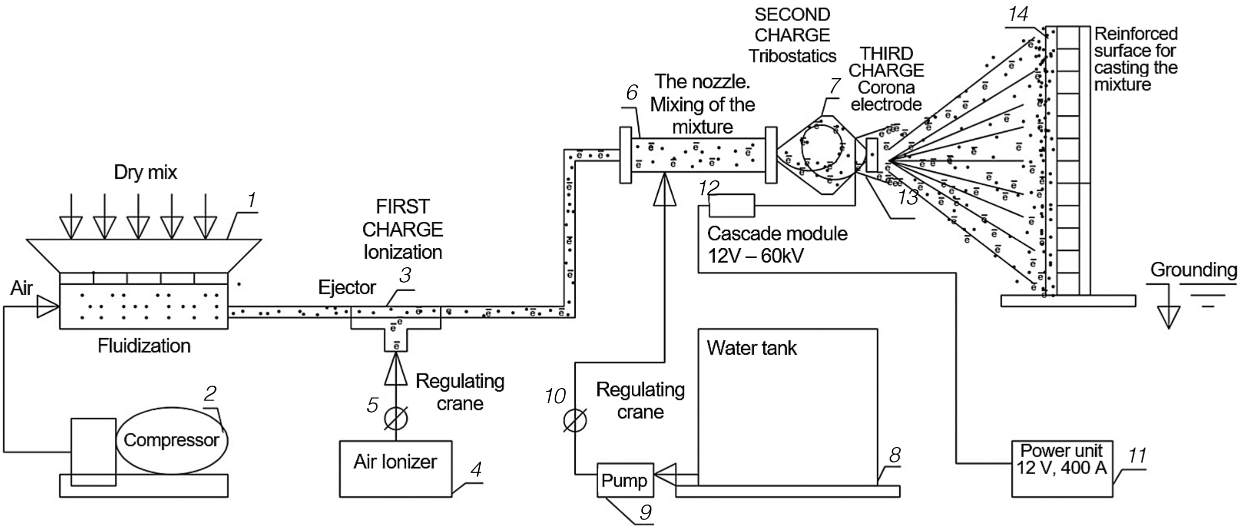

Fig. 2. Scheme of shotcrete cement-sand mixture using three-stage electrostatic charging

the first stage, the mixture is charged by 30–45 %, depending on the composition.

The second stage. The negatively charged mixture enters the sprayer *6*, consisting of an inlet nozzle *7* and a vortex nozzle *7*, where water is supplied from the tank *8* by a pump *9* through a shut-off valve *10*, which is calculated to be necessary for mixing with the dry mixture and forming shotcrete. At the inlet to the nozzle, the dry mixture is combined with water, while part of the charge is lost. To compensate for these 15 % losses, the resulting three–phase suspension is stirred by vortex motion in a nozzle made of special plastic, where due to the resulting tribostatic friction it is charged again with negatively charged electrons.

The third stage. A voltage (12 V) is supplied from the voltage generator *11* and through the cascade module *12* to the corona electrodes *13* mounted on the nozzle and insulated from breakdown by fluoroplast [9]. At this stage, the mixture passes through the ion corona and is additionally charged with negative charges by about 20 %, which in total gives a 50 % charge of the cement-sand mixture relative to the electrostatic coloring. Further, at the moment of settling on the thrown and grounded shotcrete surface *14*, two processes occur simultaneously: a change in the force vector of the aerodynamic motion of the mixture to the opposite and the discharge of negatively charged electrons. The first process causes the rebound of the finished mixture from the shotcrete surface. The second one, according to Coulomb's law, compensates for this due to three–stage ionization and, accordingly, an increase in the Coulomb force of attraction.

In addition to solving the problem of reducing the rebound, it was also assumed that the electrostatic activation of the mixture would lead to a more active wetting of the binder, acceleration of the cement dough setting without the introduction of accelerators and its more complete hydration, as well as an increase in the strength of the final shotcrete [10–12]. The introduction of electrostatics should also reduce dust formation during “dry” shotcrete due to the attraction of the gas-dust fraction to the surface to be thrown.

