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Shotcreting with Cement–Sand Mixtures Under the Influence of an Electrostatic Field

Valery Mishchenko [1], Azariy Lapidus [2], Dmitriy Topchiy [2] and Dmitriy Kazakov [1,*]

[1] Department of Technology, Construction Organisation, Expertise and Real Estate Management, Voronezh State Technical University, Voronezh 394000, Russia; oseun@yandex.ru
[2] Institute of Industrial and Civil Engineering, National Research Moscow State University of Civil Engineering, Moscow 129337, Russia; lapidusaa@mgsu.ru (A.L.); topchiydv@mgsu.ru (D.T.)
* Correspondence: k_di@list.ru; Tel.: +79-1028-86955

Abstract: One of the primary and still unresolved problems of shotcreting is the high rebound rate of the material, which reaches over 20% in "dry" shotcreting. There is a practical need to improve the very principle of shotcreting and methods for optimizing the movement of torch particles. Materials and Methods: The purpose of this study was to justify the use of the electrostatic treatment of cement–sand mortar in the process of performing shotcreting works using the dry method. It was proposed that the binder and then the finished mixture be ionized step-by-step (by passing it through a non-uniform electrostatic field formed by corona electrodes). As a result, the shotcrete will be held on the fence. Results: Analysis of the modeling results shows that the presence of an electrostatic field slows down the particle and reduces the kinetic energy of the rebound. After theoretical calculations, experiments were conducted, during which, the torch size and the plant productivity were changed, and the rebound mass was weighed. After application to the surface, prototypes were formed and subjected to strength tests. It was determined that gunning in a sharply non-uniform electric field demonstrates its practical and economic efficiency due to the uniform deposition of charged particles on the treated surface and low power consumption. Conclusions: It was established that the electrostatic treatment of a cement–sand mixture during application allows concrete particles to be retained on the shotcrete surface, the rebound of the material to be reduced and the strength of concrete to be increased.

Keywords: electrostatics; ionization; discharge electrode; adhesion; electrostatic field strength; shotcrete

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1. Introduction

The process of applying shotcrete to an enclosing structure's surface has several unresolved problems. The main difficulty is the high rebound percentage, especially with "dry" shotcreting. Reusing the rebound material is not recommended; the losses are irretrievable, and finding a solution is more than economically justified.

It has been established that the basis of the entire shotcrete process is the hydration of the binder when it is wetted with water. This complex physical and chemical process is characterized by the destruction of the surface layers of cement and the formation of hydroxide crystals. However, if water initiates the hydration process, it also hinders it by creating shells around the active centers. Various activation methods are used with the aim of overcoming this hydrate energy barrier and accelerating the formation of cement paste, which directly affects strength growth [1–5].

The nozzle operator directly regulates the water supply and can increase or decrease its volume at his discretion. It is easy to make a mistake here: too-mobile shotcrete will not achieve sufficient adhesion to the shotcrete surface during application and will begin to slide; too-rigid concrete will not have enough water for hydration, which was discussed in detail by A. Neville in an extensive study on the properties of concrete and then in the Jensen–Hansen model [6,7]. In addition, "dry" shotcrete is characterized by a fundamental disadvantage in wetting the binder: numerous experiments by various scientists show that the basic structure of shotcrete is formed within 28 days after application, but even by the end of this period, unhydrated cement grains can be found in the samples [8,9].

In addition to the wetting factor, other parameters affect the technological process: the strength of concrete depends on the compaction process, and the rebound depends on the reserve of kinetic energy and the properties of the dense medium [10–15]. Moreover, the reason for the latter is the collision of flying and laid particles and the transition of the energy of motion into the energy of compaction [16]. Since the rebound is a characteristic of the dense medium, each of the technological parameters of the shotcrete process, affecting the rebound, also change the strength of the coating. The rebound percentage can be reduced by reducing the kinetic energy, i.e., the flow rate. In this case, we use the equipment power inefficiently. In addition, the high application speed is the key to maximum compaction and, consequently, the high strength of the coating. Adhesion properties can be improved by additional treatment or priming, which will affect both the cost of the work and the materials [17,18]. The composition of the supplied mixture can be changed, but this will inevitably affect the final strength characteristics. The simplest way to reduce rebound is to reduce the equipment's power and the torch's speed, but this is not economically viable. In addition, a high application speed ensures the required compaction of the applied shotcrete.

Thus, it is undesirable to change the kinetic energy, affect the composition of the mixture, or conduct preliminary surface treatment. An analysis of the works of scientists working in this field showed that despite the significant interest that the theoretical and practical aspects of effective shotcreting attract, many problems have not been solved to date [19–25]. There is a practical need to improve the very principle of shotcreting and methods for optimizing the movement of particles.

The innovative method of the electrostatic treatment of cement–sand mixtures using a vortex nozzle satisfies this condition and is a natural continuation of the work of other scientists. With this application method, the particles of a cement–sand mixture will be held by electrostatics [26–30].

The closest studied technology for the interaction of electrostatically charged particles to prevent material loss and create a uniform coating is powder electrostatic painting (Figure 1).

Figure 1. A gun that allows surfaces to be painted using corona discharge.

When surfaces are painted, paint particles move under the influence of lines of force. Material losses are minimized since the torch bends and is attracted to the painted surface. If the master fully complies with the technology, achieving even less than 1% of paint and varnish material losses is possible.

This principle became the starting point for the development of electrostatic shotcrete technology. The condition for successful application is mandatory grounding and wetting of the surface with a humidity level of 15%. The supplied shotcrete mixture can be negatively or positively charged (Figure 2).

