The extraction of the water-air phase through a single filtration hole

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Abstract. The conducted studies allowed us to establish that the shape of the filtration holes should be subject to the above patterns. The second - it was established on the basis of the analysis of real Reynolds numbers and visual observations that the water extraction mode in the zone of action of the peristaltic wave of compaction is divided into three stages:

a) laminar spin mode;

b) turbulent spin mode;

c) intermittent spin mode.

The first stage of water extraction is determined by the classical two-dimensional (coordinate X and time t) water movement in a porous medium. Usually, this task is complicated by the presence of a water and gas phase in the squeezed stream. The first phase ends with the turbulent motion of the liquid-air phase. Turbulence as the second stage of the extraction of the water-air phase is determined by the dependence of the critical Reynolds number on the action of complex technological factors of hyper-compaction. This includes vibro-shock of peristaltic pressure and shear deformations from the reciprocating movements of the moldable mixture. The second stage ends with the transition to intermittent extraction of residual water. The third stage of extraction is characterized by the ultimate level of compaction \( P_{\text{max}} \) by breaking continuous filter channels and the transition to a submicrocellular structure of the compacted mixture [1, 2, 3, 4].

1. Introduction

The extraction of water from the mixture to be sealed will end when the difference in external pressure at the ends of the capillaries is overcome by internal capillary pressure. In this case, the pressure of the filtration resistance is proportional to the viscosity forces of the liquid phase [5, 6, 7, 8, 9, 10, 11, 12, 13, 14].
Figure 1. Model of physical modification of concrete mix from action shock-peristaltic pressure; a) concrete mix; b) transition state; v) concrete: 1 is pillar of concrete mixture; 2 is belt shock-peristaltic pressure; 3 is pressure ebra; 4 is capillary channel; 5 is perforated shape; 6 is filtration hole; 7 is hyper-compacted concrete.

Let us consider a concrete pillar exposed to a vibro-shock-peristaltic pressure field with the possibility of squeezing the air-water phase through a single filtration hole along the axis of the element in question (Fig. 1). The propagation of shock-peristaltic waves along a column of compacted concrete mix causes the formation of a capillary channel, which provides the extraction of the water-air phase of the material. The movement of the phase representing the excess mixing water is directed toward a single filtering hole under the influence of a pressure gradient. The jets of the water-air phase due to a change in the signs of vibrational pressure with a pulsating flow to the filtration hole. A thin film is formed from the jets at the inlet of the filtration hole. A separation region arises on the verge of the inlet part of the hole, the pressure in which is less than the pressure in the column of the concrete mixture being compacted. Due to the pressure difference, the air-water phase (liquid) rapidly flows out, clinging to the surfaces of a single filtration hole of external perforated shape. In this case, the visual observation revealed the decay of liquid films, the formation of droplets, and the pulsating emission of water streams out.

2. Methods
For a quantitative description of the process of squeezing excess liquid, it is advisable to introduce several parameters. Among the characteristic parameters, first of all, the thickness \( \delta \) of the liquid film,
which is formed as a result of the fluid flowing through a single filtering hole, and the length $L_c$ (trickle) of the non-disintegrated part of the film, i.e. the distance between the face of the outlet of the filtration hole and the place where the film loses its continuity and collapses as a result of an increase in the amplitudes of the capillary waves. With the film thickness $\delta$, the flow coefficient of the filtering hole $K_p$ is directly related.

The flow rate coefficient of the filtration hole $K_p \neq 1$ for two reasons. Firstly, due to energy losses due to vibro-shock-peristaltic pressures in the concrete column, as well as due to friction of the liquid on the walls of the filtration hole. Secondly, in connection with the compression (contraction) of the jet of the water-air phase caused by the flow around the inlet edges of the filtering hole. Moreover, the cross-sectional area of the air-water jet is less than the area of the filtration hole, which apparently prevents the removal of cement particles.