PROCEDURE FOR CONDUCTING EXPERIMENTS

After the development and implementation of this scheme, the authors began field tests and laboratory experiments to confirm the theoretical calculations. The research was conducted on the basis of the Voronezh State Technical University.

The water-cement ratio, V/C, was taken as 0.38. The working pressure in the sprayer was maintained in the range from 0.2 to 0.6 MPa, the departure speed was 150 m/s. The adjustment of the mortar torch was based on an assessment of the uniformity of the mixture and the characteristic greasy gloss. 6 layers 1.5–2 cm thick were applied to the vertical surface to bring the total thickness to 10 cm for further extraction of experimental samples. The layers were applied at a distance of 1 m to 50 cm at an angle of 900 to the vertical surface being thrown. Since no setting accelerator was used, the interval between applying layers ranged from 20 min to 4 hours. Shotcrete was carried out from the bottom up, the rebound material was removed and weighed in order to plot the rebound for each material.

When evaluating the results, the parameters set by GOST standards and Labor Protection Rules for the operation of electrical installations were taken into account.

Shotcrete of the enclosing surface was carried out with the application of ready–made mixtures of two types intended for “dry” shotcrete — SHOTCRETE B25 and SHOTCRETE B30, the main parameters of which are given in Tables 1 and 2.

Table 1. Main characteristics of mixtures used for experiments on electrostatic charging of shotcrete

Name of the mixture	Composition 1 (SHOTCRETE B25)		Composition 2 (SHOTCRETE B30)	
Basic Description	Dry construction for the repair of large defects by dry shotcrete method		Using high-quality cement	
Concrete class	B25 F200 W10		B30 F400 W12	
Appearance	Dry, loose grey homogeneous mixture		Dry, loose homogeneous mixture of gray color	
Filler size, mm	2.5		2.5	
The amount of mixture per 1 m³ of shotcrete, kg	200		200	
Thickness of application of one layer, mm	4		4	
Material consumption, kg/m³ (with a layer thickness of 10.0 mm)	~20		Before 20	
Average compressive strength:	MPa	kg/sm²	MPa	kg/sm²
1 day, at least	10	102	15	153
2 day, at least	15	153	20	203.9
28 days, at least	32.7	333.4	35	356.9
Water resistance	W18		W10	
Frost resistance, cycles	F1200		F1300	
Adhesion strength to the concrete surface, MPa, not less	1.5		1.5	
Water absorption, kg/m²h 0.5, no more	0.4		0.4	
Shrinkage	Unshrinkable		Unshrinkable	
Modulus of elasticity, GPa	20		25	
Content of chlorine ions, %, no more	0.1		0.1	
Class in accordance with GOST 56378–2015	R3		R3	

Table 2. Composition for the preparation of a control standard mixture of shotcrete

Indicators	Composition 1 (SHOTCRETE B25)	Composition 2 (SHOTCRETE B30)
Type of binder	Cement grade PC 400 (GOST 10178)	Cement grade PC 500 (GOST 10178)
Type of placeholder	Sand according to TU 5745-001-162168921–06	Sand according to TU 5745-001-162168921–06
Size of filler particles, mm	2.2	2.2
Compliance of the filler with the sieving curve	Respond	Respond

The efficiency of electrostatic treatment was evaluated by the following parameters:

1. Directly in the process of shotcrete — visually to accelerate the setting of cement dough, reduce the degree of rebound and reduce the gas-dust fraction.

2. In laboratory conditions — according to the acceleration and increase of strength gain in 28 days and the characteristics of cement stone.

Additional tests were carried out separately to determine and optimize the electric field strength depending on the strength characteristics and the degree of rebound.