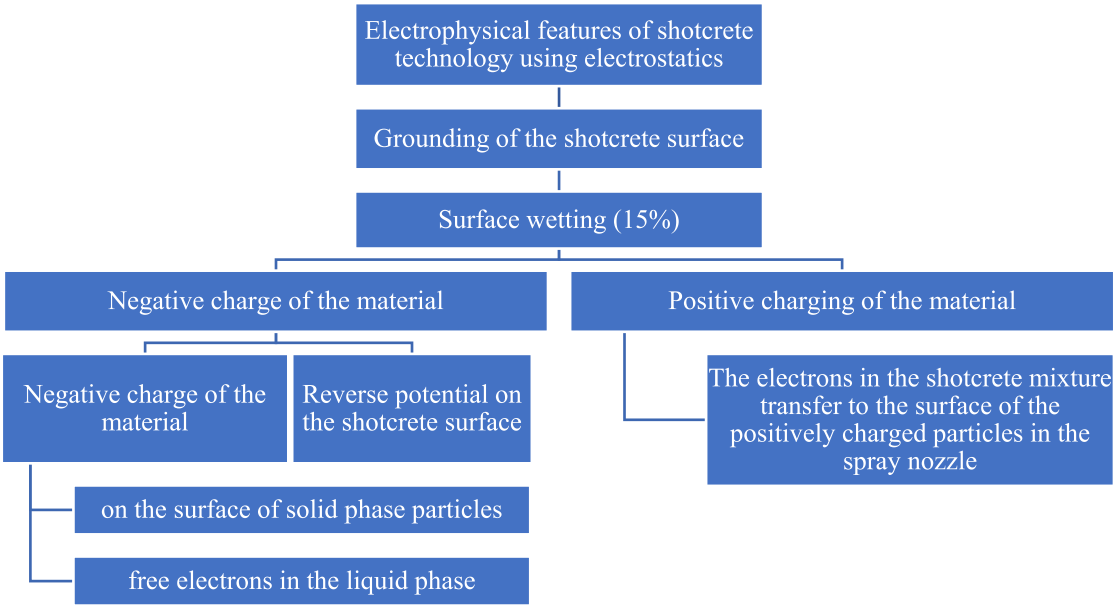

Figure 2. Electrophysical features of shotcrete technology using electrostatics.

In the first case, the negative charge is formed by the accumulation of electrons on the surface of solid-phase particles and by their growth in the liquid phase. On the gunned surface, reverse potential is created due to grounding, which forms the necessary conditions for the implementation of the process.

In the second case, electrons in the gunite mixture are transferred to the surface of positively charged particles in the spray nozzle, creating a potential difference and forming Coulomb forces.

Thus, if powder coating requires changing the trajectory of the particles, which is achieved by the action of force lines, then this is not required in gunning. Here, the main role is played by aerodynamic forces and electrostatic interaction of particles directly at the moment of material throwing, when the force vector changes sign. In addition, inertia is partially damped by a damper. Charged particles are discharged, and the force, according to Coulomb's law at the moment of contact, has the most significant value, as shown in one of the previously published works [29,30].

The key to this technology's effectiveness is the enclosing surface's ability to compensate for the potential of particles that fall on it in the torch of the sprayed shotcrete mixture [31].

Thus, it can be assumed that an effective solution to the rebound problem can be a step-by-step electrostatic treatment of the shotcrete mixture based on the Duo-mix 2000 mixing pump, similar to the application of paints and varnishes using tribo- and electrostatics.

Research on shotcreting under electrostatic treatment using a shotcrete jet was carried out at the Voronezh State Technical University (VSTU) with the assistance of the VSTU Department of Electromechanical Systems and Power Supply.

Further experiments were carried out that would allow us to study, in practice, the features of the innovative shotcrete technology with subsequent processing of the results and assessment of the strength characteristics of shotcrete, as well as the rebound value and other process parameters.

All features related to the most optimal location of the corona electrodes, the magnitude of the electric field strength, the distance from the nozzle to the grounded surface, etc., were studied.

2. Methods

The electrostatic treatment of cement–sand mixtures consists of the following 3 stages:

1. The dry shotcrete mixture enters the receiving hopper of the Duo-mix 2000 mixing pump, where compressed air is supplied from the compressor. Next, the air–powder fraction is sent to an ejector pump, where, according to the Bernoulli principle, air ionized with negative ions is supplied from an ionizer equipped with a tap. It has been experimentally determined that in the first stage, the mixture is charged by 30–45%, depending on the composition. Basically, the gas component of the mixture receives a negative charge.
2. A negatively charged mixture combines with water, losing part of the charge. To compensate for partial charge losses, the three-phase suspension is mixed in the nozzle by a vortex motion and receives an additional negative charge due to the tribostatic effect.
3. In the third stage of processing, a voltage (12 V) is supplied from the voltage generator through a cascade module to the corona electrodes mounted on the nozzle and insulated from breakdown by fluoroplast. 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 (with respect to electrostatic coloring) [32–40].

This type of treatment allows the particles of the mixture to be retained at the moment of their settling on the thrown and grounded gunite surface, which leads to both a reduction in rebound and an increase in strength characteristics [22,24,41].

Figure 3 shows a diagram of the movement of shotcrete particles along force fields during shotcreting using electrostatic treatment [42,43].

