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Production of high-quality polydisperse construction mixes for additive 3D technologies.

M D Gerasimov, **Yu V Brazhnik**, **P S Gorshkov**, **S S Latyshev**

Belgorod State Technological University named after. V. G. Shoukhov, Belgorod, Kostyukov St, 46, 308014

E-mail: mail_mihail@mail.ru

Abstract The paper describes a new design of a mixer allowing production of high quality polydisperse powders, used in additive 3D technologies. A new principle of dry powder particle mixing is considered, implementing a possibility of a close-to-ideal distribution of such particles in common space. A mathematical model of the mixer is presented, allowing evaluating quality indicators of the produced mixture. Experimental results are shown and rational values of process parameters of the mixer are obtained.

1. Introduction.

Currently, production technologies of dry polysidperse powder play an important role in growth of the global market of building materials. Such mixes have great importance not only from the point of view of aesthetic finishing and cosmetic repair, but because they are used more and more often to obtain a complete construction facility with predefined properties by means of additive technology of 3D printing. In recent years, such mixes have firmly established themselves in the construction market and are continuing their growth. All over the worlds, including China and Brazil, where currently there are the highest rates of growth of construction mixes, new developments appear for resolving concrete issues of the construction industry.

Rapid development of innovation technologies, studies of materials at the nanometer level and the complex approach open up great prospects for this field of work. The main driver for production development is, of course, large demand for modified construction mixes. With speed of residential construction constantly increasing, use of construction mixes is the best variant for both construction (due to multiple reasons, including quality, range of products, time costs during construction) and cosmetic repair or finishing. The principle "add water and apply" made them popular in the modern market [6, 7, 8].

Properties of construction mixes depend on physical, chemical and mechanical characteristics of its components, while their energy costs depend on the nature of their processing. Due to that, construction mix production shall be considered as a separate chemical processing system within the multipurpose production of different construction materials and consisting of different subsystems, consuming a significant number of diverse feeds and energy resources for production of the mixes.

The principal processes in the construction mix production that influence significantly their performance characteristics are: feed pre-processing, its dosing and mixing, distribution of small-scale chemical additives and pre-mixes throughout the main body of the product. Uniformity of the material is the foundation of required quality in modern construction mixes. Performance characteristics of the final product directly depend on uniformity of distribution of components throughout the bulk of the mix. Even minuscule deviation in the content of small-scale additives due to insufficient distribution may adversely affect both physical-and-mechanical and performance characteristics of the mix.

That is why the mixing shunt is the most critical unit of any dry construction mix plant. Thus, operation of mixing equipment is a critical step towards obtaining a high quality product.

Together with methods to lower power costs [1] in construction mix production by means of the rational mechanical mixing method, it is necessary to study the process that changes concentrations of the component of the mix in a high-speed mixing mode.

That is why creating improved mixers with lower consumption of resources and a wider range of product, produced with the same unit, is the current task for engineers in the field of construction mix production, mixers being the most important equipment in the process chain.

2. Design solution.

According to analysis of available design solutions [3, 4] for production of dry construction mix mixers, let us propose a design of a paddle-wheel mixer, where circulation of the material is along the body through the whole height of the mix layer.

The design embodies an idea of countercurrent convective flows of mixed material, both in horizontal and in vertical direction. Helical spirals, installed on the internal surface of the mixing drum, provide such flows.

A general view of the designed unit is shown in Figure 1. It consists of frame 1, with cylindrical drum 11, inside which there are screw augers installed. The drum is put in motion by driving unit 5, installed on bracket 6. The driving unit consists of an electric motor and a gearbox. For initial belt tensioning, as well as for belt adjustment during operation, there is drum drive tensioner 7. On top, the drum is covered with hard-mounted cover 8, which holds the vertical shaft and prevents outgo of mixed components from the mixing drum. There is feeding opening 10 in the cover. The shaft with the paddles is put in motion by motor 3 installed on carriage 2. Rotation from the motor to hard-mounted paddled shaft pulley 9 on the drum spindle is transfered with a vee belt transmission. There is tensioner 4 for the paddled shaft drive as well. The internal body cavity of drum spindle 12 is an unloading device for finished material.

