Selection of effective equipment for shotcrete

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Abstract The analysis of technological equipment used in the shotcrete. Defines the main technical characteristics of mixer applications in the preparation of the mixture. With regard to the technical parameters and characteristics of the mixture determined the Reynolds number. Between the Reynolds number and the rotation frequency of the drum there is a positive correlation, increasing the dependence has a linear character. The Reynolds number is found that mode-mixing of the concrete is turbulent. Analysis of technical characteristics of sprayed plants were allowed to establish the dependence of their output power.

1. Introduction
Shotcrete quality is directly determined by the uniformity of the mixture which is in its turn determined by reliability and stability of the mixers [1-6]. During the shotcrete process, a dense layer of shotcrete is applied to the surface of structures. As compared with conventional concrete, shotcrete features enhanced mechanical strength, water tightness, frost-resistance, a better adhesion to the surface of the treated structure [7]. To ensure such properties of shotcrete, a number of problems has to be solved, including obtaining uniform mixture at a simplified mixture preparation arrangement and improvement of the agitation quality of the mixture components in mixer plants. For the uniformity of components distribution and of the mixture within the total batch volume, such motion trajectories shall be imparted to the individual particles of the concrete mixture which ensure their most frequent crossings. In such statement, the component mixing process in mixer plants is reduced to the external problem of hydrodynamics [8].

2. Analysis of basic provisions
In rotary forced action mixer plants, the component particle motion orbits within the mixture ore of forced nature due to the motion of the blades. The correlation between friction and pressure is determined by various factors.

During the interaction of an axis-parallel flat blade of a mixer plant with the mixture, its motion experiences resistance determined by friction forces generated on its lateral surfaces. In a longitudinal position of the blade along the flow vector of the mixture, there will be a minimum mixture quantity on the blade, whereas in a vertical position of the blade there will be a maximum mixture quantity on it. In the mixer drum, the motion of live mixture is stipulated by the presence of the viscous component involving the mixture layers touching the walls into a joint motion. In general, the motion of a continuous medium can be described by the following mathematical equation [9]:

$$\frac{dv}{dt} = -\frac{1}{\rho} A p + \vec{F},$$

(1)
where \( \vec{v} = \{v_1, v_2, v_3\} \) — velocity vector of the elementary liquid volume;
\( \rho \) — density of the liquid;
\( p \) — reviser of the tensions;
\( \vec{F} \) — tensions vector of mass forces;
\( \Delta \) — Hamilton’s operator.

The consideration can be confined by stationary motion

\[
\frac{d\vec{v}}{dt} = 0.
\]  

(2)

The live mixture can be described as viscous fluid motion by the differential equation of Navier-Stokes. In a rotary system of cylindrical coordinates and taking into account the equation (2) for non-compressible flows, this system of flow equations can be implemented in accordance with the algorithm provided in [9].

Thereby the mixture is considered to be a continuous medium featuring certain viscosity [8]. Navier-Stokes equation for volume flow of non-compressible viscous liquid has three components [10, 11] which can be generally written as follows:

\[
\rho \left( \frac{\partial \vec{v}}{\partial t} + \sum \frac{\partial \vec{v}}{\partial x_i} \right) = -\text{grad } p + \mu \left( \sum \frac{\partial^2 \vec{v}}{\partial x_i^2} \right) + \vec{F},
\]

(3)

where \( \rho \) — material density, kg\( m^{-3} \);
\( \vec{v} \) — velocity, \( m/s \);
\( \text{grad } p \) — pressure gradient, Pa;
\( \mu \) — material viscosity, Pa\( \cdot s \);
\( \vec{F} \) — external force, N.

The problem of stationary motion of the viscous mixture flow in the mixer drum, assumed it is homogeneous, is solved by selection of trigonometrical and hyperbolic functions. The solution allows to determine the field of velocities and the hydrostatic pressure in the stationary flow of the viscous mixture moving inside the drum. This will determine the power consumed by the mixer.

3. Development of a modified methods

For the analysis of various designs of mixing mechanisms for shotcrete manufacturing, we selected the mixer plant “Turbula” of the Swiss Company “Willy A.Bachofen”. This mixer plant utilizes a six-link mechanism with a double spatial (Cardan) joint, with the drum as an intermediary shaft. The complex double elliptic motion with variable angle grants to the mixed particles all freedom grades contributing to intensive and high-quality agitation. The increased intensity of the shotcrete component mixing is obtained by increased amplitude of the drum oscillations at its tilting form one limit position to the other with simultaneously increasing angle of rotation. The oscillation amplitude of the driven shaft depends upon the geometrical dimensions of the mixer drum. The cinematic analysis has demonstrated that the point performs the motion along a complex trajectory, being elliptical in a plane slowly tilting by a certain angle along a circle with a certain radius. The point motion can theoretically be split into a transfer one and a relative one. Based on the drum dimensions, it is also possible to determine the basic parameters of the particle motion trajectory and forces acting onto the particle [13]. The most important is the problem of the selection of the design and process parameters of mixer plants compatible with shotcrete plants during shotcrete spraying. We have performed an analysis of different shotcrete plants to select as most reasonable unit the plant SO-49 PBN with 4 m\(^3\) capacity. It is well-known that the concrete in a shotcrete plant should be consumed within 2.5...3 hours, that is why it is reasonable to select the capacity of the mixer plant in accordance with the capacity of CO-49ПбН unit. In our particular case, a mixer plant was selected with 800 l load volume, 0.8 m radii and 450 kg masses [6].
The capacity and the power of the mixer plant were determined in accordance with the dependence, m³/h, [8]:

\[ G = \frac{VZK}{1000}K, \]  