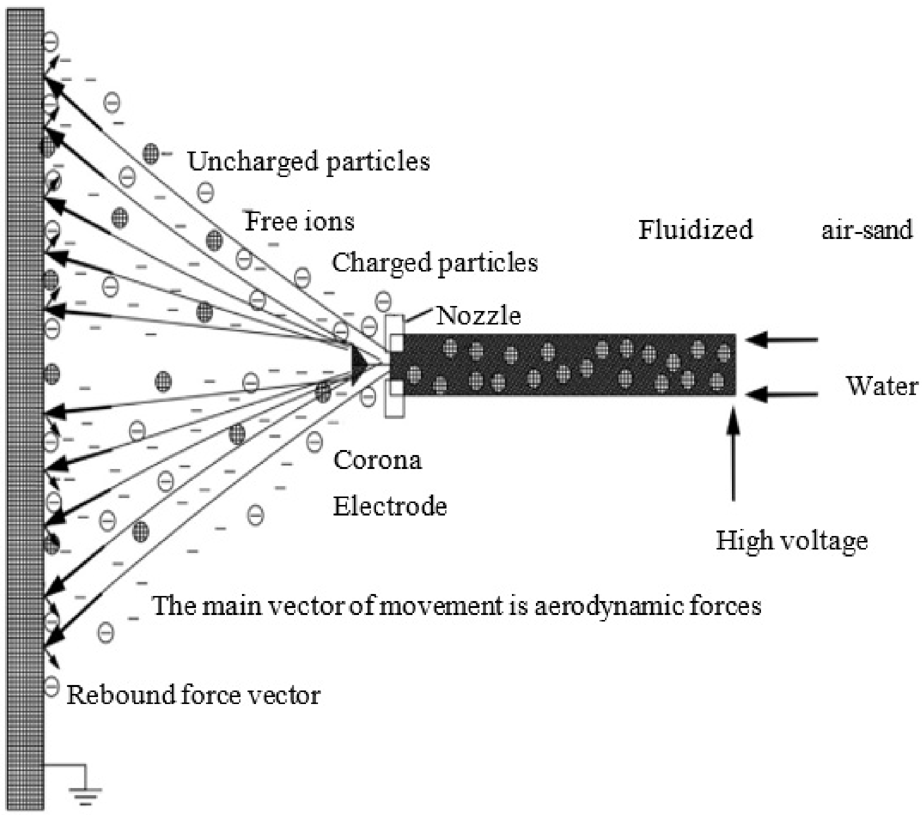

Figure 3. Scheme of movement of shotcrete particles along force fields during shotcreting.

The fluidized air–sand mixture and water enter the vortex nozzle. High voltage is applied to the corona electrodes. Both free ions and charged particles participate in the process. Aerodynamic forces determine the primary vector of motion. When the projectile hits a grounded surface, the rebound force vector decreases due to the discharge of particles. The adhesion to the enclosing structure is much better than it would be without the effect of electrostatics.

It is impossible to create a full-fledged physical and mathematical model at this stage of the work being performed, since many factors are affected, and complete modeling will not allow the results to be applied to equipment different from ours, so mathematical analysis was used to find optimality values, and the methodology of the approach was formalized. In further work, it will be possible to form a complete physical and mathematical model after data sublimation and the formation of a single database of experiments on many types of equipment.

At this stage, it is necessary to form an ideal model of the motion of shotcrete particles when applied to the surface and to accept that each particle, although moving in the flow, has its kinetic energy. The energy of the entire flow is the integral sum of the energies of all its particles. In [20], an idealized mathematical model of the interaction of a shotcrete mixture particle and pneumatic formwork is considered, and it is rightly noted that the prepared surface absorbs part of the kinetic energy Ek of the flying particle. In our case, the string is not deflected since a solid vertical surface is considered. In this case, the decrease in kinetic energy ΔE_{ko} is defined as a set of parameters, including electrostatic action, which is described by the following formula:

$$\Delta E_{ko} = a^2 \cdot \Delta E_{xt} \cdot E_{ep} \tag{1}$$

where

a—speed of particle movement;
ΔE_{xt}—amount of kinetic energy absorption $\Delta E(x,\ t)$;
E_{ep}—electrostatic field impact coefficient.

We will perform mathematical modeling, considering the movement of a shotcrete mixture particle and the results of other scientists' research in this area.

The 1st boundary value problem is solved as follows [44]:

$$\frac{\partial^2 \Delta E_{ko}}{\partial t^2} = a \frac{\partial^2 \cdot \Delta E_{xt} E_{ep}}{\partial x^2} \tag{2}$$

$$E(x,t) = \sum_{\lambda=1}^{\infty} A_\lambda \cos\frac{ak\pi t}{l} \sin\frac{k\pi x}{l} \tag{3}$$

Next, it is necessary to establish a mathematical relationship between kinetic energy and all process parameters.

The shotcrete technology requires the installation of the nozzle at an angle of 90° to the surface being sprayed. Let us designate the speed of the mixture at the exit from the nozzle as v_0 and the speed at the moment of hitting the vertical grounded enclosing structure as v_1. Then, mv is the movement of each particle of the ejected shotcrete mixture.

At the moment of impact with the surface, part of the kinetic energy is converted into potential energy; therefore, in fact, the speeds of the approaching and rebounding particles $v_2 < v_1$.

The first condition is that the nozzle is installed at a fixed distance from the shotcrete surface. The performance of the shotcrete machine is taken as Qtotal, which consists of the performance of the compressor and the supplied concrete, m^3/s, and is calculated as follows:

$$Q_{com} = Q_{sr} + Q_{con}, \tag{4}$$

It is obvious that the masses and velocities of the particles are different but must be taken as averages to form an idealized model. Moreover, here, the dependence on time t, nozzle diameter D, and productivity Q is formed when in Δt, a mixture cylinder is formed, the volume of which is determined by the following formula:

$$V = Q * \Delta t = S * v_0 * \Delta t = \frac{\pi D^2}{4} v_0 * \Delta t \tag{5}$$

where

S—nozzle cross-sectional area;
v_0—the speed of the ejected particle, which is equal to the following:

$$v_0 = \frac{4Q*}{\pi D^2} \tag{6}$$

Average particle mass is calculated as follows:

$$m = \beta \mathrm{QD}^2 \tag{7}$$

where β—numerical coefficient.

Next, we will assume that the average mass will not change. Still, the particle velocity, when passing the distance between the nozzle and the surface, will change due to both air resistance and the effect of electrostatics (Enap), which is expressed by the dependence established in [44] but is adjusted for the coefficient of the effect of the electrostatic field, as follows:

$$F = \mathrm{aE}_{ef} v_1^2 \tag{8}$$

This implies the following:

$$v_1 = \sqrt{\frac{F}{\mathrm{aE}_{ef}}} \tag{9}$$

where a—proportionality coefficient.