The frame of the experimental unit was welded from the equal iron angle and rectangular section. The rectangular section of 40×25 mm with wall thickness of 2 mm was used for manufacture of posts. There are also diagonals of the same section welded in for rigidity.

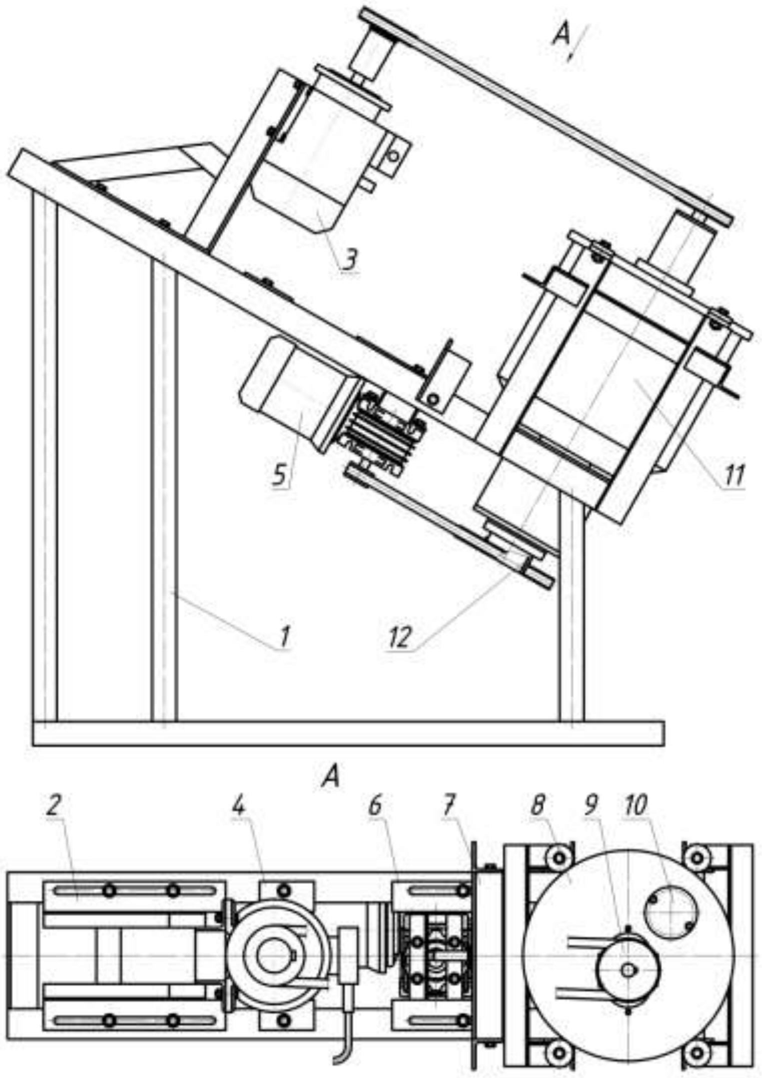

Figure 1. A general view of the paddle-wheel mixer: 1-frame; 2-motor carriage; 3- motor to drive the paddled shaft; 4 - paddled shaft drive tensioner; 5-drum drive; 6-drum driving motor carriage; 7-drum motor tensioner; 8-drum cover; 9-paddled shaft pulley; 10-feeding cover; 11-drum; 12-unloading opening.

Rectangular structure 2 was welded for installation of all the components of the mixer; this structure was then welded to the posts. It was made of equal iron angle 50 mm. The thickness of the iron is 5 mm. To hold cover 8 (see Figure 1), support frame 3 is welded from equal iron angle of 50 and 40 mm. To fix the cover, there are cylindrical washers welded to support frame 3. The washers have through holes for 10 mm bolt along their axis.

The mixer frame is designed and manufactured in such way that the installation plane of the mixing drum and other components is tilted to the horizontal plane. The tilt of the experimental unit is 29°.