Based on the visual evaluation and registration of the results, the following data on the initial setting of shotcrete were obtained (Table 3).

Table 3. Duration of initial setting of shotcrete B25 and B30

Concrete class	Initial setting, min	
	Standard	After electrostatic treatment (average time)
B25	240	56
B30	240	53

DETERMINATION OF SPECIFIC HEAT RELEASE AND REBOUND OF THE SHOTCRETE MIXTURE

Specific heat was determined using an adiabatic calorimeter according to GOST 24316–80 “Concrete. Method for determining heat release during hardening”. Control samples after electrostatics show that the formation of cement stone of the treated mixture occurs more rapidly, since hydration, which began in the nozzle, occurs faster, and the outline is better compacted. There is a uniform increase in heat generation, slowing down after about an hour (Fig. 3). Thus, electrostatic treatment cannot yet replace the use of setting accelerators, where this time is reduced to 20 min, but it accelerates the initial setting twice, which makes it possible for further scientific research.

Data on reducing the rebound of the mixture when applying shotcrete after applying electrostatics is shown in Fig. 4.

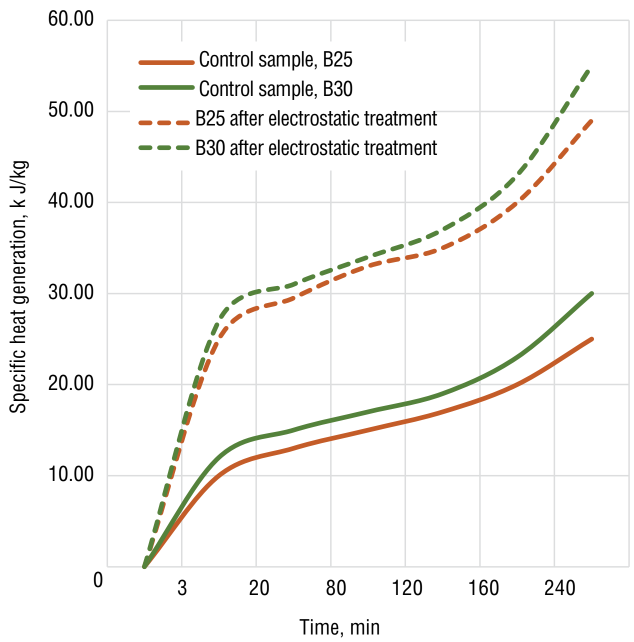

Fig. 3. Specific heat release of shotcrete samples B25 and B30 in the first 4 hours after application

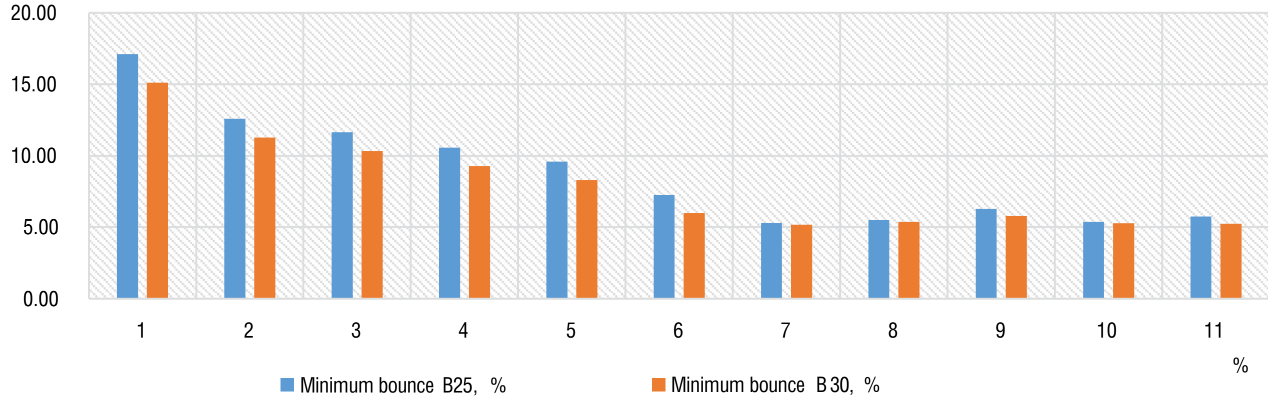

Fig. 4. Minimum rebound of shotcrete grades B25 and B30 after electrostatic treatment, %