On the other hand, there is the following relationship between the speeds of the particle flying out of the nozzle and the particle approaching the surface:

$$v_1 = v_0 * \exp\left(-\beta \frac{H}{\mathrm{QD}^2}\right) \tag{10}$$

where

H—distance, that is, the path traveled by the particle;
β—numerical coefficient.

The second factor will be denoted by E. Then, according to the Gaussian model, the energy of the "particle–surface" interaction is equal to the kinetic energy of the incoming particle of the mixture, as follows:

$$E_{\mathrm{B}} = E_k = \mathrm{mv}_1^2/2 \tag{11}$$

Considering (11), we can conclude that the kinetic energy of the incoming particle is lost on the adhesive interactions of particles on the surface, and also, when the motion vector changes, it is partially converted into rebound energy. The stronger the electrostatic effect attracts particles to the surface, the lower the residual kinetic energy of the rebound, i.e.,

$$\Delta E_{ko} \to \max \tag{12}$$

Since the mass does not change, the coefficient of kinetic energy loss is the ratio of the velocities, as follows:

$$\xi = \frac{v_2}{v_1} \tag{13}$$

Hence, taking into account the inversely proportional relationship between strength and rebound, as shown in [5], the main function will also have the character of an inverse relationship, as follows:

$$f(Q, D, H, Enap) = \lambda \ln\left(1 + \frac{1}{\sqrt{\xi}}\right) \tag{14}$$

where λ is the proportionality coefficient; this and other coefficients were formed based on the experiments conducted. They were determined graphically based on the obtained surface extrema, reflected in previously published studies [45]. Of course, this model is ideal and approximate since the basis of the study was precisely the experimental part of optimizing the basic parameters, i.e., the rate of strength gain at different productivity levels, changes in torch distance and other factors. These studies aim to form a general methodology for further experiments based on the proposed technology. Unlike a physical and mathematical model, a practical approach will allow for a more flexible approach to solving the optimization problem [46,47].

3. Results

Based on the developed physical and mathematical model of particle motion in the torch, experiments were conducted, during which, an experimental study on the influence of technological parameters on the quality of the finished surface was carried out.

Such experiments were based on the laws of classical mechanics. It was taken into account that the particle has a high speed at the moment of departure. The entire process of its movement in the spray torch is classically determined by the airflow, in which the particles of the mixture slow down (the process of energy loss). However, electrostatic field forces are included in this scheme when using electrostatics. Thus, in practice, the determining factors are as follows:

- Distance between nozzles;
- Nozzle diameter;
- Torch opening angle;
- Plant performance;
- Field strength parameters.

The decisive factor in this case is the strength of the applied mixture at different distances and voltages, as well as the degree of rebound depending on the distance to the nozzle, equipment power and voltage [45].

The tests were carried out at the VSTU test site using a Duo-mix 2000 mixing pump and an experimental, previously patented spray nozzle printed on a 3D printer. This nozzle provided the tribostatic charging stage. The ion generator for the air environment had standard power of 1.2 kW. Power was supplied to the corona electrodes from a standard power supply unit with power of 5 kW. For the experimental sketch of the shotcrete mixture, vertical fences were created at the site specifically for testing technologies when working with this mixing pump.

The resulting shotcrete samples were cut into shapes of the required size and transferred to the laboratory to analyze the strength and other physical indicators.

For the experiments, grade "B25" shotcrete was used. The main characteristics of the mixture are given in Tables 1 and 2.

Table 1. Characteristics of the shotcrete mixture used in the experiments.

Name of the Mixture	Composition 1 (Gunite B25)
Main description	Dry construction mix for repairing large defects using the "dry" gunite method
Concrete class	B25 F200 W10
Appearance	Dry, loose, gray, homogeneous mix
Aggregate size, mm	2.5
Amount of mixture per 1 m^3 of shotcrete, kg	200
The thickness of the application of one layer in mm	4
Material consumption, kg/m^3 (with a layer thickness of 10.0 mm)	~20

Table 1. *Cont.*

Name of the Mixture	Composition 1 (Gunite B25)	
Average compressive strength:	MPa	Kg/cm^2
1 day, not less	10	102
2 days, not less	15	153
28 days, not less	32.7	333.4
Water resistance	W18	
Frost resistance, cycles	F1200	
Adhesion strength to the concrete surface, MPa, not less	1.5	
Water absorption, kg/m^2h 0.5, not more	0.4	
Modulus of elasticity, GPa	20	
Content of chlorine ions, %, not more	0.1	
Class by SST 56378-2015	R3	

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

Indicators	Composition 1 (B25)
Type of binder	Cement grade PC 400 (SST 10178)
Type of filler	Sand, according to TU 5745-001-162168921-06
Size of filler particles, mm	2.2
Compliance of filler to sieving curve	Complies

The experimental equipment that was prepared for the conduction of experiments in laboratory conditions is shown in Figures 4–6. Figure 7 shows a photo of field tests conducted during the construction of a swimming pool in Voronezh.

Figure 4. Formation of the experimental setup.