The drum assembly is fixed to the frame with four M10 screws (Figure 2). The mixing drum has body 1, cylindrical in form. The bottom part of drum 2 is conical. The walls are 6 mm thick. The outside diameter of the drum is 320 mm. There are screw augers 3 welded to the internal surface of the drum, they are provided with gaps for shaft's paddles to pass. Spindle 5 is welded to the body. There are two roller bearings 4 slipped over the spindle. The outer races of the bearings are slipped over the internal surface of bearing box 9, which is in its turn fixed with screws to the mixer frame and holds the drum assembly motionless. The bearing box is covered with covers 11 and 10 on both sides. To hold the inner race of the bottom bearing in place, there are two retaining nuts 6, which prevent axial movements of the inner race. Pulley 8 is fixed with spline 7 to accommodate the belt transmission torque from the drive to the mixing drum. The pulley is forced onto the shaft. On the drum spindle, there is a key groove, preventing the pulley from turning spinning.

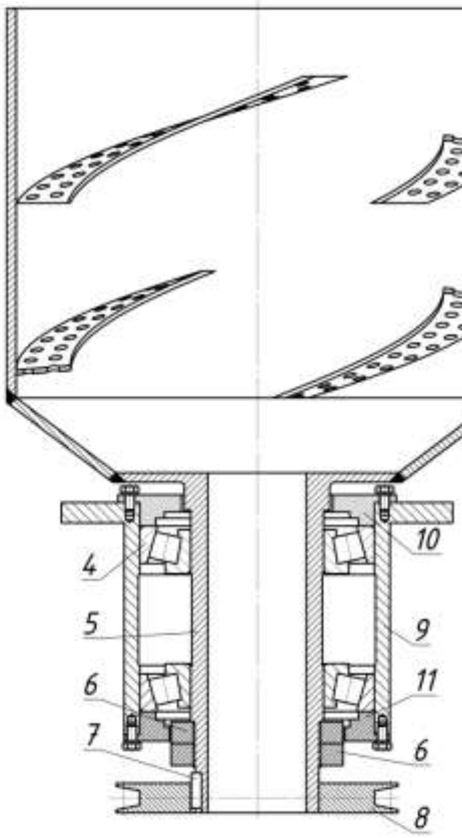

Figure 2. Drum assembly: 1- drum body; 2- conical bottom; 3-screw auger; 4- bearings; 5- spindle; 6- retaining nuts; 7- spline; 8- pulley; 9- bearing box; 11,10- covers.

Figure 3 shows the shaft with bushings and paddles installed. There are three bushings installed on the shaft: two end bushings 1 and middle bushing 2. Each bushing has three paddles 3, rotated with respect to each other at 120°. The top row paddles are rotated at 180° with respect to the other two rows. Paddle rows with bushings are spaced at 124 mm and 112 mm. The shaft is installed onto two bearings 4. The outer races of the bearings are fitted into bearing box 5. The bearing box is covered with caps 6, 7 on both sides, completed with gaskets. The bottom bearing is a cartridge type bearing. The bearing box is installed free-ended onto fixed drum cover 8. The mounting seat for the bearing box is cut in the cover. There are threaded boltholes in the cover around the mounting seat. The shaft assembly mounting seat has three installation positions: central (on the cover axis), limit (48 mm away from the central one) and intermediate position. The bearing box is fixed to the cover with screws. In the bottom part of the cover, there is a ring groove to prevent outgo of material and dusting. A gasket is installed into this ring groove.