(4)

where \( V \) – load volume, l; 
\( K_1 \) – mixture output ratio, 0.65 ... 0.7; 
\( K_2 \) – mixture utilization ratio, 0.85 ... 0.9; 
\( Z \) – number of batches per hour, determined after [8]:

\[ Z = \frac{3600}{(t_1 + t_2 + t_3 + t_4)}, \]  

(5)

where \( t_1 \) – loading time, 10...15 s; 
\( t_2 \) – mixing time, 60...120 s; 
\( t_3 \) – discharge time, 5...15 s; 
\( t_4 = 14 \) s.

The power, kW, is determined after:

\[ P_W = \frac{P_1 + P_2}{\eta}, \]  

(6)

where \( P_1 \) – power per rotation of the mixer’s working part, kW; 
\( P_2 \) – power to overcome the resistance while stirring, kW.

Mixers with drum volumes of 500, 800 and 1200 liters were considered. The mixer with a volume of 800 liters became the most comprehensive in terms of performance, pressure, feed rate and specific power consumption with existing technological equipment.

The shotcrete mix composition is selected by mass, in accordance with a method stated in VCN126-90 and under recognition of the technical specifications of the ingredients. To determine the capacities of a mixer plant with 800 l loading volume, mixtures and components should be selected, and the Reynolds number shall be determined. Considering the technical specifications of this mixer plant, Class B 30 concrete was selected, with (OK) P4 flowability, F300 frost-resistance, with mixture components CEM 1 42.5 R cement after EN 197-1, sand, with bulk density 1.5 g/cm³, density 2.63 g/cm³, crushed rock with 5...10 mm size and additives. Based on the test data, a concrete of 29.8 MPa required strength was obtained, the water tightness and the frost-resistance were compliant with W12 and F300, respectively. Concrete composition per 800 l, including dry materials: 320 kg cement, 40 kg additives, 120 kg mineral powder, 800 kg crushed rock, 724.8 kg sand and 160 l water. The fresh concrete met the requirements of comfortable placing and density. An important specification for viscous liquids including mixtures is the Reynolds number [14-15]. At Reynolds numbers exceeding some critical value, the laminar flow becomes turbulent, that is, a flow type where the particles perform chaotic motions along complex trajectories. Generally, it is described as forces of inertia vs. material viscosity ratio and determined after the following dependence:

\[ Re = \frac{Vd\rho}{\eta}, \]  

(7)

where \( V \) – characteristic velocity, 0.332 mps at \( n = 0.29 \) s⁻¹;  
\( n \) – rotation frequency of the gravity mixer pot, 0.29 rps;  
\( d \) – characteristic drum dimension, 1.9 m;  
\( \rho \) – material density, 1800 kg/m³;  
\( \eta \) – dynamic viscosity of the flowing medium, 0.28 Pa·s.

Then:
Re = \frac{0.332 \cdot 1.9 \cdot 1800}{0.28} = 4061.28 \cdot 0.0}

In this case, a dependence of the varying of the rotation frequency of the drum on Reynolds number can be evaluated after the dependency:

\[ n(Re) = \frac{2 \eta Re}{d \cdot \rho} \]  

(8)

Figure 1 shows the dependence of number Re on the drum rotation frequency

\[ n \rightarrow \eta \rightarrow 0.36 \]
\[ 0.32 \]
\[ 0.28 \]
\[ 0.24 \]
\[ 3500 \]
\[ 4000 \]
\[ 4500 \]
\[ Re \]

Figure 1. Dependence Reynolds number vs. drum rotation frequency

Analytically, the dependence of the diameter change of the drum on the Reynolds number (Figure 2) can be evaluated after the dependence

\[ d = \frac{2 \eta Re}{\eta} \]  

(9)

For the analysis of the influence of the drum diameter on the required motor power, the following dependence is used:

\[ P(d) = P_1(d) + P_2(d) \]  

(10)

Figure 2. Dependence of Reynolds number on the drum diameter

The desired dependence of the influence of the drum diameter on the required motor power will be, kW:
$$P(d) = [A_m dZ\pi + (A_s + A_t) f] \frac{\omega}{1000}.$$  \hspace{1cm} (11)

Here $A_m$ and $A_t$ are the open surface of the mixture in the drum and inner side surface of the mixer drum, m$^2$; $f$ – friction coefficient; $\omega$ – mixer drum frequency, s$^{-1}$.

If the value $Re < 2300$ then the mode is laminar at $2300 < Re < 4000$ (sometimes, 10,000 is indicated) the mode is intermediary, and if $4000 < Re$ then the mode is turbulent.

4. Conclusion
As in our case $Re$ is higher than 4000, consequently, the flow is turbulent ($Re = 4061$). In the analysed concrete mixer plant, the mixing is performed at turbulent motion of the mixture particles, that is why the agitation quality in such mode will be better than in the laminar one, consequently, the shotcrete quality will be higher.

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