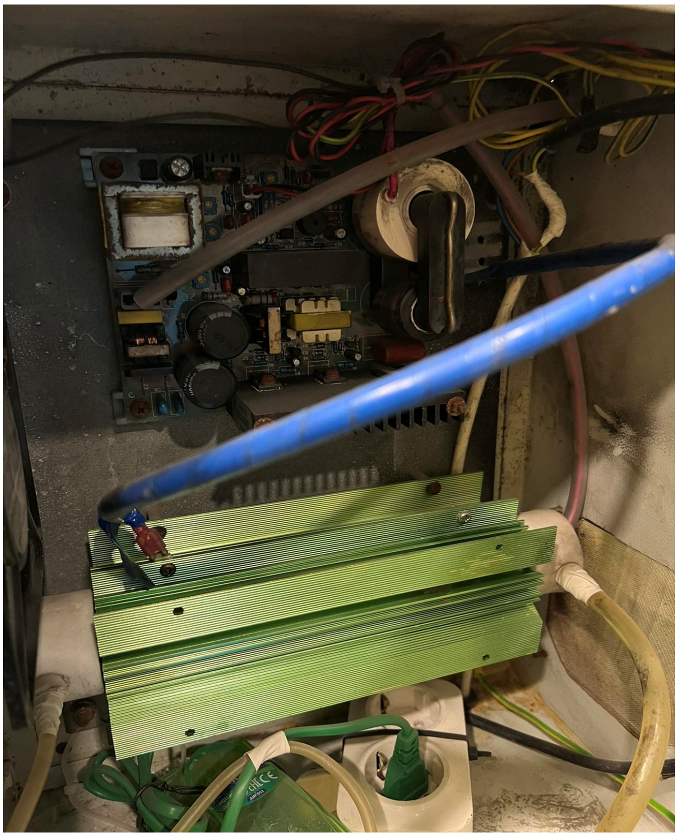

Figure 5. Power supply unit for 170 kV, 5 kW (from industrial ozonizer).

Figure 6. Nozzle with insulated corona electrodes.

Figure 7. Field tests at a Voronezh construction site (private swimming pool).

If, with the standard dry shotcrete technology, the rebound of the material was, on average, 20%, then the use of the electrostatic treatment of the cement–sand mixture reduced application losses to 5–6%. Figure 8 shows a bar chart that shows the dynamics of the rebound mass. The numbers 1–11 indicate the sample numbers: when sketching, the losses of the applied material were weighed each time, and the % rebound from the total mass of the mixture was determined. The reduction in material losses is associated with the step-by-step optimization of the main parameters, as shown in Figure 9; here, a surface reflecting the dependence of the rebound on the electric field strength and the distance to the nozzle of the shotcrete machine are shown.

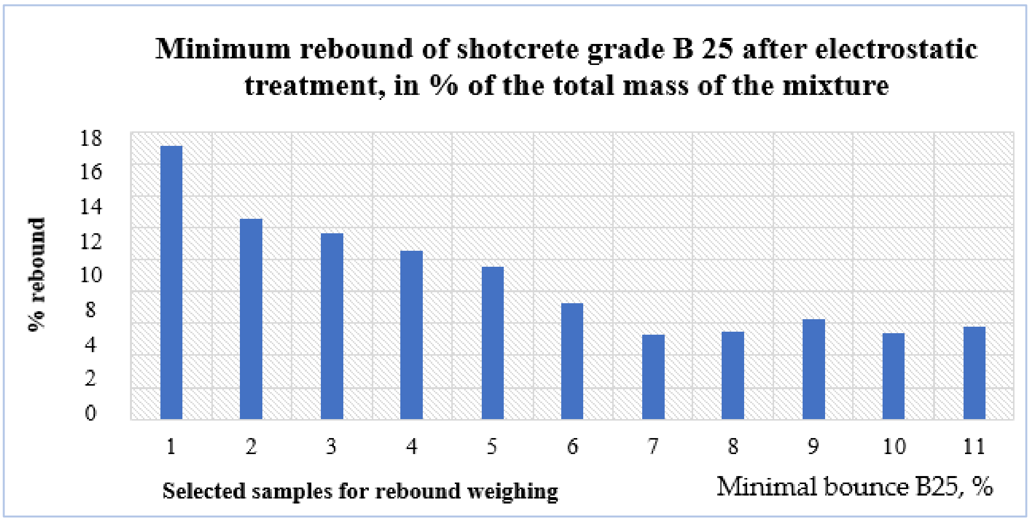

Figure 8. Minimum rebound of grade B25 shotcrete after electrostatic treatment, %.

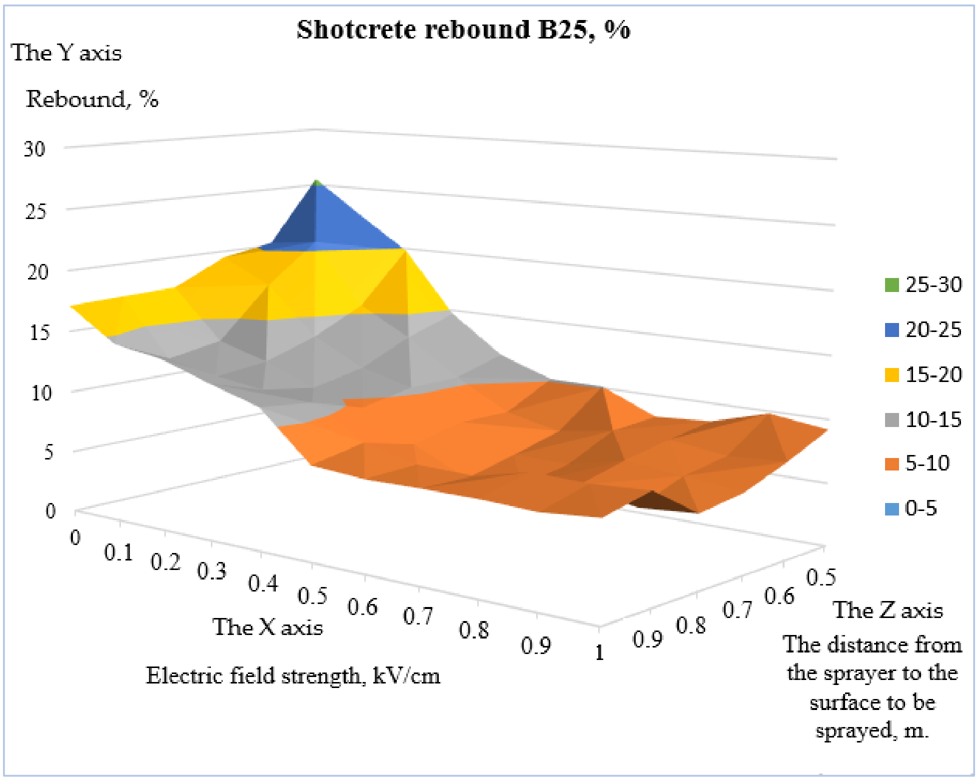

Figure 9. B25 shotcrete rebound.