### 3. Results and discussion

We use the basic equation of hydrodynamics - the Bernoulli equation, obtained from the law of conservation of energy. In our case, taking into account energy losses, the Bernoulli equation for the streams flowing from the filtering hole will have the form:

$$P_n = P_a + 0.5 \cdot \rho_1 \cdot \theta_a^2 \cdot (1 - \varepsilon_c) \star$$

where $P_n$ is the complete shock-peristaltic pressure, causing fluid outflow;

- $P_a$ is the atmosphere pressure;
- $\rho_1$ is the air-water density;
- $\theta_a$ is the flow velocity in a compressed jet section;
- $\varepsilon_c$ is the total resistance coefficient.

* The equation does not take into account the velocity distribution over the jet cross-section due to the small cross-section, i.e. the flow remains one-dimensional.

From here

$$\theta_a = \frac{2 \Delta P}{\sqrt{(1 + \varepsilon_c)\rho_1}}$$

where $\Delta P = P_n - P_a$

Denoting the compression ratio of the jet $K_c$, the fill factor of the filter hole through $K_a$, equal to the ratio of the compressed area of the jet $S_c$ to the cross-sectional area of the inlet of the filter hole $S_0 (K_a = S_c / S_0)$, we find the volumetric flow rate of the air-water phase through a single filter hole:

$$Q = S_c \cdot \theta_a = \frac{K_a}{\sqrt{(1 + \varepsilon_c)}} \cdot S_0 \cdot \frac{2 \Delta P}{\rho_1}$$

where $K_c = \sqrt{1/(1 + \varepsilon_c)}$ is the velocity coefficient of a flowing liquid stream;

Then the volumetric flow rate of the water-gas medium through a single filtration hole will be equal to:

$$Q = K_p \cdot S_0 \cdot \frac{2 \Delta P}{\rho_1}$$

where $K_p = K_a \cdot K_c$ is the flow rate of a single filtration hole. This coefficient depends, first of all, on the shape of the filtration hole, as well as on the flow regime of the liquid, and can be determined experimentally. Consider the experimental data for various forms of the outlet part of the filtration holes shown in Fig. 5.
The studied filtration holes were made by drilling in metal walls of various thicknesses. The data on the coefficients of velocity, stream compression, and fluid flow obtained experimentally can be generalized in the form of their dependences on the Reynolds criterion $Re_n$ [15]. Moreover, as the determining value of the Reynolds criterion,

$$Re_n = \frac{Re}{K_p}, \quad Re = \frac{4Q}{\pi d_0 \gamma}$$

where $d_0$ is the inlet diameter of the filtration hole; $\gamma$ is the coefficient of kinematic viscosity of a liquid. As can be seen from fig. 2, for small values of Ken, the flow coefficient $K_p$ is determined by the velocity coefficient $K_c$, and for large values, it is determined by the compression ratio of the jet or the fill factor of the filtering hole $K_a$. The obtained generalization of experimental data is valid if the criteria of Froude and Weber exceed certain values:

$$F_\gamma_n = \frac{\Delta P}{g \rho \gamma d_0} > 10; \quad W_1 = \frac{2\Delta P d_0}{K_{p,n}} > 250 ... 2500$$

where $K_{p,n}$ is the surface tension coefficient.

Figure 2. The dependence of the coefficients of the outflow from the filtration hole on the Reynolds number. $K_p$ is filter hole flow rate; $K_c$ is fluid velocity coefficient; $K_a$ is fill factor.

In this case, the lower value of $W_1$ refers to small Reynolds numbers $Re_n (Re_n < 1000)$, and the upper one to large ($Re_n > 5000$).

With a cylindrical shape of the filtration hole, the flow coefficient depends not only on the Reynolds criterion but also on the relative wall thickness of the hole ($h_0/d_0$).

When flowing around a sharp inlet edge, the flow first breaks away from the wall of the filtration hole, and then, expanding, occupies the entire cross-section. Thus, a vortex zone with reduced pressure is formed in the inlet of the filtration hole. Energy losses in such a hole occur during the flow around a sharp edge and a sudden expansion of the flow behind the vortex zone, as well as during friction of the liquid against the wall of the filtering hole. This phenomenon leads to the rapid clogging of the filtration holes and prevents the removal of particles of hydrated cement.