INVESTIGATION OF THE EFFECT OF THE MIXTURE ELECTROSTATIC TREATMENT ON THE STRENGTH OF SAMPLES

The study of the effect of electrostatic treatment of the mixture on the strength of shotcrete samples was carried out on a universal testing machine Instron 1100 HDX. For this purpose, strength tests were carried out on 6 samples of each concrete with a size of 100×100×100 mm (Fig. 5) to determine strength characteristics according to GOST 10180–2012 (according to control samples) and flexural and compressive strength according to GOST 310.4–81[2, 3]. The samples were stored in a normal hardening chamber (at t = 20 °C) and tested at the age of 1, 2, 7, 14, 28 days. The results of the change in the tensile strength are shown in the graphs (Fig. 6–13).

Fig. 5. Instron 1100 HDX universal testing machine and shotcrete samples for strength testing

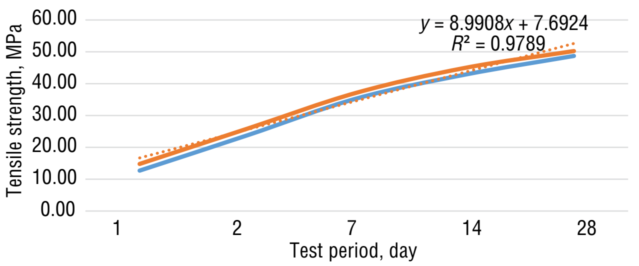

Fig. 6. Graph of changes in the compressive strength of shotcrete B25 before and after electrostatic treatment

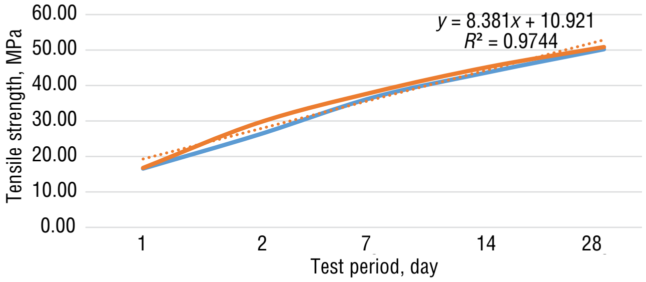

Fig. 8. Graphs of changes in the compressive strength limits of shotcrete B30 before and after electrostatic treatment

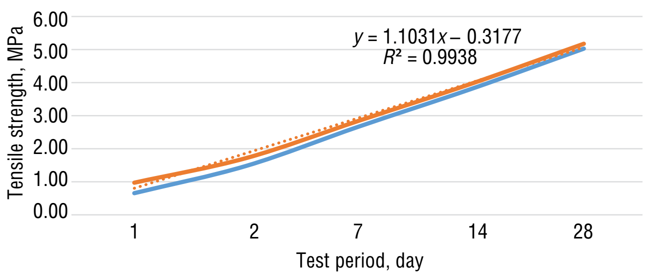

Fig. 7. Graph of changes in the bending strength limits of shotcrete B25 before and after electrostatic treatment

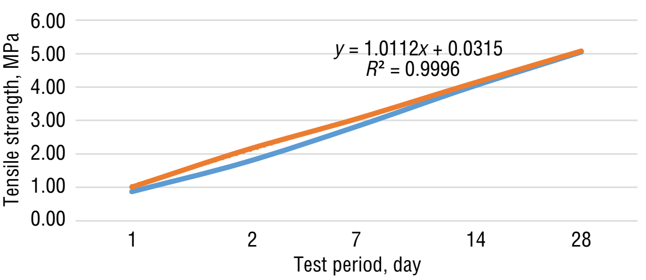

Fig. 9. Graphs of changes in the bending strength limits of shotcrete B30 before and after electrostatic treatment