During the tests, the cement–sand mixture was applied in layers. Then, cubic samples were formed from it. To study the effect of the electrostatic treatment of the mixture on shotcrete, strength tests for six "B25" samples with a size of 100 × 100 × 100 mm were performed on the Instron 1100 HDX universal testing machine (Figure 10) according to GOST 10180-2012 (according to control samples), and flexural and compressive strength were tested according to GOST 310.4-81 [46,47]. The results of the change in the tensile strength are shown in the graphs (Figures 11–14). Figures 11 and 12 reflect the increase in compressive and bending strength limits when using electrostatics during 14 days of solidification of shotcrete. An accelerated increase in strength was recorded in the first 2 days of concrete solidification; then, the speed became similar in value. Figure 13 reflects the 28-day strength of shotcrete samples that were not treated; the graph in Figure 14 shows similar results for samples after electrostatic treatment. Obviously, after complete solidification, the strength of the samples in the second case was noticeably higher.

Figure 10. Instron 1100 HDX machine and prototypes.

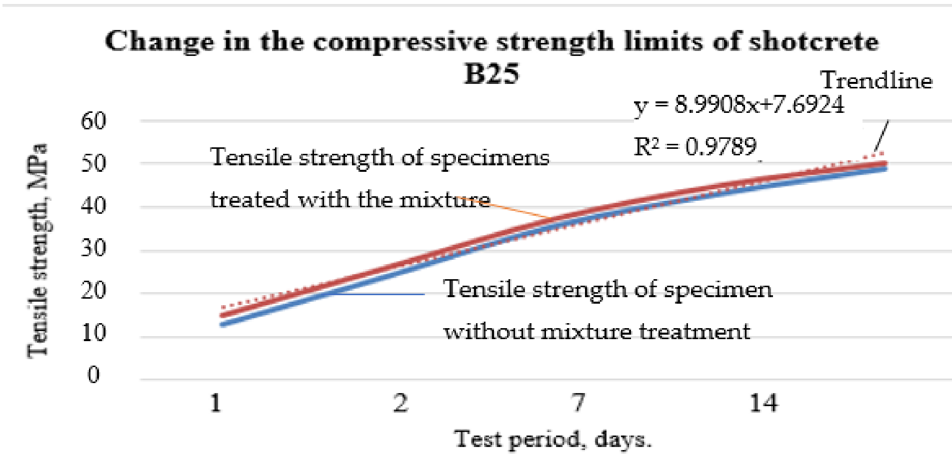

Figure 11. Graph of changes in the compressive strength limits of B25 shotcrete without treatment and with the effect of electrostatics.

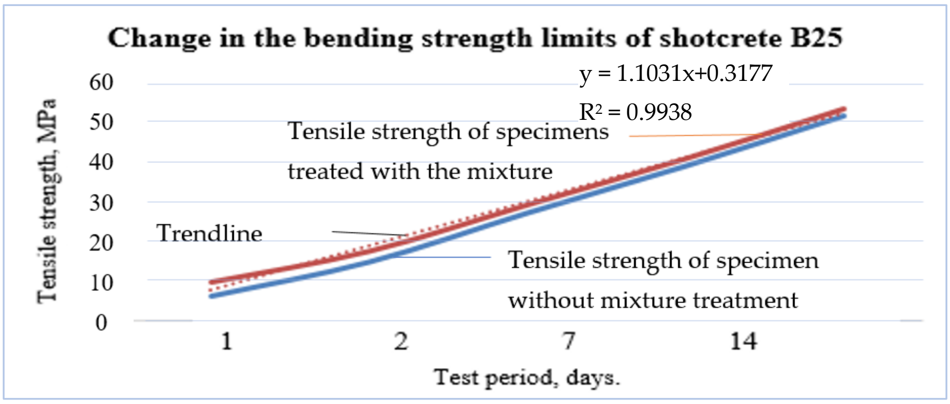

Figure 12. Graph of changes in the bending strength limits of B25 shotcrete without treatment and with the effect of electrostatics.

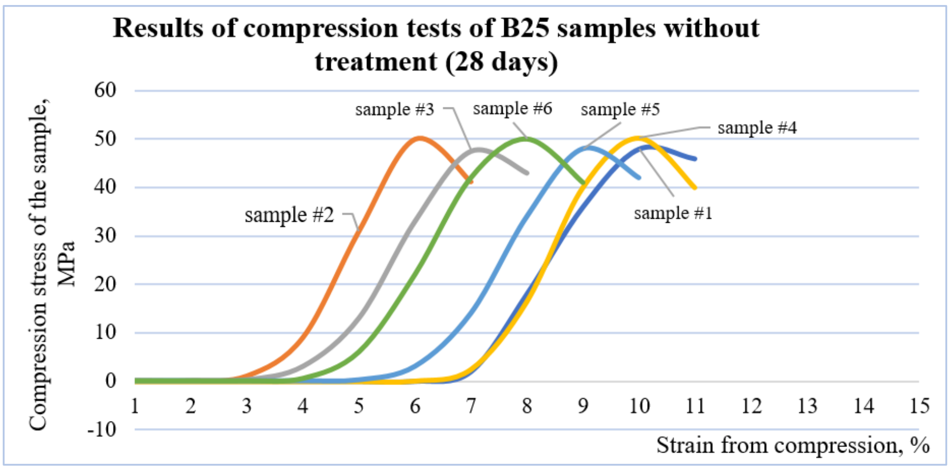

Figure 13. Results of compression tests of B25 samples without treatment (28 days).

