FORMATION OF GROUTING CURTAINS APPLYING UNSTABLE CEMENT SOLUTIONS

VENIAMIN A KHYAMYLAINEN

Kuzbass Politechnical Institute, RUSSIA

ABSTRACT

In spite of considerable experience in using of cementation while driving headings in watering rocks the density of grouting curtains does not always provide standard water inflows. It is stipulated for insufficient knowledge hydrodynamic aspects of the problem of formation of grouting screens with the help of unstable cement solutions.

Sedimentation of cement particles, filtration of liquid state along the flow and into porous blocks forming cracks are the peculiarities of the filtration of such grouts in rock cracks.

Rheology of unstable solutions while moving in the regime of sedimentation is suggested to describe as nonlinear dependency of tangential stresses from gradient of speed. In unsedimentation regime of moving with rather high speeds approximation of linear dependency is suggested, which is analogous to rheology of homogenous liquids. Filling the cracks with cementing material is considered to be sedimentation of cement particles.

Basing on the suggested approaches a mathematic model of the process of injecting of unstable solution into the hole is built. Two regimes of injection are examined: at the initial stage - with a constant expense and variable pressure in the hole; at the second stage - with a permanent pressure and variable expense in the hole. This model allows to determine all of the parameters of the technology of injection of the solution into the hole: injection pressure, cementation radius, injection time, solution expense; and to establish links between them. The estimation of the density of grouting screens according to the technology parameters of injection is possible. The data of individual theoretic researchers are confirmed by laboratory experiment on physical models of fissured mediums.

On the basis of the process of injection of unstable solution into a hole the dependency between the length of injection hole during preliminary grouting and the technological parameters of injection of the solution is determined.

The research data on hydrodynamic aspects of the problem of formation of grouting curtain allowed to work out technological scheme of preliminary cementation by holes of variable length. A given scheme of cementation takes into account the decrease of permeability of a block at every next hole on the account of the action of previous ones.

The scheme of preliminary cementation by holes of the variable length is inculcated on cal mines in Kuzbass while driving of six vertical shafts at the length of about 350m. Expected water inflow was 90-208 cu.m per hour.

In recent twenty years in the CIS (Commonwealth of Independent States) republic s and abroad a complex method of grouting of flooding rocks by cement-clay grouts has been developed in intensively introduced by the company "Specialised Association of Grouting and Geological Enterprises" (S.T.G.). Together with the development of this method in some regions of Russia (Kuznetsk and Karangand Coal Fields) methods of injection with the use of traditional cement grouts are being introduced. These methods were investigated and developed at the Institute "Kuznetskshakhtostroy" (Kuznetsk Mine Building) and the Kuzbass Politechnical Institute. This work is devoted to the analysis and summarising of them.

The peculiarity of filtration of cement solutions during grouting of fissured rocks is the sedimentation of cement particles, filtration of liquid state along the flow and into porous blocks, forming cracks. During hydrodynamic calculations cement grouts, which are heterogenous double phase mixtures in reality (suspensions) are not related neither to Newton liquids nor to tough-plastic bodies. The former statement is quite evident and based on the presence of solid cement particles in suspension. The latter statements based on impossibility of obtaining proved values of rheological characteristics (critical tension of shift and coefficient of structural toughness) because of the sedimentation of cement particles. That is why we took as a base physical introductions of the firm "Soletansh" of filtration of cement grouts as a hydraulic transport of cement particles in cracks for further improvement of the cementation methods. The filling of the cracks with cement material is accomplished by sedimentation of cement particles as a result of their sedimentation during the process of flow and as a result of the magnitude of additional sedimentation after cessation of flow, which is determined by yield of cement stone. Cement residue formed during sedimentation is packed under the pressure of the solution and does not move as the velocity of erosion according to Julstream [2] exceeds the magnitude of minimum nonsedimentation speed.