2 GOST 10180–2012. Concrete. Methods for determining the strength of control samples. URL: https://files.stroyinf.ru/Data2/1/4293782/4293782275.pdf

3 GOST 310.4–81. Cements. Methods for determining the ultimate strength in bending and compression. URL: https://files.stroyinf.ru/Data2/1/4294853/4294853167.pdf

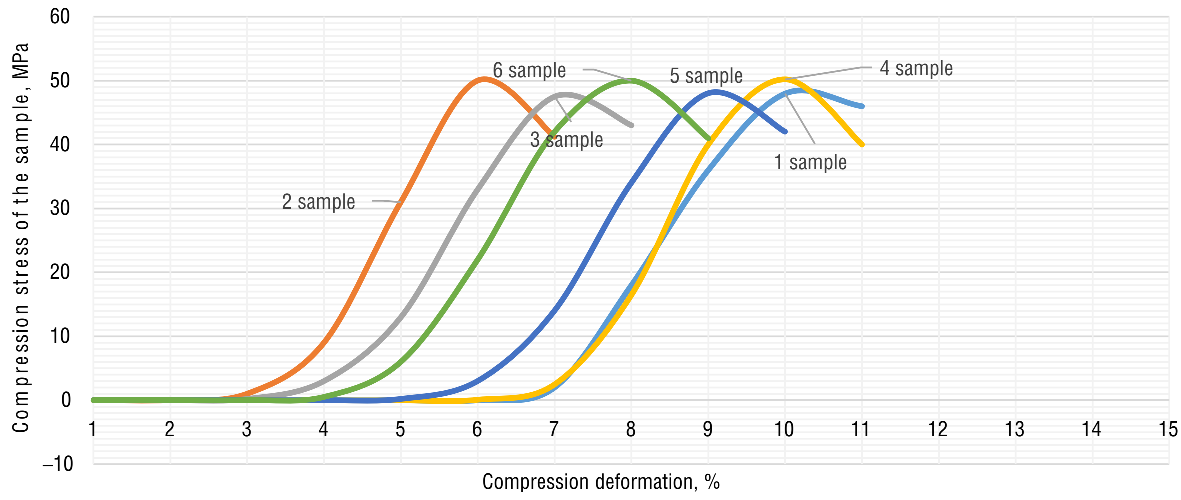

Fig. 10. Compression test of shotcrete samples B25 before electrostatic treatment (28 days)