Optimal parameters in terms of the rebound value and the strength of the finished surface depending on the torch distance and the capacity of the classic installation were determined experimentally. The efficiency of using a vortex gunning nozzle was proven in [25], where studies were conducted with a classic nozzle and then with a vortex nozzle developed by the authors of this study. Figures 15 and 16 clearly show the increase in strength and the decrease in rebound even without electrostatics, when only the distance to the nozzle and the installation's capacity based on the Duo-mix 2000 mixing pump were changed, with the other parameters being equal. Eighteen samples of shotcrete were examined. Based on the results of these experiments, fixed parameters were set for tests using electrostatics, which were a nozzle diameter of 10 mm and a mixing pump capacity of 3 m^3/h, since it was in this power range that the optimal results were observed depending on the variation in tension and the distance from the sprayer to the surface being sprayed.

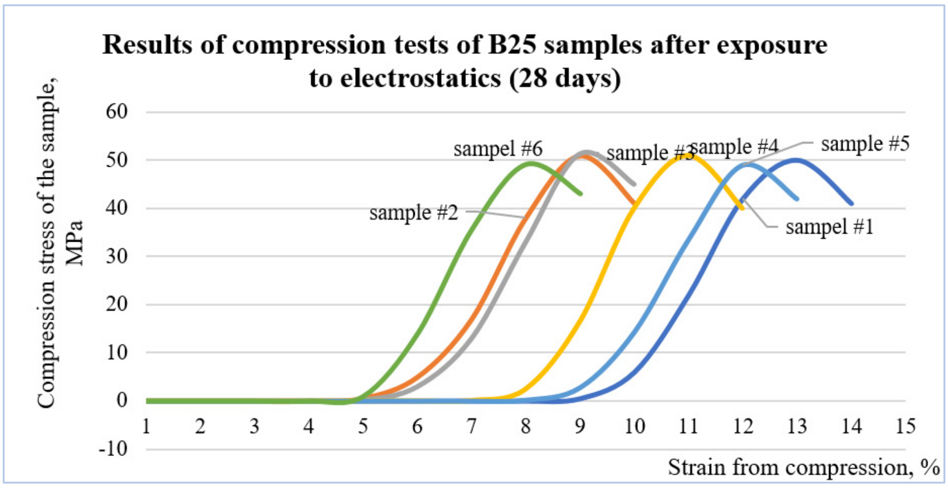

Figure 14. Results of compression tests of B25 samples after exposure to electrostatics (28 days).

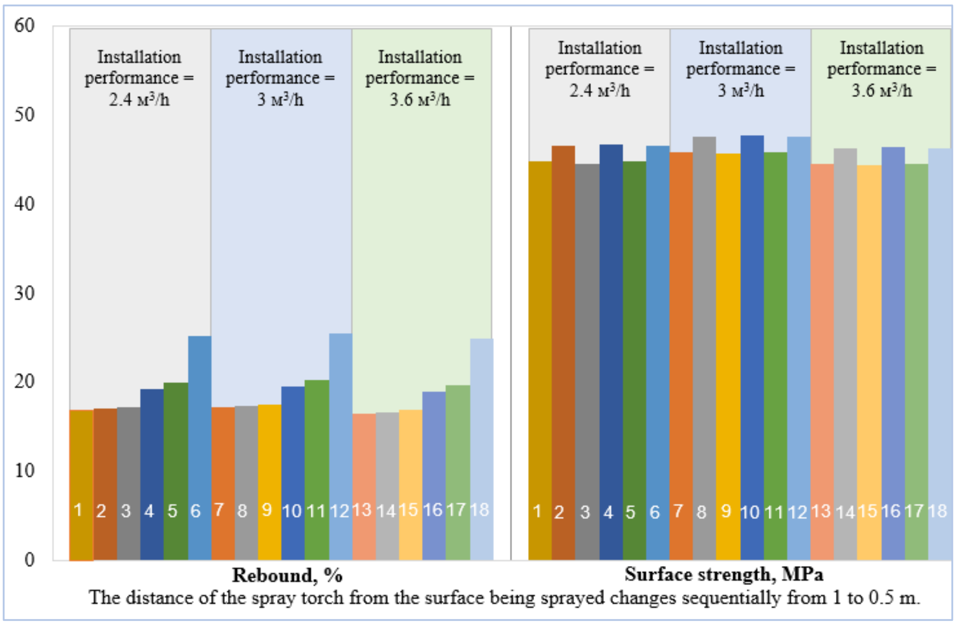

Figure 15. Average rebound and surface strength (the torch distance and the performance of the classic setup were varied).

During the experiments, it was necessary to identify the optimal parameters for corona charging for the effective electrostatic treatment of the cement–sand mixture directly on the electrodes. For this purpose, data were processed on the distance from the sprayer to the surface being sprayed and the applied voltage.

Table 3 and Figure 17 show the results of the study of the strength of the samples depending on the change in the electric field strength and the distance to the surface being sprayed.