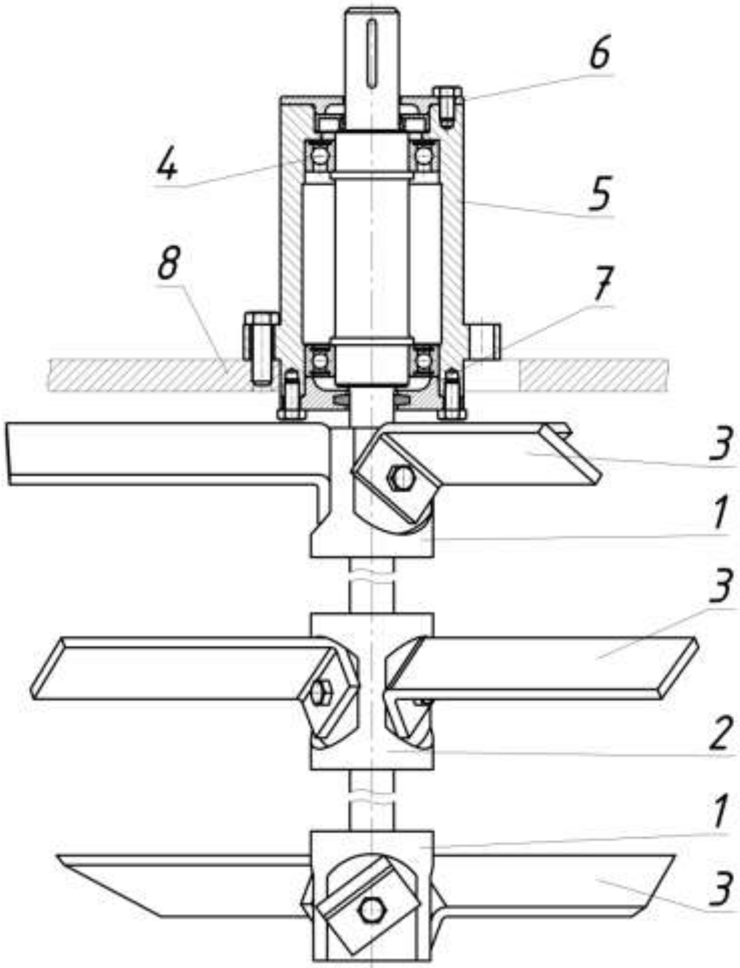

Figure 3. Shaft assembly: 1-end bushing; 2-middle busing; 3-paddle; 4- bearing; 5- bearing box; 6,7- bearing caps; 8-drum cover.

Operating principle of the mixer

The bulk material mixer operates in the following way: the components subject to mixing are loaded through feed opening 10 (Fig. 1) and enter inside drum 11. Simultaneously with loading, motor 3 is turned on and starts rotating the vertical shaft with the vee belt transmission. Due to paddle rotation, a vortex appear in the drum and starts moving the material from the top to the bottom of the drum. The material starts circulating. Some time (2-5 seconds) later, drum electrical drive 5 is turned on, it consists of the motor, a worm gear and a vee belt transmission. The drum starts rotating. The drum shall rotate in the direction opposite to that of the paddles. The drum rotational direction is selected depending on the auger's thread direction. The material is thrown about the augers by the paddles. The screw augers raise the components being mixed in vertical and horizontal direction. Moving along the auger's surface, the mixture arrives to the second row of paddles, being moved in both vertical and horizontal directions, it arrives to the middle section of the auger and moves up. There, the mixture reaches the top part of the mixing drum, where reverted paddles cut the moving mixture from the auger and direct it down towards the main flow of the mixture. After mixing, the mixture is unloaded through unloading opening 12. When the mixer is unloaded, the sequence repeats.

Thus, the proposed mixer design allows increasing uniformity of the product and reducing the mixing time by creating components circulation in both horizontal and vertical direction inside the mixing drum.

3. Qualitative indicator of the paddle mixer operation.

To evaluate qualitatively the mixer operation, one may use key component concentration and its change during the mixing as an indicator. We will consider the process of change in concentration of the key component inside the paddle mixer within the framework of a diffusion model [2]. The diffusion model corresponds to a flow with plug flotation of material, complicated with transverse mixing of fine grade material, driven by the law of diffusion.