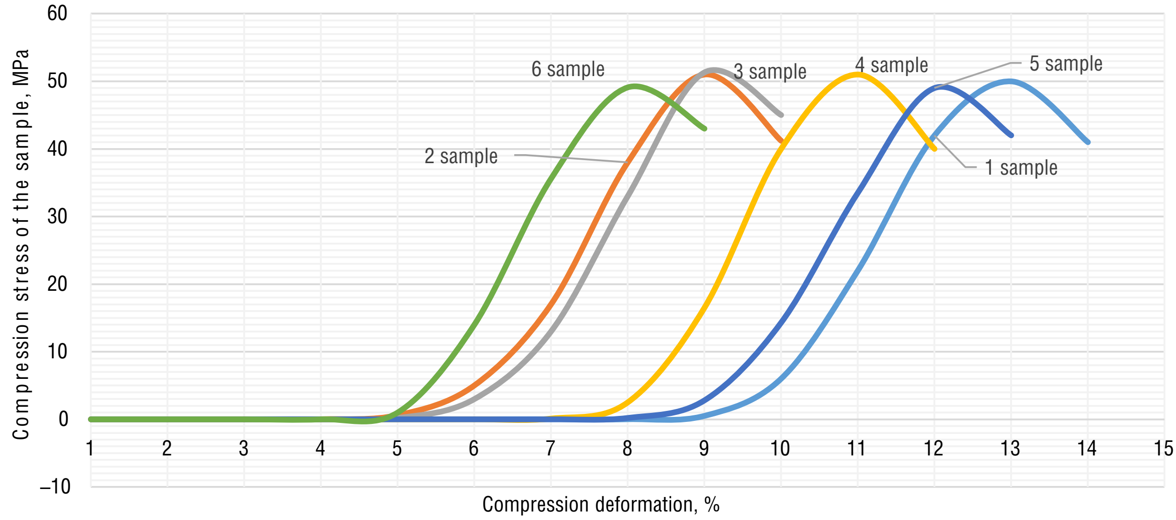

Fig. 11. Compression test of shotcrete samples B25 after electrostatic treatment (28 days)

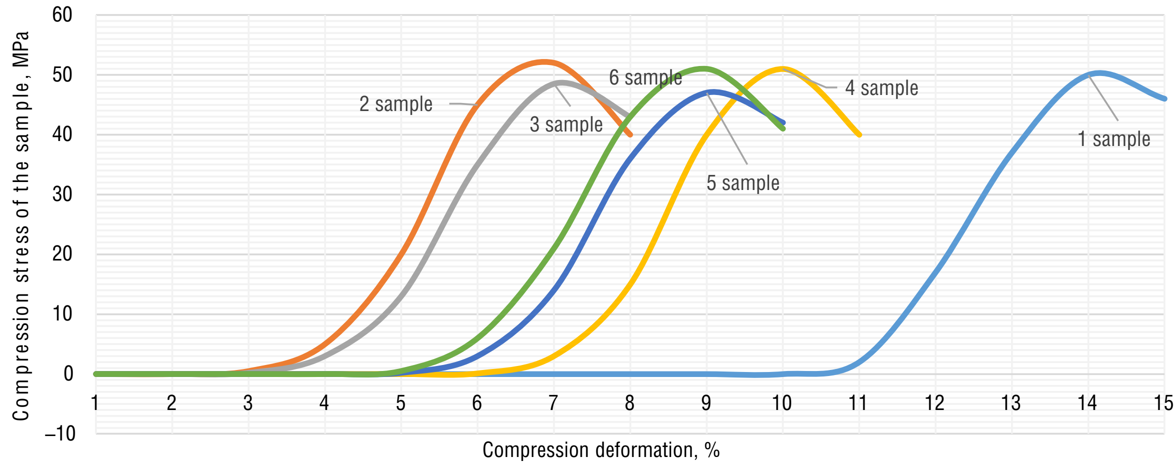

Fig. 12. Compression test of shotcrete samples B30 before electrostatic treatment (28 days)