The total loss coefficient can be determined from the equation:
\[ \varepsilon_0 = \varepsilon_0^{vx} + \lambda_{tp} \cdot \frac{h_0}{d_0} \]  

(7)

where \( \varepsilon_0^{vx} \) is the loss coefficient in the inlet section of the filtration hole (when flowing around a sharp edge and sudden expansion); \( \lambda_{tp} \) is the coefficient of friction.

Then the velocity coefficient for the cylindrical shape of the filtration hole will be

\[ K_c = \frac{1}{\sqrt{1 + \varepsilon_0^{vx} + \lambda_{tp} \cdot h_0/d_0}} \]  

(8)

![Figure 3. The dependence of the flow coefficient of the cylindrical filtration holes.](image)

Figure 3. The dependence of the flow coefficient of the cylindrical filtration holes \( K_p \) on the Reynolds number.

a is the dependence of the fluid flow from the filter hole of the thin wall \( (h_0 \approx 0) \).

1 = \( h_0/d_0 \); \hspace{1cm} 3 = \( h_0/d_0 \); \hspace{1cm} 5 = \( h_0/d_0 \); \hspace{1cm} 10 = \( h_0/d_0 \).

The results of studies of the flow of various liquids from cylindrical holes are shown in Fig. 3. Here is also given the dependence for the outflow from an opening in a thin wall (curve a, Fig. 3).

With an increasing wall thickness of the filtering hole, the flow coefficient decreases, since friction losses increase. For small values of the Reynolds criterion, the flow coefficient for a cylindrical hole is less than for a hole in a thin wall, while for large \( \text{Re} \) values, as a result of rarefaction in the compressed section of the jet, the flow coefficient for cylindrical filtration holes becomes larger than the flow coefficient for holes.

Based on experimental data in the interval \( 1 \cdot 10^2 \leq \text{Re}_n \leq 1.5 \cdot 10^5 \) and \( 2 \leq h_0/d_0 \leq 5 \) hole filtration coefficient can be calculated from the following dependence, based on research [16, 17, 18, 19].

\[ K_p = (1.03 + \frac{50h_0}{\text{Re}_n d_0})^{-1} \]  

(9)

It has been experimentally proved that for large values of the Reynolds criterion, the flow coefficient for a given value \( h_0/d_0 \) remains constant.
Figure 4. Dependence of the coefficients of outflow from conical filtration holes; a - from the taper angle of the outlet part of the holes, $\alpha_{\varphi D}$; b - from the Reynolds number $Re_n$. $K_p$ is the hole flow coefficient; $K_c$ is the liquid velocity coefficient.

The size of the flow coefficient of the filtration openings is also affected by their taper. In fig. 4a shows the experimental dependence of the flow rate and velocity coefficients on the angle of conicity (the relative thickness of the filtration hole $(h_0/d_0) = 1; 3; 5; 10$) for a large Reynolds number [20].

With an increase in the taper angle, the velocity coefficient increases monotonically, which is mainly explained by a decrease in the energy loss due to expansion after internal compression and the flow coefficient first increases, but then, reaching $\alpha_{\varphi 0} = 60\ldots 65^\circ$ of the outlet part of the filtration hole begins to decrease, despite the increase in the velocity coefficient, which is associated with the loss of compression of the jet already to the exit of the hole. The larger the $\alpha_{\varphi 0}$, the closer the conical hole in its characteristics to the hole in the thin wall [21]. The dependence of the flow coefficient on the Reynolds criterion [22] for a conical hole with a relative wall thickness $h_0/d_0 = 5$ and a taper angle $\alpha_{\varphi 0} = 120^\circ$ is shown in Figure 5 b.

This dependence is similar to that observed during the flow of liquid in cylindrical filtration holes, but in conic holes, due to lower energy losses, large values of the flow coefficient are achieved.

Different forms of filtration holes are shown in Figure 5. The flow coefficient of a cylindrical hole can be substantially increased by chamfering the input or rounding the input edge (Fig. 5 b, v), while it reaches the same values as the flow coefficient of the hole with a taper angle, close to optimal (Fig. 5 c).
The lower value of the flow coefficient obtained when testing a cylindrical hole with a very smooth entrance (Fig. 5 d), compared, for example, with the value of the flow coefficient for the hole shown in Figure 5 v, is apparently explained by a decrease in the flow coefficient due to laminarization of the flow in the absence of disturbances and, as a consequence, an increase in the friction coefficient.