According to the above said statements the rheology of unstable cement solutions may be described by the following equations:

$$\tau = \begin{cases} \tau_0 + \mu\left(\frac{d\upsilon}{dh}\right)\frac{\ln(a^* - \tau_0/\mu)}{\ln a^*}, & 0 < \frac{d\upsilon}{dh} \leq a^*; \\ \mu\frac{d\upsilon}{dh}, & \frac{d\upsilon}{dh} \geq a^*, \end{cases} \quad (1)$$

where τ - is tangential tension in solution layer, Pa;
τ_0 - ultimate dynamic stress of shift, Pa;
μ - coefficient of structural or dynamic toughness, Pas;
$\frac{dv}{dh}$ - gradient of speed according to the height of the flow - h, S^{-1}.

Magnitude a^* is determined by the magnitude of critical (minimum non-sedimentation) speed $v_{\kappa p}$ and orientally may be equal to $a^* = v_{\kappa p}/0{,}5d$, where d - is a diameter of a cross-section of a flow. Magnitude $v_{\kappa p}$ and consequently a^* characterizes the transition to a non-sedimentary regime of motion.

At low speed of solution flow and consequently low magnitude of speed gradient dv/dh in the regime of intensive sedimentation unstable solution conducts as a plastic body. At $dv/dh \to 0$ $\tau \to \tau_0$ speed v and gradient dv/dh being increased tough properties develop. Unlinear rheological dependence transmits fluently into linear law of friction of homogenous liquids. Besides physical essence of coefficient μ changes slightly; coefficient of structural toughness transmits into the coefficient of dynamic toughness.

On the base of rheological approach a mathematic model of the approach of injection of unstable solution into the hole is built [3]. In terms of linear unstationary filtration the following equation is obtained for definition of pressure distribution:

$$\sum_{i=1}^{3} \frac{\partial}{\partial x_i} \left(F_i \frac{\partial P}{\partial x_i} \right) = \rho_0 \beta^* \frac{\partial P}{\partial t} . \tag{2}$$

where - is pressure of the solution, Pa;

ρ_0 - the density of the solution without pressure, kg/cu.m;

β - coefficient of compressibility of the solution, Pa-1;

F_i - main components of the tensor of the physical state of the system "massif-cement solution", taking into account the change in permeability of the massif owing to sedimentation of cement particles, s;

x_i - Decant co-ordinates;

t - time, s.

In case of quasi-isotropic medium - $F_1 = F_2 = F_3 = k/\nu m$

where k - is coefficient of permeability, sq.m;

ν - coefficient of kinematic toughness of the solution, sq.m/s;

m - coefficient of crack vacuum.

Let us examine plane-radial filtration during injection of the solution through individual hole into non-uniform quasi-isotropic massif. Studied regularities of physical peculiarities of cementation show that filtration is realised in three-layer medium; in the zone first to the hole [R_{ck}, R_{kp}] non-sedimentation movement is realised; in the second zone [R_{kp}, R] the movement is realised above the subsided solid state; in the third zone [R, R_B] the movement of filtrated along the length of flow liquid state is realised. Following the linear law of deformation of the rock massif under the influence of liquid pressure, the function of physical state of the system "rock massif-solution" may be presented in such a way:

$$F = \begin{cases} \dfrac{k_0}{\nu m_0} f(P,\beta), & R_{ck} \leq r \leq R_{kp}; \\ \dfrac{P_{kp}}{r \nu m_0} f^2(P,\beta), & R_{kp} \leq r \leq R; \\ \dfrac{k_0}{\nu_B m_0} f^2(P,\beta), & R \leq r \leq R_B, \end{cases} \tag{3}$$

where $f(P,\beta)=1+\beta(P-P_n)$ β - is deformation characteristics of the massif (complex parameter of fissure state), Pa-1;

P_n - bedded pressure of underground waters, Pa;

k_0, m_0 - values of k and m in the initial state of the massif (before injection);

ν_B - coefficient of kinematic toughness of filtrated liquid state, sq.m/s.