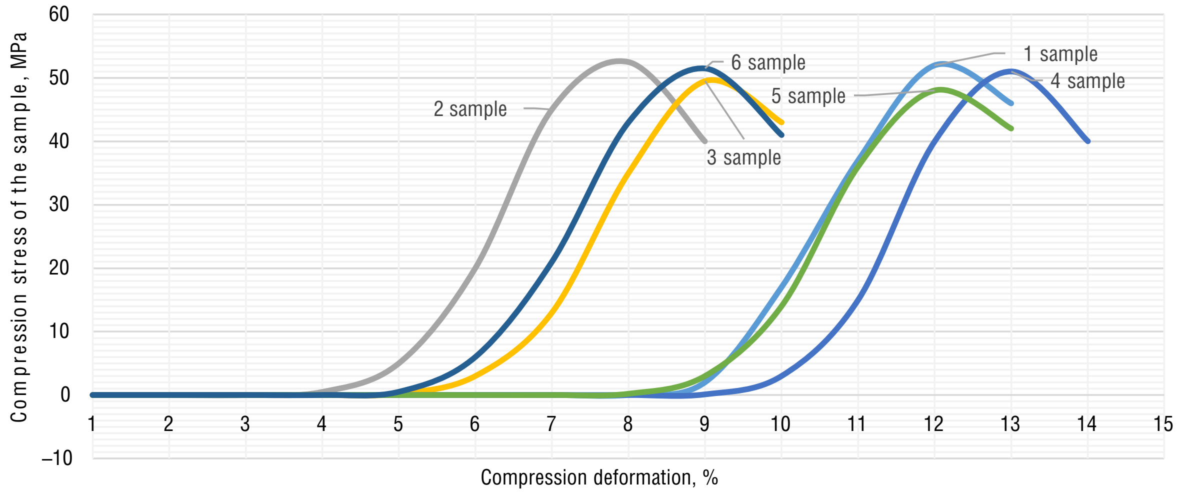

Fig. 13. Compression test of shotcrete samples B30 after electrostatic treatment (28 days)

CONCLUSION

We conclude that the electrostatic treatment allows to speed up the time of the initial setting of the cement dough. From the point of view of strength gain, the mixture of concrete B25 reacted more strongly to electrostatic charging, and in concrete B30, the acceleration of strength gain was noted at the early stages of hardening, then it approaches standard indicators.

It was revealed that the acceleration of setting and the increase in the strength of shotcrete occurs due to faster hydration of the mixture.

In addition, the use of electrostatics during shotcrete makes it possible to reduce dust formation in the working room due to the attraction of particles along force lines to the working surfaces.

Experimental data showed that the effect of electrostatic treatment on rebound is almost the same: the indicator decreased from 20–25 % to 5–6 %, but for stronger concretes, the volume of the mixture lost during application is less by 0.5–1 %.

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Влияние трехступенчатой ионизации на структурообразование бетонной смеси при торкретировании

В статье рассматривается проблема снижения отскока и пылеобразования, а также повышения прочности торкрет-бетона. Известно, что при «сухом» торкретировании отскок особенно значителен, поскольку смесь при смешивании различных фаз не успевает приобрести достаточные адгезионные свойства. В результате происходит невосполнимая потеря значительной части наносимого материала. Образование кристаллических центров, обеспечивающих набор прочности бетона, также происходит медленнее, чем при «мокром» торкретировании, поскольку контакт вяжущего с водой в сопле торкрет-машины слишком кратковременный. Это приводит к снижению прочностных характеристик, замедлению схватывания торкрет-бетона. В качестве решения данной задачи был разработан метод нанесения бетонной смеси на ограждающие конструкции с применением ранее запатентованной экспериментальной форсунки и электростатической обработки. Данный способ давно и успешно применяется при окрашивании различных поверхностей, а его модернизация позволит внедрять электростатику в торкретирование. Предлагается поэтапная ионизация вяжущего, а затем и готовой смеси, в результате чего торкрет-бетон будет притягиваться к торкретируемой конструкции по силовым линиям. Для получения эмпирических данных и подтверждения теоретических расчетов проводились лабораторные испытания, в ходе которых формировались образцы как исходного торкрет-бетона, так и подвергавшегося воздействию электростатики. Во время нанесения смеси фиксировалась величина отскока на различных расстояниях сопла с закрепленной на нем форсункой от торкретируемой поверхности. Образцы полученного бетона исследовались на универсальных испытательных машинах с целью определения удельного тепловыделения, а также предела прочности на сжатие и изгиб. Проведенные опыты показали, что электростатическая обработка позволяет ускорить время первичного схватывания цементного теста за счет более быстрой гидратации смеси. Зафиксировано улучшение показателей по набору прочности торкретбетона и значительное уменьшение отскока.

Ключевые слова: *торкретирование, электростатика, ионизирование, коронирующий электрод, отскок материала, зарядка частиц, плотность торкрет-бетона, прочность торкрет-бетона*

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