4. Conclusions
1. It is shown that the physical modification of concrete is carried out by the extraction of excess water, which occurs in laminar, turbulent, and intermittent modes. Equations are obtained on the laws of motion of the air-water phase, depending on the applied pressures and permeability parameters of the concrete mixture and the filtration holes of the mold.
2. It is proved that a quantitative description of the extraction process of the air-water phase can be made using classical filtration laws, taking into account the degree of gas contamination by air bubbles and the final intermittent mode of water extraction.

References
[1] Akhverdov I N 1981 Fundamentals of concrete physics Stroyizdat (Moscow)
[2] Bazhenov Yu M 1983 High strength fine-grained concrete for reinforced cement structures. Stroyizdat (Moscow)
[3] Bazhenov Yu M 1978 Concrete technology Stroyizdat (Moscow) pp 455
[4] Khasanov B B Saiganov A Ya 1987 A device for the manufacture of products from concrete mixtures A.S. N 1357239, Bull. Inventions 45
[5] Malgorzata L 2019 Modified pavement quality concrete as material alter-native to concrete applied regularly on airfield pavements Materials Science and Engineering 603 (3)
[6] Huang K Ding T Xiao J Singh A 2019 Modification on Recycled Aggregates and its Influence on Recycled Concrete Institute of Physics Publishing 323 (1)
[7] Baydjanov D Abdakhmanova K Kropachev P Rakhimova G 2019 Modified concrete for producing pile foundations Magazine of Civil Engineering 86 (2) pp 3-10
[8] Popov A P Tsionsky A L Khrupunov V A 1979 Production of reinforced concrete pressure vibrohydropressed pipes Stroyizdat (Moscow)
[9] Bazhenov Yu M Komar A G 1984 Technology of concrete and yellow-concrete products Stroyizdat (Moscow)
[10] Akhverdov I N High strength concrete Stroyizdat (Moscow)
[11] Makarov A S 1969 Centrifugation of concrete mixtures in continuous and perforated forms Journal - In the book. Calculation and manufacturing technology of reinforced concrete pressure pipes. Stroyizdat (Moscow)

[12] Chekhovsky E G 1970 Laboratory work in soil science and soil mechanics Stroyizdat (Moscow)

[13] Berg O Ya Pisanko G N Khromets Yu P 1971 High strength concrete Stroyizdat (Moscow)

[14] Savinov O A Lavrinovich E V 1986 Vibration technology for compaction and molding of concrete mixtures Stroyizdat (Moscow)

[15] Altshul A D 1970 Hydraulic resistance Nauka (Moscow)

[16] Ashikhmin V I Geller Z I Skobeltsyn Yu A 1961 The outflow of real fluid from external cylindrical nozzles Journal Oil industry 9 pp 55-59

[17] Geller Z I Skobeltsyn Yu A 1965 Comparison of flow coefficients of external cylindrical nozzles and holes in a thin wall 7 Oil industry 4 pp 60-62

[18] Geller Z I Skobeltsyn Yu A 1963 The outflow of real liquid from long and very short external cylindrical nozzles Journal News of universities. Oil and gas. (Baku) 8 pp 77-82

[19] Geller Z I Skobeltsyn Yu A 1963 The outflow of real liquid from external cylindrical nozzles at low Reynolds numbers 7 Oil industry 8 pp 62-65

[20] Agroskin I I Dmitriev G T Pikapov F I 1954 Hydraulics Gosenergo-izdat (Leningrad)

[21] Khasanov B and Mirzaev T 2019 Production of extra-strong concrete axisymmetric products E3S Web of Conferences 97 doi:10.1051/e3sconf/20199706011

[22] Asaturian A Sh Sviridov V P Bolodov N G 1961 The movement of real fluid in conical tubes and nozzles Journal Oil industry 2 pp 60-64