The distribution of the pressure was determined by the method of consequent changes of stationary states. Two regimes of injection are examined: at the initial stage - with the constant expense $Q_{CK}=Q^0_{CK}=const$ and variable (increasing) pressure $P_{CK}(t)$ on the hole; at the second stage - with the constant pressure $P_{CK}=P^0_{CK}=const$ and variable (decreasing) expense on the hole $Q_{CK}(t)$

Dependence of the cementation radius on the time $R(t)$ at the first stage of injection is concluded from the equation of material balance

$$Q^0_{CK}\cdot t = 2\pi \ell m_0 \int_{R_{CK}}^{R_B} f(P,\beta)\, r\, dr, \tag{4}$$

and at the second stage of injection - from the differentiated on t and integrated on t and R of equation of material balance

$$-\frac{2\pi \ell k_0}{3\beta\mu}(t-t_1) = 2\pi \ell m_0 \int_{R_{CK}}^{R}\left[\frac{1}{\varphi(R)}\frac{d}{dR}\int_{R_{CK}}^{R_B}\psi(R,r)\,dr\right]dR, \tag{5}$$

where ℓ - is the length of a hole, m;

μ - coefficient of dynamic toughness of the solution, Pa s;

t_1 - the time of injection of the solution, Pa s;

$\varphi[R(t)], \Psi[R(t), r]$ - consequent subintegrated suctions, determined by common integral of equation (2) together with the expression (3).

With the usage of equations (4) and (5) a system of alge-braic, transcendental and intergrodifferential equations was obtained, which describes unstational process of injection from the moment of delivery of the solution into the hole till cessation of its injection [3].

This derived mathematic model allows to determine all the parameters of the technology of the injection of the solution into the hole: the pressure of injection, dimensions of the zone of cementation, the time of injection, expense and concentration of the solution, regime of injection and to establish relations between them.

The derived model of the process of solution injection into the hole allowed to introduce the criterium of the density of grouting curtain as

$$J = \frac{K V_n}{V_H} \geqslant 1 , \qquad (6)$$

where V_n - is the increment of the volume of cavities in cemented zone by deformation of the massif under the influence of injection pressure, cu.m;

K - coefficient of regeneration of the initial volume of cavities after removal of the injection pressure, accounting residual deformation of the massif;

V_H - the volume of unfilled cavities after injection is stopped, cu.m.

Values V_n and V_H are determined according to the formulas

$$V_n = 2\pi \ell m_0 \beta \int_{R_{ck}}^{R} (P - P_n)\, r\, dr; \qquad (7)$$

$$V_H = \begin{cases} 2\pi \ell m_0 (1-B) \int_{R_{ck}}^{R_{kp}} [1+\beta(P-P_n)]\, r\, dr + \int_{R_{kp}}^{R} \frac{Q_{ck}(1-B)}{\vartheta_{kp}}\, dr, & R_{kp} > R_{ck} \\ \int_{R_{ck}}^{R} \frac{Q_{ck}(1-B)}{\vartheta_{kp}}\, dr, & R_{kp} \leq R_{ck}, \end{cases} \qquad (8)$$

where B is the yield of cement stone.

The qualitative density of grouting curtain may be estimated according to the quantity of residual water inflow into heading

$$Q_0 = \xi Q_1 + Q_2, \qquad (9)$$

where Q_0 - residual water inflow after cementation, cu.m/s;

Q_1 - water inflow from cracks, admitting solution (opening of the cracks $\delta > 0{,}1 \div 0{,}2 \cdot 10^{-3} \mu$) before cementation, cu.m/s;

ξ - coefficient of decrease of water inflow from cracks, admitting solution after cementation;

Q_2 - water inflow from pores and microcracks which are impossible to cement, cu.m/s.