According to the mentioned-above information, the main equation for change in concentration of the key component may be formulated as follows:

$$\frac{\partial C}{\partial t} = -\bar{v}_z \cdot \frac{\partial C}{\partial z} + \frac{\bar{D}_r}{r} \cdot \frac{\partial}{\partial r} \cdot \left(r \cdot \frac{\partial C}{\partial r} \right), \tag{1}$$

where C is the key component concentration in the mixture;

$\bar{v}_z$ is an average value of axial circulation of material Oz;

$\bar{D}_r$ is an average value of transverse mixing coefficient of the mixture.

Basing on formula (1) and taking into account that the transverse mixing coefficient of the fine grade material is defined as a product of radial speed of material and its path length along this direction [5], let us find the necessary formula for change of key component concentration during mixing powdered materials:

$$C(t,r) = \frac{C_H}{J_0\left(\psi_1 \cdot \frac{d}{2 \cdot R}\right)} \cdot \exp\left(-\frac{\psi_1^2 \cdot l^2 \cdot A \cdot \left(1 + \frac{3 \cdot d}{2 \cdot l}\right)}{18 \cdot R^2} \cdot \omega \cdot t \right) \cdot J_0\left(\psi_1 \cdot \frac{r}{R}\right), \tag{2}$$

where d is the rotor shaft diameter, m;

ω is an angular velocity of the rotor, s^{-1};

R is the internal radius of mixer's body, m;

C_H is the starting concentration of the key component in the mixture;

J_0 is Bessel function of the first kind;

ψ_1 is the first root of the Bessel function of the first kind;

l is the length of the mixing paddle, m;

Obtained formula (2) allows describing the changes in concentration of the fine grade material key component in the paddle mixer depending on design ($l,\ d,\ R$) and process parameters ($\omega,\ t$).

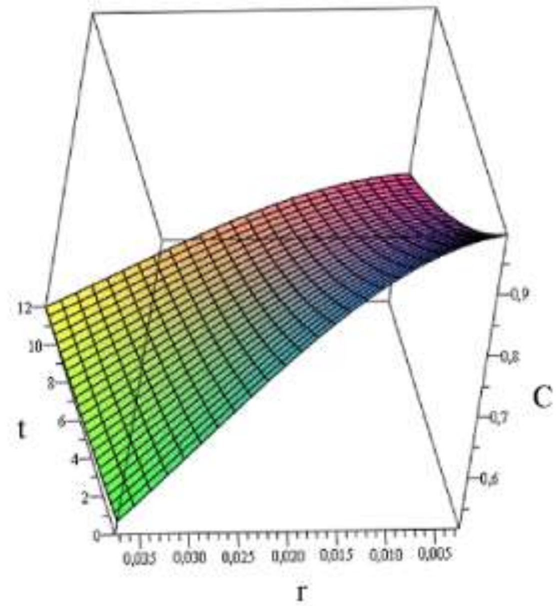

Figure 4. Dependency graph for changes in fine grade material concentration in the paddle mixed depending on time and distance from the rotational axis for the following values: ω=0.4; ψ=2.404; l=0.035; λ=0.84; d=0.005; R=0.04; C_k=0.5; C_0=1.

Visual interpretation of dependency (2) is shown in Figure 4 and allows concluding that the principle factor influencing the key component concentration is the exponential factor.

4. Determination of rational parameters of the mixer.

Study of operation of the proposed mixer design was conducted in two stages [1]. At the first stage, mixing of polydisperse powders in a mock-up model was observed; the model closely followed the design of the experimental unit at a smaller scale. The body of the model was made of transparent PVC. Recording of mix components movements was performed with a high-speed video camera Sony HXR-NX5M.