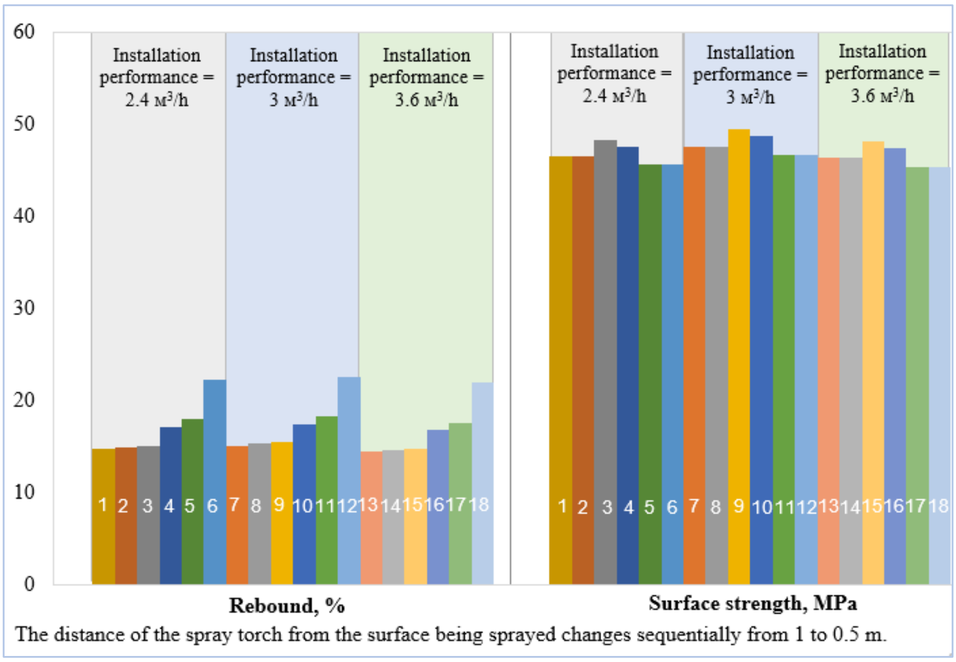

Figure 16. Average rebound and surface strength (the torch distance and the performance of the installation with a nozzle for vortex application of the mixture without the use of electrostatics were changed).

Table 3. Dependence of rebound on electric field strength and distance to the thrown surface of B25 shotcrete.

Distance from the Sprayer to the Surface Being Sprayed, m.	Rebound, % At Electric Field Strength, kV/cm										
	0	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1
1	17.12	14.50	13.87	12.51	11.31	7.51	7.21	7.29	7.31	7.17	7.58
0.9	17.28	12.59	11.64	11.20	10.80	8.33	7.37	7.20	8.27	8.20	8.46
0.8	17.43	13.35	12.17	10.58	9.60	7.29	5.31	5.50	6.30	5.40	5.77
0.7	19.47	17.50	13.56	11.46	10.40	8.20	6.22	6.19	7.23	6.77	6.29
0.6	20.23	20.70	15.60	13.33	10.47	8.17	7.25	7.98	7.94	7.37	7.63
0.5	25.52	22.60	19.82	14.70	11.66	10.15	10.12	8.24	8.53	9.82	9.21

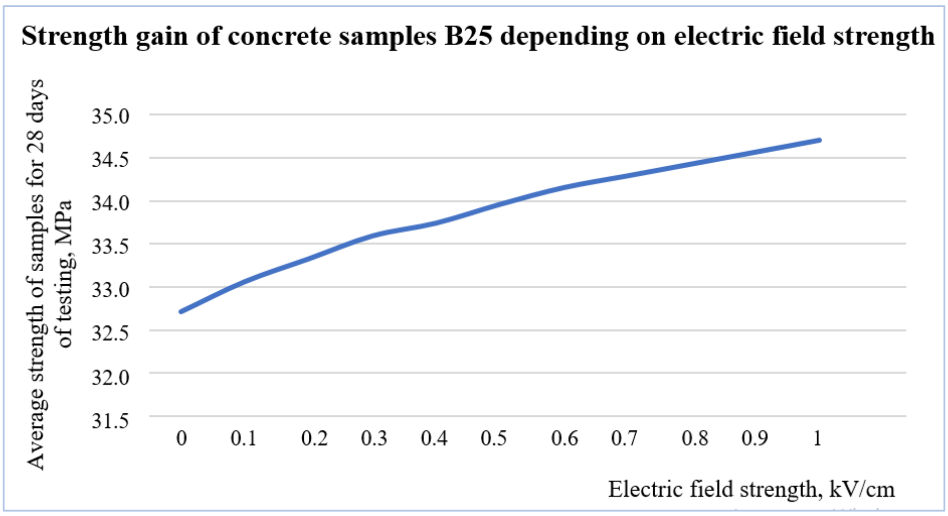

Figure 17. Strength gain of B25 concrete samples depending on the electric field strength.

4. Discussion

Experiments have shown that the effect of electrostatics on the shotcrete mixture leads to a decrease in rebound by an average of 5–6%, with its lowest value observed at a distance of 0.8 m and in the intensity range of 0.6–0.7 kV/cm, followed by stabilization of the graphs, i.e., a further increase in intensity does not significantly affect the rebound. Since the results for B25 shotcrete vary in a small range, and the deviations are minor, it is possible to recommend a distance to the thrown surface of 0.8 m and the limits of intensity change within 0.6 kV/cm. Analyzing the theoretically obtained proportions of the developed mathematical model, as well as the experimental results, it can be concluded that the presence of electrostatic field intensity slows down the particle and reduces the kinetic energy of the rebound, due to which, its amount decreases without reducing the power of the equipment. This model is ideal since several studies [19,20] clearly show that particles in a jet of shotcrete move not as individual particles but in portions. The lowest rebound of the mixture of 4.75% was achieved by combining electrostatic and turbostratic charging and ionized gas.

5. Conclusions

In this study, the use of electrostatics in the shotcreting of cement–sand solutions is justified, which reduces the rebound from 20% in dry shotcrete to 5–6%.

A scheme of interaction of force vectors caused by aerodynamic and Coulomb effects on particles of cement–sand mixtures during shotcreting is formed.

An ideal model has been developed for the movement of shotcrete mixture particles in an electrostatic field when applied to the surface to be sprayed.

It has been experimentally determined that the use of electrostatics makes it possible to reduce the time of initial setting of the cement dough due to the more active hydration of the mixture. The acceleration of strength gain is noted in the early stages of hardening; then, it approaches the standard indicators.

The optimal electrostatic field strength is 0.6 kV/cm, and the distance from the sprayer to the surface to be sprayed is 0.8 m.

It is established that the location of the corona electrode should be in the center of the atomizer. For more uniform ionization with lower energy consumption, it is necessary to consider the use of several electrodes, which will be the subject of further research.

The proposed technology of "dry" shotcrete is most economically justified for carrying out such large-scale works as mass housing and industrial construction, strengthening road slopes, the construction of seaports and coastal protection structures and the creation of subway tunnels, where material losses due to rebound are simply enormous, and the need for the high strength of the resulting surface is extremely high.

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