Value ξ may be orientally determined from the formula

$$\xi = \frac{6{,}25\, Q_{ck}^2 (1 - B)^2}{\pi^2 R\, \vartheta_{kp} m_0^2 \delta_0 \ell}, \qquad (10)$$

where Q_{ck} - is the expense of solution at the end of injection, cu.m/s;

δ_0 - medium opening of cracks admitting solution, m.

Qualitative cementation by unstable solution is possible when the final expense Q_{CK} is equal to zero. As a result of this agreement the expression for determination of critical radius of cementation is obtain [4].

$$R = R_{CK} + \frac{k_0\left\{\left[1+\beta(P-P_n)\right]^{2,5}-1\right\}}{2,5\, m_0 \mu \vartheta_{KP} \beta} \tag{11}$$

its main difference from the formulas for determining of the radius of extension of tough plastic grouting solutions by F Y Kipko, Vitke is in the difference of rheological characteristics:

rheodynamic complex $\mu \vartheta_{KP}$ - the characteristics of directly moving solution without cementation and the kinematics of sedimentation of cemented particles identical to the product of critical stress of shift to characteristic linear dimensions of the cracks.

The length of the cement hole must correspond to absorbing ability of the hole, efficiency of injection facilities and is determined from the expression

$$\begin{aligned}(\gamma-\gamma_B)\frac{\ell^2}{2} + \left[P_M + \gamma h_{CT}(\gamma-\gamma_B)h_n\right]\ell - \frac{\mu R m_0 \vartheta_{KP}}{k_0}\ell - \\ - \Delta P^0_{CK}\ell - \int_0^\ell \Delta P_{CK}(z)\,dz = \frac{(\mu_B \ln\sqrt{C_B}-\mu)Q_{CK}}{2\pi k_0},\end{aligned} \tag{12}$$

where ℓ - is the length of the permeable zone, m;

γ, γ_B - specific weight of the solution and water H/cu.m;

P_M - indication on the pressure gauge, Pa;

ΔP^0_{CK} - the pressure losses during overcoming the hydraulic resistance when the solution flows along the impermeable area of the hole and in the pipeline leading to the hole, Pa;

$\Delta P_{CK}(z)$ - pressure losses at the permeable area of the hole, Pa;

h_{CT} - the height from static level of ground waters to the point of pump installation, m;

h_n - the height from the roof of water-bearing level to static level of ground waters, m;

$Q_{ск}$ - the expense of the solution in the hole, cu.m/s.

In order to check up the correctness of the mathematic model of the process of injection of the solution into the hole experimental investigations were made estimating the results of filling of the fissures with cement material using the model of fissured strained medium [4]. This model allows to examine planeradial flow in the fissure at a distance of 2.5m from the hole. The principle peculiarity of the experimental laboratory model was that the strained block was taken out beyond the filtration chamber containing the slot and transmission of the pressure of the solution onto the strained block with the help of punches arranged uniformly along the length of the flow.

As an elastically strained block rubber was chosen according to the criteria of Newton mechanical similarity. The scale converters for the capacity of the strained block, complex parameter of fissure state and the drop of pressure along the length of the flow were determined. The obtained dependencies between the distribution of the pressure along the flow, the final pressure drop, radius of cementation, strained and filtration properties of rock massif were checked up.

On the basis of the results of fulfilled researches technological scheme of preliminary cementation through the holes of variable length was worked out. The main idea of the introduced scheme is in the registration of the reduction of the massif permeability at the next in turn hole due to the cementation through preceding ones. According to the equation (12) it allows to increase the length of each following cement hole. Cementation is performed with the help of a number worked out technical solutions: periodical examination of conformity of absorbing ability of the hole to the productivity of cement pump in the process of drilling; controlling the injection pressure according to the changes of rock permeability; definition of rational methods of decreasing of liquid state filtration into the popres and microfissures of rocks; controlling the quantity of chemical solutions and methods of injection of their components into the rock massif having processed them chemically before hand.

LIST OF LITERATURE

For the article by Veniamin A Khyamyalyainen "Formation of Grouting Curtains Applying Unstable Cement Solutions".

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