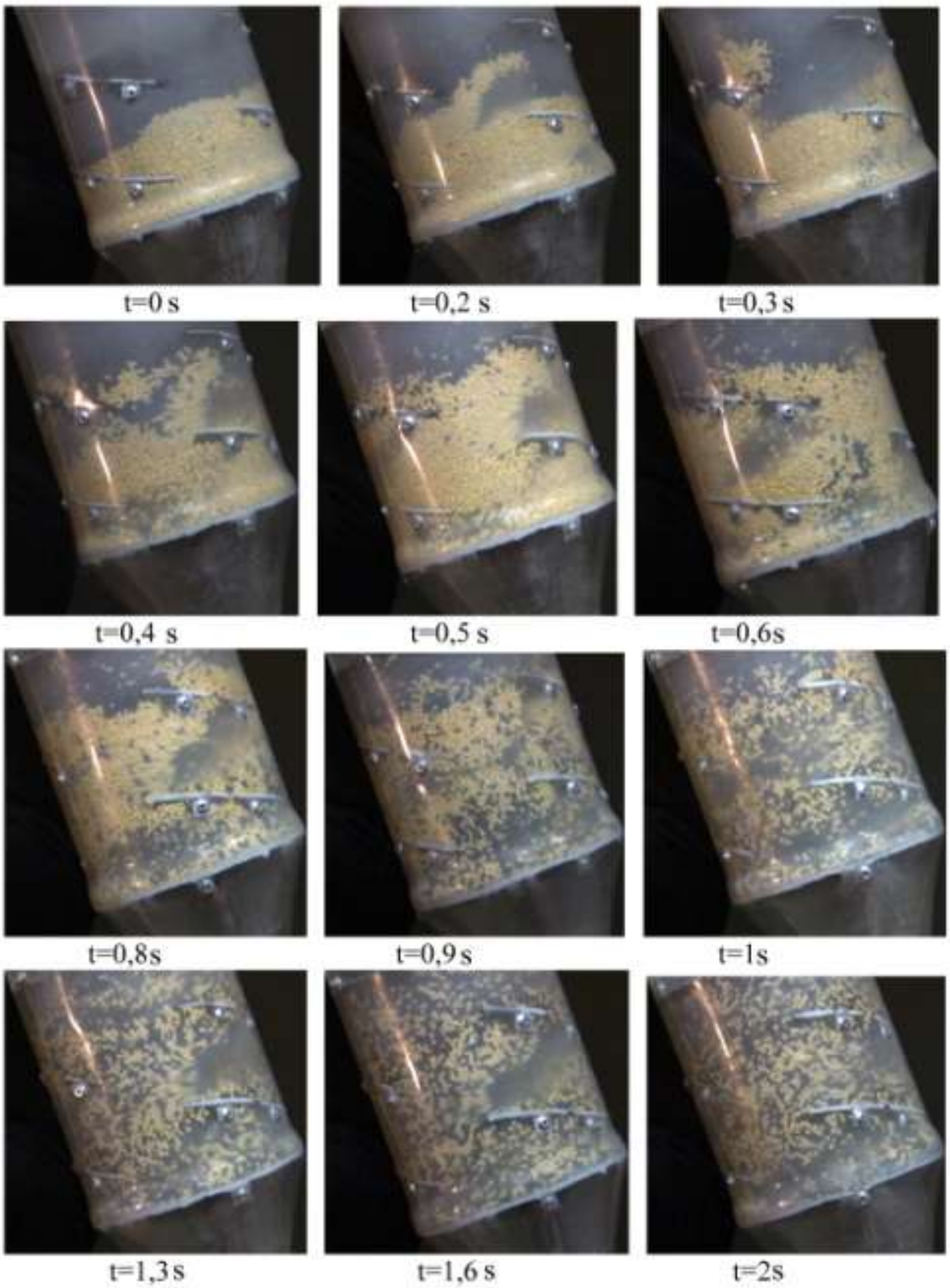

Figure 5. Movement of mix components inside the mock-up model in different moments of time.

Analysis of high-speed recording has shown that the material on the surface of the helix is involved in a pulsating movement. Such characteristic of the movement is caused by the fact, that the material, being displaced by the paddle goes up for a certain height and, by condition of ideal incompressible fluid, transfers its kinetic impulse to the layer of material on the surface of the helix. At that, the time necessary for the material to rise is directly proportional to the frequency with which a paddle passes over a certain screw auger.

After the paddle passes, there is a trace formed, where mix components are almost completely absent. This freed volume is taken by the material coming from the loser threads of the screw auger, which is an initial condition for a new impulse of material movement. It was also determined that with increasing rotor's rotational speed, and, as a result, frequency of a paddle passing under the screw auger, the material starts filling the trace only partially, leading to lower volume of material displaced by the paddle and lower value of momentum transfer. With a further increase in RPM, the paddle trace becomes completely unfilled and thus, transfer of energy to the material on the surface of the screw auger stops. It is explained that the time during which the paddle passes under the helix is insufficient to fill the volume of the trace.

At the second stage of studying the mixer operation, laboratory testing was performed [1]. From the results of these tests, rational parameters (Fig. 6) were obtained for operation of the proposed mixer design.

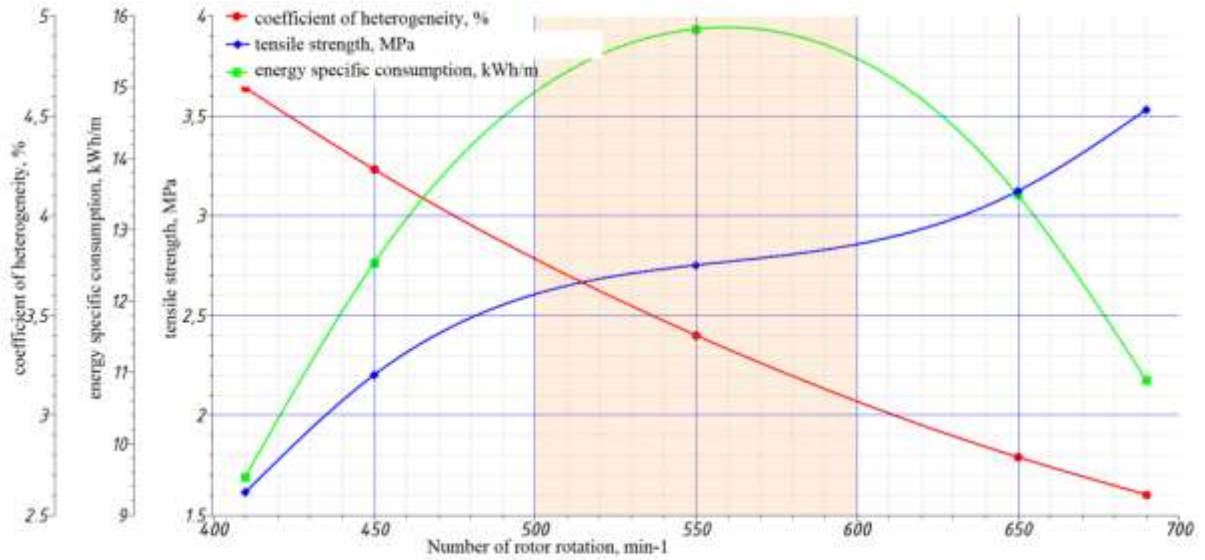

Figure 6. Dependency diagram for mixer operation and rotor's speed.

From Figure 6 it is obvious that when the rotor speed changes from 410 to 690 rpm, the key component concentration coefficient has a minimum value of 2.6% at 690 rpm, breaking strength has its maximum value of 15.9 MPa at 550 rpm, and power consumption has a minimum value of 1.6 kWh/t at the speed of 410 RPM.

Analyzing this dependency, one may say that the most rational rotor speed would be from 500 to 600 rpm (shaded area in Figure 6). Such values were selected on the assumption that the minimum compression strength of hardened mortar stone after 28 days shall be at least 15 MPa, heterogeneity factor shall not exceed 4% for high quality mixes, and power consumption shall be minimized.

5. Conclusion

Design and implementation of high-efficiency mixing equipment, allowing production of high-quality powders for additive applications in construction, is an important and timely task for researchers and industrial equipment designers. Development of 3D printing in construction imposes stricter quality requirements for components and their production process. Mixing, being a key stage in the process, influences the quality of a final product and thus shall be constantly improving.

The proposed mixer design allows increasing uniformity of the product and reducing the mixing time by creating components circulation in both horizontal and vertical direction inside the mixing drum, thus significantly raising quality of polydisperse powders.

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